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Information Needs for Characterization of High-Level Waste Repository Sites in Six Geologic Media

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APPENDIX A-1

REMOTE SENSING AND SURFICIAL GEOLOGIC MAPPING TECHNIQUES FOR HIGH LEVEL NUCLEAR WASTE REPOSITORY SITING INVESTIGATIONS

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November 1, 1981

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1.0 INTRODUCTION

Surficial geologic mapping is an important part of siting investigations, principally because of its role in identifying adverse conditions which may be hazardous to a nuclear waste repository. The compilation of a surficial geologic map consists of the partly sequential process of identifying and evaluating: 1) landforms, 2) geologic structure, 3) bedrock lithology and surficial materials, and 4) geologic processes.

The mapping of surface morphology and geologic structure can be taken as the first steps in surficial geologic mapping. The next is make interpretations about these forms and structures, and to ascribe a genesis to them. This has to be done with full regard to both the bedrock and surficial materials associated with each feature and to the past and present processes operating in a region.

In this manner, and in conjunction with the geologic investigations (such as the application of geologic dating techniques discussed in Section 4.0), these studies can lead to a reconstruction of the geologic history of a region or site and to an evaluation of the present and future integrity of a potential repository site.

Furthermore, each of these elements of the mapping process, including surface morphology, can be of fundamental importance in the investigation of nuclear waste repository siting. Areas of high relief, for example, may represent areas of tectonic instability or high erosion potential. The identification of floodplains and alluvial fans, and hence of areas of high flood potential, is very largely based on land form (e.g. Schick, 1972). Slope form is important in recognizing areas of potential, present and past landslide activity (e.g. Brunsden, 1972).

Geologic structures, such as joints, fractures and faults are potential adverse conditions in the site selection process. They represent zones of weakness, movement, possible conduits for fluids and regions of anomalous properties compared to the general rock mass. They also increase the time and cost of investigations and complicate the modeling necessary for design. The presence of these features does not necessarily exclude a site; joints and fractures may be closed or sealed by mineral deposition and would not act as conduits and may be barriers to flow, and some faults can be shown to have had no movement for millions of years. However, in selecting general site areas risks and benefits of areas exhibiting these features need to be carefully considered.

The dip, inclination, or attitude of the units in the rock column or section need to be considered both from a construction standpoint and as indicators of past geologic stability. Flat or nearly horizontal units will probably be easier to tunnel through, mine and support if needed. Steeply dipping or inclined units, in general, indicate past deformation or movement and would likely be avoided if other areas can be found. Any geologic section with units of different inclinations or dip within the rock column may indicate the presence of erosion or weathering surfaces that might be selectively weak or permeable. Low and fairly uniform inclination or dips are probably most desirable.

In siting investigations, an analysis of the origin and processes affecting the features of the ground surface is critical to effective planning. The mapping of alluvial features and their correct interpretation, for example, is crucial in determining the extent of floodplains and of areas susceptible to flooding.

This report will present a discussion of geologic mapping techniques which may be employed in repository siting investigations. Such techniques are applicable for obtaining information about the earth's surface at any scale of investigation; from regional (precharacterization) to site specific (characterization). The major change from regional to more site specific investigations is only in the scale and level of detail of the studies. Therefore, this report is applicable to both phases of the siting program.

Initial siting investigations will tend to focus on the regional identification of structural geologic features and lithologic changes from interpretations of small-scale remote sensing imagery and aerial photographs. These interpretations can be refined and checked by preliminary field mapping. Where determined necessary, critical features can then be mapped in detail to help determine a viable site location (precharacterization). If a site can be located where critical features (such as Quaternary fault traces) are not present within a specified radius, characterization studies can provide a more detailed description of the surficial units and their properties through the interpretation of large scale aerial and photographs and detailed field mapping.

The first section of this report will discuss the techniques involved in surficial geologic mapping, including the analysis of remote sensing imagery, field mapping and detailed borehole and excavation logging. This will be followed by a discussion of the mapping of geologic features which are critical to siting investigations.

2.0 MAPPING TECHNIQUES

Surficial geologic mapping involves the use of a wide range of measurement and interpretative techniques which generally fall into one of three fields: 1) the analysis of remote sensing imagery and topographic maps, 2) field mapping techniques such as the use of a plane table or a brunton compass, and 3) detailed logging of boreholes or excavations. The initial stage of mapping frequently involves the use of remote sensing imagery from satellites on aircraft. An efficient program of mapping requires the full integration of remote sensing techniques with a wide range of field and interpretative skils. The value of such an integrated program has been described by Ray (1960):

> "In geologic mapping maximum use of aerial photographs is attained by closely intergrating field and photogeologic studies. It generally is desirable to precede the field phase of geologic study by a study of aerial photographs, which should include the compilation of a preliminary map on which all interpretations, however reliable or questionable, have been quoted. Such a preliminary photogeologic study affords several advantages: it may point out areas that must be mapped primarily by field methods; it may eliminate or reduce extensive field surveys in certain areas; it may direct attention to anomalous areas where detailed field study is particularly warranted; and it commonly provides a basis for organizing the geologic plan of field study. In addition, attention is directed to those areas where field study will most likely result in

establishing criteria that will permit a refinement of further photogeologic mapping. Also, a preliminary study of photographs gives a geographic familiarity of the area that would be useful in choosing camp sites, routes of traverse, and optimum locations of instrument survey stations."

The structure of a mapping program, including the balance between the use of remote sensing imagery and field techniques, is strongly dependent on the nature of a particular siting project, and the level of detail required in the analysis. However, it is possible to generalize an approach to the development of a geologic mapping program which will be valuable in siting investigations. This section will discuss the techniques available for such a program.

Table 1 presents the application, resolution, cost, time to acquire, advantages and disadvantages of the various types of remote sensing data presented in this chapter. The table also gives examples of specific applications of remote sensing as they apply to the six siting media.

2.1 Remote Sensing

Remote sensing refers to techniques for obtaining information about an object without coming into direct physical contact with that object (Sabins, 1978). This general definition encompasses a broad range of techniques employed primarily by the aerial photograph interpreter and the geophysicist. Remote sensing as used in this chapter is limited to satellite and aircraft supported methods that detect and measure electromagnetic energy; light, heat, and radio waves. Geophysical remote sensing techniques, such as gravity, magnetic, and electrical surveys, that measure other detectable forms of energy are discussed in Appendix B.

It is not possible within the framework of this report to discuss fully the principles and applications of geologic remote sensing. For more complete reviews, the reader is referred to Richason (1978), Sabins (1878) and Taranik and Trautwein (1976) among others. Furthermore, the development of satellite remote sensing technology is in its infancy.

TABLE–1 REMOTE SENSING TECHNIQUES AND CHARACTERISTICS

CHARACTERISTICS / REMOTE SENSING TECHNIQUE	APPLICATION AND MEDIA PREFERENCE	RESOLUTION	COSTS	TIME TO ACQUIRE	ADVANTAGES	DISADVANTAGES AND RESTRICTIONS
SATELLITE IMAGERY						
1a. LANDSAT STANDARD BLACK AND WHITE AND FALSE COLOR COMPOSITE PRINTS AND TRANSPARENCIES.	1. REGIONAL OVERVIEW OF SITING REGIONS. 2. INTERPRETATION OF REGIONAL GEOLOGIC STRUCTURE, LINEAMENTS, GENERAL STRATIGRAPHY, LAND FORMS, AND DRAINAGE PATTERNS. 3. APPLICABLE TO ALL MEDIA.	1a. 79mX79m GROUND RESOLUTION CELL.	$8–$50/SCENE	1–4 WEEKS	1. REGIONAL ANALYSIS IN SHORT TIME. 2. REPETITIVE DATA. 3. AVAILABLE IN MANY AREAS.	1. RESOLUTION. 2. RESTRICTED BY PERCENT OF CLOUD COVER, SNOW COVER, AND QUALITY VARIATIONS. 3. RESTRICTED CONTRAST ON STANDARD PHOTOGRAPHIC PAPER.
1b. RETURN BEAM VIDICON		1b. 26m–40m	$8–$50/QUARTER SCENE			1. LIMITED AVAILABILITY 2. LOWER QUALITY THAN MSS.
2. LANDSAT COMPUTER COMPATABLE TAPES (CCT) AND DIGITAL IMAGE ENHANCEMENT.	1. REGIONAL OVERVIEW OF SITING REGIONS. 2. INTERPRETATION OF REGIONAL GEOLOGIC STRUCTURE, LINEAMENTS, AND GENERAL STRATIGRAPHY. 3. APPLICABLE TO ALL MEDIA.	79mX79m GROUND RESOLUTION CELL.	1. $200/CCT 2. $200/SCENE	1. 4–16 WEEKS (DEPENDS ON LOCATION OF ORIGINAL CCT)	1. AVAILABILITY 2. REGIONAL ANALYSIS IN SHORT TIME. 3. IMPROVE DATA BY REMOVING CONFUSING SYSTEM IRREGULARITIES AND MAXIMIZING DATA PRESENTATION.	1. 2. ONE TIME CONTRAST STRETCH AND EDGE ENHANCEMENT FOR ENTIRE SCENE.
			1. PRIVATE INDUSTRY CONTRACT COST VARIABLE TO THOUSANDS OF DOLLARS.	1. 4–16 WEEKS (DEPENDS ON LOCATION OF ORIGINAL CCT)	1. SAME AS 1–3 ABOVE. 2. ABILITY TO CUSTOM DESIGN ENHANCEMENT PACKAGE. 3. INTERACTIVE INVOLVEMENT.	1. TIME 2. COSTS
3a. SKYLAB S–190A MULTISPECTRAL CAMERA 3b. SKYLAB S–190B EARTH TERRAIN CAMERA	1. REGIONAL OVERVIEW OF SITING REGIONS. 2. INTERPRETAION OF GEOLOGIC STRUCTURE, LINEAMENTS, AND GENERAL STRATIGRAPHY. 3. APPLICABLE TO ALL MEDIA.	3a. BLACK AND WHITE–60m COLOR–85m INFRARED–145m 3b. BLACK AND WHITE–15m COLOR AND COLOR INFRARED–30m	3a. $8–$50/SCENE 3b. $6–$50/SCENE	1–4 WEEKS	1. REGIONAL ANALYSIS IN SHORT TIME. 2. RESOLUTION.	1. CLOUD COVER AND SNOW COVER 2. LIMITED AVAILABILITY
4. SEASAT (L-BAND RADAR).	1. REGIONAL OVERVIEW OF SITING REGIONS. 2. INTERPRETATION OF REGIONAL GEOLOGIC STRUCTURE, LINEAMENTS, AND GENERAL STRATIGRAPHY 3. APPLICABLE TO ALL MEDIA. SPECIAL	25m–75m	$5–$105/SCENE	2–8 WEEKS	1. RESOLUTION. 2. INDEPENDENCE OF WEATHER CONDITIONS. 3. ABILITY TO	1. LOW INCIDENT ANGLE ACCENTUATES DISTORTION (LAYOVER) IN RUGGED

	JOINTING IN GRANITES AND BASALTS.				OF VEGETATION. 4. REGIONAL ANALYSIS.	RESTRICTED TO LOW RELIEF AREAS 3. LIMITED AVAILABILITY
5. HEAT CAPACITY MAPPING MISSION (HCMM)– THERMAL INFRARED IMAGERY AND DAYTIME VISIBLE IMAGERY.	1. REGIONAL OVERVIEW OF SITTING REGIONS 2. DISCRIMINATION OF ROCK TYPES AND GEOLOGIC STRUCTURE 3. INTERPRETATION OF SOIL MOISTURE AND GROUND–WATER FEATURES SUGGESTIVE OF FAULTING 4. APPLICABLE TO ALL MEDIA.	500m–600m	SELECTED IMAGES AVAILABLE FREE. NO STANDARD ORDERING COST.	2–8 WEEKS	1. THERMAL INERTIA DATA 2. REGIONAL ANALYSIS	1. EFFECTS OF WEATHER CONDITIONS. 2. LIMITED AVAILABILITY
AIRCRAFT IMAGERY						
6. RADAR	1. BEST SUITED FOR REGIONAL STUDIES BUT CAN BE USED FOR SITE SPECIFIC INVESTIGATIONS. 2. INTERPRETATION OF REGIONAL GEOLOGIC STRUCTURE, LINEAMENTS, AND GENERAL STRATIGRAPHY 3. APPLICABLE TO ALL MEDIA–SPECIAL APPLICATION TO FRACTURING AND JOINTING IN GRANITES AND BASALTS AND IN AREAS OF DENSE VEGETATION	VARIABLE– DEPENDENT ON SYSTEM. GENERALLY HIGH. 3m–30m	ABOUT $125 FOR AVAILABLE DATA. THOUSANDS OF DOLLARS FOR CUSTOM PRODUCTS.	1–3 WEEKS	1. ABILITY TO DIRECT THE LOOK DIRECTION. 2. HIGH GROUND RESOLUTION. 3. INDEPENDENT OF TIME OF DAY AND CLOUD COVER. 4. ABILITY TO REDUCE THE EFFECTS OF VEGETATION	1. LIMITED AVAILABILITY. 2. COST TO FLY NEW. 3. LAYOVER IN AREAS OF RUGGED TERRAIN.
7. THERMAL INFRARED	1. REGIONAL TO SITE SPECIFIC STUDIES. 2. DIFFERENTIATION OF ROCK TYPES AND INTERPRETATION OF FEATURES SUGGESTIVE OF FAULTING. 4. APPLICABLE TO ALL MEDIA.	VARIABLE. CAN BE DETERMINED BY FLIGHT ALTITUDE AND THE INSTANTANEOUS FIELD OF VIEW OF THE DETECTOR.	$20,000 FOR FIRST SITE IN REGION, $5,000 FOR SUBSEQUENT SITES	2–6 WEEKS	1. INDEPENDENT OF TIME OF DAY. 2. THERMAL INERTIA DATA.	1. SENSITIVE TO WEATHER CONDITIONS. 2. LIMITED AVAILIBILITY. 3. COST TO FLY NEW. 4. TOPOGRAPHY DOMINATES POST-SUNRISE IMAGE.
8. STEREO AERIAL PHOTOGRAPHS INCLUDING BLACK AND WHITE PANCHROMATIC, NORMAL COLOR BLACK AND WHITE INFRARED, AND COLOR INFRARED.	1. REGIONAL TO SITE SPECIFIC STUDIES 2. ALL GEOLOGICAL INTERPRETATIONS 3. APPLICABLE TO ALL MEDIA. 4. REFINEMENT OF INTERPRETATIONS FROM SATELLITE IMAGERY.	VARIABLE, BASED ON SCALE OF PHOTOGRAPHS WHICH IS DETERMINED BY THE CAMERA HEIGHT AND THE FOCAL LENGTH OF THE LENS	$3–8/FRAME FOR FRAMES AVAILABLE FROM GOVERNMENT AGENCIES WITH SPECIAL ENLARGEMENTS UP TO $50 $3–60/FRAME FROM PRIVATE INDUSTRY COST TOAQUIRE HIGHLY VARIABLE BASED ON DISTANCE FROM HOME BASE, SIZE AND SHAPE OF AREA TERRAIN CONDITIONS. ELEVATION , AND WEATHER.	1–4 WEEKS 1–4 WEEKS 3–8 WEEKS	1. STEREOGRAPHIC VIEWING (3-DIMENTIONS) 2. BLACK AND WHITE PANCHROMATIC AND INFRARED BEST FOR INTERPRETING TONAL ANOMALIES. 3. INFRARED BEST FOR INTERPRETING SOIL MOISTURE CHANGES AND WATER CONDITIONS. 4. COMPARISON OF DIFFERENT YEARS OF DATA 5. AVAILABILITY OF BLACK AND WHITE PANCHROMATIC.	1. DISTORTION AND VERTICAL EXAGGERATION
8a LOW SUN ANGLE AERIAL PHOTOGRAPHS	1. BEST SUITED FOR SITE SPECIFIC STUDIES 2. INTERPRETATION OF SUBTLE GEOLOGIC STRUCTURES.	SAME AS STANDARD AERIAL PHOTOGRAPHS	APPROXIMATELLY THE SAME AS STANDARD AERIAL PHOTOGRAPHS	VARIABLE	1. DETECTS SUBTLE DIFFERENCES IN RELIEF	1. TONAL DIFFERENCES OBSCURED 2. LIMITED AVAILABILITY

Extreme care must therefore be taken to update the recommendations in this report as the techniques of remote sensing imagery acquisition and interpretation develop.

This section will begin with a discussion of a number of important principles in the application of remote sensing imagery to geologic studies. The different types of remote sensing techniques available for a siting investigation of a high level nuclear waste repository will then be briefly described and evaluated. A review will be made of the various types of satellite imagery, including Skylab and Landsat (ERTS), as well as the more limited and newly available data from such programs as Seasat and the Heat Capacity Mapping Mission (HCMM). The section will conclude with a discussion of aircraft imagery including radar, thermal infrared, and stereo aerial photographs.

2.1.1 Principles of Geologic Mapping From Remote Sensing Imagery

Bases for Geologic Interpretations from Image Data

Geologic interpretations of remote sensed image data are ultimately dependent on four factors:

1. The geologist's understanding of the fundamental aspects of image formation.

2. The geologist's ability to detect, delineate, and classify radiometric image data; recognize patterns; and identify landscape surface characteristics as expressed on imagery.

3. The geologist's ability to interpret geomorphic processes from their static, surface expression as landscape characteristics on imagery.

4. The geologist's ability to conceptualize dynamic processes both above and below the surface responsible for the evaluation of features expressed on imagery.

In the interpretative process, factors (1) and (2) above, are directly related to the static elements displayed on the imagery. Correct identification of landscape characteristics is dependent on an understanding of the physical principles governing the interaction of Electromagnetic radiation (EMR) with the earth and its detection by a remote-sensor system. The interpretations of the static elements displayed on imagery may be referred to as "image interpretation " which defines the surface characteristics of a coverage area and is strongly influenced by the image scale and resolution (see below).

Factors (3) and (4) listed above are related to both static and dynamic elements that are not detected by the sensor and are not displayed on the imagery. If all four factors are applied in interpretating imagery, a "geologic interpretation" is derived in which surface characteristics of the landscape are integrated with subsurface geologic relationships. Thus the third factor in geologic interpretation from imagery relates relief, landforms, drainage and cover types to the temporal aspects of fluvial, glacial, aeolian, extrusive igneous or surficial gravity processes. The last factor relates all of the factors previously considered in imagery interpretation and stratigraphic, structural, intrusive and metamorphic attributes to the temporal aspects of tectonic, igneous, diagenetic and metamorphic processes.

Image Scale and Image Resolution

Image scale is defined as the ratio of the measured distance between two points on imagery to the measured distance between the same two points on the ground. The smaller the value of the ratio, the smaller the scale of the imagery. A 1:1,000,000 scale Landsat image is referred to as small scale in contrast to large scale aerial mapping photographs at 1:20,000 scale. Areal coverage of an 18.5 by 17.8 cm Landsat image is 32,930 square kilometers, compared to over 18 square kilometers covered by a standard 9x9 inch (nominal size) aerial mapping print. The combination of aircraft and satellite imagery now available provides a variety of different scales of imagery for analysis of the Earth's surface.

Image resolution is defined as a measure of the smallest ground radiometric element that can be recorded on an image. Resolution of a radiometric element on imagery is a function of:

1. Dimensions of the ground element.

2. The difference in reflected or emitted radiometric energy between the ground element and its background.

3. The shape and orientation of the ground element with respect to illuminating radiation.

4. Resolving characteristics of the imaging system. The system's spectral, radiometric, and spatial (areal) resolving power.

5. Location of ground element with respect to nadir (the point directly below the satellite).

Detection of a resolved radiometric element by an analyst is dependent upon the following:

1. The contrast in reflected or emitted radiometric energy between the radiometric element and surrounding radiometric background.

2. The radiometric uniformity of surrounding background against which the radiometric element is imaged.

3. The areal extent of the radiometric background.

4. The regularity of the shape of the radiometric element.

5. The radio of the radiometric element's length to width.

6. The regularity of groups of similar radiometric elements.

Table 2 shows that the size of areas resolved on the ground increases as image scale decreases for photographic systems. Radiometric elements resolved on imagery are not necessarily detected by analysts. Even when an interpreter detects radiometric elements it does not directly follow that they are easily identified objects. Detected radiometric elements that are of a size and radiometric nature close to the limits of system resolution are usually difficult to identify.

TABLE 2

GROUND RESOLUTION ON IMAGERY

SCALE OF UNENLARGED DATA	TYPE OF IMAGERY	USUAL MINIMUM AREA DETECTED BY INTERPRETERS
1:20,000	Black and White Mapping Photography1/	1 sq m
1:70,000	Black and White Mapping Photography1/	8 sq m
1:120,000	Color Reconnaissance Photography1/	20 sq m
1:950,000	Color Skylab Photography (S-190B)2/	400 sq m
1:3,370,000	Landsat Imagery (MSS)3/	10,000 sq m

1/ Ground resolution is primarily limited by camera and film resolution.

2/ Skylab S-190B camera system has better resolution than most aerial mapping camera systems.

3/ Landsat system resolution is limited by the instantaneous field of view of the multispectral scanner.

(Taranik and Trautwein, 1976).

Geologic Importance of Temporal Analysis

In some circumstances, geologic interpretation of imagery may be greatly assisted by the changes in surface conditions with season. Using repetitive coverage, such as that afforded by the Landsat satellites (see below), phenological changes in vegetation, changes in the amount of moisture contained in soils, rocks and plants; and in some aras, changes in snow cover can be observed. Identification of lineaments is greatly assisted by low-sun-angle illumination in winter months and can be aided by thin, but continuous, snow cover. In arid regions, annual vegetation often thrives in locations where ground water is near the surface.

Integration of Different Scales of Analysis

The analysis of remotely sensed data involves a recognition of the symmetrical distribution, or patterns, of image elements. Such patterns may be differentiated by their shape, internal organization and, particularly, size. During the interpretative process it is often convenient and efficient to identify first the largest patterns and then the nested, smaller patterns on the imagery. In this manner it is possible to associate a larger pattern with the smaller elements that comprise it and aid its identification An example of such an analytical procedure can be illustrated in the case of wide, flat-bottomed valley, identified on the basis of a large pattern's organization, shape and size. Such a feature may not be interpreted as a flood plain until the analyst identifies a river system with natural levees from smaller patterns within the valley.

The term "scale" when applied to such an analysis of patterns is different from the scale of the image itself. Several scales of analysis may be possible on imagery of a given scale although the dimensions and the resolution of the image may impose upper and lower limits on the scale of analysis. Table 3 attempts to demonstrate the utility of employing several types (and scales) of imagery in obtaining recognizable patterns, which can be continuously analyzed on successively smaller scales of analysis.

Development of Geologic Models

In the interpretation of geologic relationships developed from a particular scale of analysis, geologists must infer relationships that cannot be directly observed. This problem can be approached by the construction of conceptual, 3-dimensional geologic models. In the field a geologist may plot the strike and dip of rock strata onto a map and construct a cross-section to predict important relationships. Similarly, remote sensing allows the geologist to view the landscape in synoptic format, and if the surface characteristics are well defined on the imagery and patterns of geologic significance can be identified, geologic models can often be rapidly developed.

The development of geological models enables analysis of field data (and imagery) to identify key areas that require analysis in greater detail (at higher resolution and larger scale). An efficient approach to the analysis of an area that is ultimately to be evaluated by ground-based methods is to employ several scales of image analysis, and eventually to integrate information derived from these analyses with data derived from field investigations. Usually geological models are developed and employed in a variety of different ways in geological analysis. Often the analyst has a preconceived geological model in mind prior to analyzing the imagery. If the preconceived geological model was developed from suitable ground data and/or from experience in similar geologic settings, landscape patterns identified on imagery can be interpreted in terms of their correlation with the model. The analysis of small-scale imagery, that covers large areas, sometimes presents problems to analysts with preconceived geological models in mind; this is because their geological experience and available ground data are often limited to small areas. An interpreter with a preconceived model in mind, may introduce bias in his interpretation and incorrectly determine geological relationships, unless care is taken to carefully consider all factors of the interpretation process.

Interpretative bias in the analysis of imagery may be eliminated by starting with the smallest scale imagery available for an area to be analyzed. This imagery should be analyzed objectively using a systematic pattern recognition procedure, and without the influence of ancillary geologic information (published maps, etc.). This analysis should define regional trends and relationships (a model). The analysis should proceed to larger scales, using larger scale imagery in key areas identified in the previous analysis, if the imagery is available. Sometimes the

TABLE 3

SCALES OF IMAGERY THAT MAY BE UTILIZED TO RECOGNIZE PATTERNS

ON SUCCESSIVELY SMALLER SCALES OF ANALYSIS

Imagery	Format	Scale	Coverage	Landforms
Landsat	7.3 x 7.0 ins. (18.5 x 17.8 cm)	1:1,000,000 (1":15.8 mi)	12,500 mi^2 (32,930 12 mi^2)	Flat bottomed valley concordant within sinuous mountain ranges.
High altitude aerial reconnaissance photography.	9 x 9 ins. (22.9 x 22.9 cm)	1:120,000 (1":10,000')	290 mi^2 (742 km^2)	Meandering river and oxbow lakes.
Standard black and white, low altitude aerial mapping photography.	9 x 9 ins. (22.9 x 22.9 cm)	1:20,000 (1":1666')	7.2 mi^2 (18.6 km^2)	Natural levees and splay lakes.

AFTER: TARANIK and TRAUTWEIN (1976).

interpretation of small-scale imagery can be revised (the model can be refined) through analysis of larger scale imagery. Eventually a point is reached where ground data or additional remote-sensing data are required in key areas to resolve conflicts in, or confirm the validity of, the interpretation. At this point the analyst should bring as much ancillary geologic information as possible (maps, etc.) to bear on the analysis and should determine if additional information can be extracted from the imagery. The careful image analyst will plot this additional information on a separate overlay because it is easy to interject information from an existing, and not necessarily accurate, map into that derived from interpretation of imagery. This separation also allows information not appearing on the maps, etc. (new information) to be evaluated. At this point in the analysis, a conceptual geologic model should be defined, and key ground analysis areas should be identified. Remote-sensor data should be acquired over these key areas if such data will support field work and will provide additional information. Field visits to key areas may require that imagery interpretation and, consequently, the geological interpretation (the model) be revised. Often the entire analysis proceeds in an iterative fashion and culminates in large-scale, ground-based geologic mapping of site-specific target areas. The technique economically conserves resources because the entire area under analysis does not have to be completely "walked out" on the ground.

2.1.2 Satellite Imagery

Landsat

Landsat imagery is the most widely used satellite data in geotechnical/geological studies. Table 4 (Short, 1977) demonstrates the versatility of Landsat imagery for geological investigations, and notably its usefulness in interpreting large, regional geologic structures and general geologic/ lithologic characteristics. The Landsat (formerly ERTS) satellites have been continuously collecting various types of data useful for geologic interpetations since the early 1970s (USGS, 1979), using Multispectral Scanner (MSS) and Return Beam Vidicon (RBV) sensing systems. However, only limited RBV data is available because of mechanical malfunctions on the satellites.

TABLE 4

APPLICATIONS OF LANDSAT TO GEOLOGY

Map Editing

- Boundary and contact location
- Stratigraphic and/or "remote sensing" unit discrimination
- Scale-change corrections
- Computer-processed "materials" units map

Landform analysis

- Regional or synoptic classification and mapping
- Thematic geomorphology (e.g., desert, glacial, volcanic terrains)

Structural geology

- Synoptic overviews of tectonic elements
- Appraisal of structual styles
- Lineaments (and "linears") detection and mapping
- Metamorphic and intrusion patterns
- Recognition of circular features

Lithologic identification

- Color-brightness (spectral reflectance) classification
- Ratio techniques
- Photogeologic approach

Mineral exploration

- Reconnaissance geologic mapping
- Lineaments trends (especially intersections)
- Surface coloration (blooms and gossans)
- Band ratio color renditions

Engineering and environmental geology

- Dynamic geologic process (sedimentation and coastal processes, sea ice, active glaciers, permafrost effects, landslides and mass wasting, shifting sand seas, land erosion)
- Strip mining, surface fractures-mine safety
- Construction materials

(Short, 1977)

The MSS measures electromagnetic energy and records spectral signatures in four wavelengths (measured in micrometers um), designated bands 4 through 7.

Band Number	Wavelength (um)	Portion of Electromagnetic Spectrum
4	0.5 - 0.6	Green
5	0.6 - 0.7	Red
6	0.7 - 0.8	Photographic IR
7	0.8 - 1.1	Photographic IR

The MSS systems collect sunlight reflected from subjects on earth in proportion to the sensitivities of each MSS band. The multispectral scanners on the Landsat spacecraft have capabilities of distinguishing different wavelengths and frequencies of energy which are reflected by different targets and scenes. Each target, because of the different materials of which it is composed, produces its own characteristic spectral signature. Dry soils, for example, reflect more radiation in the red and near-infra-red wavelengths, while wet soils reflect less in all bands of the spectrum because of the light absorbing properties of water in the soil.

Although each MSS band produces images which are of value in themselves, all bands should be consulted for the optimum interpretation of each feature or event. Because of the different wavelength responses of the MSS sensors, some targets are not imaged in a particular band, while other objects may be degraded and not usable for identification. The same target in the same scene, however, may be resolved with greater fidelity in another MSS band. While certain spectral responses tend to characterize each MSS band, attempts to generalize the capabilities of bands should be approached with caution because reflectance patterns may not be the same in all imaging situations.

Band 4 detects and registers blue-green wavelengths which are radiated from objects. This band is most useful for studying the characteristics of water bodies. In some instances water depths and turbidity in standing water can be detected in scenes imaged in this band. Band 4 is sensitive to water pollution patterns, submarine features such as shoals and reefs and atmospheric phenomena. The disadvantages of imagery from Band 4 include a lack of discrimination of surface scenes because of Rayleigh scattering in the atmosphere, minimum penetration of clouds and haze, and the lack of grey-scale contrasts in topographic and cultural features.

Bank 5 is sensitive to radiation in the red wavelengths close to the outer region of human vision. Generally, this band is best for producing images which distinguish topographic and man-made features, and appears to provide the best spectral region for imaging bedrock and snow. Richason (1978, p. 176) suggests that if only one Landsat MSS image is to be acquired, Band 5 should be obtained because of its wide range of general imaging capabilities.

Band 6 registers targets whose reflectance is at a maximum in the red and near-infrared spectral area beyond human vision. This band can detect stress in vegetation and as cloud penetration is improved over Band 5, more surface detail is available when scenes are thinly overcast by clouds and haze. Water and land interfaces are discriminated in this band; however, Band 6 imagery can be mistakenly interpreted such that shallow water or heavy sediment loads appear to be land.

Band 7 is the second MSS near infra-red band. It is best suited for distinguishing differences between land and water areas. Detailed observations of drainage basin networks, shorelines and wetlands are maximized by the use of imagery from this spectral band. On the other hand, Band 7 is impractical for studying the intrinsic characteristics of water bodies because water appears almost solidly black. Maximum cloud and haze penetration is produced by this band; however, this has minimal applicability because, with the exception of hydrologic features, topographic and land use detail is very indistinct in Band 7.

A fifth channel is included in the MSS package on Landsat 3, which senses in the Thermal infra-red region (10.4 - 12.6 um). Radiation reaching the sensor in this spectral band is emitted from the ground surface as a function of temperature. Landsat 3, therefore, has the capacity to image surface temperatures and to detect targets by contrasting the temperature of the target and its background.

Unlike the MSS systems which produce a continuous scan of the surface of the earth over which they are transported, the Return Beam Vidicon (RBV) systems shuttered individual scenes upon command when they were operational. During their short periods of operation, they sensed targets in the spectral range of 475 nm to 830 nm by three television cameras. On Landsat 3, the RBV system has been modified to include two panchromatic cameras which will generate side-by-side images rather than the superimposed images of the same target areas which were characteristic of the systems on Landsats 1 and 2.

When they were operative during the early orbits of the satellites, the RBV systems registered scenes in three bands of the spectrum. These RBV bands were designated as 1, 2, and 3 in order to differentiate the nomenclature of the RBV bands from those of the MSS bands. The wavelengths and color bands of the RBV systems are as follows:

Band 1	475-575 nm	Green
Band 2	580-680 nm	Red
Band 3	690-830 nm	Near infrared

The principal advantage of the RBV camera systems over that of the MSS systems is its geometric fidelity, or relative mapping accuracy. For this reason it was to have been used extensively for cartographic purposes. When the systems were shut off, cartographers decided to attempt to use the MSS images for mapping. The MSS imagery, when properly processed, yielded unexpectedly good imagery for mapping because of its global coverge, near real-time transmission, orthogonality, relatively small spatial errors, and its ability to measure radiation beyond the capabilities of conventional film. Furthermore, the MSS system possessed similar automation capabilities and wavelength-extensions into the infrared as that of the RBV systems. For these reasons, many mapping projects which were originally planned for RBV imagery were completed satisfactorily by use of MSS data.

Paper images and positive and negative transparencies are available for both forms of data in black and white for all bands and as a false color composite (MSS only) which combines bands 4, 5 and 7. These products can be acquired at nominal scales ranging from 1:3,369,000 to 1:250,000 as standard products from the Earth Resources Observation Systems (EROS) Data Center in Sioux Falls, South Dakota (Table 5). In addition to the paper products, computer compatible tapes (CCTs) of the original data are available.

TABLE 5

COSTS FOR STANDARD REMOTE SENSING PRODUCTS FROM THE UNITED STATES GEOLOGICAL SURVEY EROS DATA CENTER

PRICE LIST

STANDARD REMOTE SENSING DATA

U. S. DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

SATELLITE DATA

	NOMINAL IMAGE SIZE	PRODUCT MATERIAL	BLACK & WHITE UNIT PRICE	BLACK & WHITE PRODUCT CODE	COLOR UNIT PRICE	COLOR PRODUCT CODE
STANDARD LANDSAT	55 8mm (2 2 in)	Film Positive	$ 8.00	11	NA	NA
	55 8mm (2.2 in)	Film Negative	10 00	01	NA	NA
	18 5cm (7.3 in)	Paper	8 00	23	$12.00	63
	18 5cm (7.3 in)	Film Positive	10.00	13	15 00	53
	18 5cm (7.3 in)	Film Negative	10 00	03	NA	NA
	37.1cm (14 6 in)	Paper	12.00	24	25.00	64
	74 2cm (29 2 in)	Paper	20 00	26	50.00	66
	COLOR COMPOSITE GENERATION				$50 00	69

NOTE: 1) Portrayed in false color (infrared) and not true color.
2) Cost of product from this composite must be added to total costs
3) Not applicable for MSS Band 8 or RBV Subscenes
4) Master composite retained at EDC.

	TRACKS	BPI	FORMAT	MSS All Bands Available PRODUCT CODE	MSS All Bands Available PRICE	RBV Single Subscene PRODUCT CODE	RBV Single Subscene PRICE	Set of Four RBV Subscenes PRODUCT CODE	Set of Four RBV Subscenes PRICE
CCT	9	800	TAPE SET	183 B	$200 00	183 C	$200 00	183 D	$400 00
	9	1600	TAPE SET	184 B	200 00	184 C	200 00	184 D	400 00

MANNED SPACECRAFT DATA

	IMAGE SIZE	NOMINAL SCALE	PRODUCT MATERIAL	BLACK & WHITE UNIT PRICE	BLACK & WHITE PRODUCT CODE	COLOR UNIT PRICE	COLOR PRODUCT CODE
SKYLAB S190A	55 8mm (2 2 in)	1:285000	Film Positive	$ 8 00	11	$10 00	51
	55 8mm (2 2 in)	1:285000	Film Negative	10 00	01	NA	NA
	16 3cm (6 4 in.)	1:1000000	Paper	8 00	23	12 00	63
	32 5cm (12 8 in)	1 500000	Paper	12 00	24	25 00	64
	65.0cm (25 6 in.)	1:250000	Paper	20 00	26	50.00	66
SKYLAB S190B	11.4cm (4.5 in)	1:950000	Paper	$ 6 00	22	$ 8 00	62
	11.4cm (4.5 in)	1:950000	Film Positive	8 00	12	12.00	52
	11.4cm (4 5 in.)	1:950000	Film Negative	10.00	02	NA	NA
	21.8cm (8 6 in)	1:500000	Paper	8 00	23	12 00	63
	43.4cm (17.1 in.)	1:250000	Paper	12.00	24	25.00	64
	86 9cm (34 2 in.)	1:125000	Paper	20.00	26	50.00	66

AIRCRAFT DATA

	IMAGE SIZE	PRODUCT MATERIAL	BLACK & WHITE UNIT PRICE	BLACK & WHITE PRODUCT CODE	FILM SOURCE
INDEXES	25.4x30.5cm (10x12 in.)	Paper	$ 5.00	36	B & W – Size A
	OTHER	Paper	5 00	37	B & W – Size B

AIRCRAFT DATA Continued

	IMAGE SIZE	PRODUCT MATERIAL	BLACK & WHITE UNIT PRICE	BLACK & WHITE PRODUCT CODE	COLOR UNIT PRICE	COLOR PRODUCT CODE
AERIAL MAPPING	22 9cm (9 0 in)	Paper	$ 3 00	23	$ 7 00	63
	22.9cm (9 0 in)	Film Positive	5 00	13	15 00	53
	22 9cm (9 0 in)	Film Negative	6 00	03	NA	NA
	45 7cm (18 0 in)	Paper	10 00	24	25 00	64
	68 6cm (27 0 in)	Paper	15 00	25	30 00	65
	91 4cm (36 0 in)	Paper	20 00	26	50 00	66
NASA RESEARCH	56 8mm (2 2 in)	Film Positive	$ 3 00	11	$10 00	51
	55 8mm (2 2 in)	Film Negative	4 00	01	NA	NA
	11.4cm (4 5 in)	Paper	3 00	22	7 00	62
	11.4cm (4 5 in)	Film Positive	4 00	12	12 00	52
	11.4cm (4 5 in)	Film Negative	5 00	02	NA	NA
	22.9cm (9.0 in)	Paper	3.00	23	7 00	63
	22 9cm (9 0 in)	Film Positive	5.00	13	15 00	53
	22.9cm (9 0 in)	Film Negative	6 00	03	NA	NA
	22 9x45.7cm (9x18 in)	Paper	6 00	31	20 00	69
	22.9x45.7cm (9x18 in)	Film Positive	10.00	14	30 00	56
	22 9x45.7cm (9x18 in.)	Film Negative	12.00	04	NA	NA
	45.7cm (18.0 in.)	Paper	10.00	24	25 00	64
	68 6cm (27.0 in)	Paper	15 00	25	30 00	65
	91.4cm (36.0 in)	Paper	20.00	26	50 00	66

NOTE: MODIFIED FROM PRICE LIST FOR STANDARD REMOTE SENSING DATA, JANUARY, 1979, U.S. GEOLOGICAL SURVEY.

The MSS imaging data have a ground resolution cell (that is the smallest ground radiometric element that can be recorded on an image) of approximately 79m x 79m. Ground resolution for the RBV data is variable, ranging from 26m to 40m. (For a fuller discussion of image scale and resolution, refer to Section 2.1.1, and Townsend, 1981.)

An advantage of a standard Landsat image is that its format and coverage presents an excellent overview and allows a reasonably fast interpretation of the geology of a region. Another advantage is the repetitive nature of the Landsat data which 1) allows temporal analysis of surface conditions, 2) almost always assures the availability of a nearly cloud-free scene regardless of the area, and 3) enables the interpreter to choose the most advantageous sun angle (based on time of year scene was taken) for the type of interpretation in which he is interested. The limitations of the Landsat data are derived primarily from the overall resolving power of the imagery; the complications arising from cloud cover, snow cover, and quality of the transmitted data; and from the limitations inherent in the photographic paper products, especially those associated with the wide range of contrast due to the regional nature of the coverage.

The standard Landsat product can be restored and enhanced in two basic ways; photographically and digitally. Photographic enhancement improves the contrast of the overall image by one or many photographic reproductions of the image, or parts of the image, which photographically maximize the scenes contrast.

Digital image restoration and enhancement is performed by a computer on the standard image CCTs. Image restoration attempts to make the image closely resemble the original scene by correcting geometric distortions and other system variables.

According to Goetz and Rowan (1981):

> "The advantage of digital over photographic processing is that transformations applied to the data are precisely known and repeatable and are not subject to the vagaries of complex chemical processing."

Following restoration, the MSS digital data can be selectively enhanced to accentuate certain aspects of the image.

The most commonly used enhancements for geological interpretations are "contrast stretch" which selectively maximizes the contrast of the scene or subscenes, and "edge enhancement" which helps accentuate linear spectral changes typically associated with faults and lineaments.

The EROS Data Center provides a standard enhancement package on specific scenes which includes a single contrast stretch and an edge enhancement for $200/scene. The interpreter also has the option to purchase CCT's and have a private firm perform selected enhancements to best suit his needs. Typically, the more selected the enhancements the more costly the product.

Image restorations and enhancements are helpful in interpretation because they primarily accomplish two functions: 1) they eliminate confusing linear system irregularities of the image (i.e. sixth-line dropout), and 2) they improve the original product to provide maximum data for interpretation. The advantage of having image enhancements performed by private industry is that it allows the interpreter to custom design the image to his specific interests. This may include a number of different contrast sketches on different portions of a Landsat scene. The disadvantages of custom digital image enhancements are 1) the time required to purchase CCT's (up to 4 months) and 2) the expense (thousands of dollars).

Geological interpretation of Landsat imagery is increasingly being assisted by the application of computer technology. The more sophisticated types of analysis use computer programs that develop spectral information analogous to a multiband spectral signature. The numerical characters of classification programs are designed to use these spectral data for identifying earth surface features. Further information on digital and machine processing of multispectral data is provided by Sabins (1978, Ch. 7) and Richason (1978, Ch. 16).

Whether using such computer assisted processing techniques or standard imagery, geologic interpretation involves the application of the principles discussed above in Section 2.1.1. In particular, the image resolution and false-color parameters of object recognition need to be applied in conjunction with considerations of pattern, size, shape, shadows, texture, tone and association. (See texts such as

Sabins (1978) and American Society of Photogrammetry, 1960 for a more complete discussion of these factors).

Landsat MSS images are especially suitable for studying the relationships between landforms and major structural featues, because each image displays approximately 34,000 square kilometers with uniform illumination, and the scene contast can be optimized through digital processing.

One of the most striking results of the analysis of Landsat MSS images has been the discovery of numerous, previously unmapped regional linear features. These features, referred to as lineaments, are alignments of regional morphological features, such as streams, escarpments and mountain ranges, and tonal features that in many areas are the surface expression of fracture or fault zones. Preliminary identification of other geological features such as landforms (surface morphology), generalized lithologic variations, and drainage patterns can also be interpreted on the standard Landsat image in a relatively short and economical time period. However, detailed drainage analyses and lithologic/geologic mapping must be supplemented with additional office and field data.

Further discussion of the application of Landsat imagery to the identification and analysis of geologic features and materials significant to the siting of a nuclear waste repository is contained in Section 3.1.

Skylab

The other main source of satellite data for geological interpretation is from the manned Skylab missions flown between May 1973 and April 1974 (NASA, 1974). These Skylab missions used three basic forms of imaging equipment: 1) Multispectral camera (Experiment S-190A), 2) Earth Terrain camera (S-190B Experiment), and 3) Multispectral Scanner (S-192 Experiment). These first two experiments allowed the generation of high resolution vertical photographs with overlapping flight lines from which precise scientific measurements and mapping could be conducted from using stereoscopic views of earth terrain.

The salient features of the Multispectral and Earth Terraine camera systems are summarized in Tables 6 and 7. The multispectral unit consisted of six precision cameras, with

TABLE 6

MULTISPECTRAL CAMERA STATION CHARACTERISTICS

Station	Filter	Filter Bandpass Micrometer	Film Type: Eastman Kodak	Estimated Ground Resolution Meters (Feet)
1	CC	0.7-0.8	EK 2424 (B&W infrared)	73-79 (240-260)
2	DD	0.8-0.9	EK 2424 (B&W infrared)	73-79 (240-260)
3	EE	0.5-0.88	EK 2443 (color infrared)	73-79 (240-260)
4	FF	0.4-0.7	SO-356 (hi-resolution color)	40-46 (130-150)
5	BB	0.6-0.7	SO-022 (Panatomic-X B&W)	30-38 (100-125)
6	AA	0.5-0.6	SO-022 (Panatomic-X B&W)	40-46 (130-150)

Note: After NASA - Johnson Space Center, Skylab Earth Resources Data Catalog, p. 7.

TABLE 7

EARTH TERRAIN CAMERA FILM CHARACTERISTICS

Film Type: Eastman Kodak	Wratten Filter	Filter Bandpass Micrometer	Estimated Ground Resolution Meters (Feet)
SO-242 (hi-resolution color)	None	0.4-0.7	21 (70)
EK 3414 (hi-definition B&W)	12	0.5-0.7	17 (55)
EK 3443 (infrared color)	12	0.5-0.88	30 (100)
SO-131 (hi-resolution infrared color)	12	0.5-0.88	23 (75)

Note: After NASA-Johnson Space Center, Skylab Earth Resources Data Catalog, p. 11.

matched optical systems. The 70 millimeter film width provided sufficient size for tentative analysis and case of enlargement of the two black and white, two black and white near infrared and two color image renditions. The Earth terrain camera system was designed to provide very high ground resolution of 17 - 30 m as a prerequisite for accurate feature detection. This system demonstrated that geological and land use features could be discerned almost as clearly from a 435 km (270 miles) orbit as from high altitude aircraft systems. The field of view of the earth terrain camera, however, far exceeds the lower altitude aircraft reconnaissance systems. The types and nominal scale of the film products available from the multispectral and Earth Terrain camera experiments are summarized in Table 8 and 9.

Paper images and film transparencies for the scenes taken by experiments S-190A and S-190B are available from EROS. Scales range from 1:2,850,000 to 1:250,000 and 1:950,000 to 1:125,000, respectively. Costs are presented in Table 5.

The products of these two standardized camera systems are those of principal applicability to most general concerns in remote sensing because they are most readily available for the greatest aerial coverage in renditions which are easily interpreted. Of serious concern are the photo products, in that film positives, while offering the highest resolution are rather small for ease of handling and require considerable magnification to benefit from the resolution scales produced. In print format, the standard products can be more easily adapted to the mapping of spatial patterns, although loss of resolution is a problem. One solution to this dilemma is the purchase of both formats.

For geologic interpretations of the imagery, a combination of the sensor data products is advisable, since each system and station has inherent advantages and limitations. With respect to the six stations of the multispectral camera system, each provides spectral and spatial differentiation capacities suited to particular applications.

All of the infrared stations penetrate haze for effective discrimination of land-water boundaries, such as surface water, soil moisture, and drainage patterns. Referring to

TABLE 8

MULTISPECTRAL CAMERA DATA PRODUCTS

Scale Nominal	Image Size Inch (cm)	Enlargement	Products			
			Black and White		Color	
			Transparency	Print	Transparency	Print
1:2,850,000	2.25 x 2.25 (5.72 x 5.72)	1.00X	Positive Nevative	None	Positive	None
1:1,000,000	6.41 x 6.41 (16.29x16.29)	2.85X	Positive Negative	Positive	Positive	Positive
1: 500,000	12.83 x 12.83 (32.50x32.50)	5.70X	Positive	Positive	None	Positive
1: 250,000	25.65 x 25.65	11.40X	Positive	Positive	None	Positive

Note: After NASA-Johnson Space Center, Skylab Earth Resources Data Catalog, p. 8.

TABLE 9

EARTH TERRAIN CAMERA DATA PRODUCTS

Scale Nominal	Image Size Inch (cm)	Enlargement	Products			
			Black and White		Color	
			Transparency	Print	Transparency	Print
1:950,000	4.50 x 4.50 (11.43x11.43)	1.0X	Positive Negative	None	Positive	Positive
1:500,000	8.55 x 8.55 (21.72x21.72)	1.9X	None	Positive	None	Positive
1:250,000	17.10 x 17.10 (43.43x43.43)	3.8X	None	Positive	None	Positive
1:125,000	34.20 x 34.20 (86.87x86.87)	7.6X	None	Positive	None	Positive

Note: After NASA-Johnson Space Center, Skylab Earth Resources Data Catalog, p. 11.

Table 8, Station 3, in color infrared, adds special utility in assessing vegetation vigor and areas of recent environmental disturbance by extraction, exploitation, or construction. In contrast, Stations 4, 5, and 6 trade away the spectral discriminating advantages of infrared channels for greater spatial resolving powers in visible wavelengths. They are most appropriate for land use data-base mapping. Each has additionally unique capabilities, such as Station 4, in high-resolution color for water penetration; Station 5, which has the best image definition and resolution, for geologic mapping; and Station 6 for a versatile array of soil, vegetation, and snow cover mapping. A definitive study of regional environmental resources and geology would thus favor integrated data from several stations, e.g., Stations 1, 2, and 5 or any other useful combination.

The high resolution of the Earth Terrain camera system makes it very useful for geological interpretations. For example, sometimes the interpreter can distinguish cultural features such as fence lines and roads that can be mistaken for faults and/or lineaments on the Landsat imagery.

The third major imaging system carried on Skylab was the multispectral scanner which traced a 74 kilometer-wide swath with a set of 13 detectors covering a total range of wavelengths from 0.41 to 12.50 micrometers. The spectral bands of energy reflected and radiated from the earth's surface were stored on digital magnetic tape and can be computer processed in the same way as in the Landsat multispectral scanning system. However, many of the tape records are marred by noise, that must be removed by digital processing. As a consequence, only a limited number of image strips have been produced (Sabins, 1978).

Seasat

The Seasat satellite was designed to collect data primarily for oceanographic studies and was operated between June and October, 1978. On board the satellite was a synthetic aperature radar imaging system which collected L-band (23.5cm wavelength) radar data with a ground resolution range from 25m to 75m (NOAA, 1980). Even though an emphasis was placed on collecting oceanographic data, the satellite managed to collect significant imagery covering nearly the entire North American continent.

Seasat imagery is available from the Environmental Data and Information Service, NOAA, Washington, D.C. Two types of images are produced; optically correlated and digitally processed. Costs range from $5 to $105 for the optically correlated images (the most readily available) and $72 to $112 for the digitally processed image (Table 10).

The advantages of radar imagery are discussed in the next section of this report under aircraft imaging systems. However, unique to Seasat is the high altitude and regional coverage best suited to interpretations of regional geologic structures. A major disadvantage of Seasat is that it was designed to collect data on the low relief of the oceans surface or the surface of large ocean ice bodies. This design called for a very high depression angle (67° to 73°) which causes pronounced distortion or layover in rugged terrain. Therefore, Seasat images are best suited for analysis in low level terrain.

Heat Capacity Mapping Mission (HCMM)

The satellite for the Heat Capacity Mapping Mission (HCMM) Project was launched in April, 1978, and terminated in October, 1980 (NASA, 1980). Data from the HCMM Project presents a measure of the thermal infrared energy of an area. Selected data on thermal inertia are available from the repetitive daytime-nighttime imagery. Resolution is 500m for the nighttime image to 600m for the daytime image.

HCMM data are available in positive and negative prints and transparencies and as CCTs. Limited data on temperature differences and apparent thermal inertia are also available from the National Space Science Data Center, World Data Center A, Greenbelt, Maryland. There are presently no standard ordering procedures and cost schedules for the HCMM data.

These data may be helpful in discriminating rock types, detecting soil moisture changes, making water runoff predictions from monitoring snow fields, mapping surface thermal gradients, and mapping geologic structures.

TABLE 10

COSTS FOR STANDARD SEASAT PRODUCTS

UNITED STATES DEPARTMENT OF COMMERCE
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
ENVIRONMENTAL DATA AND INFORMATION SERVICE
NATIONAL CLIMATIC CENTER
SATELLITE DATA SERVICES DIVISION
ROOM 100, WORLD WEATHER BUILDING
WASHINGTON, D.C. 20233
(301) 763-8111 Commercial or 763-8111 FTS

PRICE LIST FY81

Item #	Description (Black and White Products)	Unit Price
2	8 In. x 10 In. Contact Paper Print	$ 4.00
1	10 In. x 10 In. Contact Paper Print	$ 4.00
8	10 In. x 10 In. Paper Print Enlargement	$ 6.75
5	20 In. x 20 In. Paper Print Enlargement	$ 8.00
3	16 In. x 20 In. Paper Print Enlargement	$ 7.75
4	30 In. x 30 In. Paper Print Enlargement	$ 12.00
7A	10 In. x 10 In. Contact Dupe Negative from Positive	$ 5.50
7	10 In. x 10 In. Contact Positive Transparency from Negative	$ 5.50
6	10 In. x 10 In. Contact Negative from Negative	$ 8.25
11	35mm Slide from Transparency, Print, or Art	$ 4.25
9	35mm Slide from Negative	$ 7.00
16	Construct Original 16mm Operational Movie Loop (6 Hrs.)	$ 39.75
15	Construct Original 16mm Operational Movie Loop (12 Hrs.)	$ 54.50
14	Construct Original 16mm Operational Movie Loop (24 Hrs.)	$105.00
12	Duplicate of 16mm Movie - 50 Ft. Strip (Positive or Negative)	$ 8.75
13	Duplicate of 16mm Operational Loop (Positive or Negative)	$ 8.75
24	Duplicate of 100-Ft. Roll 35mm Positive Microfilm	$ 16.50
25	Duplicate of 100-Ft. Roll 35mm Negative Microfilm	$ 16.50

NOTE: A Minimum Charge of $5 will be made for any single order.
A Charge of $ .50 will be made for Gridding each GOES product.

SEASAT 70MM SYNTHETIC APERTURE RADAR (SAR) IMAGERY

SEASAT SAR imagery reproduced from original 70mm negatives are available in 70mm formats as paper prints, duplicate negatives, and positive transparencies. These products are produced in lengths from 10 in. to an entire roll (36-180 feet). Prices for an entire 36 ft. roll containing all four subswaths are listed below. Longer rolls are proportionately higher in price.

Description (Per 36 Ft. Increment)	Unit Price
70mm Contact Paper Print	$ 50.00
70mm Positive Transparency	$ 55.00
70mm Duplicate Negative	$105.00

SEASAT SAR CUSTOM ORDERS

Custom Orders (less than a full roll) are priced as listed below for each 1/4-Subswath.

Description	Dupe Negative	Positive Transparency	Contact Print
Less than 10 Inch Section	$11.25	$7.50	$6.75
10 Inch - 4 Feet	$11.25/Ft.	$6.00/Ft.	$5.75/Ft.
5 - 9 Feet	$ 6.25/Ft.	$3.50/Ft.	$3.00/Ft.
10 - 14 Feet	$ 4.50/Ft.	$2.50/Ft.	$2.25/Ft.
15 - 19 Feet	$ 4.00/Ft.	$2.25/Ft.	$2.00/Ft.
20 - 25 Feet	$ 3.75/Ft.	$2.00/Ft.	$1.75/Ft.
More than 25 Feet	$ 3.50/Ft.	$1.75/Ft.	$1.50/Ft.

MAGNETIC TAPES (CCTS)

The charges for a direct one-for-one tape copy at the stated densities are as follows:

7 Track at 200, 556, or 800 BPI	$ 72 (includes cost of tape)
9 Track at 800 or 1,600 BPI	$ 72 (includes cost of tape)
9 Track at 6,250 BPI	$112 (includes cost of tape)

Multiple Inputs, Selective Copying

$20 per input tape plus $72 (1600 BPI) or $112 (6250 BPI) per output tape.

Mass Storage (TBM) to CCT

AVHRR/GAC Data sets. $50 per input data set plus $72 (1600 BPI) or $112 (6250 BPI) per output tape.

Mass Storage (TBM) to CCT

TOVS Data sets. $10 per input data set plus $72 (1600 BPI) or $112 (6250 BPI) per output tape.

2.1.3 Aircraft Imagery

Radar

Radar is an active remote sensing system, in that the system supplies the energy to be measured and records the amount of energy returned from the earth's surface as a grey-scale image. Essentially, radar is a system which uses microwaves (with wavelengths between 1mm and 11cm) instead of light waves to image an object. This is accomplished by sending out short powerful pulses of microwave-frequency energy at regular intervals in a certain direction. When these pulses strike a target they are reflected back to the source (receiver), whereupon the time and distance to the target and the intensity of reflection can be measured and displayed.

There are many possible transmitter-signal configurations, depending upon the intended use of the radar system. For most geologic studies, the most important is a radar system referred to as side-looking. Side-looking radars scan a path to side of the flight path of the aircraft carrying the radar system. Since the antenna looks at right angles to the direction of flight, this system is referred to by the acronym SLAR - Side Looking Airborne Radar.

Microwave wavelengths are typically not affected by atmospheric absorption or scattering, and because radar supplies its own energy, the data can be collected at any time (day or night) and during most weather conditions. Light tones on the image represent the strongest signal return and dark tones the weakest signal return. These returns vary based on the look direction (the direction from which the radar energy is emitted) of the specific radar system. For example, city street networks oriented perpendicular to the look direction appear as bright white, indicating a strong signal response. When oriented acute to parallel to the look direction, city streets appear as various scales of grey to nearly black.

Typically, signal response is an indicator of surface roughness. A bright response due to a maximum signal return indicates a rough surface, while a dark response indicates a smooth, flat surface. The complexities and diversities of radar imagery are too extensive to be discussed fully in this chapter. For further details refer to Sabins, 1978, Chapter 6.

Radar imagery is typically acquired in strips hundreds of kilometers long and tens of kilometers wide, at a scale of 1:150,000 or smaller, and so is best suited for regional studies. Ground resolution varies with the type of radar system used and is dependent on many factors. Generally radar has a high ground resolution in the range of 3m - 30m.

Airborne radar imagery is typically presented as a strip of grey-scale imagery in contrast to the single frame of an aerial photograph. Limited images are commercially available primarily from private industry. More often radar imagery must be specially flown to meet the particular needs of a specific project. Generally the cost is about $125 for purchasing available strips of data (generally at a scale of 1:150,000), to thousands of dollars for a custom product.

SLAR imagery is very similar in appearance to black-and-white aerial photography. Consequently, the basic interpretive techniques developed for photographic analysis are applicable to radar systems. Analyses of tone, texture, shape and pattern are recognition elements which contribute to the interpretation of geologic data from radar imagery as well as from aerial photography. It should be remembered, however, that radar is an active sensor and the causes of tone, texture, shape and pattern variation are different from those associated with passive sensors operating in this portion of the electromagnetic spectrum.

The characteristics of radar imagery make it best suited for regional faulting and structural analyses. Radar can be helpful in identifying joint and fracture patterns in exposed rock units and even more subtly can aid in distinguishing different rock types based on their surface roughness.

Advantages of airborne radar include: 1) the ability to direct the look direction to enhance subtle structural features, 2) high ground resolution, 3) independence of time of day and cloud cover, and 4) the ability to reduce the effects of vegetative cover. These features make radar imagery desirable for regional geologic studies when it is available. However, a number of limitations associated with radar imagery must also be considered: 1) the distortion or layover produced in high relief terrain, 2) the limited availability of commercial coverage, and 3) the high cost to acquire new data.

Thermal Infrared

Thermal IR sensors measure the natural radiated energy of the materials at the ground surface. Heat energy, mostly from the sun, is stored in the crust of the earth and is continuously emitted at varying rates which are determined by the intrusive emissivity of an object and its temperature. The spectral band usually classified as infrared extends from wavelengths of about 0.7 micrometers to wavelengths of 1000 micrometers. The atmosphere blocks much of this band, but certain wavelengths are passed through atmospheric "windows" and can be detected by air-borne and space-borne sensors.

The record of this radiated energy is presented as a greyscale image strip, which looks very similar to black and white aerial photographs and radar imagery. Lightest tones represent the warmest radiant temperatures and darkest tones the coolest temperatures. Like radar imagery, thermal infrared imagery is independent of the time of day, but is sensitive to weather conditions and requires clear, good weather. Though not dependent on the time of day, thermal IR imagery is best flown during predawn hours for geological use. During daylight hours the effects of differential solar heating result in topography dominating the image.

Ground resolution of thermal IR imagery is variable and dependent on the flight altitude and the instantaneous field of view of the detector.

Thermal IR is expensive to acquire and typically only available through private industry, as essentially all IR imagery is obtained on a contract basis with little storage of data. The most important variable influencing the cost of infrared imagery is that of data processing. As a consequence, the cost to obtain imagery for a target site in an area without previous coverage will be on the order of $20,000, of which half will be a result of processing costs. Imagery for additional sites in the same area will cost on the order of $5,000 a site. Furthermore, costs will also be highly variable due to the sensitivity of the detectors, weather conditions and the associated flight delays and standby costs.

In geologic studies, the primary advantage of thermal infrared imagery, which resembles a photograph of reflected light energy, is the ability to distinguish the thermal characteristics of earth materials by observing daytime and nighttime signatures of the same area. Most earth materials have known thermal respnses that make it possible to differentiate rock types, map surface moisture changes, and map geologic structures based on these thermal characteristics.

Stereo Aerial Photographs

Stereo aerial photographs are the most versatile of the remote sensing techniques. Their uniqueness is due to the stereo viewing capability which allows the interpreter to see a 3-dimensional representation of the ground surface. Aerial photographs record electromagnetic energy between 0.4um and 3.0um, with the visible portion extending from 0.4um to 0.7um and the reflective infrared portion from 0.7um to 3.0um.

Aerial photographs are recorded on film and typically presented as 9" x 9" film positive or negative transparencies and/or contact prints. Four types of stereo aerial photographs are available: 1) black and white panchromatic, 2) normal color, 3) black and white infrared, and 4) color infrared. Black and white panchromatic photographs are the most widely used for two basic reasons; they are the most readily available and the most economical. When possible, interpretation is enhanced by viewing two or three different types of aerial photographs of the same area.

Ground resolution of aerial photographs is variable and dependent on the camera height and the focal length of the lens. Minimum ground separation is a commonly used term which refers to the minimum distance between two objects on the ground at which they can be resolved on a photograph (Sabins, 1978). Table 11 presents an example of the types of features observable at different ground separations.

Aerial photographs are available from many private businesses and government agencies at a wide range of scales (i.e. 1:12,000, 1:24,000, 1:80,000, etc.).

Costs for obtaining aerial photographs are highly variable. Standardized prices are typically found at all government sources who produce large quantities every month. Prices generally range from about $3 to $8 per frame for a standard 9" x 9" aerial photograph, up to around $50 for specific enlargements (Table 5).

TABLE 11

FEATURES RECOGNIZABLE ON AERIAL PHOTOGRAPHS AT

DIFFERENT MINIMUM GROUND SEPARATION VALUES

Minimum Ground Separation	Recognizable Features
15m	Geographic features, such as shorelines, rivers, mountains and water can be identified.
4.5m	Settled areas may be differentiated from undeveloped land.
1.5m	Roadways can be identified.
0.15m	Front of automobiles can be distinguished from the rear.
0.5m(1)	People can be counted, particularly if there are shadows and if the individuals are not in crowds.

(Rosenblum, Table 2, 1968).

(1) Approximate minimum ground separation on typical aerial photograph at scale 1:40,000.

Prices are even more variable for obtaining a standard 9" x 9" aerial photograph from private industry. Typically, the price is dependent on the size of the order. For example, commercial suppliers usually charge a set-up fee plus, in the case of color photography, a color balance fee, on all orders. Combined, these initial fees can range from $25 to $60, regardless of the size of the order. After the initial fees, individual photos are usually charged by the number in the order (the more photos ordered the lower the per frame cost). Therefore, typical costs for standard stereo aerial photographs can range from as little as $3 per frame for large orders to about $60 per frame for single frame orders (Ertec Airborne Systems, 1981).

Costs for having aerial photographs flown to study a particular area are highly variable. Many factors contribute to this cost; i.e. distance from home base (mobilization-demobilization), shape of the area to be covered, terrain conditions, elevation, scale of desired photos, and weather.

Many aerial photographers have a mobilization fee of about $100 to $150 for around a 100-mile radius from their home base. This cost rapidly escalates beyond the 100-mile radius by about $1.50 for each additional mile. The shape of the study area determines the number of flightlines necessary to cover the area.

Typically a square or rectangular area is easiest. Flying accuracy and camera corrections are easiest for relatively flat terrain with the procedure becoming more complex and typically more expensive as the complexity of the terrain increases. Elevation is another important factor because of the altitude limitations of standard aerial photograph reconnaissance aircraft. Based on the ground elevation, the camera focal length, and the altitude limitations of the aircraft, the subcontractor could have to rent a jet versus a standard aircraft, substantially increasing costs. The main cost effect of weather comes from causing numerous mobilization costs and delays which mean additional expenses.

Low sun angle aerial photographs are a special form of stereo aerial photographs taken in the early morning or late afternoon sunlight to help detect subtle differences in relief. Basically their characteristics, resolution, and availability are the same as regular aerial photographs.

An advantage of low sun angle photographs is their ability to accentuate small topographic differences such as fault scarps, in low terrain areas. However, because of the low sun angle, tonal differences are less apparent on low sun angle photographs than on standard aerial photographs (Sabins, 1978). The cost of contracting low sun angle photographs may also be a disadvantage because of the very limited time of day suitable to fly such missions. Therefore, a combination of standard aerial photographs and low sun angle photographs is most desirable in low terrain areas.

The geologic information obtained from an aerial photograph depends on a wide range of factors including the predominant rock type (igneous, metamorphic, or sedimentary), surface morphology and vegetative cover. Typically, sedimentary rock areas, due to the differential weathering characteristics of the sediments, yield the most geologic information from aerial photographs. Metamorphic rocks generally yield the least amount of information (Ray, 1960). Geologic mapping from aerial photographs is discussed in detail in a number of texts including Allum (1966), Miller (1961), American Society of Photogrammetry (1961), and Ray (1960).

The most reliable geologic interpretations will tend to be based on all four forms of aerial photographic imagery. Color and black and white panchromatic photographs are typically the starting point and are best suited for an overall interpretation of geologic structures (including active and potentially active faults), and lithologic characteristics. Tonal anomalies are best recognized on black and white panchromatic and infrared photographs. Infrared photographs are best suited to identifying groundwater discharge locations and soil moisture changes indicative of faulting.

The interpretation of stereo aerial photographs provides a transition between the data from the satellite and aircraft imagery and actual field mapping. Aerial photographs and topographic maps provide the basis and often the base on which ground data are delineated. Following completion of field mapping, these data are transferred to a selected basemap and can be combined with the data from other technical disciplines to provide a geological basis for site selection.

The details of geologic mapping and interpretation from aerial photographs are presented in many texts including Compton (1962), but essentially involves the application of the techniques discussed in Section 2.1.1. Interpretation must involve an analysis of the size and shape of objects, shadow, the tone and texture of the imagery and the recognition of patterns. The use of aerial photographs in the analysis of geologic features critical to repository siting will be discussed more fully in Section 3.1.

2.2 Field Mapping

In areas where the geologic interpretation of remote sensing imagery is uncertain, or where critical features are located, field mapping will be required. Such geologic mapping may be conducted at many scales of analysis, ranging from reconnaissance programs (applicable to precharacterization studies) to the detailed field measurement of geologic structures. The techniques of field mapping are reported in many references, notably Compton (1962), and the reader is referred to these texts for the details of the methodologies discussed in this section.

In order for field mapping to be most effective (and efficient in terms of time and cost) it must be fully integrated into a program which includes the use of remote sensing imagery. Field mapping can then provide a final element in the development of a comprehensive geologic model (see Section 2.1.1. The regional geologic setting of local studies, for example, should be thoroughly investigated at an early stage in the program, otherwise the significance of many rock units or structures examined in detail may be overlooked.

Three levels of mapping studies should be considered in a program: (1) regional reconnaissance studies of rock units and structure, (2) mapping at intermediate scales of 1:24,000 to 1:62,500 around the area of a target site, and (3) detailed mapping studies of the target site at scales larger than 1:24,000. The first two levels of mapping define the location and nature of the final stage in the program.

Reconnaissance and intermediate level mapping investigations will typically rely heavily on the use of remote sensing imagery, but field checking may involve the use of such equipment as a brunton compass to survey landforms, and measure the strike and dip of strata. At the third level of more detailed studies (or in situations where no reliable maps or large scale imagery is available) more precise measurement techniques will generally be required. Surveying equipment, such as an alidade and plane table, will be required for the precise location of landforms, geologic structures, and lithology. Control points must be numerous and accurate.

The detailed methodologies and mapping programs developed will be highly dependent on the requirements and problems of a particular siting investigation, and therefore lie outside of the scope of this generic discussion. The reader is referred to the references cited above for guidance during a particular study. Generalized estimates of costs for a mapping program, which includes field mapping, are presented in Section 2.4.

2.3 Trench and Borehole Logging

If a geologic feature critical to expository siting, such as a possible fault or a zone of frequent jointing, is poorly exposed, trenching or the drilling of boreholes may be required as part of a detailed mapping study to establish the structual and stratigraphic relationships at a target site. The primary advantages of using a trench, rather than drilling boreholes, are that: (1) it provides a continuous profile of the exposed strata, joints and features, (2) fault characteristics are readily observed, and (3) in-situ samples can be obtained for dating or other types of analysis. If a trench is to be excavated, this may be done quickly in unconsolidated deposits or weathered material with the use of a commercial backhoe (rubber-tired or track-mounted) at a cost of approximately $50 an hour.

Trench Excavation and Logging

The details of trench design and excavation will depend heavily on the specific problems to be addressed. Trenching at right angles to the strike, for example, is particularly effective for uncovering steeply dipping planar structures such as a contact or thin bed. An example of a system of trenches designed to investigate Quaternary faulting is described by Kirkham (1977).

The trench wall cuts can be plotted as vertical cross-sections directly on a plane table, by constructing a vertical projection (Compton, 1962, p. 172) or by producing a scaled drawing on grided paper. An alternate approach is to use an enlarged photograph of a face as a base on which to plot contacts, structural features, locations of samples and so on. Dimensions can be scaled or estimated from the point if the distances between a few key points on the photograph are measured in the field.

The scale of logging in the trench is dependent on the needs of a particular study, but also on the amount of detail which is mappable. Typical scales vary between 1"=5' and 1"=50'.

During mapping, complete descriptions of all geologic features should be made (e.g. rock types, bedding, fracturing, jointing, shear zones, etc.), using a standard classification system. All features, geologic and otherwise (including ledges and breaks in slope) should be located and drawn on the base map.

Borehole Logging

Boreholes may be drilled to determine the position of geologic structures, to measure subsurface units and to sample materials at depths or in material which are unsuitable for trenching. Suitable drilling equipment for borehole excavation is discussed by Compton (1962, p. 73) and drilling applications for waste repository siting is discussed in Appendix D.

The logging of a borehole consists of recording information obtained during drilling (such as the rate of drill penetration or the nature of the cuttings from the borehole), or by further examination of the borehole when drilling is completed. Such techniques, which include geophysical logging are discussed in more detail in Appendix C.

At this level of detail, the surface mapping program must be closely integrated with the borehole drilling and logging program.

2.4 Results and Costs of a Surficial Geologic Mapping Program

When a mapping project is completed, the "geologic model" which has been developed can be applied to the development of the geologic history of a target region or site. Such a program must include the application of geologic dating techniques as part of the mapping process (see Section 4.0) in order to establish a time framework for the proposed model. The collection of samples for dating analysis can occur throughout the field mapping portion of the program.

The geologic history can be used in turn to predict future geologic trends and hence the continued viability of a potential site. For example, a study must establish whether (or with what frequency) active faulting has occurred in a region during the Quaternary and whether there is a potential for movement in the future.

The methodologies to be use in such studies are clearly dependent on the nature of a specific project and the skill of the geologic team. Examples of the application of geologic interpretation to siting investigations are reported by Winograd (1981) and Witherspoon (1981).

Mapping Systems

The results of the analysis described above must finally be presented in a map to be used by other technical disciplines and for planning decisions. In the development of the International Institute of Aerial Survey and Earth Sciences (I.T.C.) systems of mapping, guidelines were laid down which help to maximize the usefulness of such a map (Verstappen, 1970):

1) The mapping system should be flexible, allowing the adoption of symbols appropriate for the area concerned.

2) Maps should be as simple as possible (to counteract cartographic problems and aid in interpretation).

3) The system should be applicable for mapping at all scales.

4) General maps should be supplemented by special purpose maps to aid in the discussion of particular areas or problems.

Examples of published, general-purpose maps which may provide a model for maps prepared for siting investigations include those of I.T.C. (Verstrappen, 1970), and a map included in the Manual of Detailed Geomorphic Mapping (Demeck, 1972).

General Cost Estimates for a Surface Mapping Project

The costs of mapping are highly dependent on the characteristics and problems of specific projects. In particular, the level of detail required (e.g. precharacterization or characterization) and the balance between the use of remote sensing imagery and field mapping, both strongly influence project costs. For example, possible Quaternary faulting may be identified by aerial photo interpretation, but a detailed investigation of such faulting (including the dating of movement) will often require the generation of data from boreholes and trenches. Furthermore, in a number of problems (such as establishing the extent of jointing in a granite media) additional subsurface investigations will often be required beyond detailed surface mapping.

Approximate cost and time estimates for surface geologic mapping projects, applicable to the needs of characterization, are presented in Table 12. The cost estimates are presented as a range in an attempt to encompass both the simplest interpretations (i.e. least expensive) and highly complex situations (most expensive).

The main variables that affect the cost involved in remote sensing interpretations are: 1) the scale of the remote sensing data, 2) the terrain complexity, 3) the quality of the data, 4) the vegetative cover, and 5) the number of frames to be investigated. Under the more complex circumstances (e.g. rugged terrain with extensive vegetation cover) high interpretative costs are further augmented by the need for extensive field mapping.

TABLE 12

COST AND TIME SUMMARY

SURFACE GEOLOGIC MAPPING TECHNIQUES

	Approximate Cost	Approximate Time
Remote sensing Interpretation		
1:4200 photo analysis	\$1750-\$3500(1)	5-10 Mandays
Detailed Surface Mapping		
(for 12 mi^2 site area)	\$12,000-\$18,000	20-30 Mandays
General Mapping		(10-15 field days for two-man crew)
Detailed Structure Analysis(2)	\$6,000	10 Mandays (15 field days for two-man crew)
Excavation Logging		
Reconnaissance	\$1200/day(3)	10,000 ft^2/day(3)
Detailed logging at 1"=10'	\$1200/day(3)	1500 ft^2/day(3)

NOTES:

(1) Does not include cost of large scale sterographic aerial photos.

(2) Only applicable where bedrock is exposed at the surface. Cost and time in addition to general mapping.

(3) Typical production rate and daily cost for 2-man field crew. Rates will vary according to access, difficulty of cleaning off the excavation, and particularly, complexity of geologic conditions. Logging of critical relationships at larger scale would require additional time.

The cost of surface mapping and evaluation logging will be dependent on the complexity of the geologic conditions, but will also be strongly influenced by such practical considerations as the ease of access and the particular difficulties of excavating a trench at a site. As a consequence, the costs and time involved in field mapping must be carefully assessed for each project individually.

3.0 USE OF GEOLOGIC MAPPING TO EVALUATE TECHNICAL CRITERIA FOR REPOSITORY SITING

In the siting of waste repositories, a number of geologic features are of critical importance in determining the viability of a potential site. Such limiting characteristics include the presence of Quaternary fault traces, structural controls on the integrity of a host medium, as well as the erosional history and flooding potential of a site. To enable the discernment of suitable repository sites, such critical features will need to be accurately mapped and analyzed, a process requiring the careful integration of remote sensing and field mapping techniques. Furthermore, geologic mapping may provide valuable information for related disciplines (including hydrology, geoengineering, geochemistry and climatology) which are also involved in siting investigations.

This section will begin with a discussion of the role of mapping in the analysis of the geomorphology, stratigraphy, lithology, structural geology and tectonics of a potential repository site. This will be followed by a brief discussion of the possible applications of geologic mapping techniques to related disciplines in siting investigations.

3.1 Geologic Mapping of a Potential Repository Site

3.1.1 Geomorphology

The mapping and analysis of surface morphology is a fundamental step in the evaluation of other geologic criteria for repository siting. Furthermore, landforms themselves may be of considerable importance in siting investigations. The identification of floodplains and alluvial fans and hence areas of high flood potential, for example, is very largely based on land form. The dissolution of domed salt may be recognized by the occurrence of "pseudo-karst" features on the land surface (Sweeting, 1972).

At many scales, the mapping of surface form is most simply achieved by using topographic maps as a base. Landscape units can be sketched in through an analysis of map contours. Information from remote sensing imagery, most commonly panchromatic aerial photographs at a scale of 1:40,000 or larger, can then be superimposed on this base map. Where topographic maps are not available, overlays can be made directly from aerial photographs or other remote sensing imagery.

Mapping Geomorphic Processes

In practice, surficial geology maps rarely show a distribution of processes, only the distribution of landforms resulting from defined processes. Furthermore, in repository siting investigations little time is available to measure surficial processes and the identification of a feature's origin has to be based on its morphology, materials and the past history of an area. This is, however, essentially an interpretation and hence is open to debate.

In siting investigations an analysis of the origin and processes affecting the features on the ground surface is critical to effective planning. The mapping of alluvial features and their correct interpretation is crucial in determining the extent of floodplains and of areas susceptible to flooding. Significant time and costs can be saved if such interpretations are based largely on remote sensing imagery (for example, areas of high erosion potential may be indicated by the presence of an active gully system), but field verification of important sites will be necessary.

3.1.2 Stratigraphy and Lithology

Bedrock Studies

Mapping techniques for solid rock vary more with geographic setting than with the repository media. In areas of good exposures, such as desert regions and low lying plains, remote sensing imagery can be used extensively. In areas of uniform surface materials or thick vegetative cover, however, extensive fieldwork will be required, resulting in the associated increases in time and cost.

At regional and intermediate scales of mapping (see Section 2.2.4), lithologic mapping may be effectively conducted through interpretation of Landsat imagery. Several types of imagery can be used, each of which may be digitally processed to enhance the diagnostic properties. In the visible and new infrared regions, the most diagnostic properties of rocks are brightness, spectral radiance, and the spatial distribution of landforms. Brightness differences shown in conventional black-and-white photographs and single Landsat MSS bands allow discrimination of some units, but more separation is usually achieved if one analyzes color-composite images which incorporate three spectral bands and hence display spectral radiances. Landsat color-infrared composite images consisting of MSS bands 4, 5, 7 are widely used for lithologic studies, because they present information about the brightness and spectral reflectance of rocks and landforms. In the color-infrared composite image, dark rocks (mainly basic volcanic flows and scattered sedimentary rocks) and a wide range of bright rock types are readily separated. However, color differences, representing spectral reflectance variations, are very subtle, except for the red resulting from the high reflectance of vegetation in MSS band 7 relative to bands 4 and 5. Another complicating factor is that the radiance variations are primarily related to changes in the topographic slope. Color-ratio composite images can be used to display spectral reflectance differences in color, while subduing brightness variations due to topographic slope, but this technique is limited to regions having no more than 35 to 40% vegetation cover (Goetz and Rowan, 1981).

An alternative to spectral studies is the use of parameter thermal inertia, which characterizes the response of rocks and soils to diurnal heating and cooling. This approach has primarily involved thermal infrared sensing from aircraft (see Section 2.1.3). Because thermal inertia is a body property, some distinctions are possible that cannot be obtained from spectral reflectance and emittance data alone. For example, limestone and dolomite are readily seperable on the basis of the significantly higher thermal inertia of dolomite, even though these rocks are spectrally similar in the mid-infrared, and the visible and near-infrared regions. In general, this technique is especially effective for distinguishing among sedimentary rocks.

At more detailed levels of mapping (and particularly for stratigraphic analysis), stereo aerial photographs at a scale of 1:40,000 or larger, and field studies (section 2.1.4) remain fundamental techniques.

There are many distinctive properties of bedrock that can be mapped and recorded on a surficial geology map. For repository siting, studies in areas of sedimentary rocks will tend to concentrate on the attitude, thickness, and continuity of beds. In granitic and basaltic terrain mapping studies must concentrate on fracture and joint orientation and spacing (see Section 3.1.3).

The extent and value of the mapping which can be carried out on a potential host medium will depend to a large degree on the topography, vegetation and existence of suitable outcrops, but some other factors will also depend on the bedrock involved. Bedded and domed salt deposits would not typically be exposed in outcrops and, if exposed, would be much altered by dissolution. As a result, limited direct information on these media would be obtained from surface mapping. One exception may be that careful analysis of "pseudo-kast" features formed by subsurface salt dissolution would provide information on the rate at which dissolution is occurring. Shale and tuff may be directly observed in outcrop and under favorable conditions considerable information on the extent and continuity of these potential host beds may be obtained from surface mapping.

Surficial Deposits

The study of the nature and stratigraphy of surficial deposits is particularly important in evaluating the nature and rates of surficial processes which affect the stability of the land surface. As such, the mapping and possibly a detailed geomorphic analysis, of surficial deposits is an important element of site characterization. Such studies are varied in nature and specific to particular geologic problems, such as a determination of the age of the fault offsetting Quaternary deposits or the calculation of the rate of scarp retreat.

The techniques of mapping such surficial deposits are explained in a number of text, including those of Flint (1971), Birkeland (1974) and Schumm (1977). A great deal of information may be obtained from an analysis of aerial photographs and topographic maps, such as the superpositional relationships and hence relative ages of deposits, their morphology and degree of erosion. An example of such an approach is a study by Hunt and Mabey (1966) of alluvial fans in Death Valley, California, in which they related differences in fan morphology to tectonic activity. However, field work is then required to verify this work, particularly when an attempt is being made to date deposits.

Of considerable importance for siting investigations is the potential for the erosional (and climatic) history of a potential repository site to be established by the study of surficial deposits. One common approach has involved the analysis of stream terraces. The methods used in terrace correlation are discussed in Leopold and Miller (1960). Scott (1963), for example, has studied the terraces that flank the eastern boundary of the Front Range of the Colorado Rockies, south of Denver. This study attempted to interpret the Quaternary geomorphic history of this region and is important as a model for repository studies as it illustrates the impact of erosional and depositional processes on Cretaceous shale strata which are potential host media. It is important to note, however, that recent geomorphic research (e.g. Schumm, 1977) has stressed the complex nature of the response of geomorphic systems to environmental change. Interpretations of surficial deposits in terms of the climatic or erosional history of an area must consider these complex interactions.

3.1.3 Structural Geology and Tectonics

A principal attribute of a high level nuclear waste repository site must be a high degree of physical inaccessibility. Fractures, joints and faults provide potential flowpaths for groundwater which may transport contaminants to the biosphere. Furthermore, the generation of heat by the waste introduces the additional requirement of chemical and mechanical stability under the controlling stres fields, and these characteristics will be strongly influenced by geologic structure. Surficial geologic mapping can provide a great deal of information of geologic structure. Surficial geologic mapping can provide a great deal of information of geologic structure, but in siting investigations this must be supplemented by data from subsurface programs such as geophysical surveys (Appendix B) and borehole studies (Appendices C and D).

Mapping of Regional Structural Features

Landsat MSS images are especially suitable for studying the relationships between landforms and major structural features, because each image displays approximately 34,000 square kilometers with uniform illumination, and the scene contrast can be optimized through digital processing of the radiance values (see Section 2.1.2). One of the most striking results of the analysis of Landsat imagery has been the discovery of numerous, regional linear features, such as streams, escarpment and mountain ranges, and tonal features that in many areas are the surface expression of fracture or fault zones (e.g. Goetz and Rowan, 1981).

Several factors influence the detection of lineaments. One of the most important is the angular relationship between the linear feature and the illumination source. In general, features that trend parallel to the illumination source are not detected as readily as those that are oriented perpendicularly. Moreover, moderately low illumination angles are preferred for the detection of subtle topographic linear features. Because the Landsat satellites are in a sun-synchronous orbit, the only choice of illumination that is available is a specific area stems from seasonal variations. Although these variations are important, some features are not well displayed in Landsat images and the lineament data set is biased.

Side-looking radar (SLAR) provides a means of overzoning the limitations of Landsat imagery due to solar illumination, because SLAR images are formed by transmitting bursts of energy to the surface and recording the returned signal on film or digital tape. The azimuth and illumination angle depend on the "look direction" and "look angle" of the system, which may be modified to most effectively analyze a particular problem.

The usefulness of SLAR imagery in delineating fracture fracture zones is demonstrated in a study of the Haysi, Virginia-Kentucky gas field by Ryan and Owens (1975). They concluded from an evaluation of several types of images (including Landsat, black and white infrared, thermal-infrared and SLAR imagery) that the SLAR images recorded from several look directions were superior for mapping individual lineaments.

As noted in Section 2.1.3, the acquisition and processing of SLAR imagery is relatively expensive when compared with readily available Landsat images. However, the importance of fracture or fault zones as technical suitability criteria in siting investigations may justify the use of SLAR imagery in many studies.

Whatever form of imagery is employed in the analysis of lineaments, field mapping and subsurface data (particularly seismic surveys) are essential for interpreting the lineament data and understanding the regional tectonic framework. Lineaments are often the result of linear escarpments, slope breaks, vegetation changes or some combination of the above. None of these features are exclusively controlled by structure, and their origin must be determined by field mapping.

When fault traces have been identified from remote sensing imagery, they should be sketched tentatively on a base map. Compton (1962) suggests that these possible faults should then be examined and either proved by the mapping of adjoining rock units or disproved by tracing contacts or beds across them. When the presence of fault traces are indicated by a regional study, further, more detailed studies may be required at selected locations even during precharacterization investigations.

Detailed Studies

Even at a precharacterization stage of siting investigations, some detailed site-specific studies may be required to determine the recency of movement and to establish the structural and stratigraphic relationship associated with faulting. These relationships allow an interpretation of the nature and recurrence interval of tectonic activity. The recency of movement can best be determined by establishing the age of the youngest material disturbed by a fault. This may require the use of a wide range of stratigraphic techniques applicable to Tertiary and Quaternary deposits, as well as the application of relative and absolute dating techniques (see Section 4.0). If a fault is poorly exposed, trenching or the drilling of boreholes may be required to establish the structural and stratigaphic relationships associated with a fault zone (e.g.Kirkham, 1977).

Detailed Mapping of Fracture and Joint Patterns

The mapping of surface morphology, commonly from stereo aerial photographs at a scale of 1:40,000, can enable the identification of zones of high jointing or fracture density. In granitic terrain, for example, characteristic landforms, such as tors, are associated with extensive (closely spaced) fracturing or jointing. The extrapolation of such surface observations to a subsurface repository location, however, requires considerable care because of the influence of overburden pressure on the degree of jointing. As a consequence detailed subsurface mapping of joint orientation, spacing and lengths are required for an adequate evaluation of a potential repository site. Witherspoon and others (1981) have summarized the results of such a study of a granitic rock mass in Sweden. This study included a statistical analysis of joint geometrics, based on the results of logging of underground boreholes and comprehensive surficial mapping of underground mine drifts.

3.2 Application of Geologic Mapping Techniques to Non-Geological Technical Criteria

Geologic mapping techniques can provide a wide range of supplemental information for other technical disciplines involved in repository siting investigations. Of particular importance are the remote sensing techniques discussed in Section 2.1, but field mapping techniques can also be useful in, for example, hydrologic and environmental studies.

3.2.1 Geoengineering Studies

Many elements of bedrock geology which are identified by surficial mapping can provide valuable information for geoengineering programs. Detailed studies of the mechanical and chemical properties of the rock at a potential repository site can be designed on the basis of the results of remote sensing analyses (notably of Landsat MSS imagery and the thermal properties of the earth's surface) and of detailed field mapping (e.g. measurements of joint orientation and spacing).

3.2.2 Hydrologic Studies

Surficial mapping techniques can be used in conjunction with other disciplines in ground-water investigations (e.g. Davidson, 1973) to determine potential aquifers as well as areas of ground-water recharge and discharge. However, the primary application for surficial mapping is possibly in the analysis of surface water and flood potential.

Flood Hazard Mapping

The need for flood-hazard information in precharacterization studies makes imperative an evaluation of alternate techniques to standard engineering flood line and regional flood analysis. Varied mapping techniques may be appropriate for different localities depending on the local hydrologic regime, the level of detail involved and the funds available to finance the study. A geomorphic approach to flood hazard mapping can be used effectively at a regional scale to provide interim information prior to a detailed site specific study.

Wolman (1971) has noted that floodplains may be mapped by occasional flood, botanic, soil and physiographic approaches. Traditional engineering hydraulic-hydrologic methods have been considered to be the most desirable for planning and management purposes, such as in urban areas (Wiitala and others, 1961). However, these methods also tend to be expensive, costing over $1,000 per mile for delineating flood profiles by backwater curve analysis of large scale topographic maps (Wolman, 1971, p. 1984). In contrast, the mapping of topographic features or soil types that may correlate to flood levels can cost as little as $1 to $4 per mile (Wolman, 1971).

Occasional Flood Method

This approach involves establishing flood lines on the basis of aerial photographs taken during flood events, historic evidence of floods and local observation of flood heights (Wolman , 1971). Remote sensing offers many advantages for providing wide coverage of inundated areas. Unfortunately, poor weather may inhibit low-level aerial surveys of floods. Orbital space platforms for earth resource sensors have an important advantage in this regard. Their multidate images allow continuous monitoring of river conditions without necessitating emergency plans for aerial surveys of broad areas.

A striking example of the use of satellite imagery for occasional flood mapping occurred in the spring of 1973, when severe flooding affected the entire alluvial valley of Mississippi River. Optical data processing techniques were used to produce a variety of multispectral composites of ERTS-1 imagery taken before, during and after overbank flooding (Deutsch and Ruggles, 1974). The entire lower Mississippi River from St. Louis to the Gulf of Mexico could be depicted in a single view. An important discovery was that the effect of flooding on the reflectance characteristics of the floodplain allow the delineation of areas from which flood water had recently receded. This eliminates the need for continuous monitoring of the flood crest.

Botanic Approach

Many regional ecological studies have suggested that some zonation of vegetation tends to occur along river valleys. Biologic assemblage mapping by the University of Texas Bureau of Economic Geology (Wernund and Waddell, 1974), for example, has shown that a bottomland cypress-pecan assemblage can be easily recognized in the process of environmental geologic mapping from aerial photographs. However, the factors which influence the zonation of vegetation in river-bottom environments are complex. Particular combinations of soil conditions and water supply appear to be the dominant controls. As flooding is not a primary cause of zonation, botanical flood studies should be combined with other techniques in flood hazard evaluation.

Soils Method

Wolman (1971) has suggested that locally both soils and topography may correlate with specific flood heights. Recekndorf (1973) found that the soils approach did an adequate job of delineating areas in Oregon flooded by 100-year return period events when mapped soils were compared with hydrologic studies of flood frequency.

Geomorphic Method

Geomorphic techniques for flood plain mapping should not be confused with simple physiographic correlation of specific topographic features with flood discharges of a known frequency. The former approach involves the more extensive investigation of morphology, sedimentology, distinctive erosion features, time morphology, sedimentology, distinctive erosion features, time sequences of channel abandonment, and the compilation of existing soil, botanic and hydrologic information. This concept is similar to Reckendorf's "combination method" for the construction of flood plain maps in Oregon. Reckondorf developed a base map by mapping typical geomorphic flood plain features and associated terraces from aerial photography and selected field studies. The available soils, vegetational, historical flood and hydrologic-hydraulic information was then superimposed on the delineated flood plain. Reckendorf found that there is, in general, a strong correlation between geomorphic flood plain surfaces and river stages for floods of particular frequencies, notably the 100-year average recurrence interval event.

An example of flood hazard mapping using orbital remote sensing imagery is described by Baker (1976) in the Colorado River Valley between Austin and La Grange, Texas. The channel forms of the Colorado River Valley were mapped from MASA generated high-altitude color aerial infrared (Type SO 117) photography (1:116,000 scale). The map (Fig 1) revealed cross-cutting relationships for distinct assemblages of channel patterns associated with multiple levels of the Colorado River floodplain. The imagery easily distinguished these channel forms from upland topography and from the modern active channels of the river.

Comparison of the mapped channel forms to historic and calculated regional flood lines (Fig. 2) showed that the low sinuosity channels on the older terraces are flooded by rare, high magnitude events (e.g. 100 year flood). The distinctive younger bars and channels are flooded with greater frequency, probably in the 2 to 15 year recurrence interval range. An upper boundary to the flood hazard zone is provided by the scarps bordering the alluvial valley of the Colorado River. Baker (1974) notes that water from the largest historic Colorado River flood reached this margin in 1935.

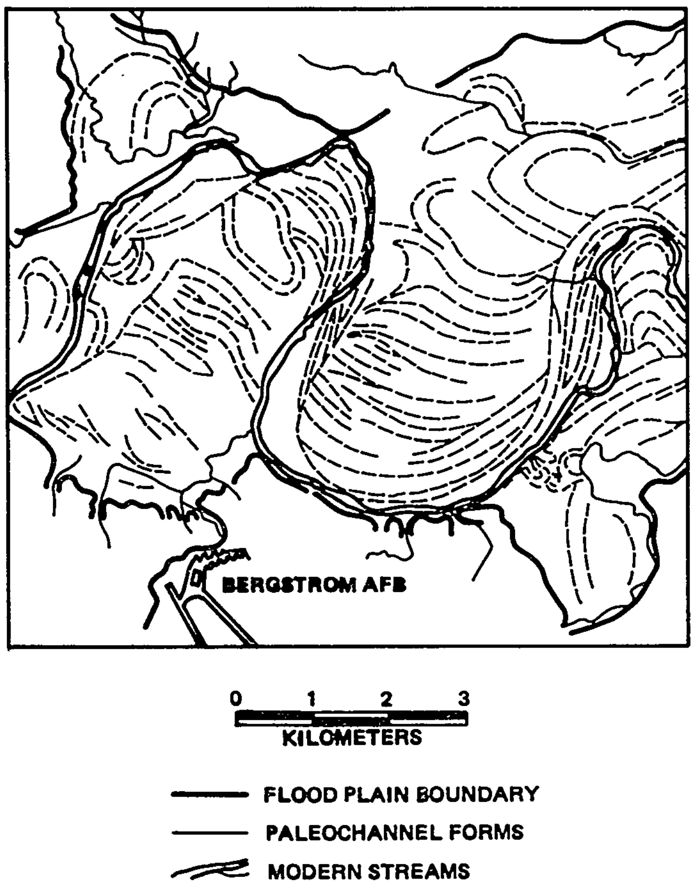

FIGURE 1 COLORADO RIVER FLOOD PLAIN FEATURES NEAR AUSTIN, TEXAS MAPPED FROM HIGH ALTITUDE COLOR AERIAL INFRARED IMAGERY (BAKER, 1976)

GEOMORPHIC FLOOD PLAIN FEATURES		FLOOD HAZARD ZONES	
------	YOUNGER BARS AND CHANNELS	----	INTERMEDIATE FREQUENCY
______	CHANNELS ON OLDER TERRACES	++++	100 YEAR FLOOD
⊥⊥⊥⊥⊥⊥	SCARPS BORDERING ALLUVIAL VALLEY	●●●●●	1935

FIGURE 2 COMPARISON GEOMORPHIC FLOOD PLAIN FEATURES OF THE COLORADO RIVER TO REGIONAL FLOOD LINES FROM HISTORIC AND HYDROLOGIC SURVEYS (BAKER, 1976)

3.2.3 Geochemistry and Mineral Resource Exploration

Remote sensing techniques and Landsat MSS imagery in particular, have proven to be extremely valuable for geochemical mapping and mineral exploration by (1) allowing the mapping of the regional and local fracture systems that control ore bodies, and (2) allowing the detection of surface alteration effects associated with ore deposits. The combination of such mapping techniques with additional geophysical and geochemical data to evaluate the mineral resources in northern Sonora, Mexico, has been reported by Raines and others (1978). Because only reconnaissance geologic maps are available, and accessibility was difficult, analysis of lineaments and limonitic occurrences from Landsat imagery was used initially to identify promising areas for more detailed geologic mapping and geochemical surveys.

3.2.4 Other Disciplines

Remote sensing imagery is now widely used in the analysis of weather and climate (e.g. Richason, 1978, Ch. 18), and environmental and land use studies (Sabins, 1978, Ch. 9). Geological mapping can be of significance for climatological studies, as the analysis of landforms, surficial deposits and erosional processes can be applied to the reconstruction of paleoclimatological and paleohydrologic condition (e.g. Schumm, 1977). Surficial geologic maps can also act as a valuable based for further environmental or land use studies.

4.0 DATING OF GEOLOGIC FEATURES

A final step, essential in the reconstruction of the geologic history of a region and in establishing its suitability as a repository site, is the dating of the geologic features and materials discussed above. Such dating may either be in absolute terms, using numerical techniques, or may be relative using relative-age or correlation methods.

Correlations of relative-age techniques include the establishment of a relative chronology based on stratigraphic correlation, or the chemical or physical characteristics of deposits. Faults, for example, can be dated by the study of the surficial deposits which they transect. A relative chronology of alluvial fan or stream terrace deposits may be established based on their stratigaphic position (often mapped from aerial photographs) and surface measures such as the degree of weathering or soil development on a deposit (Birkeland, 1974). Such a relative scale can be fixed if more of the mapped units are dated by other techniques.

Numerical methods on dating include the use of historical records and tree rings (dendrochonology) to establish geologic history, but more commonly include radiometric dating techniques which are based on the spontaneous decay of certain radioactive elements into others. These methods give a date in years with a definable error, which depends on the method and the age of the material in question.

A number of well developed radiometric dating techniques and some of the more commonly used correlation and relative age methods of dating are outlined in Table 13. This table was designed to indicate: 1) what techniques are available, 2) to what time ranges they are applicable, and 3) on what types of rock or deposits they can be used. It should be noted that the table is a general summary and is not intended to be a users manual. For details on principles, methodology and sample preparation, the reader should consult the literature on specific techniques. Further information on these techniques is available from reviews such as those by Pierce (1978), Cullingford and others (1980) and Hamilton (1961) as well as the specific references listed in Table 13.

SUMMARY TABLE OF GEOLOGIC DATING TECHNIQUES

TABLE: 13

NUMERICAL METHODS (rows 1–7)

METHOD	GUIDE TO SELECTED REFERENCES	APPROXIMATE AGE RANGE YEARS (RESOLUTION)	MINIMUM EXPECTABLE UNCERTAINTY ①	APPLICATION OR TYPE OF MATERIAL	REMARKS
(1) HISTORICAL RECORDS	15	0 – 6,000 (± 0%) (± 2%)	0% (500 YRS)	PRIMARILY USED IN STUDY OF ALLUVIAL DEPOSITS AND PROCESSES	REQUIRES PRESERVATION OF RECORD, AND APPLICABILITY DEPENDS ON QUALITY AND DETAIL OF RECORD. LIMITED TO ABOUT ~ 400 YRS IN WESTERN HEMISPHERE
(2) CARBON-14 (C^{14})	3, 5, 7, 11, 18, 24	100 – >40,000 (± 100%) (± 2%)	1% (15,000 YRS)	CHARCOAL, WOOD, SEEDS, BURNED BONES WIDELY USED - QUATERNARY STUDIES N.B. GLACIAL AND PLUVIAL LAKE DEPOSITS	DEPENDS ON AVAILABILITY OF CARBON. SUBJECT ERRORS DUE TO CONTAMINATION, NOTABLY ON OLDER DEPOSITS AND IN CARBONATE MATERIAL (E.G., MOLLUSK, SHELLS, MALL, CALICHE). RANGE CAN BE EXTENDED TO 70,000 YEARS BY ENRICHMENT TECHNIQUES, BUT 0.02% CONTAMINATION WILL PRODUCE APPARENT AGE OF 70,000 YRS. FROM "DEAD" SAMPLE
(3) URANIUM-SERIES (U-SERIES)	11, 14	5,000 – >300,000 (± 50%) (± 10%)	5% (100,000 YRS)	CARBONATES. (CORAL, MOLLUSKS, BONE) POTENTIALLY USEFUL FOR TRAVERTINE AND SOIL CALICHE	VARIETY OF SCHEMES: TH-230/U-234 (MOST COMMON) U-234/U-238 (RANGE BACK TO 600,000 YRS); Pa-231/U-235, U He (0 – >2 M.Y.) AND Ra 226/Th-230 (<10,000 YRS). ERRORS DUE TO LACK OF CLOSED SYSTEM - COMMON, ESPECIALLY IN MOLLUSCS AND BONE
(4) POTASSIUM-ARGON (K-Ar)	11, 28	50,000 – >2,000,000 ② (± 20%) (± 2%)	2%	DIRECTLY APPLICABLE ONLY TO IGNEOUS ROCKS AND GLAUCONITE	REQUIRES K-BEARING PHASES SUCH AS FELDSPAR, MICA, GLASS ETC. SUBJECT TO ERRORS DUE TO EXCESS ARGON, LOSS OF ARGON OR CONTAMINATION
(5) FISSION TRACK	6, 17	50,000 – >2,000,000 ② (± 40%) (± 5%)	5% (1 – 2 M.Y.)	DIRECTLY APPLICABLE ONLY TO IGENOUS ROCKS, INCLUDING VOLCANIC ASHES	REQUIRES URANIUM BEARING MATERIAL (ZIRCON, SPHENE, APATITE, GLASS) SUBJECT TO ERRORS DUE TO TRACK MISIDENTIFICATION AND TO TRACK ANNEALING
(6) DENDROCHRONOLOGY	22	0 – 9,000 (± 0%) (± 2%)	0 – 1% (<5,000 YRS)	WOOD (INITIALLY REQUIRES SECTION OF TREE AT LEAST TO CENTER)	REQUIRES EITHER DIRECT COUNTING BACK FROM PRESENT OR CONSTRUCTION OF CHRONOLOGY BASED ON VARIATION IN ANNUAL RING GROWTH. RESTRICTED TO AREAS WHERE TREES OF REQUIRED AGE OR ENVIRONMENTAL SENSITIVITY PRESERVED
(7) VARVE CHRONOLOGY	7	0 - 12,000 (± 0%) (± 10%)	0 – 1% (<8,000 YRS)	BASED ON DEPOSITION OF LAKE SEDIMENTS - VALUABLE IN FLUVIAL, LACUSTRINE AND GLACIAL STUDIES	REQUIRES EITHER DIRECT COUNTING OF VARVES OR CONSTRUCTION OF CHRONOLOGY BASED ON OVERLAPPING SUCCESSION OF CONTINUOUS VARVED LAKE SEDIMENTS SUBJECT TO ERROR IN MATCHING SEPERATE SEQUENCES AND TO MISIDENTIFICATION OF ANNUAL LAYERS
(8) LICHENOMETRY	26	50 – 8,000 (± 10%) (± 25%)	10% (<1000 YRS)	BASED ON LICHEN GROWTH RATE USEFUL IN DATING GLACIAL DEPOSITS	USEFUL ONLY IN ENVIRONMENTS WITH STABLE ROCK SUBSTRATES FOR LICHEN GROWTH (ARCTIC AND ALPINE). TECHNIQUE MUST BE CALIBRATED BY OTHER METHODS. SUBJECT TO ERROR DUE TO LOCAL LICHEN KILL, MOISTURE VARIATION AND MISIDENTIFICATION. AGE LIMIT OFTEN<4,000 YRS.
(9) OBSIDIAN HYDRATION	8, 9	100 – >2 M.Y. ② (20%) (± 30%)	10% (100,000 YRS)	REQUIRES PRIMARY OR TRANSPORTED OBSIDIAN	DEPENDS OTHER TECHNIQUES FOR CALIBRATION, SUBJECT TO ERRORS DUE TO TEMPERATURE HISTORY, VARIATIONS IN CHEMICAL COMPOSITION
(10) TEPHRA-HYDRATION	23	1,000 – >2 M.Y. ② (± 100%) (± 70%)	50% (100,000 YRS)	REQUIRES VOLCANIC GLASS - SAME AGE AS DEPOSIT BEING DATED	SAME LIMITS AS OBSIDIAN HYDRATION AND GEOMETRY GLASS SHARDS AND BUBBLE CAVATIES
(11) THERMOLUMINESCENCE	1, 2	2,000 – 250,000 (± 50%) (± 10%)	5% (100,000 YRS)	PRIMARILY USED IN ARCHAEOLOGY ALSO APPLIED VOLCANIC STUDIES	APPLICABLE TO FELDSPAR, QUARTZ AND POSSIBLY CALCITE, RELATIVE TO CALIBRATION BY OTHER TECHNIQUES. ABSOLUTE DATES FOR POTTERY AND CERAMICS IN RANGE 400 – 10,000 YRS.
(12) AMINO ACID RACEMIZATION	12	100 – 1 M.Y. (± 50%) (± 50%)	20% (100,000 YRS)	REQUIRES SHELL OR SKELETAL MATERIAL. SHELL PROTEIN MORE RELIABLE	RATE OF RACEMIZATION IS STRONGLY DEPENDANT ON TEMPERATURE AND LEACHING HISTORY. PRESENTLY USED MOSTLY AS RELATIVE AGE (OR CORRELATION) TECHNIQUE
(13) RATE OF DEPOSITION	7, 21	0 – >2 M.Y. ② (5 – 50%)	5% ③	BASED ON THICKNESS OF SEDIMENTS	REQUIRES RELATIVELY CONSTANT RATE OF DEPOSITION OVER INTERVALS CONSIDERED. CALCULATIONS BASED ON SEDIMENT THICKNESS BETWEEN HORIZONS DATED BY OTHER

RELATIVE AGE METHODS	(14) SOIL DEVELOPMENT	3, 7, 10, 24	100 –>2 M.Y. (± 100%) (± 90%) ②	25% (100,000 YRS)	WIDELY USED DATING GLACIAL AND ALLUVIAL SEDIMENTS	BASED ON VARIETY OF SOIL FEATURES, ALL OF WHICH DEPENDANT ON OTHER FACTORS APART FROM TIME (PARENT MATERIAL, CLIMATE, VEGETATION, TOPOGRAPHY) MOST EFFECTIVE WHEN OTHER VARIABLES EVALUATED, PRECISION VARIES WITH SOIL PROPERTY MEASURED
RELATIVE AGE METHODS	(15) WEATHERING	3, 7, 20, 24	100 –>2 M.Y. (± 50%) (± 50%) ②	15% (100,000 YRS)	INCLUDES: DEVELOPMENT WEATHERING RINDS; SOLUTION HOLLOWS; GRUSSIFICATION; DESERT VARNISH	SAME LIMITATIONS AS SOIL DEVELOPMENT, PRECISION VARIES WITH WEATHERING FEATURE MEASURED
RELATIVE AGE METHODS	(16) PROGRESSIVE LANDFORM MODIFICATION	7,27	100 –>2 M.Y. (± 100%) (± 100%) ②	50% (100,000 YRS)	COMMON FEATURES USED: SLOPE DEVELOPMENT; DEGREE OF DISSECTION	COMMONLY ERGOTIC ASSUMPTION APPLIED, DEVELOPMENT DEPENDS ON MANY FACTORS APART FROM TIME (N.B. STRUCTURE)
RELATIVE AGE METHODS	(17) GEOMORPHIC POSITION	7, 10, 20	0 –>2 M.Y. (± 100%) (± 100%) ②	70% (100,000 YRS)	APPLIED: TERRACE AND MORAINE SEQUENCES	SIMILAR LIMITATIONS TO LANDFORM MODIFICATION, BUT OFTEN USEFUL IN DETERMINING AGE SEQUENCE
CORRELATION METHODS	(18) PALEOMAGNETISM	11, 25	0 –>2 M.Y. (5 – 20%) ②	③ 5%	MEDIUM GRAINED SANDS TO CLAYS. MOST IGNEOUS AND METAMORPHIC ROCKS	REQUIRES MATERIAL WITH REMNANT MAGNETISM. DEPENDS ON CORRELATION OF MAGNETIC PROPERTIES WITH KNOWN CHRONOLOGY OF MAGNETIC VARIATION. SUBJECT TO ERRORS DUE TO CHEMICAL MAGNETIC OVERPRINTING AND PHYSICAL DISTURBANCE
CORRELATION METHODS	(19) TEPHRA-CHRONOLOGY	13, 16	0 –>2 M.Y. (2 – 10%) ②	③ 2%	PRIMARILY USED AS MARKER HORIZON	BASED ON X-RAY FLUORESCENT SPECTRUM ANALYSIS OF TEPHRA (VOLCANIC GLASS) USEFUL IN CORRELATION AS ASH ERUPTION - INSTANTANEOUS GEOLOGIC EVENT
CORRELATION METHODS	(20) FOSSILS + ARTIFACTS	11, 18	0 –>2 M.Y. (10 – 50%) ②	③ 10%	BASED ON FOSSIL OR FOSSIL ASSEMBLAGE (e.g. PALYNOLOGY)	DEPENDS ON AVAILABLITY OF FOSSILS. RESOLUTION DEPENDS ON RATE OF EVOLUTION AND ON CALIBRATION BY OTHER TECHNIQUES. SUBJECT TO ERRORS DUE TO MISIDENTIFICATION AND INTERPRETATION
CORRELATION METHODS	(21) STABLE ISOTOPES	4	0 –>2 M.Y. (5 – 20%) ②	③ 5%	MOST WIDELY USED IN DEEP OCEAN AND ICE CAP CORES	DEPENDS ON CORRELATION OF SEQUENCE OF ISOTOPIC CHANGES WITH DATED MASTER CHRONOLOGY
CORRELATION METHODS	(22) STRATIGRAPHIC SEQUENCE AND OTHER PHYSICAL PROPERTIES	19, 21	0 –>2 M.Y. (5 – 50%) ②	③ 5%	TIME-STRATIGRAPHIC, ROCK-STRATIGRAPHIC BIO-STRATIGRAPHIC UNITS; AND UNCONFORMITIES	DEPENDS ON EQUIVALENCE OF UNITS. GIVES ONLY SEQUENCE OF UNITS UNLESS AT LEAST ONE UNIT CAN BE DATED BY OTHER METHODS

NOTES:

① LIMITS ARE THOSE BETWEEN WHICH TECHNIQUE IS NORMALLY APPLIED. APPROXIMATE RESOLUTION AT EACH LIMIT GIVEN IN PARENTHESES.

② METHODS APPLICABLE TO PRE-QUATERNARY (> 2 M.Y.) MATERIALS

③ WHERE RESOLUTION MOSTLY DEPENDANT ON FACTORS OTHER THAN AGE SINGLE RANGE OF RESOLUTION GIVEN

TABLE:

1. AITKEN,
THERMO
ARCHAE

2. BERRY,
JOURNA

3. BIRKELA

4. BROECK
AND THE
REVIEW

5. CULLING
TIME SCA

6. FLEISCH
PROBLEM
EVOLUTI

7. FLINT, R

8. FRIEDMA

9. FRIEDMA
TO DATIN
SCIENCE

10. GILE, L.H

11. HAMILTO

12. HARE, P.

13. IZETT, S.
CORRELA
TEXAS, W
QUATERN

14. KU, T.L.

15. LADURIE

13 (CONT.)

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A-2

APPENDIX A-2

SUBSURFACE MAPPING METHODS FOR SITE CHARACTERIZATION

BY

ERTEC ROCKY MOUNTAIN, INC.

DENVER, COLORADO

NOVEMBER 1, 1981

INTRODUCTION

The purpose of underground mapping is to provide a detailed description of subsurface geologic conditions which may bear on site characterization. This mapping should emphasize those features of the host media which affect hydrologic, geochemical and geomechanical properties. The most critical features for this are: discontinuities (density, width, extent, etc.); variations in mineralogy, lithology and texture; mineralogy and extent of joint infilling materials; small-scale folding, and any associated small-scale structures; joints; bed, interbed or flow contacts; and fractured or brecciated zones.

It is assumed that the work would be conducted, or at least supervised, by a geologist with previous underground mapping experience and with either surface or underground mapping experience in both igneous and sedimentary rocks. The requirements for the work are outlined below.

METHODS

Prior to mapping, all openings should be carefully surveyed and large-scale maps (1" = 5' is recommended) prepared for chest height (walls) and back (roof) as a base for mapping. Spads (nails for plumb-bob) should be established at 100-foot intervals throughout the horizontal workings, and surveyed depths established from the pilot shaft.

The shaft walls and underground ribs (tunnel walls) and backs (tunnel roofs) should be hosed down with water, if necessary, so a clean surface is available for mapping. In salt media, this cleaning step must either be omitted or done with a saturated brine to prevent dissolution. Tapes should be extended down from spads within the shaft and along level lines surveyed on the rib wall at chest height (four feet above the floor) and a tape hung for control during mapping. A collapsible folding rule in tenths of a foot should be used for measurements above and below the tape. For mapping the back, a tape should similarly be extended between spads.

Geologic maps should be prepared on the one inch = five feet base maps prepared during surveying, and all geologic features which can be represented at this scale recorded. Customary geologic mapping symbols and a standard color code should be employed for all mapping.

While mapping tapes are in place, systematic photographs of sufficient quality to show features of one-half inch or more should be taken of all exposed rock surfaces. Photographs taken at this time will permit correlation between photos and geologic mapping. Ektachrome is probably the best film to use, but experiments should be made with alternatives. Photographs should not be taken directly on, as flash reflection will yield unusable photos; photos should be taken at a slight angle.

LEVEL OF EFFORT

It is recommended that all underground rock exposures in bedrock be mapped. This would require initiating mapping in the shaft at the surface of bedrock and continuing on all ribs (walls) of the shaft prior to the emplacement of any grout, liners, etc. and continuing throughout all underground workings, including the shaft station, drifts, raises, winzes, and rooms. Within horizontal and incline workings, both ribs and the back (ceiling) should be mapped.

The geologic complexity of the various media varies considerably, as will the time required to provide detailed mapping. In terms of degree of complexity, dome salt, basalt, and tuff are probably roughly comparable, whereas shales and bedded salt will be geologically more simple, and granites the simplest. The average mapping time for one rib of an eight-foot high drift is estimated to be one hour for twenty feet, but will vary from one-half hour for granites up to two hours for dome salt and tuffs. For a drift eight feet high and eight feet wide, twenty linear feet of mapping would require on the average about three hours and would cover 480 square feet.

Detailed mapping of a shaft or drift at a scale of one inch = five feet will cost $650.00 per day for one experienced geologist (in 1981 dollars). Typical mapping rates for the various media (in ft^2/day) depend on the complexity of geologic conditions and are as follows:

Medium	Mapping Rate (ft^2/day)
Granite	2400
Shale	1200
Basalt	600
Tuff	600
Bedded Salt	1200
Dome Salt	600

The reliability of subsurface mapping techniques is a function of: 1) the capability and experience of a qualified geologist, and 2) the scale of mapping. It should be emphasized that both considerable mapping and underground mapping experience are a requisite for this technique. Furthermore, the shaft rib and back mapping should be carefully correlated with surface mapping and core logging in all conceivable geologic respects, i.e., texture, grain size, alteration, mineralogy, etc., and available geophysical data to assure that no subtle geologic changes which might strongly affect the site integrity are overlooked.

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APPENDIX B-1

GRAVITY TECHNIQUE

BY

Ertec Western, Inc.

Long Beach, California

November 1, 1981

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NRC INFORMATION NEEDS

1.0 DESCRIPTION OF THE GRAVITY TECHNIQUE

1.1. Physical Principle

Gravity is the force of attraction between bodies because of their mass. Each particle of mass attracts every other particle of mass with a force whose magnitude is proportional to the product of their masses and inversely proportional to the square of the distance between them. The constant of proportionality is named the Universal Gravitational Constant.

$$F = \frac{GmM}{r^2}$$

where

F = force of attraction on m due to M (dynes)

G = Universal Gravitational Constant ($6.670.10^{-8}$ dyne $cm^2/gram^2$

m,M = two masses (grams)

r = distance between mass centers (centimeters)

The gravitational field strength of the earth often called "the attraction" or "gravitational acceleration," is

$$g = \frac{F}{m} = \frac{GM}{r^2}$$

M = mass of the earth

m = the attracted mass (e.g., the gravimeter sensing element)

g = 980 cm/sec^2 (very nearly)

The unit of cm/sec^2 is named the gal in honor of Galileo. The gal is inconveniently large for the small magnitudes encountered in gravity exploration--the milligal ($10^{-3}cm/sec^2$) is the unit commonly used in exploration.

The attraction is a vector, since it has both magnitude and direction. In gravity exploration, the vertical component of the attraction is used. The vertical component of attraction of a point mass M at depth z is:

$$G = \frac{GM}{r^2} \cdot \frac{Z}{r}$$

Mass (M) is equal to density (ρ) times volume (V) so the vertical attraction of an infinitesimal volume (dV) is:

$$dg_z = \frac{G\rho dV}{r^2} \cdot \frac{Z}{r}$$

The vertical attraction of a distributed mass is the sum of the contributions of all the infinitesimal volumes.

$$g_z = G\int \frac{z}{r^3} \rho dV$$

Where the density ρ is a function of location. In exploration for buried masses, ρ is the density contrast -- i.e., the difference in density between the mass of interest and its surroundings.

In sum, the vertical gravitational attraction depends on the geometric distribution of density. Horizontal density variations must exist in order to produce gravity anomalies which give information about the subsurface.

Corrections

There are further considerations when exploring on the planet Earth. It spins, and is not spherical, so that the measured values of gravity depend on latitude. The value of gravity at sea level, g_o, as a function of the latitude, L, is given by the geodetic formula for gravity on the International Ellipsoid as:

$$g_o = 978.0490(1+0.0052884\sin^2 L-0.0000059\sin^2 2L) \text{ gals.}$$

The rate of gravity increase with latitude is 1.307 sin2L milligals/mile with a maximum value of 1.307 milligals/mile at 45^o latitude.

For gravity measurements not made at sea level, one must account for the decrease of gravity with distance from the center of the earth. The magnitude of the decrease is 0.09406 milligals per foot of increased elevation. This is called the "free air" effect.

Of course, measurements made at elevations above sea level are not made in the air. There is a considerable amount of mass between the station and sea level. That mass increases the measured value of gravity by 0.1276ρ milligals per foot of material of density ρ. This is called the Bouguer effect. The total elevation correction E, accounts for both free air effect and Bouguer effect:

$$E = (0.09406 - 0.01276\rho)h$$

where

$$h = \text{elevation}$$

The correction E is added to the measured values of gravity to adjust them to a common reference at sea level. The corrected measurements minus the theoretical sea level gravity g_o are called the Simple Bouguer Anomaly (SBA).

Where there is substantial local topography it is necessary to correct for the effect of terrain. Terrain masses above the point of measurement decrease the measured gravity, and lack of mass below the point of measurement also decreases the measured gravity. The effect varies with distance from the station and the density of the material and is approximately proportional to the square of the average elevation difference of the area with respect to the point of measurement. When the terrain corrections are added to the SBA the result is the Complete Bouguer Anomaly (CBA). The anomalies of interest in gravity exploration are usually small perturbations of the CBA which must be separated by removal of the regional trend (Nettleton, 1954). The separated anomaly is called the residual. It is the form in which gravity data are analyzed and mathematically modeled. See, for example, Dobrin (1976) for a general discussion of gravity exploration.

1.2 Mathematical Modeling

Given the gravity observations and the evidence from geology, seismic surveys, drill logs, etc., the process of interpretation is as follows:

1. postulate the likely form of the anomaly source.
2. calculate the theoretical anomaly.
3. compare it with the residual gravity.
4. adjust the model iteratively until the theoretical gravity has approached the observed gravity to the desired degree of tolerance.

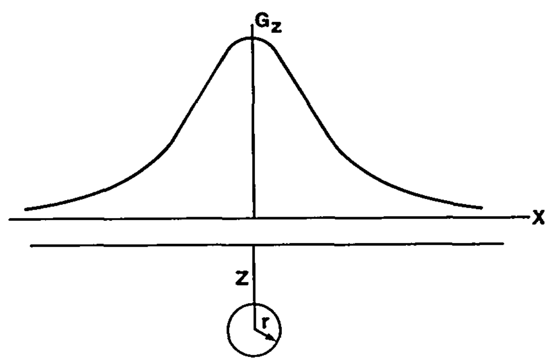
The theory of potential fields shows that there is not a unique solution to the problem. An infinite number of density distributions could create the same anomaly. Where a unique solution to a particular modeling problem exists, it is a consequence of the constraints imposed by the interpreter's choice of a model.

Mathematical models can be complex, but usually there is insufficient knowledge of the subsurface to justify a detailed model. The shape of a body is the least well defined of the characteristics affecting the anomaly (Romberg, 1958).

1.2.1 Sphere

A sphere model can closely approximate a density inhomogeneity whose dimensions are roughly equivalent, up to as much as 2 to 1 in ratio, especially if the dimensions are small compared with the depth. The expression for the vertical attraction of a sphere is (following Nettleton, 1971):

$$g_z = 8.52\,\sigma \frac{R^3}{z^2}\left[\frac{1}{(1+x^2/z^2)}\right]$$

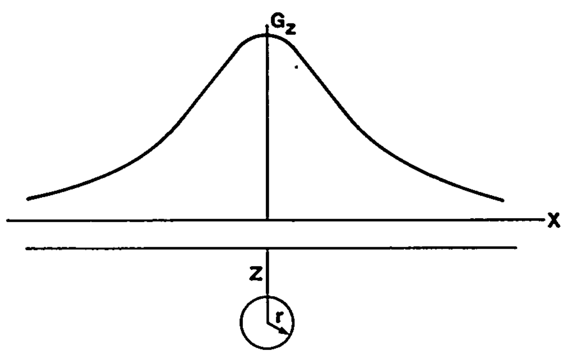


Where lengths are in kilofeet and density σ is in grams per cubic centimeter. The term in brackets gives the shape of the anomaly while the other gives the amplitude. The sphere is often used in modeling salt domes.

1.2.2 Horizontal Cylinder

A horizontal cylinder model approximates elongated bodies, especially when the long dimension is 3 or more times the length of the short dimension. The equivalent expression for the vertical attraction of a horizontal cylinder is:

$$g_z = \frac{12.77\,\sigma R^2}{z}\left[\frac{1}{1 + x^2/z^2}\right]$$

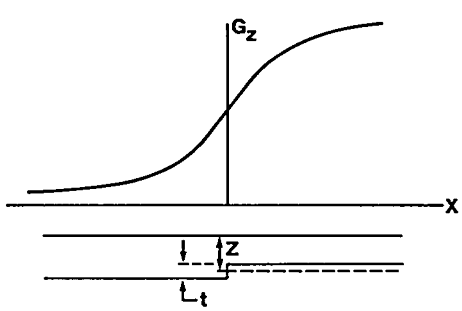


Linear maxima, or minima, anomalies could be created by narrow horst or graben-like features. Narrow anticlines and synclines can produce similar anomalies.

1.2.3 Thin Fault

A fault with small vertical throw t, in comparison to its depth can be treated as if all of its anomalous mass were condensed onto a median plane. The expression then is:

$$g_z = 12.77\,\sigma t\left(\tfrac{1}{2} + \frac{1}{\pi}\tan^{-1}\frac{x}{z}\right)$$



A practical rule of thumb (Nettleton, 1942) for estimating the total changes across a fault is 1 milligal for each 100 feet of unit density contrast material; or, t = (100/) g feet.

Other basic works which deal with gravity and modeling are Heiland (1940); Nettleton (1940), Garland (1965), and Grant and West (1965). Basic computer algorithms for modeling bodies of arbitrary shape are given by Talwani, Worzel, and Landisman (1959) for two-dimensional bodies (i.e., long bodies) and by Talwani and Ewing (1960) for three-dimensional bodies.

Constraints

Since gravity model solutions are guaranteed non-unique by potential theory, a great deal depends upon the interpreter. The interpreter must use all available information about depths and densities to constrain the models. The ideal information would be from a well-positioned set of drill holes logged by borehole gravimeter. Other types of density logs and core-sample densities are the second choice. Surface sample densities may not be representative of the bulk density at depth. Given the constraints of drill-hole data, mathematical gravity models will reliably interpolate between holes.

1.3 Geologic Sources of Gravity Anomaly

The geologic sources of gravity anomalies which are of interest for the purpose of nuclear waste containment are breaches of the host medium and boundaries of the host medium. Breaches include faults, fractures, and intrusions while boundaries include depths to top and bottom, and the lateral limits of the host medium.

A fault produces a gravity anomaly when it causes a vertical displacement of mass as when a stratigraphic throw parts a layer of contrasting density. An intrusion creates a gravity anomaly by introducing a local inhomogeneity of density, as in a dike or sill.

The boundaries of the host medium may be detected if there is local horizontal density variation as in the case of a salt dome, or where there is basement topography or intra-basement density changes, or where there is topography on the host medium.

1.3.1 Salt Dome

A salt dome produces a negative gravity anomaly approximately like that of a buried sphere. The anomaly is negative because the density of salt is about 2.2 gm/cm^3 while the surrounding sediment may be 2.3 gm/cm^3, thus the density contrast is -0.1 gm/cm^3.

The Humble Salt Dome in Harris County, Texas, is more than 20,000 feet in diameter and less than 2,000 feet below the surface, but its gravity anomaly is less than 14 milligals--only about 14 millionths of total gravity.

1.3.2 Bedded Salt, Tuff, and Shale

A horizontal layer of uniform thickness, whatever its density, does not create an anomaly in surface gravity. In order to estimate the depth to the top of a bed there would have to be significant topographic irregularities on it. In order to estimate depth to the bottom of a bed there would have to be large topographic irregularities on its base or abrupt intrabasement density changes.

The density of tuff and shale are both about 2.4 ± 0.3 gm/cm^3.

1.3.3 Granite

Granite batholiths and stocks create positive gravity anomalies since the density of granite is about 2.7 ± 0.1 gm/cm^3 while surrounding sediments are generally less. Compared to alluvium, the contrast may be as large as +0.6 gm/cm^3.

1.3.4 Basalt

Flood basalt layers, as in the Columbia Plateau of eastern Washington, do not produce gravity anomalies where they are layers of uniform thickness. Where flood basalts have inundated irregular topography it may be possible to estimate the depth to the irregular bottom of the flow.

The density of basalt is about 2.8 ± 0.2 gm/cm^3.

2.0 THE CONTRIBUTION OF GRAVITY

Gravity surveys are effective in detection and size estimation of large features such as:

- o Faults having vertical throw across layers with contrasting densities.
- o Igneous intrusions (dikes, sills).
- o Diapiric intrusions (salt domes, batholiths).

Gravity surveys may give some information about:

- o Depth to host rock--especially when calibrated by one or more drill-hole density logs.
- o Uplift or subsidence potential (isostatic anomaly).

Under special conditions gravity may indicate:

- o Extreme bedrock incision (but only with microgravity precision and extremely shallow depths).

3.0 RESOLUTION

3.1 Theoretical Resolution

Definitions (Sheriff, 1973) of resolution:

1. The ability to separate two features which are very close together. The minimum separation of two bodies before their separate identity is lost on the resultant map.

2. The smallest change in input that will produce a detectable change in output.

3. The ability to localize an event seen through a window; usually taken as the half width of the major lobe.

Definition 1 is related to precision (reproducibility): if a measurement process has small random errors, it is said to have high precision. The above definitions are unrelated to accuracy: if a measurement process has small systematic errors it is said to have high accuracy (Meyer, 1975). In analogy with target shooting, precision produces tight groups whereas accuracy puts the centers of the groups on the mark.

Definition 2 defines sensitivity which refers to the detection capabilities of instruments and also to total systems of measurement, processing, and interpretation.

Definition 3 refers to sampling theory and survey design.

3.2 Geologic Factors

Resolution is best for anomalies which are sharply localized and of large magnitude. The magnitude of gravity anomalies depends on:

a. The volume of the anomalous body.

b. The density contrast.

c. The geometric factor.

The sharpness depends mainly on c, the geometric parameter that has the greatest influence is depth. The ability to distinguish separate bodies strongly depends on the ratio of horizontal separation to depth (Romberg, 1958).

3.3 Measurement Factors

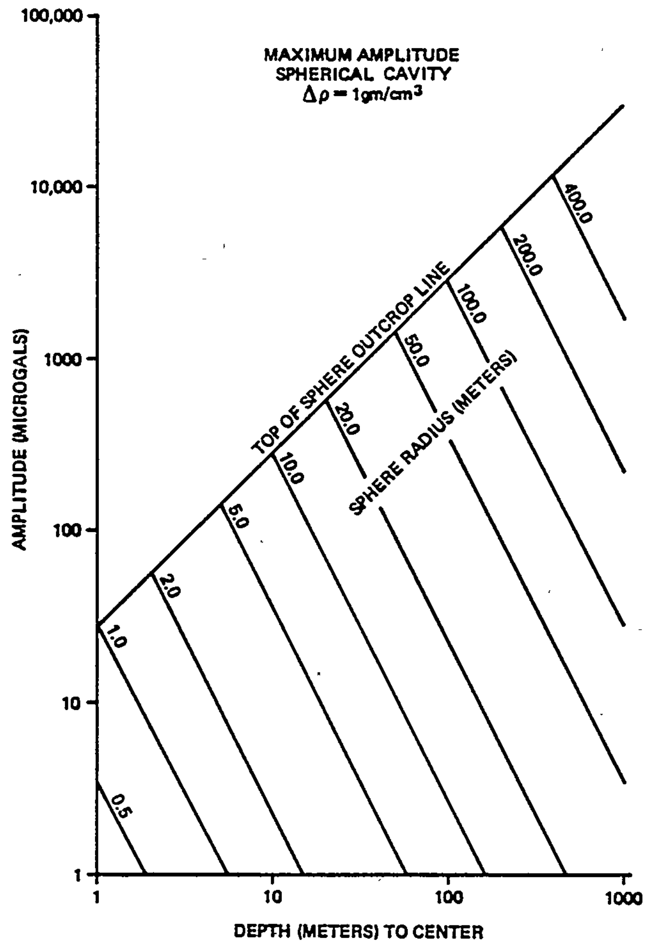
Measurement factors fall into two categories:

1. Instrument sensitivity (and noise).

2. Sampling density.

Gravity survey data is generally repeatable to 0.1 mgal, often to 0.05 mgal, and rarely to 0.01 mgal (LaFehr, 1980). Under ideal conditions in a careful micro-gravity survey anomalies of 3 to 5 microgals are detectable (LaFehr, 1979). Figures 1 and 2 show the anomaly amplitudes calculated for spheres and infinite horizontal cylinders of unit density contrast (cgs). Figure 3 shows the depths and diameters for which it is possible to detect concentrated anomalies (spheres). The figures are from LaFehr (1979).

Sampling density refers to the spacing of survey lines and measurements. The sample spacing required to detect an anomaly of wavelength L must be no greater than 1/2 L, the Nyquist wavelength. For reconnaissance, the sample spacing



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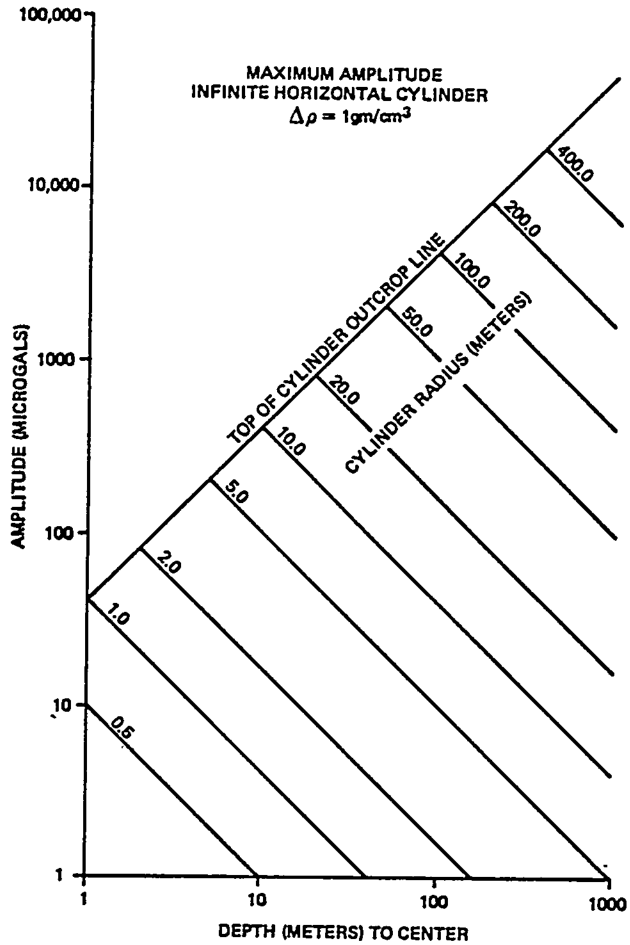
SURFACE ANOMALY-MAXIMUM AMPLITUDES DUE TO SPHERES OF UNIT DENSITY CONTRAST

5-81

FIGURE 1



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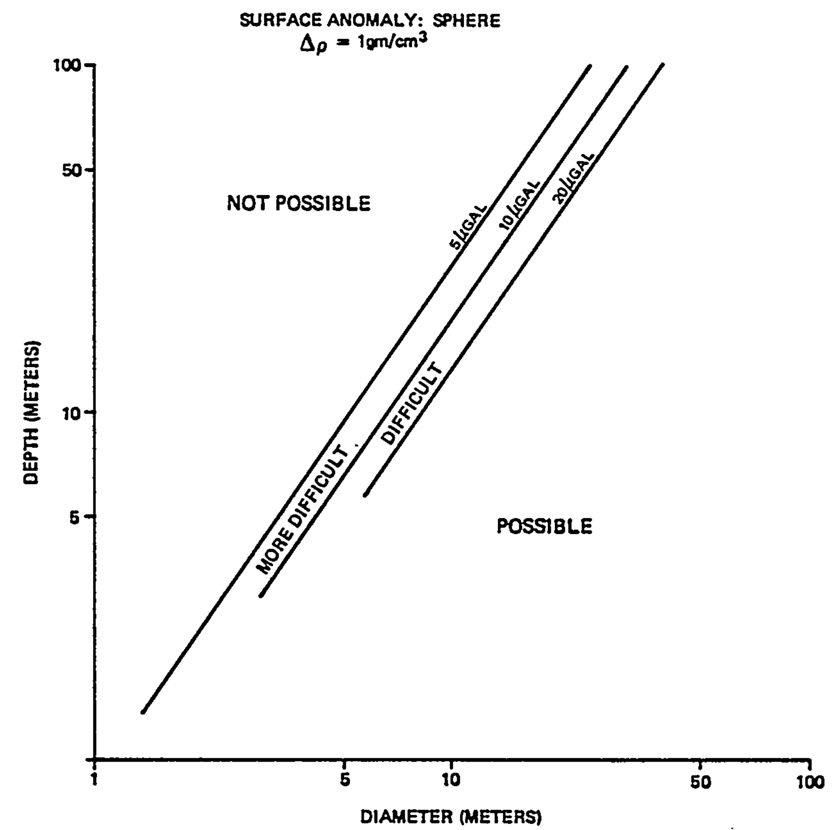
MAXIMUM AMPLITUDE, INFINITE HORIZONTAL CYLINDERS OF UNIT DENSITY CONTRAST

5-81

FIGURE 2



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DEPTH/DIAMETER RELATIONSHIP
FOR DETECTABLE /NON DETECTABLE
SPHERICAL BODIES OF
UNIT DENSITY CONTRAST

5-81 FIGURE 3

should not be much greater than the half-width (i.e., half the width of the anomaly at half its amplitude) of the smallest anomalies of interest. For the most concentrated anomaly, the sphere, this spacing is 77% of the depth. For a long cylindrical body, it equals the depth.

3.4 Data Processing Factors

Computer processing of gravity data generally requires the creation of a uniform grid of values from a more or less nonuniform distribution of field measurements. The grid spacinq affects resolution. For the best resolution the grid spacing should equal the average field spacing in well-covered areas.

The gridding process involves the use of a local-averaging operator to assign values to the grid points. The sharpness of its weighting function determines the graininess of the grid representation.

The isolation of anomalies by removal of the regional gravity trend is often accomplished by the use of various grid operators which are essentially filters. The high-pass filter response affects the resolution.

Further discrimination of anomalies is attempted by the construction of 1st and 2nd derivative maps. 1st derivative maps display slopes while 2nd derivative maps display curvature, both of which are intimately related to resolution.

Mathematical continuation of the measured gravity field downward toward the depth of the anomalous mass sharpens the anomaly, but also magnifies the noise contained in the data.

References for this section are Nettleton (1971), Dobrin (1976), and Fuller (1967).

3.5 Noise Factors

Noise in geophysical surveys is of three types:

1. instrument noise.
2. disturbance field noise.
3. terrain noise.

Instrument noise has been made lower than the threshold of other noise sources and is now unimportant. The disturbance field noise for gravity is earth tides. The terrain noise includes geologic noise, topographic noise and location errors. Geologic noise is caused by incomplete topographic correction due to lack of detailed knowledge of the subsurface density distribution. Location errors include elevation errors and latitude correction errors. The order of magnitude of average terrain noise is about 0.05 mgals. Reference for this section: Ward and Rogers (1967).

4.0 RELIABILITY

4.1 Reliability of the Gravity Method

The reliability of the results of gravity surveys depends on the amount of independent evidence available concerning geologic structure and formation densities. A single borehole gravimeter log would serve to calibrate a surface gravity survey over a considerable area. Correlation with seismic and magnetic surveys may greatly reduce ambiguity. Joint gravity-magnetic analysis yields more information than both methods applied separately.

4.2 Factors That Reduce Reliability

The anomaly-to-noise ratio and the lack of detailed density information are the main factors that reduce reliability.

4.3 "No-Record" Situations

A "no-record" situation in a gravity survey is caused by a lack of density contrast--the target density being not significantly different than its surroundings. Uniform horizontal layering, whatever the densities, also produces no anomalies.

4.4 Reliability Table

The above considerations can be summarized in a table:

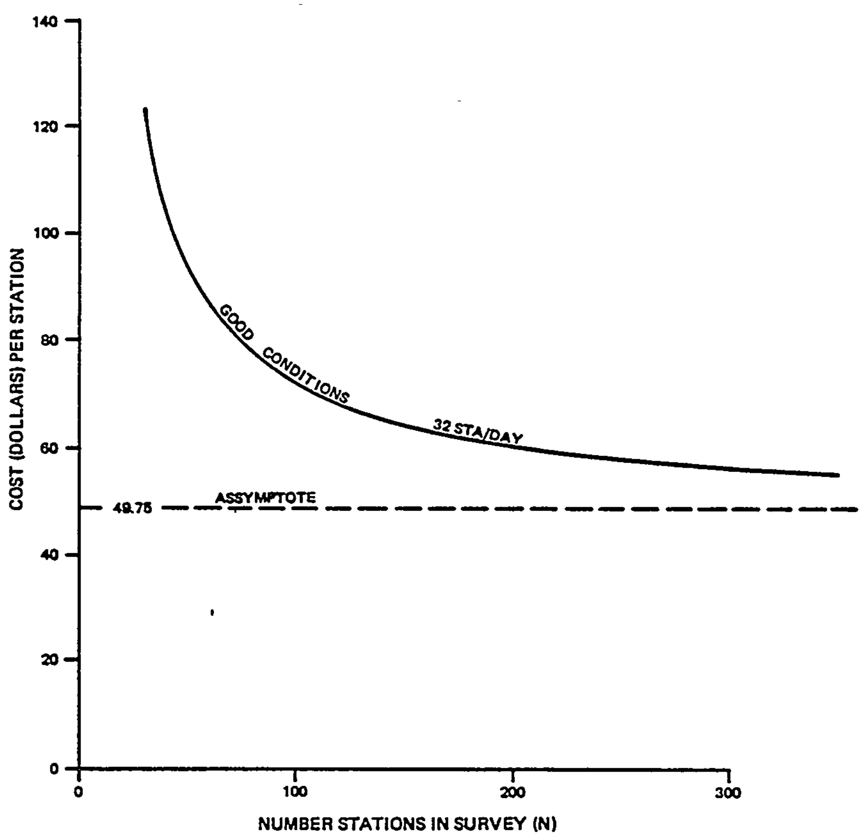
FACTOR	RELIABILITY Most	Intermediate	Least
Anomalous volume	great	intermediate	small
Density contrast	great	intermediate	small
Depth	shallow	intermediate	deep
Concentration	sphere	lens	thin layer
Density from	borehole gravimete	density logs, core samples	generalized tables, surface samples
structure from	drill logs	seismic, magnetic, resistivity	geologic inference alone

5.0 COSTS

The cost of a gravity survey depends on the number of stations and their separation, the terrain, the weather, the location of the survey, and other factors. All costs presented herein are in 1981 dollars. Under good conditions a surveying crew of two, and a gravimeter crew of two, using two vehicles, with station separation of a mile or less, can do about 30 stations per day at a cost of about $50 per station.

The estimate is based on experience. The cost may be divided into fixed costs (mobilization) and daily costs (salary, subsistence, equipment costs). For example, with a fixed cost of $2,400 and a daily cost of $1,560 with a production rate of 32 stations per day, the cost per station versus the number of stations is shown graphically in Figure 4.

The time required for such a survey is exemplified in Figure 5.



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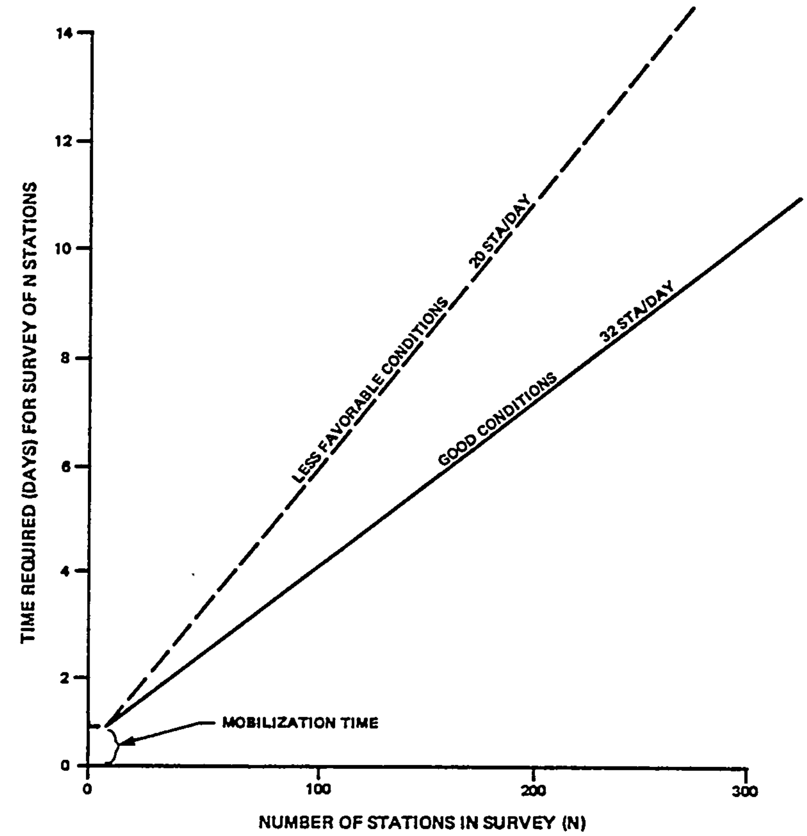
COST OF GRAVITY SURVEY

5-81

FIGURE 4



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TIME REQUIRED FOR GRAVITY SURVEY

5-81

FIGURE 5

In rugged terrain requiring helicopter access, station costs are on the order of $250.00.

6.0 CRITERIA FOR GRAVITY SURVEYS

The most important criteria are the choice of a sampling pattern and the precision of the station gravity values. The sampling pattern for reconnaissance should be as near to a square-gridded network as is feasible. The grid spacing should not be greater than the half-width of the anomaly of interest.

The precision of the reduced data should be such that two standard deviations of the normal distribution of error is less than the half-height ofthe anomaly of interest (then at least 95% of the observations can detect the anomaly). For example, if the usual standard deviation is about 0.05 mgals, then 0.10 mgals would be the half-height of the detectable anomaly. Estimating from Figures 1 and 2, that size of the anomaly is equivalent to a unit-density-contrast sphere o radius 200m (or a horizontal cylinder of radius 80m) at 1000m depth-to-center. The half-width of the sphere anomaly is about 77% of 1000m so that the grid spacing should be 770 m or less.

A surveying error of 1 foot of elevation will produce a a gravity error of 0.07 mgal. A latitude error of 100 feet will produce a gravity error of 0.03 mgals at mid-latitudes. Thus, elevations need to be known to about 0.1 feet and latitude to about 10 feet for precise results.

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TABLE 1

APPLICABILITY OF THE GRAVITY METHOD TO THE IDENTIFICATION AND DEFINITION OF SUBSURFACE GEOLOGIC FEATURES

I FEATURES ASSOCIATED WITH ONE OR MORE HORIZONTAL PLANES		RANKING 1	2	3	4
A. DEPTH TO:	1. BEDDED SALT			X	
	2. SHALE			X	
	3. BASALT			X	
	4. TUFF			X	
	5. WATER TABLE				X
	6. BEDROCK			X	
	7. BASEMENT			X	
	8. ANGULAR UNCONFORMITY		X		
	9. PARACONFORMITY				X
	10. LOW-ANGLE FAULT			X	
B. THICKNESS OF:	1. BEDDED SALT				X
	2. SHALE				X
	3. BASALT				X
	4. TUFF				X
	5. OVERBURDEN				X
	6. SEDIMENTARY STRATUM IN GENERAL				X
	7. SILL				X
C. ANGLE OF:	1. INCLINED STRATA				X
	a. LIMB OF ANTICLINE OR SYNCLINE			X	
	b. MONOCLINE OR HOMOCLINE			X	
	2. LOW-ANGLE FAULT			X	
	3. AXIAL PLANE OF RECUMBENT FOLD				X

TABLE 1, GRAVITY (CONT'D)

		Ranking 1	2	3	4
II. FEATURES ASSOCIATED WITH ONE OR MORE VERTICAL PLANES					
A. LOCATION OF:	1. HIGH-ANGLE FAULT	X			
	2. FRACTURE ZONE		X		
	3. BRECCIA ZONE			X	
	4. IGNEOUS INTRUSIVE CONTACT	X			
	5. SALT DOME CONTACT	X			
B. WIDTH OF:	1. DIKE	X			
	2. FRACTURE ZONE		X		
	3. BRECCIA ZONE			X	
	4. SALT DOMES	X			
C. ANGLE OF:	1. FAULT PLANE		X		
	2. IGNEOUS INTRUSIVE CONTACT		X		
	3. SALT DOME CONTACT		X		
	4. AXIAL PLANE OF NORMAL FOLD			X	
III. OTHER FEATURES					
A. DEPTH TO:	1. BURIED EROSIONAL SURFACE		X		
	2. IGNEOUS INTRUSIVE BODY	X			
	3. SALT DOME	X			
	4. SOLUTION FEATURES				X
	5. MASSIVE SULFIDE DEPOSIT		X		

TABLE 1, GRAVITY (CONT'D)

B. DETERMINATION OF:		RANKING 1	2	3	4
	1. ROCK TYPE			X	
	a. BEDDED SALT			X	
	b. SHALE			X	
	c. BASALT			X	
	d. TUFF			X	
	e. GRANITE			X	
	2. GEOTHERMAL CONDITIONS			X	

KEY TO RANKING

1. FREQUENTLY APPLICABLE
2. OCCASIONALLY APPLICABLE
3. SELDOM APPLICABLE
4. NOT APPLICABLE

TABLE 2

DETECTABILITY OF GEOLOGIC FEATURES AND ACCURACY OF SUBSURFACE MEASUREMENTS USING THE GRAVITY METHOD

NOTE: 1. CONTRAST IS DENSITY CONTRAST
2. SEE END OF CHART FOR KEY TO RANKING

		LOW CONTRAST				MEDIUM CONTRAST				HIGH CONTRAST			
		0-5M	5-300 M	300-900M	> 900 M	0-5 M	5-300 M	300-900 M	> 900 M	0-5 M	5-300 M	300-900 M	> 900 M
I. DEPTH TO:	1. BEDDED SALT	5	4	4	4	5	4	4	4	5	4	4	4
	2. SALT DOME	5	4	4	4	5	3	3	3	5	3	3	3
	3. SHALE	5	4	4	4	5	4	4	4	5	4	4	4
	4. BASALT	5	4	4	4	5	4	4	4	5	4	4	4
	5. TUFF	5	4	4	4	5	4	4	4	5	4	4	4
	6. GRANITE	5	4	4	4	5	4	4	4	5	4	4	4
	7. BURIED EROSIONAL SURFACE	5	4	4	4	5	4	4	4	5	4	4	4
	8. WATER TABLE	5	5	5	5	5	5	5	5	5	5	5	5
	9. BEDROCK	5	4	4	4	5	4	4	4	5	4	4	4
	10. BASEMENT	5	4	4	4	5	4	4	4	5	4	4	4
	11. CONTACT	5	5	5	5	5	5	5	5	5	5	5	5
	12. ANGULAR UNCONFORMITY	5	4	4	4	5	4	4	4	5	4	4	4
	13. PARACONFORMITY	5	5	5	5	5	5	5	5	5	5	5	5
	14. LOW ANGLE FAULT	5	4	4	4	5	4	4	4	5	4	4	4
II. ANGLE OF:	1. INCLINED STRATA	5	5	5	5	5	5	5	5	5	5	5	5
	2. LIMB OF ANTICLINE OR SYNCLINE	5	5	5	5	5	4	4	4	5	4	4	4
	3. MONOCLINE OR HOMOCLINE	5	5	5	5	5	4	4	4	5	4	4	4
	4. FAULT PLANE	5	5	5	5	5	4	4	4	5	4	4	4
	5. AXIAL PLANE OF FOLD	5	5	5	5	5	5	5	5	5	5	5	5
	6. IGNEOUS INTRUSIVE CONTACT	5	5	5	5	5	4	4	4	5	4	4	4
	7. SALT DOME CONTACTS	5	5	5	5	5	4	4	4	5	4	4	4

TABLE 2, GRAVITY (CONT'D)

	LOW CONTRAST				MEDIUM CONTRAST				HIGH CONTRAST			
	0-5 M	5-300 M	300-900 M	> 900 M	0-5 M	5-300 M	300-900 M	> 900 M	0-5 M	5-300 M	300-900 M	> 900 M
III. SIZE OF: 1. SOLUTION FEATURE	5	5	5	5	5	5	5	5	5	5	5	5
2. MASSIVE SULFIDE DEPOSIT	5	4	4	4	5	4	4	4	5	3	4	4
3. SALT DOME	5	4	4	4	5	4	4	4	5	4	4	4
4. FAULT OFFSET	5	4	4	4	5	3	3	3	5	3	3	3

KEY TO RANKING

I. ACCURACY OF DEPTH

1. ± 1-5% OF DEPTH
2. ± 5-15% OF DEPTH
3. ± 15-30% OF DEPTH
4. ± > 30% OF DEPTH
5. NOT DETECTABLE

II. ACCURACY OF ANGLE

1. ± 1-5 DEGREES
2. ± 5-15 DEGREES
3. ± 15-30 DEGREES
4. ± > 30 DEGREES
5. NOT DETECTABLE

III. MINIMUM SIZE FOR DETECTION

1. TINY (1 CM - 1 M)
2. SMALL (1 M - 9 M)
3. MEDIUM (10 M - 99 M)
4. LARGE (> 100 M)
5. NOT DETECTABLE

TABLE 3

RELIABILITY OF IDENTIFICATION OF
GEOLOGIC FEATURES USING THE GRAVITY METHOD

NOTE: 1. CONTRAST IS DENSITY CONTRAST
2. SEE END OF CHART FOR KEY TO RANKING

	LOW CONTRAST				MEDIUM CONTRAST				HIGH CONTRAST			
	0-5 M	5-300 M	300-900 M	> 900 M	0-5 M	5-300 M	300-900 M	> 900 M	0-5 M	5-300 M	300-900 M	> 900 M
I. HORIZONTAL FEATURES												
1. BURIED EROSIONAL SURFACE	4	3	3	4	4	3	3	3	4	3	3	3
2. WATER TABLE	4	4	4	4	4	4	4	4	4	4	4	4
3. BEDROCK	4	3	3	4	4	3	3	3	4	3	3	3
4. BASEMENT	4	3	3	4	4	3	3	3	4	3	3	3
5. CONTACT	4	4	4	4	4	4	4	4	4	4	4	4
6. ANGULAR UNCONFORMITY	4	3	3	4	4	3	3	3	4	3	3	3
7. PARACONFORMITY	4	4	4	4	4	4	4	4	4	4	4	4
8. LOW-ANGLE FAULT	4	3	3	4	4	3	3	3	4	3	3	3
9. INCLINED STRATA	4	4	4	4	4	4	4	4	4	4	4	4
9a. LIMB OF ANTICLINE OR SYNCLINE	4	3	3	4	4	2	2	3	4	2	2	3
9b. MONOCLINE OR HOMOCLINE	4	3	3	4	4	2	2	3	4	2	2	3
II. VERTICAL FEATURES												
1. HIGH-ANGLE FAULT	4	2	2	2	4	1	1	1	4	1	1	1
2. FRACTURE ZONE	4	3	3	4	4	2	2	3	4	2	2	3
3. BRECCIA ZONE	4	3	3	4	4	2	2	3	4	2	2	3
4. IGNEOUS INTRUSIVE CONTACT	4	2	2	3	4	1	1	2	4	1	1	1
5. SALT DOME CONTACT	4	2	2	2	4	1	1	1	4	1	1	1
6. DIKE	4	2	2	3	4	1	1	2	4	1	1	1

TABLE 3, GRAVITY (CONT'D)

	LOW CONTRAST				MEDIUM CONTRAST				HIGH CONTRAST			
	0-5 M	5-300 M	300-900 M	> 900 M	0-5 M	5-300 M	300-900 M	> 900 M	0-5 M	5-300 M	300-900 M	> 900 M
III. OTHER FEATURES												
1. IGNEOUS INTRUSIVE BODY	4	2	2	2	4	1	1	1	4	1	1	1
2. SALT DOME	4	2	2	2	4	1	1	1	4	1	1	1
3. SOLUTION FEATURES	4	4	4	4	4	4	4	4	4	4	4	4
4. MASSIVE SULFIDE DEPOSIT	4	3	3	4	4	2	2	3	4	2	2	2
IV. COMPOSITION												
1. BEDDED OR DOMED SALT	4	3	3	3	4	3	3	3	4	2	2	2
2. SHALE	4	4	4	4	4	4	4	4	4	4	4	4
3. BASALT	4	4	4	4	4	3	3	3	4	2	2	2
4. TUFF	4	4	4	4	4	4	4	4	4	4	4	4
5. GRANITE	4	4	4	4	4	3	3	3	4	2	2	2
6. ROCK TYPE IN GENERAL	4	4	4	4	4	3	3	3	4	3	3	3

KEY TO RANKING

1. GOOD RELIABILITY (ONE OR TWO POSSIBLE INTERPRETATIONS)
2. FAIR RELIABILITY (THREE OR FOUR POSSIBLE INTERPRETATIONS)
3. POOR RELIABILITY (FIVE OR MORE POSSIBLE INTERPRETATIONS)
4. NOT IDENTIFIABLE

APPENDIX B-2

AUDIO-FREQUENCY MAGNETOTELLURIC TECHNIQUE

B-2

BY

Ertec Western, Inc.

Long Beach, California

November 1, 1981

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AUDIO-FREQUENCY MAGNETOTELLURIC TECHNIQUE (AMT)

1.0 DESCRIPTION

1.1 Purpose

The audio-frequency magnetotelluric technique (AMT) is a method of exploration that determines earth resistivities from measurements of electromagnetic wave components. Its purpose is to determine the subsurface distribution of resistivity values, so that interpreters, using the values, may determine the subsurface distribution of rock units and geologic features, such as faults and fracture zones.

The AMT method is capable of yielding useful results for depths ranging from several meters to several thousand meters. However, because other resistivity methods provide better resolution at shallow depths, the AMT method is particularly useful when relatively deep soundings are desired. It is also useful in penetrating surface, or near-surface, high resistivity cover that is difficult for other resistivity methods.

1.2 Principle

If an electromagnetic wave impinges on the earth's surface, it will penetrate the surface and propagate to a depth which depends on the frequency of the wave, the resistivity of the ground and the magnetic permeability of the ground. A wave which has propagated to the depth at which it has approximately 37 percent of the strength it had at the surface is said to have penetrated to one "skin depth."

The expression for skin depth is:

$$S = \sqrt{\frac{p}{\pi u f}},$$

where

S is skin depth in meters

p is resistivity in ohm-meters

f is frequency in hertz

u is magnetic permeability in henries per meter

If the resistivity of the ground is measured at a point on the surface of the earth, it will reflect the resistivity of the ground below that point to a depth proportional to the skin depth associated with the frequency at which the resistivity measurement was made. If, then, the resistivity is measured at the same point but at a lower frequency, the new resistivity value will reflect the resistivity of the ground to a greater depth, which is proportional to the new skin depth. The difference between the first resistivity measured and the second resistivity measured will be an indication of the resistivity of that vertical interval of ground between the two skin depths. By measuring resistivities over a range of frequencies (approximately 10 hertz to 10,000 hertz) and plotting the values against frequency, a resistivity sounding curve can be made, an example of which is shown in Figure 1.

For an impinging wave of a particular frequency, the associated resistivity is determined by measuring the wave's horizontal electric field in one direction and, simultaneously, the wave's horizontal magnetic field at 90 degrees to that direction. The ratio of these two measurements is then used in the following expression to give the apparent resistivity:

$$p \text{ (apparent)} = \frac{1.26 \times 10^5 \times (E/H)^2}{f},$$

where E, the electric field, is in volts per meter; H, the magnetic field, is in ampere-turns per meter; f is in hertz; and p is in ohm-meters (Strangway, et al, 1973).

1.3 Source of Electromagnetic Waves

The source of the electromagnetic waves is primarily lightning discharges associated with thunderstorms constantly occurring somewhere around the world. The energy from these storms is propagated through the cavity between the ionosphere and the earth's surface to all points on the earth. At a given point, such energy, in the form of horizontally polarized plane waves, impinges on the surface with a range of frequencies that includes the 10 hertz to 10,000 hertz spectrum on which the AMT method is based. The energy

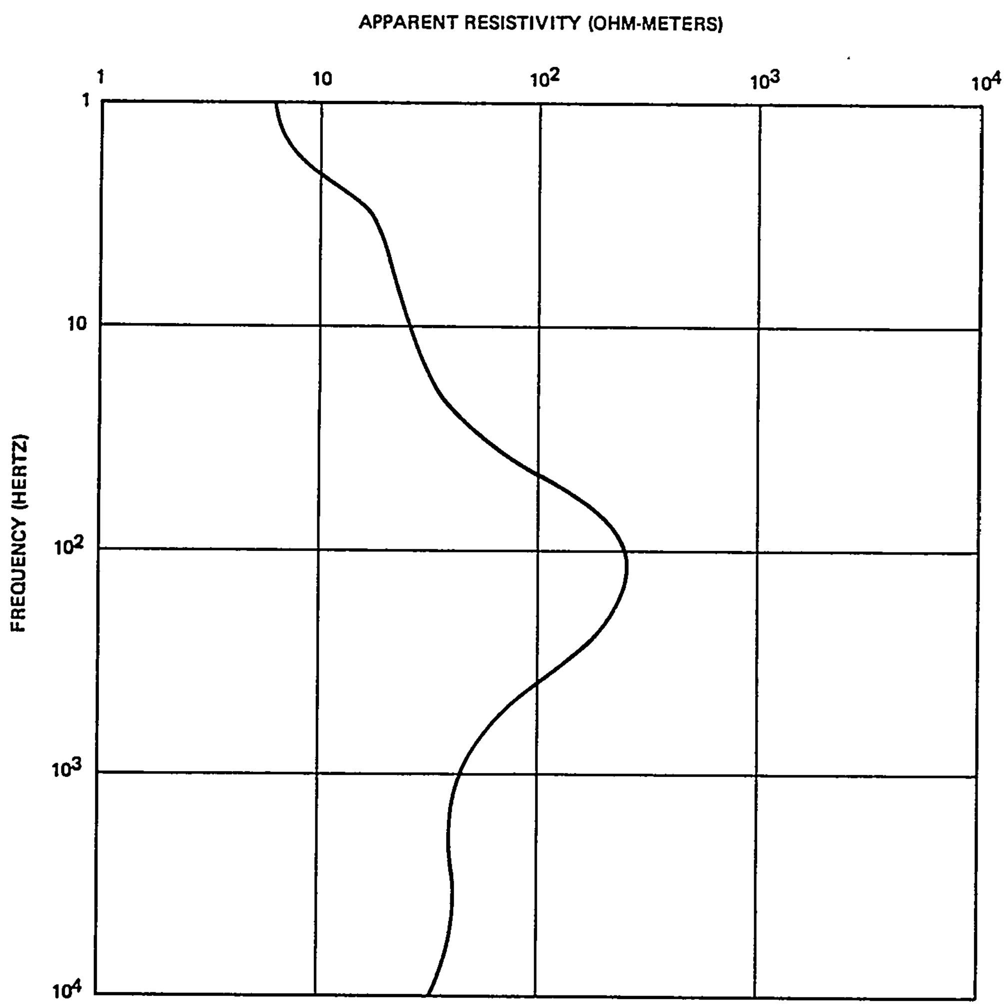

FIGURE 1 AMT SOUNDING CURVE

content of the waves varies with frequency, but such variations do not affect AMT results, since the ratio, E/H, is independent of the energy content.

1.4 Field Method

With the AMT method, resistivity soundings are made at a number of nearby points and correlations are made between adjacent points.

The electric field, E, is determined by placing two electrodes in the ground approximately 15 to 30 meters apart, depending on the strength of the EM waves, and measuring the potential difference between them at the desired frequency.

The magnetic field, H, is determined with a highly sensitive magnetometer placed in the ground. This may be a coil of many turns, whose long axis is oriented perpendicular to a line between the electric field electrodes.

If the orientation of the electric field and magnetic field sensors is not aligned with the dominant geologic structure, then the apparent resistivity measured is not strictly valid. In such cases, additional measurements of both fields are required for a complete description of the magnetotelluric impedance and a valid determination of the apparent resistivity. The additional measurements are usually made at 90 degrees to the first set of measurements.

2.0 APPLICABILITY TO INFORMATION NEEDS

2.1 General

The AMT method is useful in defining geologic features and phenomena that exhibit significant resistivity contrasts between themselves and adjacent or surrounding media. The method is, therefore, generally applicable to the same things that other resistivity methods are applicable to. However, with respect to such methods, AMT has several important advantages, which are listed below:

1. AMT can penetrate high-resistivity surface layers more effectively;

2. AMT can penetrate to greater depths; and

3. AMT provides better resolution at greater depths.

These advantages make the AMT method the most practical resistivity method for exploring at depths between about 300 meters and 2 kilometers.

Applications of the magnetotelluric (and AMT) method have been suggested by Cagniard (1953) and described by Dobrin (1960), Niblett and Sayn-Wittgenstein (1960), Rankin (1962), Reddy and Rankin (1971), Srivastava (1963, 1965, 1967), Vozoff (1972), and others. These applications pertain mostly to horizontal features, but several pertain to vertical features.

2.2 Horizontal Features

Probably the best application of the AMT method is to those geologic features that are, or are close to, horizontal and have vertical resistivity contrasts. An example is stratified rocks, such as a flat-lying section of sedimentary rocks. Thus, AMT may be useful in sounding a sedimentary basin of intermediate depth. Another example is low-angle discontinuities, such as a low-angle fault. AMT may be useful in locating thrust faults.

2.3 Vertical Features

A single AMT sounding will not define nor locate vertical geologic features, such as a vertical fault. However, by using two or more soundings located closely enough together, such features may be recognized.

As indicated in Section 1.4, in the vicinity of pronounced geologic structure, which may include vertical geologic features, the apparent resistivities may be influenced by the orientation of the sensors. In such cases, it may be necessary to orient the sensors parallel to the structures or make additional measurements at 90 degrees to the original orientation.

2.4 Applicability to Host Media

In general, because of a lack of resistivity contrast, those geologic features that occur completely within the subject host media would not be detectable by the AMT method.

Important exceptions may be faults, fractures, joints and other porous and permeable features that could contain moisture and, therefore, exhibit low resistivity with respect to the medium in which they occur.

The following comments relate to the applicability of the AMT method to the individual media in a gross sense.

a. Bedded salt - large resistivity contrasts may be expected between bedded salt and overlying and underlying strata. If the salt bed is moist or water-saturated, it would have extremely low resistivity. If the salt bed is very dry, it would have high resistivity. In either case, it would likely be differentiable from its surroundings.

b. Domed salt - domed salt also occurs bounded by sedimentary strata. Therefore, the comments made about bedded salt are applicable to domed salt as well.

c. Shale - because of its ability to absorb and retain moisture, shale usually has low resistivity, on the order of 2×10^2 ohm-meters, the value depending primarily on the degree of water-saturation. Limestones and sandstones, on the other hand, range as high as 10^8 ohm-meters (Telford, et al, 1975). Therefore, it is likely that a shale unit, bounded by coarser-grained strata, would be detectable and differentiable. This may not be true, however, if the entire sedimentary section is saturated with water having a high salt content. Such water may then mask intrinsic resistivity contrasts.

d. Granite - unless it is faulted, fractured or jointed, a granite body, primarily because of its intrinsically low porosity and permeability, would have intermediate to high resistivity (3×10^2-10^6 ohm-meters (Telford, et al, 1976). Thus, it is likely that a granite body would be differentiable from its surroundings. Because of the textural and structural homogenity of granite and its relatively high resistivity, ruptures of the granite, such as faults and fractures, that result in increased porosity and permeability may be detectable, depending on size, depth and other factors.

e. Tuff - because of the variability of the petrological characteristics of tuff, it is difficult to generalize about the applicability of the AMT method to detecting this type of rock. But, precisely because of this variability, any AMT interpretation with respect to tuff would be relatively unreliable.

f. Basalt - like tuff, the petrological nature of basalt is highly variable, ranging from "tight", unfractured rock to highly permeable fractured and/or vesicular basalt. The resistivity of such rock has a very broad range, and, consequently, AMT interpretations would be ambiguous and generally unreliable.

2.5 Resistivities of Host Media

As indicated above, the host medium have resistivities that are variable. Listed below are the ranges of resistivity that may be expected for each medium.

Medium	Resistivity (ohm-meters)
Salt	1(wet) - 10^6 (dry)
Shale	$2 \times 10^1 - 10^3$
Granite	$3 \times 10^2 - 10^6$
Tuff	$2 \times 10^3 - 10^5$
Basalt	$3 \times 10^2 - 10^7$

2.6 Applicability Chart

Table 1 shows which geologic features and parameters the AMT method is potentially applicable to. The actual applicability in a specific situation would depend on a number of factors, which are discussed in the following section.

3.0 DETECTABILITY AND RESOLUTION BY THE AMT METHOD

Whether or not a geologic feature or parameter is detectable by the AMT method depends on several factors. These are listed below.

a. The resistivity contrast between the geologic feature or parameter and the adjacent or surrounding media. Other factors being constant, a feature exhibiting a large resistivity contrast is more easily detectable and its dimensions resolvable than the same feature with a marginal resistivity contrast.

TABLE 1

APPLICABILITY OF THE AMT METHOD TO THE IDENTIFICATION AND DEFINITION OF SUBSURFACE GEOLOGIC FEATURES

I FEATURES ASSOCIATED WITH ONE OR MORE HORIZONTAL PLANES

		RANKING 1	2	3	4
A. DEPTH TO:	1. BEDDED SALT	X			
	2. SHALE	X			
	3. BASALT	X			
	4. TUFF		X		
	5. WATER TABLE		X		
	6. BEDROCK	X			
	7. BASEMENT	X			
	8. ANGULAR UNCONFORMITY	X			
	9. PARACONFORMITY		X		
	10. LOW-ANGLE FAULT		X		
B. THICKNESS OF:	1. BEDDED SALT		X		
	2. SHALE		X		
	3. BASALT		X		
	4. TUFF			X	
	5. OVERBURDEN		X		
	6. SEDIMENTARY STRATUM IN GENERAL		X		
	7. SILL		X		
C. ANGLE OF:	1. INCLINED STRATA			X	
	a. LIMB OF ANTICLINE OR SYNCLINE			X	
	b. MONOCLINE OR HOMOCLINE			X	
	2. LOW-ANGLE FAULT			X	
	3. AXIAL PLANE OF RECUMBENT FOLD			X	

TABLE 1, AMT (CONT'D)

			RANKING 1	2	3	4
II. FEATURES ASSOCIATED WITH ONE OR MORE VERTICAL PLANES						
	A. LOCATION OF:	1. HIGH-ANGLE FAULT		X		
		2. FRACTURE ZONE		X		
		3. BRECCIA ZONE			X	
		4. IGNEOUS INTRUSIVE CONTACT		X		
		5. SALT DOME CONTACT		X		
	B. WIDTH OF:	1. DIKE			X	
		2. FRACTURE ZONE			X	
		3. BRECCIA ZONE			X	
		4. SALT DOMES		X		
	C. ANGLE OF:	1. FAULT PLANE			X	
		2. IGNEOUS INTRUSIVE CONTACT			X	
		3. SALT DOME CONTACT			X	
		4. AXIAL PLANE OF NORMAL FOLD				X
III. OTHER FEATURES						
	A. DEPTH TO:	1. BURIED EROSIONAL SURFACE				X
		2. IGNEOUS INTRUSIVE BODY	X			
		3. SALT DOME	X			
		4. SOLUTION FEATURES		X		
		5. MASSIVE SULFIDE DEPOSIT	X			

TABLE 1, AMT (CONT'D)

		RANKING 1	2	3	4
B. DETERMINATION OF:	1. ROCK TYPE			X	
	a. BEDDED SALT			X	
	b. SHALE			X	
	c. BASALT			X	
	d. TUFF			X	
	e. GRANITE			X	
	2. GEOTHERMAL CONDITIONS		X		

KEY TO RANKING

1. FREQUENTLY APPLICABLE
2. OCCASIONALLY APPLICABLE
3. SELDOM APPLICABLE
4. NOT APPLICABLE

b. The <u>size</u> of the feature. A large feature may be detectable at relatively great depth, even with a moderate resistivity contrast.

c. The <u>depth</u> of the feature. Since the apparent resistivity measured at the surface is a composite of all resistivities down to a depth determined by the frequency at which the measurement was made, the deeper a feature is, the more difficult it is to detect and measure.

d. <u>The number and spacing of stations</u>. This factor is a controllable factor and is determined by a number of considerations, including cost. From a technical point of view, the number and spacing of stations is determined by the objective of the survey. In general, it is desirable to use enough closely spaced stations (0.5 to several kilometers) to be able to corroborate the existence of a feature, to establish its continuity, if such exists, and to reduce or eliminate statistical aberrations.

e. <u>The number of frequencies</u> at which the apparent resistivities are measured. It is clear from a consideration of the AMT principle that resistivities should be measured at closely spaced frequencies, sufficient to enable the plotting of a smooth, continuous profile. Such spacing will be determined to some extent by the rapidity with which resistivity values change.

Table 2 is entitled "Detectability of Geologic Features." It indicates which geologic features and parameters are detectable and resolvable by the AMT method.

4.0 RELIABILITY OF THE METHOD

Interpretation of AMT results may be aided by comparing sounding curves with theoretical curves. Figure 2 (from Strangway, 1973) shows an example of a two-layer configuration. Other configurations, including three- and four-layer configurations, have been developed.

If a geologic situation differs appreciably from the model an interpreter is attempting to apply, the interpretation, obviously, will not be reliable. It is, therefore, important to know as much about the general geologic situation as possible before attempting to apply a particular model.

TABLE 2

DETECTABILITY OF GEOLOGIC FEATURES AND ACCURACY OF SUBSURFACE MEASUREMENTS USING THE AMT METHOD

NOTE: 1. CONTRAST IS RESISTIVITY CONTRAST
2. SEE END OF CHART FOR KEY TO RANKING

		LOW CONTRAST 1.1-2.5/1				MEDIUM CONTRAST 2.5-10/1				HIGH CONTRAST 10+/1			
		0-5M	5-300 M	300-900M	> 900 M	0-5 M	5-300 M	300-900 M	> 900 M	0-5 M	5-300 M	300-900 M	> 900 M
I. DEPTH TO:	1. BEDDED SALT	3	4	5	5	2	3	4	5	1	2	3	4
	2. SALT DOME	3	4	5	5	2	3	4	5	1	2	3	4
	3. SHALE	3	4	5	5	2	3	4	5	1	2	3	4
	4. BASALT	3	4	5	5	2	3	4	5	1	2	3	4
	5. TUFF	3	4	5	5	2	3	4	5	1	2	3	4
	6. GRANITE	3	4	5	5	2	3	4	5	1	2	3	4
	7. BURIED EROSIONAL SURFACE	3	4	5	5	2	3	4	5	1	2	3	4
	8. WATER TABLE	3	4	5	5	2	3	4	5	1	2	3	4
	9. BEDROCK	3	4	5	5	2	3	4	5	1	2	3	4
	10. BASEMENT	3	4	5	5	2	3	4	5	1	2	3	4
	11. CONTACT	3	4	5	5	2	3	4	5	1	2	3	4
	12. ANGULAR UNCONFORMITY	3	4	5	5	2	3	4	5	1	2	3	4
	13. PARACONFORMITY	3	4	5	5	2	3	4	5	1	2	3	4
	14. LOW ANGLE FAULT	3	4	5	5	2	3	4	5	1	2	3	4
II. ANGLE OF:	1. INCLINED STRATA	3	4	5	5	3	3	4	5	2	3	4	5
	2. LIMB OF ANTICLINE OR SYNCLINE	3	4	5	5	3	3	4	5	2	3	4	5
	3. MONOCLINE OR HOMOCLINE	3	4	5	5	3	3	4	5	2	3	4	5
	4. FAULT PLANE	3	4	5	5	3	3	4	5	2	3	4	5
	5. AXIAL PLANE OF FOLD	3	4	5	5	3	3	4	5	2	3	4	5
	6. IGNEOUS INTRUSIVE CONTACT	3	4	5	5	3	3	4	5	2	3	4	5
	7. SALT DOME CONTACTS	3	4	5	5	3	3	4	5	2	3	4	5

TABLE 2, AMT (CONT'D)

	LOW CONTRAST 1.1-2.5/1				MEDIUM CONTRAST 2.5-10/1				HIGH CONTRAST 10+/1			
	0-5 M	5-300 M	300-900 M	> 900 M	0-5 M	5-300 M	300-900 M	> 900 M	0-5 M	5-300 M	300-900 M	> 900 M
III. SIZE OF: 1. SOLUTION FEATURE	5	4	5	5	2	4	5	5	2	3	4	5
2. MASSIVE SULFIDE DEPOSIT												
3. SALT DOME												
4. FAULT OFFSET												

KEY TO RANKING

I. ACCURACY OF DEPTH

1. ± 1-5% OF DEPTH
2. ± 5-15% OF DEPTH
3. ± 15-30% OF DEPTH
4. ± > 30% OF DEPTH
5. NOT DETECTABLE

II. ACCURACY OF ANGLE

1. ± 1-5 DEGREES
2. ± 5-15 DEGREES
3. ± 15-30 DEGREES
4. ± > 30 DEGREES
5. NOT DETECTABLE

III. MINIMUM SIZE FOR DETECTION

1. TINY (1 CM - 1 M)
2. SMALL (1 M - 9 M)
3. MEDIUM (10 M - 99 M)
4. LARGE (> 100 M)
5. NOT DETECTABLE

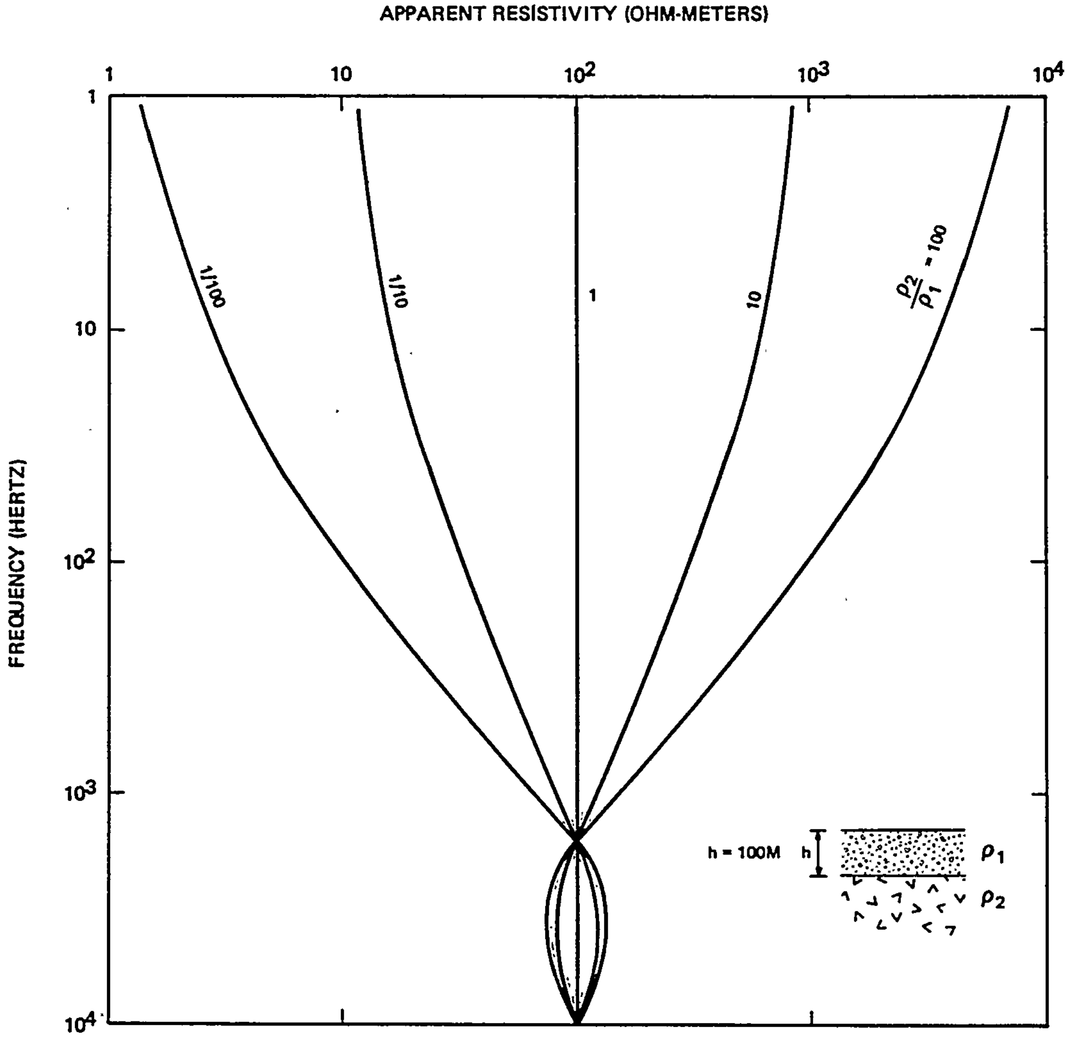

FIGURE 2 THEORETICAL TWO-LAYER SOUNDING CURVES
(AFTER STRANGWAY, 1973)

In general, the AMT method is reasonably reliable in simple situations involving nearly horizontal, layered features, particularly when the layers are few in number. It is also reasonably reliable in situations of pronounced vertical features, such as faults, dikes, or mineralized zones.

The reliability of the method diminishes with the following:

1. increasing geologic complexity, allowing for multiple interpretations;

2. decreasing resistivity contrast;

3. increasing depth;

4. decreasing size of "target" feature;

5. decreasing station density; and

6. decreasing frequency measurements.

Table 3, structured similarly to Table 2, shows the reliability of interpreting geologic features using the AMT method.

5.0 COSTS AND TIME

An AMT survey crew varies from 2 men to 6 men, depending on the number of stations in the survey. If a large number of stations is to be occupied, the additional men precede the instrument crew in order to prepare stations in advance.

The costs of a 4-man crew are shown below (all costs are in 1981 dollars):

Personnel (10 hour day)

1 Instrument Operator	$ 520/day
1 Assistant	340/day
2 Helpers	620/day

TABLE 3

RELIABILITY OF IDENTIFICATION OF GEOLOGIC FEATURES USING THE AMT METHOD

NOTE: 1. CONTRAST IS RESISTIVITY CONTRAST
2. SEE END OF CHART FOR KEY TO RANKING

	LOW CONTRAST 1.1-2.5/1				MEDIUM CONTRAST 2.5-10/1				HIGH CONTRAST 10+/1			
	0-5 M	5-300 M	300-900 M	> 900 M	0-5 M	5-300 M	300-900 M	> 900 M	0-5 M	5-300 M	300-900 M	> 900 M
I HORIZONTAL FEATURES												
1. BURIED EROSIONAL SURFACE	–	–	–	–	–	–	–	–	–	–	–	–
2. WATER TABLE	3	4	4	–	2	3	4	–	1	2	4	–
3. BEDROCK	3	4	4	–	2	3	3	–	1	2	3	–
4. BASEMENT	–	4	4	4	–	3	3	4	–	2	2	3
5. CONTACT	3	4	4	4	2	3	3	4	1	1	2	2
6. ANGULAR UNCONFORMITY	3	4	4	4	3	3	4	4	2	3	3	4
7. PARACONFORMITY	4	4	4	4	3	3	4	4	2	3	3	4
8. LOW-ANGLE FAULT	3	4	4	4	3	3	4	4	2	3	3	4
9. INCLINED STRATA	4	4	4	4	3	3	4	4	2	3	3	4
9a. LIMB OF ANTICLINE OR SYNCLINE	4	4	4	4	3	3	4	4	2	3	3	4
9b. MONOCLINE OR HOMOCLINE	4	4	4	4	3	3	4	4	2	3	3	4
II. VERTICAL FEATURES												
1. HIGH-ANGLE FAULT	2	3	4	4	2	3	4	4	1	2	3	4
2. FRACTURE ZONE	3	3	4	4	3	3	4	4	2	3	3	4
3. BRECCIA ZONE	3	3	4	4	3	3	4	4	2	3	3	4
4. IGNEOUS INTRUSIVE CONTACT	2	3	4	4	2	3	4	4	2	2	3	4
5. SALT DOME CONTACT	2	3	4	4	1	2	3	4	1	1	2	3
6. DIKE	3	3	4	4	2	2	3	4	2	2	3	4

TABLE 3, AMT (CONT'D)

	LOW CONTRAST 1.1-2.5/1				MEDIUM CONTRAST 2.5-10/1				HIGH CONTRAST 10+/1			
	0-5 M	5-300 M	300-900 M	> 900 M	0-5 M	5-300 M	300-900 M	> 900 M	0-5 M	5-300 M	300-900 M	< 900 M
III. <u>OTHER FEATURES</u>												
1. IGNEOUS INTRUSIVE BODY	3	3	4	4	2	2	3	4	2	2	3	4
2. SALT DOME	2	3	4	4	1	2	3	4	1	1	2	3
3. SOLUTION FEATURES	2	3	4	4	2	2	3	4	1	2	3	4
4. MASSIVE SULFIDE DEPOSIT	2	3	4	4	2	3	3	4	1	2	3	4
IV. <u>COMPOSITION</u>												
1. BEDDED OR DOMED SALT	3	3	4	4	2	2	3	4	1	2	3	4
2. SHALE	3	4	4	4	2	2	3	4	1	2	3	4
3. BASALT	3	4	4	4	2	2	3	4	1	2	3	4
4. TUFF	4	4	4	4	3	3	4	4	2	3	4	4
5. GRANITE	3	4	4	4	2	2	3	4	1	2	3	4
6. ROCK TYPE IN GENERAL	3	4	4	4	2	3	4	4	2	3	4	4

<u>KEY TO RANKING</u>

1. GOOD RELIABILITY (ONE OR TWO POSSIBLE INTERPRETATIONS)
2. FAIR RELIABILITY (THREE OR FOUR POSSIBLE INTERPRETATIONS)
3. POOR RELIABILITY (FIVE OR MORE POSSIBLE INTERPRETATIONS)
4. NOT IDENTIFIABLE

Personnel Expenses

4 men	160/day

Equipment and Supplies

Instruments and sensors		260/day
Vehicles (2)		200/day
	TOTAL	$2,100/day

Under "average" conditions of reasonable accessibility and favorable weather conditions, a 4-man crew can occupy 4 to 8 stations per day. Thus, the field cost of a 4-man AMT survey would be $215 to $525 per station.

Data reduction is usually accomplished in the field, so that the costs outlined above essentially include the calculations necessary to generate a sounding curve. Interpretation of the curve and its correlation with a geologic model may require from as little as an hour to several days of complex modelling studies.

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APPENDIX B-3

SEISMIC REFRACTION TECHNIQUE

By

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Long Beach, California

November 1, 1981

B-3

SEISMIC REFRACTION TECHNIQUE

1.0 DESCRIPTION

1.1 Purpose

The seismic refraction method is a means of determining subsurface geology by analysis of elastic waves (vibrations) that have traveled through earth materials. The method is capable of yielding useful results for depths ranging from a few meters to several thousand meters.

1.2 Principle

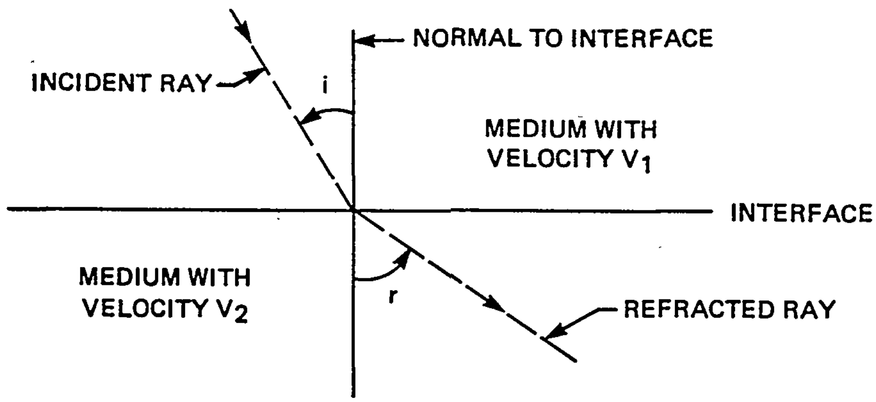
The seismic refraction method is based on the measurement of travel times of compressional body waves, or P-waves. P-waves propagate through earth materials at velocities which are determined by the elasticity and density of the materials. Seismic energy is transmitted through three dimensional space in a succession of wavefronts. However, rays, constructed perpendicular to the wavefronts, are more readily visualized and are typically used to describe the parameters involved in the method.

A seismic ray starts at an energy source, which is usually either an impact or an explosion. When it travels through a material at one velocity and impinges upon another material that propagates it at a different velocity, it will be bent, or refracted, as shown in Figure 1. The ray is refracted according to Snell's law:

$$\frac{\sin i}{\sin r} = \frac{V_1}{V_2}$$

where

- i is the angle of incidence (measured from the normal) at which the ray impinges on the interface;
- r is the angle of refraction (also measured from the normal) into the next medium;
- V_1 is the propagation velocity corresponding to the angle of incidence; and



ANGLE i = ANGLE OF INCIDENCE
ANGLE r = ANGLE OF REFRACTION

FIGURE 1 ELEMENTS INVOLVED IN REFRACTION OF RAYS

V_2 is the propagation velocity corresponding to the angle of refraction.

The seismic refraction method depends on rays that have been "critically refracted," which occurs when a ray impinges on an interface at the angle of incidence that produces an angle of refraction equal to 90 degrees. Since the sin of 90 degrees is one, Snell's law for this special case is:

$$\sin i_c = \frac{V_1}{V_2}$$

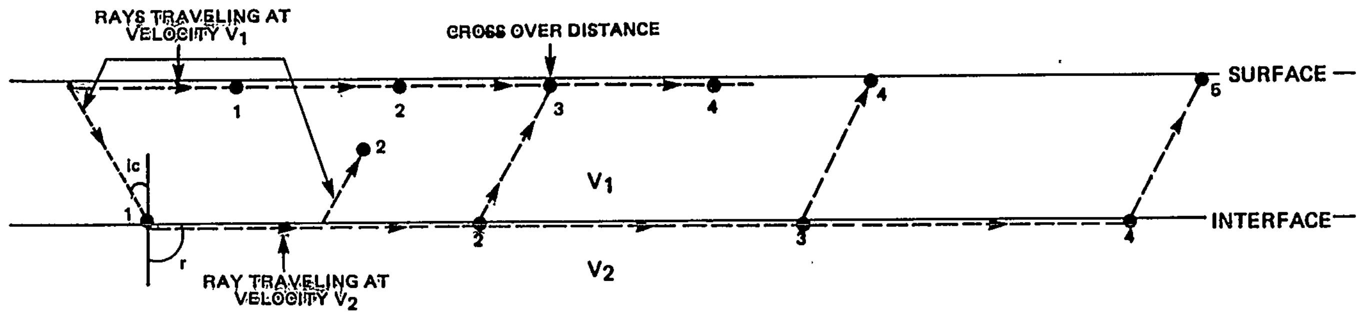
where

i_c is the critical angle of incidence and, in this case, V_1 is, by definition, slower than V_2.

The critically refracted ray just grazes the interface as it travels along at the higher velocity in the second medium. As it travels, it is continuously impinging on the interface. The result is that rays are continuously being refracted back into the slower medium at an angle of refraction that is equal to the critical angle of incidence.

Consider the case of a layer of earth material overlying a second layer with a faster seismic wave propagation velocity. In this case, it is possible to record rays at the surface that have traveled down through the slower material, have entered the faster material at the critical angle, have traveled along the interface, and have been refracted back to the surface through the slower material. This path is illustrated in Figure 2. Depending on the thickness of the overlying, slower material and the ratio of the two velocities, there is a distance beyond which the critically refracted rays will arrive back at the surface (as "first arrivals") before the rays traveling directly through the overlying, slower layer get there. The distance at which the two rays arrive at the same time is called the "cross over," or "critical" distance. There is a different (longer) cross-over distance for each deeper layer in the geologic section. Seismic refraction interpretations usually deal only with first arrivals.

If arrival times are measured at two places beyond the cross-over distance (Figure 2), the difference in arrival times is related to the speed of travel in the deeper layer. In the ideal case of homogeneous materials with the interface



EXPLANATION

• = ENERGY SOURCE

● 1,2,3,4,5 = NUMBERS REPRESENT TIME UNITS SO THAT DISTANCE TRAVELED BY DIRECT AND REFRACTED WAVES CAN BE SEEN AT SUCCESSIVE INCREMENTS OF TIME

i_c = CRITICAL ANGLE OF INCIDENCE

r = ANGLE OF REFRACTION = 90°

FIGURE 2 CROSS-SECTION VIEW OF SEISMIC RAYS IN TWO-LAYER EARTH parallel to the surface, the true velocity of the deeper material can be calculated by dividing the arrival time difference into the distance between the two places where the travel times were measured. Since ideal conditions usually do not exist, all velocities determined from individual shot locations (energy source-points) are considered to be "apparent" velocities. Determination of true velocities requires that data be obtained from waves traveling through the materials from opposite directions.

1.3 Field Layout

The conventional application of the seismic refraction method involves emplacing a number of geophones at some regular interval along a straight line across the ground. The geophones are connected to a multiple conductor cable that is connected in turn to a recording system. A single such set-up is called a "spread," which typically contains 12 or 24 geophones. A "line" is usually made up of two or more spreads linked end to end, but a single, isolated spread is also referred to as a line. A record is made by generating energy (shooting) at some point in line with the geophones. Typically, several records are made for each set-up, usually from shots at both ends and the center of the spread and, frequently, from shots offset a considerable distance (in-line) from the ends.

The distances between geophones and between shots and geophones are chosen based on the desired depth of penetration and resolution. High resolution requires small geophone intervals. The distance from shot to geophones must be several times greater than the desired depth of penetration.

1.4 Data Reduction and Interpretation

The first step is to measure on the records the time it took for energy to travel from the shots to the geophones in the spread. The next step is to plot the travel times versus distance. The resulting graph (T-D graph) is the most commonly-used basis for interpretation of seismic refraction data. An example of a T-D graph is shown in Figure 3. From inspection of the T-D graph, the interpreter decides how many refracting layers are represented by the travel times and formulates a mental model of any structure that is indicated. He then computes apparent and true velocities for each of the recognized layers. There are many approaches to

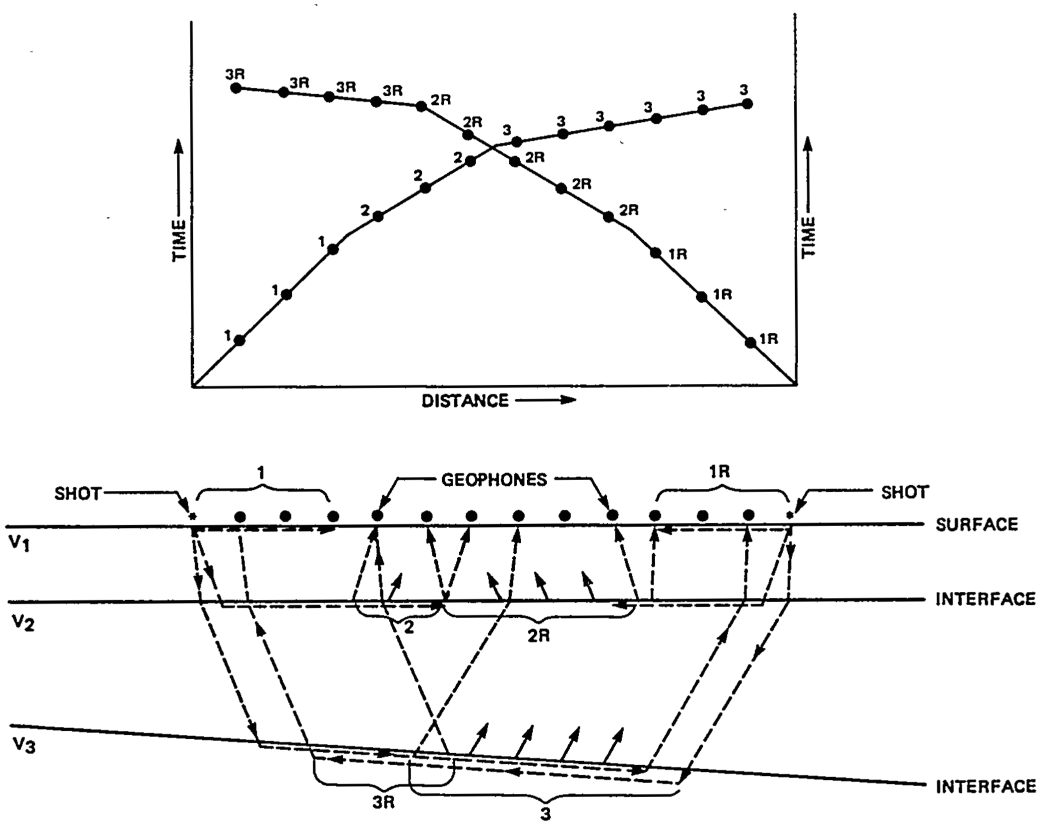


FIGURE 3. RELATIONSHIPS BETWEEN LAYERS, TIME DISTANCE GRAPHS AND SUBSURFACE COVERAGE

computing the velocities and the velocity-depth profile from a set of refraction data. The simplest is to treat the subsurface as a series of homogeneous, plane layers. In these cases, apparent velocities are calculated as the inverse slope of a line drawn through a set of contiguous points on the T-D graph, and depths are computed near the shot points based on layer intercepts or cross-over distances. Other techniques, which allow more detailed modeling, include delay-time methods, wave-front methods, ray tracing methods, reciprocal methods and combinations.

Two other aspects of seismic waves which are used infrequently to aid in interpreting a refraction problem are their frequency and amplitude. When these are considered, it is usually in a qualitative sense to help decide between alternative models.

2.0 APPLICABILITY TO INFORMATION NEEDS

2.1 General

The seismic refraction method is usually applicable in situations where adjoining geologic materials have greatly different seismic wave propagation velocities. For example, an overburden of alluvium on limestone, a saturated zone in alluvium, a shale layer over a granite body, and shale and sandstone layers terminating at the contact with a salt dome are situations where large velocity contrasts exist. Table 1 rates the applicability of the method for investigating a number of targets in a generic sense.

The best results are obtained from the method if the following conditions are present:

1. homogeneous, thick layers;

2. sharp boundaries between layers,

3. velocity ratio across (upper to lower) interfaces of 3:4 or less; and

4. small dip angles of layers and boundaries.

TABLE 1

APPLICABILITY OF SEISMIC REFRACTION METHOD TO THE IDENTIFICATION AND DEFINITION OF SUBSURFACE GEOLOGIC FEATURES

I FEATURES ASSOCIATED WITH ONE OR MORE HORIZONTAL PLANES

		RANKING 1	2	3	4
A. DEPTH TO:	1. BEDDED SALT			X	
	2. SHALE			X	
	3. BASALT			X	
	4. TUFF			X	
	5. WATER TABLE	X			
	6. BEDROCK	X			
	7. BASEMENT		X		
	8. ANGULAR UNCONFORMITY			X	
	9. PARACONFORMITY			X	
	10. LOW-ANGLE FAULT			X	
B. THICKNESS OF:	1. BEDDED SALT				X
	2. SHALE			X	
	3. BASALT				X
	4. TUFF			X	
	5. OVERBURDEN	X			
	6. SEDIMENTARY STRATUM IN GENERAL		X		
	7. SILL			X	
C. ANGLE OF:	1. INCLINED STRATA		X		
	a. LIMB OF ANTICLINE OR SYNCLINE		X		
	b. MONOCLINE OR HOMOCLINE		X		
	2. LOW-ANGLE FAULT			X	
	3. AXIAL PLANE OF RECUMBENT FOLD				X

TABLE 1, SEISMIC REFRACTION (CONT'D)

		RANKING 1	2	3	4
II. FEATURES ASSOCIATED WITH ONE OR MORE VERTICAL PLANES					
A. LOCATION OF:	1. HIGH-ANGLE FAULT		X		
	2. FRACTURE ZONE			X	
	3. BRECCIA ZONE			X	
	4. IGNEOUS INTRUSIVE CONTACT		X		
	5. SALT DOME CONTACT			X	
B. WIDTH OF:	1. DIKE			X	
	2. FRACTURE ZONE			X	
	3. BRECCIA ZONE			X	
	4. SALT DOMES			X	
C. ANGLE OF:	1. FAULT PLANE				X
	2. IGNEOUS INTRUSIVE CONTACT			X	
	3. SALT DOME CONTACT			X	
	4. AXIAL PLANE OF NORMAL FOLD				X
III. OTHER FEATURES					
A. DEPTH TO:	1. BURIED EROSIONAL SURFACE			X	
	2. IGNEOUS INTRUSIVE BODY			X	
	3. SALT DOME			X	
	4. SOLUTION FEATURES				X
	5. MASSIVE SULFIDE DEPOSIT				X

TABLE 1, SEISMIC REFRACTION (CONT'D)

B. DETERMINATION OF:		RANKING 1	2	3	4
	1. ROCK TYPE				
	a. BEDDED SALT			X	
	b. SHALE				X
	c. BASALT			X	
	d. TUFF				X
	e. GRANITE			X	
	2. GEOTHERMAL CONDITIONS				X

KEY TO RANKING

1. FREQUENTLY APPLICABLE
2. OCCASIONALLY APPLICABLE
3. SELDOM APPLICABLE
4. NOT APPLICABLE

2.2 Applicability to Host Media

Resolution of the method decreases as the depth of investigation increases. The method is expected to be of little use for investigations in the repository zone, where high resolution is needed, but may find application in studies of overlying materials, as they may influence ground-water evaluations or the design of surface facilities. The applicability table shows that, in a generic sense, the reliability of the interpretation may be less than in other methods. A special application of the refraction method can be used to determine the location of a near-vertical boundary, such as the edge of a salt dome or igneous stock. This application is called the "asplanatic curve" method. It requires one or more boreholes into or near the dome or stock.

3.0 RESOLUTION AND DEPTH OF PENETRATION

Generalized judgments as to the ability to detect or resolve typical geologic features with the seismic refraction method are summarized in Table 2.

3.1 Instrumentational

Depth resolution is controlled, in part, by timing resolution. In most recording systems, relative travel times can be resolved to approximately 0.5 millisecond, if the recorded waves have high frequencies and large amplitudes. However, when shot to geophone distances are several hundred to thousands of feet, arrival times frequently can be resolved to no better than a few milliseconds, because the waves have low frequencies and low amplitudes. The timing accuracy affects the accuracy of velocity calculation, of depth computation, and resolution of changes in depth along a refractor. The change in depth corresponding to a change in travel time is roughly proportional to the velocity in the material overlying the refractor. If the overlying material has a velocity of 5000 feet per second, a 5-foot change in refractor depth would cause approximately a 1 millisecond change in travel time.

Resolution or recognition of features along a refractor requires that the features extend horizontally at least as far as the interval between geophones.

TABLE 2

DETECTABILITY OF GEOLOGIC FEATURES
AND ACCURACY OF SUBSURFACE MEASUREMENTS
USING THE SEISMIC REFRACTION METHOD

NOTE: 1. CONTRAST IS VELOCITY CONTRAST
2. SEE END OF CHART FOR KEY TO RANKING

		LOW CONTRAST .85				MEDIUM CONTRAST .65				HIGH CONTRAST .5			
		0-5M	5-300 M	300-900M	> 900 M	0-5 M	5-300 M	300-900 M	> 900 M	0-5 M	5-300 M	300-900 M	> 900 M
I. DEPTH TO:	1. BEDDED SALT	2	3	4	4	2	2	3	3	1	2	2	3
	2. SALT DOME	2	3	4	4	2	2	3	3	1	2	2	3
	3. SHALE	2	3	4	4	2	2	3	3	1	2	2	3
	4. BASALT	2	3	4	4	2	2	3	3	1	2	2	3
	5. TUFF	2	3	4	4	2	2	3	3	1	2	2	3
	6. GRANITE	2	3	4	4	2	2	3	3	1	2	2	3
	7. BURIED EROSIONAL SURFACE	2	3	4	4	2	2	3	3	1	2	2	3
	8. WATER TABLE	2	3	4	X	2	2	3	X	1	2	2	3
	9. BEDROCK	2	3	4	4	2	2	3	3	1	2	2	3
	10. BASEMENT	2	3	4	4	2	2	3	3	1	2	2	3
	11. CONTACT	2	3	4	4	2	2	3	3	1	2	2	3
	12. ANGULAR UNCONFORMITY	2	3	4	4	2	2	3	3	1	2	2	3
	13. PARACONFORMITY	2	3	4	4	2	2	3	3	1	2	2	3
	14. LOW ANGLE FAULT	2	3	4	4	2	2	3	3	1	2	2	3
II. ANGLE OF:	1. INCLINED STRATA	2	2	3	3	1	1	2	2	1	1	2	2
	2. LIMB OF ANTICLINE OR SYNCLINE	2	2	3	3	1	1	2	2	1	1	2	2
	3. MONOCLINE OR HOMOCLINE	2	2	3	3	1	1	2	2	1	1	2	2
	4. FAULT PLANE	X	5	5	5	5	5	5	5	5	5	5	5
	5. AXIAL PLANE OF FOLD	X	5	5	5	5	5	5	5	5	5	5	5
	6. IGNEOUS INTRUSIVE CONTACT*	X	4	4	4	X	4	3	4	X	4	2	3
	7. SALT DOME CONTACTS*	X	4	4	4	X	4	3	4	X	4	2	3

*USING APLANATIC CURVE METHOD

TABLE 2, SEISMIC REFRACTION (CONT'D)

	LOW CONTRAST .85				MEDIUM CONTRAST .65				HIGH CONTRAST .5			
	0-5 M	5-300 M	300-900 M	> 900 M	0-5 M	5-300 M	300-900 M	> 900 M	0-5 M	5-300 M	300-900 M	> 900 M
III. SIZE OF: 1. SOLUTION FEATURE	5	5	5	5	3	4	5	5	2	3	5	5
2. MASSIVE SULFIDE DEPOSIT	5	5	5	5	5	5	5	5	5	5	5	5
3. SALT DOME	X	X	X	X	X	X	X	X	X	X	X	X
4. FAULT OFFSET	2	3	3	4	2	2	3	3	2	2	2	3

KEY TO RANKING

I. ACCURACY OF DEPTH

1. ± 1-5% OF DEPTH
2. ± 5-15% OF DEPTH
3. ± 15-30% OF DEPTH
4. ± > 30% OF DEPTH
5. NOT DETECTABLE

II. ACCURACY OF ANGLE

1. ± 1-5 DEGREES
2. ± 5-15 DEGREES
3. ± 15-30 DEGREES
4. ± > 30 DEGREES
5. NOT DETECTABLE

III. MINIMUM SIZE FOR DETECTION

1. TINY (1 CM - 1 M)
2. SMALL (1 M - 9 M)
3. MEDIUM (10 M - 99 M)
4. LARGE (> 100 M)
5. NOT DETECTABLE

VELOCITY CONTRAST (RATIO OF VELOCITIES ACROSS INTERFACE)

LOW = .85
MEDIUM = .65
HIGH = .5

X: SITUATION WHICH IS GEOLOGICALLY OR GEOMETRICALLY IMPROBABLE

Subsurface coverage on most layers in a refraction survey is discontinuous, unless many shots and overlapping spreads are used in the survey. For this reason, the achievable horizontal resolution varies along most lines. This can be understood by reference to Figure 3, which shows how different segments of the T-D graph represent different parts of the subsurface on different layers.

3.2 Phenomenological

The ability to resolve or recognize the presence of successively deeper layers when dealing with refracted rays depends on; (a) having successively higher propagation velocities; (b) the ratios of the velocities in the layers; (c) the thickness of layers and geophone spacing; and (d) the shot to geophone offset distance.

a) Velocity succession:

Since rays are refracted according to Snell's law, if a downgoing ray impinges on a layer with lower velocity, it will be refracted toward the normal and thus cannot return to the surface by traveling through the underlying lower velocity layer.

b) Velocity rates:

Data representing different layers are recognized as changes in slope on the T-D graph. If the velocity ratio is near 1, the change in slope will be subtle and not readily recognized.

c) Layer thickness and geophone spacing:

At least two arrivals from a layer are required before it can be resolved. Several arrivals are required before the apparent velocity can be considered to be reliable. To meet this requirement a layer must be several times thicker than the geophone spacing. The thickness required depends on the ratios of the layer velocity to the velocities above and below it. It may be impossible to obtain a first arrival refraction from a relatively thin layer, especially when velocity contrasts are small. In fact, there is a zone at the bottom of every interpreted layer in which a higher velocity layer of small contrast cannot be recognized, nor excluded. This is called the blind zone. If an unrecognized layer occurs in the blind zone, it is called a hidden layer.

d) <u>Offset distance</u>:

Since depth of penetration is a function of shot to geophone offset distance, the depth to which layers can be resolved can be increased by placing shots farther from a spread and/or increasing the geophone interval.

Another factor which affects the resolution of the refraction method is the wavelength of the seismic pulse. For detection, both the source and receiver must be several wavelengths from the refractor. For accurate velocity measurement, the layer thickness must be at least one wavelength.

4.0 RELIABILITY OF THE SEISMIC REFRACTION METHOD

Several factors that can limit the reliability of an interpretation of seismic refraction data have been described in previous sections. Any interpretation will have some degree of ambiguity, and this discussion will point out conditions which contribute to ambiguity. However, it should be borne in mind that the method has been successfully applied to exploration and engineering problems for several decades.

The fundamental ambiguity is in recognizing the number of layers that have been encountered and establishing their true velocity, in view of the fact that more than one set of geologic conditions may produce similar T-D graphs. Another factor is that the points on a T-D graph usually are somewhat scattered instead of falling exactly on straight lines. Many ambiguities can be reduced by recording data from several shot points. For example, in the T-D graph in Figure 3, there is no overlap in subsurface coverage for layers 2 and 3 and, consequently, their true velocities cannot be accurately established unless the refractors are plane. Interior shot points could provide overlapping coverage for layer 2 and provide more data on layer 1 velocity, and exterior shot points could provide overlap in layer 3.

In all cases, ambiguities will increase as the offset distances and the depth of penetration increase. Some geologic conditions which cause complications in the T-D graph and adversely affect the reliability of interpretation are:

1. Thin layers,
2. Small velocity contrasts,
3. Continuous velocity increase with depth,

4. Large dip angles or changing dips of layers,
5. Lateral velocity variations within layers,
6. Hidden layers,
7. Velocity inversions, and
8. Vertical discontinuities (faults).

As in all geophysical methods, the reliability of refraction interpretations is improved when geologic information from other sources is available.

Table 3 generalizes the reliability of interpretations versus velocity contrasts and depth of features. Specific surveys may be more or less reliable than indicated, depending on such factors as actual geologic conditions, wave amplitudes and frequency, signal to noise ratio, and density of data.

5.0 TIME

Many variables influence the time required to lay out and record a spread. Some of these are: terrain, vegetation, weather, geophone interval, type of energy source, size of shot if using explosives, and number of shot points per spread. The time may be as short as 10 minutes for a spread with 5- or 10-foot geophone intervals to several days for a spread with 200 foot geophone intervals and large shots offset several miles. When shots of several thousand pounds of explosives are detonated, they should be recorded by more than one recording system and spread to improve the cost effectiveness.

6.0 COSTS

The factors listed as variables that affect field time also have a direct bearing on the costs of a survey. The costs of commercial applications of the method typically fall in the $3,000 to $15,000 per mile range (in 1981 dollars).

TABLE 3

RELIABILITY OF IDENTIFICATION OF GEOLOGIC FEATURES USING THE SEISMIC REFRACTION METHOD

NOTE:
1. CONTRAST IS VELOCITY CONTRAST
2. SEE END OF CHART FOR KEY TO RANKING

	LOW CONTRAST .85				MEDIUM CONTRAST .65				HIGH CONTRAST .5			
	0-5 M	5-300 M	300-900 M	> 900 M	0-5 M	5-300 M	300-900 M	> 900 M	0-5 M	5-300 M	300-900 M	> 900 M
I. HORIZONTAL FEATURES												
1. BURIED EROSIONAL SURFACE	3	3	3	3	2	3	3	3	2	2	3	3
2. WATER TABLE	2	2	3	X	2	2	3	X	2	2	X	X
3. BEDROCK	1	2	2	3	1	2	3	3	1	1	2	2
4. BASEMENT	2	3	3	3	1	2	3	3	1	1	2	3
5. CONTACT	3	3	3	3	3	3	3	3	3	3	3	3
6. ANGULAR UNCONFORMITY	3	3	3	3	3	3	3	3	3	3	3	3
7. PARACONFORMITY	3	3	3	3	3	3	3	3	3	3	3	3
8. LOW-ANGLE FAULT	3	3	3	3	3	3	3	3	3	3	3	3
9. INCLINED STRATA												
9a. LIMB OF ANTICLINE OR SYNCLINE	X	3	3	3	X	3	3	3	X	3	3	3
9b. MONOCLINE OR HOMOCLINE	3	3	3	3	3	3	3	3	3	3	3	3
II. VERTICAL FEATURES												
1. HIGH-ANGLE FAULT	2	3	3	3	1	2	3	3	1	1	2	3
2. FRACTURE ZONE	3	3	4	4	3	3	3	4	3	3	3	3
3. BRECCIA ZONE	3	3	4	4	3	3	3	4	3	3	3	3
4. IGNEOUS INTRUSIVE CONTACT	2	3	4	4	2	2	3	3	1	1	2	3
5. SALT DOME CONTACT	2	3	4	4	2	2	2	3	1	1	2	3
6. DIKE	2	3	4	4	2	2	3	4	1	1	2	3

TABLE 3, SEISMIC REFRACTION (CONT'D)

	LOW CONTRAST .85				MEDIUM CONTRAST .65				HIGH CONTRAST .5			
	0-5 M	5-300 M	300-900 M	> 900 M	0-5 M	5-300 M	300-900 M	> 900 M	0-5 M	5-300 M	300-900 M	< 900 M
III. OTHER FEATURES												
1. IGNEOUS INTRUSIVE BODY	3	3	3	3	2	2	3	3	1	1	2	2
2. SALT DOME	2	2	2	2	2	2	2	2	1	1	2	2
3. SOLUTION FEATURES	4	4	4	4	3	3	4	4	3	3	4	4
4. MASSIVE SULFIDE DEPOSIT	4	4	4	4	4	4	4	4	4	4	4	4
IV. COMPOSITION												
1. BEDDED OR DOMED SALT	3	3	3	3	3	3	3	3	2	2	2	2
2. SHALE	3	3	3	3	3	3	3	3	3	3	3	3
3. BASALT	3	3	3	3	3	3	3	3	3	3	3	3
4. TUFF	3	3	3	3	3	3	3	3	3	3	3	3
5. GRANITE	3	3	3	3	3	3	3	3	3	3	3	3
6. ROCK TYPE IN GENERAL	3	3	3	3	3	3	3	3	3	3	3	3

KEY TO RANKING

1. GOOD RELIABILITY (ONE OR TWO POSSIBLE INTERPRETATIONS)
2. FAIR RELIABILITY (THREE OR FOUR POSSIBLE INTERPRETATIONS)
3. POOR RELIABILITY (FIVE OR MORE POSSIBLE INTERPRETATIONS)
4. NOT IDENTIFIABLE

VELOCITY CONTRACT (RATIO OF VELOCITIES ACROSS INTERFACE)

LOW = .85
MEDIUM = .65
HIGH = .5

X: SITUATION WHICH IS GEOLOGICALLY
OR GEOMETRICALLY IMPROBABLE

APPENDIX B-4

DIRECT-CURRENT ELECTRICAL RESISITIVITY METHOD

BY

Ertec Western, Inc.

Long Beach, California

November 1, 1981

B-4

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DIRECT-CURRENT ELECTRICAL RESISTIVITY METHOD (DCR)

1.0 DESCRIPTION OF THE DCR METHOD

1.1 Purpose

The purpose of the direct-current resistivity method of exploration (DCR) is to determine the subsurface distribution of resistivity values in order to locate and define geologic features of interest. Although the method was developed originally to aid exploration for electrically conductive mineral deposits, such as massive, metal-sulfide deposits, it is now widely used for the following additional purposes:

a. to determine depths to one or more horizontal planes, across which resistivity values change substantially. Associated geologic features would include depth of overburden, layered strata, horizontal faults, unconformities and ground water table;

b. to locate one or more vertical planes, across which resistivity values change substantially. Associated features would include vertical faults, fracture zones, breccia zones, dikes and vertical contacts; and

c. to locate and define buried or hidden rock or mineral masses, whose resistivities are substantially different from their surroundings. Such geologic features would include igneous intrusives and certain types of mineral deposits.

The DCR method is particularly useful to depths of approximately 300 meters. Under some circumstances, it is used to explore to greater depths, but resolution and diagnosticity fall off rapidly with depth. Below 300 meters, the geologic features of interest must be very large to be detectable by the method.

1.2 Principle

The resistivity of a substance is a measure of the ability of the substance to transmit electric current. In the MKS system, resistivity is defined as the resistance of a sample of the substance which is cylindrical in shape and is one square meter in cross-section and one meter long.[10] As defined here, resistivity is an intrinsic characteristic of the substance and is independent of the volume of the substance.

In the DCR method of exploration, a potential difference is applied between two grounded electrodes located some distance apart on the surface of the ground. Current will flow between the electrodes and will be distributed in a way that depends on the distribution of resistivity values. Figure 1A shows the current flow in a case where the ground is homogeneous with respect to resistivity. The lines shown are "current lines", and the strength of the current at any point in the subsurface is indicated by how closely spaced the lines are - the closer the spacing, the stronger the current.

Figure 1B shows the distribution of the electric field associated with the current flow. The lines shown connect points of equal potential and are everywhere perpendicular to the current lines (since current flows from high potential to low potential). The equipotential lines are regularly distributed, reflecting the homogeneous nature of the subsurface.

The electric field may be measured by determining the potential difference between electrodes P_1 and P_2 (figure 1B). The resistivity, then, is given by the following expression:[10]

$$P = 2 \frac{V}{I} / F(R's)$$

where

p is resistivity in ohm meters

V is potential difference in volts

I is current in amperes

F (R's) is a coefficient whose value depends on the distances between the current and potential electrodes.

If the ground is electrically homogeneous, the resistivity values measured are the same everywhere and are independent of the positions of all electrodes. In such a case, the resistivity measured is the <u>true</u> resistivity. However, if the ground is not electrically homogeneous, then the current (and associated electric field) will be distributed differently, depending on the subsurface distribution of resistivity. This is illustrated in Figure 2, where a flat-lying layer of rock at depth, d, below the surface is of higher resistivity than the surface material. The resistivity measured in this case will not be the true resistivity of the upper layer. Rather, it will be a composite of the resistivities of the upper and lower layers. Such a composite resistivity is termed "apparent resistivity."

Measured resistivities are almost always apparent resistivities, because the subsurface is seldom electrically homogeneous. By making a number of measurements of apparent resistivity in an area, it is frequently possible to determine certain aspects of the subsurface geology. The analysis and interpretation of resistivity data are discussed in the section entitled "Interpretation."

1.3 Factors Influencing Resistivity

The factors that determine the resistivity of a geologic substance are:[13]

1. porosity and permeability: shape and size of pores, number, size, and shape of interconnecting passages;

2. the extent to which pores are filled by water, i.e., the moisture content;

3. concentration of dissolved electrolytes in the contained moisture;

4. temperature of the phase (ice has very high resistivity); and

5. amount and composition of colloids.

These factors relate primarily to the concentration and mobility of charged particles, such as sodium or calcium cations, that allow the flow of current through the substance. A very dry substance, even though it may contain highly dissociable salts, would have a high resistivity. A very wet substance, if it does not contain dissolved salts, would also have a high resistivity. For example, the glacial tills of Canada usually have fairly high resistivities, even though they are often moist or wet, because they have been leached of soluble salts. The following list shows the porosity of certain earth materials, which are ranked in order of decreasing resistivity.[13] It illustrates the dependency of resistivity on porosity.

Material	Porosity (%)
1. Igneous and metamorphic rocks	1/2 - 2
2. Dense limestones and sandstones	3 - 4
3. Clays and sands in general	8 - 15
4. Porous clays, sands, sandstone, cellular limestone, and dolomite	15 - 40
5. Marl, loess, clay, and sandy soil	40 - 75
6. Peat, diatomaceous earth	80 - 90

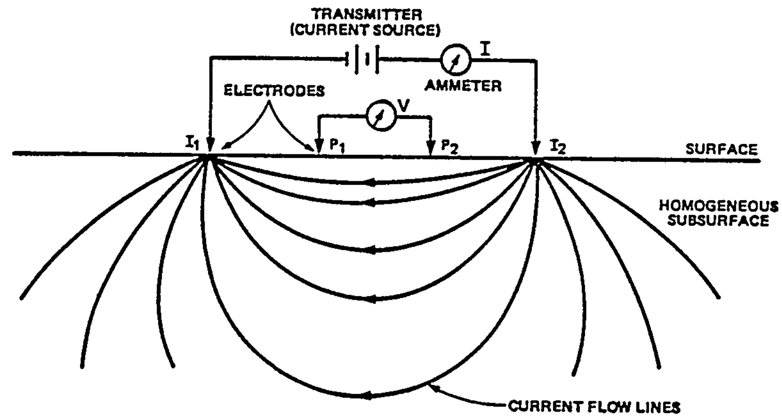
Resistivity values of earth materials range from a low of less than one ohm-meter for certain clays to over 1×10^8 ohm-meters for some granites or dry sandstones.[3] Such wide variation of resistivity is one of the factors of the DCR method that makes it useful as an exploration tool.

1.4 Field Equipment and Methods

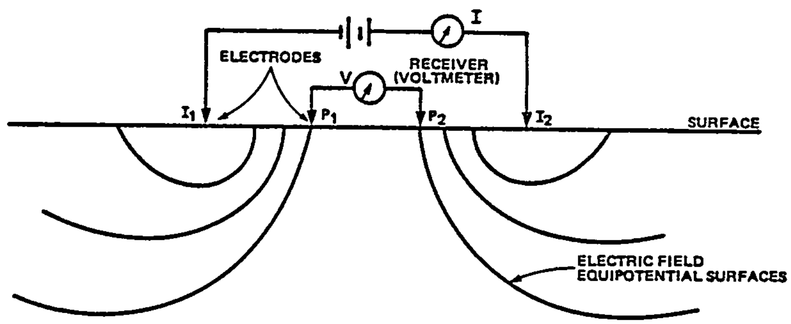
Resistivity equipment consists of the following items:

1. an electrical generator
2. a transmitter
3. a receiver
4. potential and current electrodes
5. cabling and connectors
6. vehicles, etc.

Instrumentation varies greatly, ranging from "shallow-penetrating" (several meters) to "deep penetrating" (several thousand meters). Commercial transmitters can generate from 0.03 amperes to over 100 amperes of current at voltages of up to 2,000 volts. Receivers are available that can measure potential differences in the low nanovolt range, where natural electrical noise frequently becomes the limiting factor.



A. SUBSURFACE CURRENT FLOW PATTERN



B. DISTRIBUTION OF THE ELECTRIC FIELD ASSOCIATED WITH RESISTIVITY MEASUREMENTS

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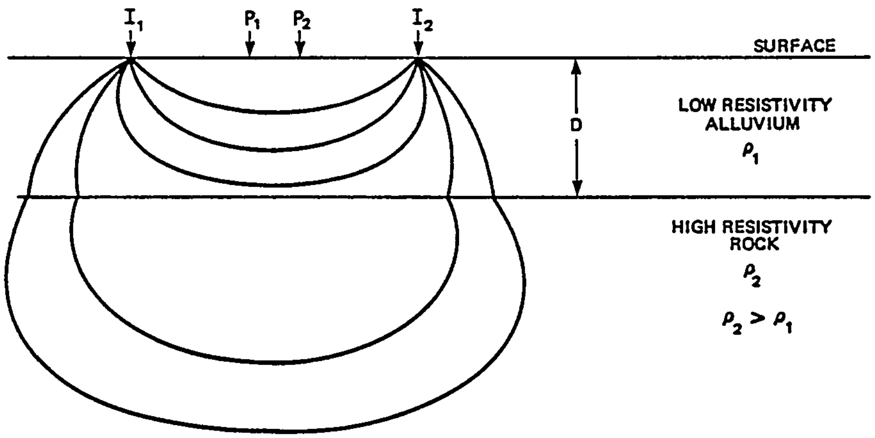
	NRC	

GROUND PENETRATION OF A RESISTIVITY MEASUREMENT

6-81 FIGURE 1

Compiled by ______ Drawn by ______ Checked by ______ Approved by ______



EFFECT OF SUBSURFACE STRUCTURE ON CURRENT DISTRIBUTION

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RESISTIVITY EFFECT OF SUBSURFACE STRUCTURE	
6-81	FIGURE 2

Compiled by ____ / Drawn by ____ / Checked by ____ / Approved by ____ /

From a theoretical point of view, the depth penetration of a resistivity survey is not determined by the amount of current that is made to flow in the ground, but, rather, by the configuration of the electrode array used to measure the resistivity. In general, the greater the distance between the outermost electrodes, the greater the depth penetration. However, if the distance becomes too large, the signal strength between the potential electrodes becomes too small to measure accurately.

Over the years, many electrode arrays have been developed, usually in an effort to optimize one or more of the following:

1. depth penetration

2. resolution of subsurface features

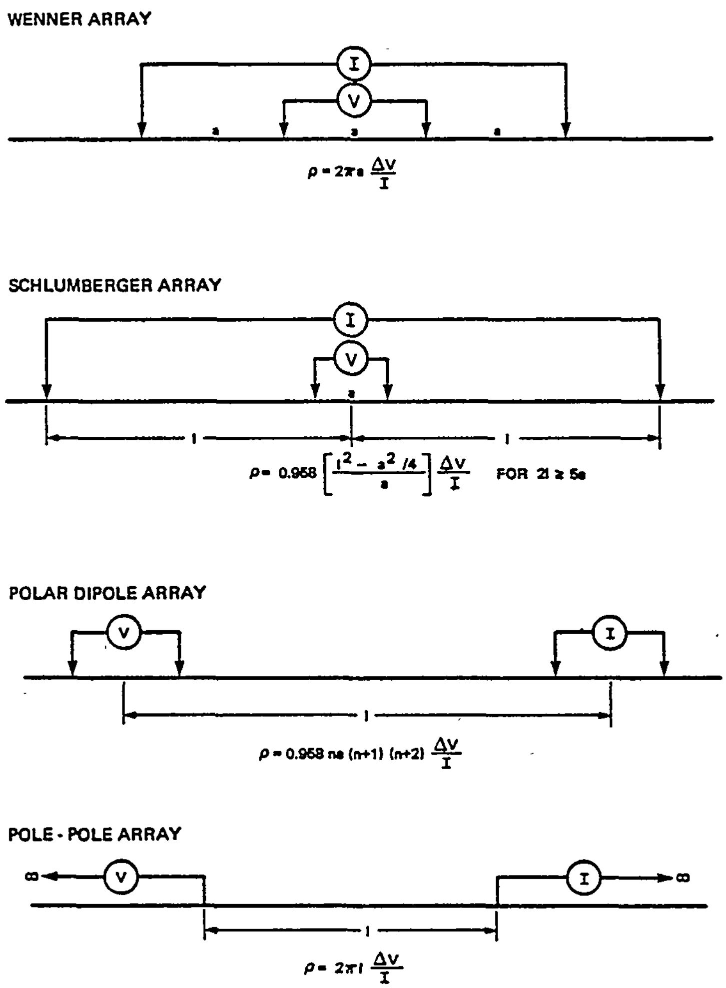
3. ease of interpretation

4. ease of operation

The first two factors are incompatible, in the sense that the greater the depth penetration a particular array provides, the poorer the resolution of subsurface features. Figure 3 shows several of the more commonly used resistivity arrays, in order of increasing depth penetration (and decreasing resolution). The Wenner and the Schlumberger arrays, even though they are the shallowest penetrating, are widely used, particularly by engineering and construction firms and others usually concerned with shallow depths (less than 100 feet). For exploration purposes and moderate depth penetration, the polar dipole array is probably the most commonly used. For maximum depth penetration the pole-pole array is used.

The term "depth penetration" in DCR surveys is a widely misunderstood term. Several formulas or rules-of-thumb are in use that are either not accurate or are ambiguous. Perhaps the best concept of depth penetration is "that depth which contributes most to the total signal (potential difference) measured on the ground surface".[15] Under this definition, the depth penetrations of the several arrays illustrated are:

Array	Depth Penetration
1. Wenner	0.11 L



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COMMONLY USED RESISTIVITY ELECTRODE ARRAYS AND APPARENT RESISTIVITY EQUATIONS

6-81

FIGURE 3

Compiled by ______ / Drawn by ______ / Checked by ______ / Approved by ______

2. Schlumberger 0.125 L

3. Polar dipole 0.195 L

4. Pole-pole 0.35 L

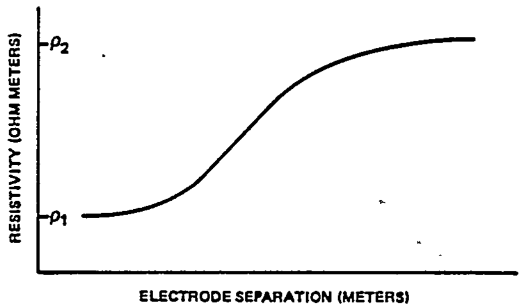
where L is the distance between the outermost electrodes, whether they be current electrodes or potential electrodes. For the pole-pole array, L is the distance between the inner-most electrodes.

Two distinctly different types of DCR surveys are commonly used. A vertical sounding expands the spacing between the electrodes along a straight line, while the central point of the array remains fixed. Because L is increased, the depth penetration is increased, and the variation of resistivity as measured at the surface reflects changes of material with increasing depth (such as horizontal stratification). A second type of survey, a profiling survey, employs fixed electrode spacings. The entire array is moved between measurements without changing the electrode configuration. This type of array has a more or less fixed depth penetration and is used to define lateral variations in resistivity, such as those that may be exhibited by a vertical fault.

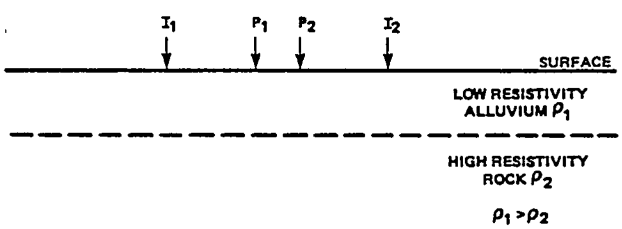
1.5 Interpretation

Data from a vertical sounding survey are plotted as a curve of apparent resistivity versus electrode spacing. The curve is matched against theoretical curves, which have been constructed for various layered models. The result is a semi-quantitative interpretation of the resistivities and thicknesses of the underlying layers (see figure 4). Profiling data are plotted at the center of the array location, and the result can be either a cross-sectional model of a vertical or near-vertical structure (see figure 5) or a contour map of resistivity values. With the polar dipole array, both types of surveys are frequently conducted simultaneously, so that both a vertical sounding and a profile are generated. Figure 6 shows the results of such an approach.

Interpretation is usually a combination of curve matching and qualitative modeling. As with most other geophysical techniques, DCR interpretation frequently is enhanced if other geophysical and geological data are available.



A. TYPICAL RESISTIVITY SOUNDING CURVE



B. INTERPRETED GEOELECTRIC SECTION

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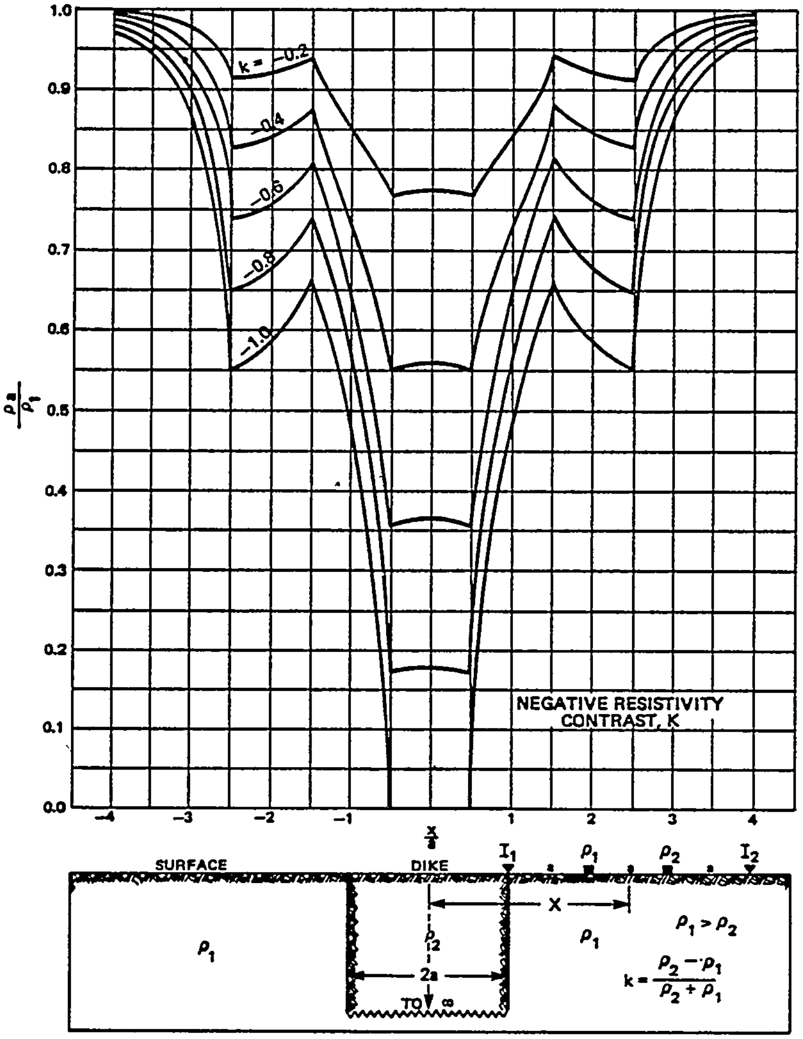
TYPICAL RESISTIVITY
SOUNDING SURVEY RESULTS

6-81

FIGURE 4

Compiled by ________ / Drawn by ________ / Checked by ________ / Approved by ________



THEORETICAL CURVES OF A HORIZONTAL PROFILE ACROSS A VERTICAL DIKE SHOWING VARIOUS RESISTIVITY CONTRASTS, K (COOK AND VAN NOSTRAND)

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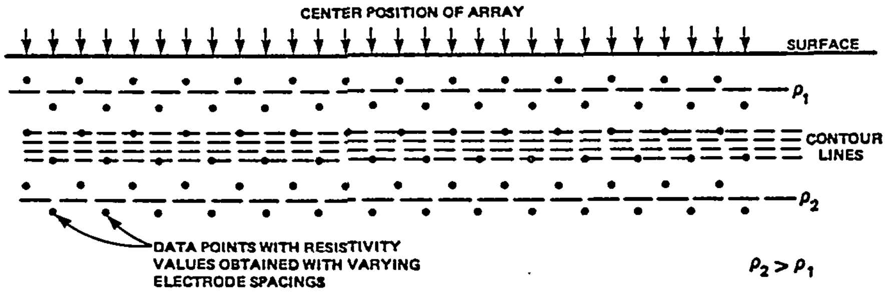
TYPICAL PROFILE SURVEY OVER A VERTICAL STRUCTURE

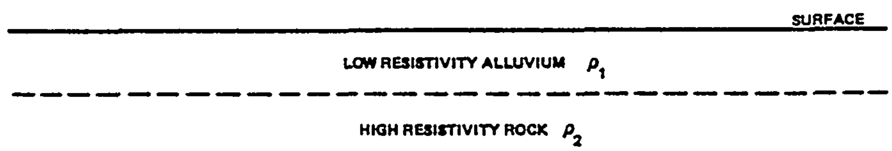
6-81

FIGURE 5

Compiled by ____ / Drawn by ____ / Checked by ____ / Approved by ____



A. RESISTIVITY DATA AND PSEUDO DEPTH SECTION



B. INTERPRETED GEOELECTRIC MODEL

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TYPICAL POLAR-DIPOLE
SURVEY RESULTS

6-81

FIGURE 6

Compiled by ______ Drawn by ______ Checked by ______ Approved by ______

2.0 APPLICABILITY OF THE DCR METHOD

2.1 General

DCR surveys usually are performed to complement other methods of exploration and as an economical way to extend exploration coverage provided by more costly techniques. DCR surveys are useful only when the target provides a detectable thickness and a resistivity contrast with the surrounding media.

Many structural and hydrologic features can be explored with the DCR method. A sounding survey may help to determine the thicknesses of individual beds in a layered subsurface. Horizontal profiling may be able to map the areal extent of geologic features such as faults or fractured zones and intrusive bodies.

Solution features, such as solution cavities in carbonate rocks, joint openings, and large gas-bubble cavities in volcanic rocks, whether open or filled, frequently exhibit large resistivity contrasts with the host media and may be detected by the DCR method. The method can provide information relating to ground water investigations and may detect depth to water table, location, shape and depth of buried aquifers, limits of water contamination and ground water circulation trends. Buried aquifers that consist of "clean" sands and gravels usually have a very high resistivity when saturated with fresh water and may be detected by surface measurements. Table 1 summarizes the geologic applications of resistivity.

2.2 Applicability to Host Media

The applicability of the resistivity technique to investigating the six candidate host media is discussed below.

Salt Formations

Bedded and dome salt formations are usually surrounded by sedimentary rocks and can appear as a very conductive layer (less than 1 ohm-meter) when saturated with water or have a resistivity value as high as 10^6 ohm-meters when dry.[3] The DCR method may identify the salt mass, its degree of saturation, and certain structural conditions, which may be found with salt formations.

TABLE 1

APPLICABILITY OF THE DCR METHOD TO THE IDENTIFICATION AND DEFINITION OF SUBSURFACE GEOLOGIC FEATURES

I FEATURES ASSOCIATED WITH ONE OR MORE HORIZONTAL PLANES

		Ranking 1	2	3	4
A. DEPTH TO:	1. BEDDED SALT	X			
	2. SHALE	X			
	3. BASALT	X			
	4. TUFF		X		
	5. WATER TABLE	X			
	6. BEDROCK	X			
	7. BASEMENT		X		
	8. ANGULAR UNCONFORMITY		X		
	9. PARACONFORMITY		X		
	10. LOW-ANGLE FAULT		X		
B. THICKNESS OF:	1. BEDDED SALT	X			
	2. SHALE	X			
	3. BASALT	X			
	4. TUFF		X		
	5. OVERBURDEN	X			
	6. SEDIMENTARY STRATUM IN GENERAL	X			
	7. SILL		X		
C. ANGLE OF:	1. INCLINED STRATA		X		
	a. LIMB OF ANTICLINE OR SYNCLINE			X	
	b. MONOCLINE OR HOMOCLINE			X	
	2. LOW-ANGLE FAULT		X		
	3. AXIAL PLANE OF RECUMBENT FOLD			X	

TABLE 1, DCR (CONT'D)

II. FEATURES ASSOCIATED WITH ONE OR MORE VERTICAL PLANES

		RANKING 1	2	3	4
A. LOCATION OF:	1. HIGH-ANGLE FAULT	X			
	2. FRACTURE ZONE	X			
	3. BRECCIA ZONE	X			
	4. IGNEOUS INTRUSIVE CONTACT	X			
	5. SALT DOME CONTACT	X			
B. WIDTH OF:	1. DIKE	X			
	2. FRACTURE ZONE	X			
	3. BRECCIA ZONE	X			
	4. SALT DOMES	X			
C. ANGLE OF:	1. FAULT PLANE		X		
	2. IGNEOUS INTRUSIVE CONTACT		X		
	3. SALT DOME CONTACT		X		
	4. AXIAL PLANE OF NORMAL FOLD			X	

III. OTHER FEATURES

		1	2	3	4
A. DEPTH TO:	1. BURIED EROSIONAL SURFACE		X		
	2. IGNEOUS INTRUSIVE BODY	X			
	3. SALT DOME	X			
	4. SOLUTION FEATURES		X		
	5. MASSIVE SULFIDE DEPOSIT	X			

TABLE 1, DCR (CONT'D)

B. DETERMINATION OF:		RANKING 1	2	3	4
	1. ROCK TYPE		X		
	a. BEDDED SALT	X			
	b. SHALE	X			
	c. BASALT		X		
	d. TUFF		X		
	e. GRANITE		X		
	2. GEOTHERMAL CONDITIONS	X			

KEY TO RANKING

1. FREQUENTLY APPLICABLE
2. OCCASIONALLY APPLICABLE
3. SELDOM APPLICABLE
4. NOT APPLICABLE

Resistivity profiling may be used to locate breccia pipes which occur in bedded salts as large vertical structures. These are formed by a solution mechanism and may be detected as low resistivity anomalies.

Shale

Shale beds contain large amounts of clay particles and, thus, adsorb water and mobile ions. Therefore, they have very low resistivity values (1-500 ohm meters)[3] and appear in resistivity measurements as low-valued anomalies. Because shales have low permeability, water transport occurs principally through fracture zones, and resistivity surveys may locate these fractures if they are of sufficient size.

Granite

Granite, like shale, has low porosity and permeability, and as a result, very high resistivity ($300-10^6$ ohm meters).[14] Consequently, unless it is highly weathered or fractured or too deep, it is usually detectable and mappable by the DCR method.

A principal goal in evaluating granite as a repository medium would be to determine the extent of fracturing and faulting in the granite, since such structures are the primary pathways for water transport. The DCR method may be applicable to the detection and mapping of these structures.

Basalt

Basalt, like granite, usually has low porosity and permeability and, consequently, normally exhibits high resistivity (10 to 10^7 ohm meters).[14] However, basalt can be vesicular, or jointed or fractured, and may exhibit low resistivity.

Tuff

The porosity and permeability of tuff vary considerably. For example, welded tuff may show very high resistivity, while devitrified tuff may show low resistivity. Once the type of tuff has been identified, the DCR method may be used to locate fracture zones, faults, intra-tuff bedding and other structural features that could have a bearing on repository selection.

3.0 RESOLUTION OF THE DCR METHOD

The DCR method has several inherent limitations that affect its ability to resolve certain geologic features. A measured apparent resistivity represents a weighted average of resistivities over a large volume of material. This tends to produce smooth resistivity curves, which do not result in high degrees of resolution. Also, near-surface materials contribute more heavily to surface measurements than do deeper materials, which must be relatively large and must contain substantial resistivity variations before their effects can be discerned.

A given resistivity sounding curve can correspond to a variety of layer thicknesses and resistivities. The principle of layer equivalence states that it is not possible to distinguish between two beds of different thicknesses and resistivities if they have the same T value. The T value of a bed is the product of its thickness and resistivity.

As in other geophysical methods, horizontal resolution of the DCR method is dependent on station density. For profiling, the spacing between stations should be no greater than one-half the horizontal width of the target being sought. Vertical resolution is dependent on the incremental increases in electrode spacing as a sounding curve is developed. The smaller the increments, the more accurate the sounding curve and the better the resolution.

Resolution is inversely proportional to depth. The deeper a target, the more difficult it is to resolve. Table 2 shows, in a qualitative way, the relationship between resolution, depth and geologic feature.

4.0 RELIABILITY OF INTERPRETATION

Because the resistivities of geologic materials are so variable, it is not possible to unambiguously identify the materials. In addition, because of the interdependency of depth or thickness and resistivity values, it is not possible to develop a unique structural model from a sounding curve.

The use of auxiliary geologic or geophysical data improves reliability by helping to limit the number of causative possibilities. The interpretation of profiling surveys conducted

TABLE 2

DETECTABILITY OF GEOLOGIC FEATURES AND ACCURACY OF SUBSURFACE MEASUREMENTS USING THE DCR METHOD

NOTE: 1. CONTRAST IS RESISTIVITY CONTRAST
2. SEE END OF CHART FOR KEY TO RANKING

		LOW CONTRAST 2:1				MEDIUM CONTRAST (10-99):1				HIGH CONTRAST (100+):1			
		0-5M	5-300 M	300-900M	> 900 M	0-5 M	5-300 M	300-900 M	> 900 M	0-5 M	5-300 M	300-900 M	> 900 M
I. DEPTH TO:	1. BEDDED SALT	3	4	5	5	2	3	4	5	1	2	3	5
	2. SALT DOME	3	4	5	5	2	3	4	5	1	2	3	5
	3. SHALE	3	4	5	5	2	3	4	5	1	2	3	5
	4. BASALT	3	4	5	5	2	3	4	5	1	2	3	5
	5. TUFF	3	4	5	5	2	3	4	5	1	2	3	5
	6. GRANITE	3	4	5	5	2	3	4	5	1	2	3	5
	7. BURIED EROSIONAL SURFACE	3	4	5	5	2	3	4	5	1	2	3	5
	8. WATER TABLE	3	4	5	5	2	3	4	5	1	2	3	5
	9. BEDROCK	3	4	5	5	2	3	4	5	1	2	3	5
	10. BASEMENT	3	4	5	5	2	3	4	5	1	2	3	5
	11. CONTACT	3	4	5	5	2	3	4	5	1	2	3	5
	12. ANGULAR UNCONFORMITY	3	4	5	5	2	3	4	5	1	2	3	5
	13. PARACONFORMITY	3	4	5	5	2	3	4	5	1	2	3	5
	14. LOW ANGLE FAULT	3	4	5	5	2	3	4	5	1	2	3	5
II. ANGLE OF:	1. INCLINED STRATA	3	4	5	5	2	3	4	5	1	2	3	5
	2. LIMB OF ANTICLINE OR SYNCLINE	3	4	5	5	2	3	4	5	1	2	3	5
	3. MONOCLINE OR HOMOCLINE	3	4	5	5	2	3	5	5	1	2	3	5
	4. FAULT PLANE	3	4	5	5	2	3	4	5	1	2	3	5
	5. AXIAL PLANE OF FOLD	3	4	5	5	2	3	4	5	1	2	3	5
	6. IGNEOUS INTRUSIVE CONTACT	3	4	5	5	2	3	4	5	1	2	3	5
	7. SALT DOME CONTACTS	3	4	5	5	2	3	4	5	1	2	3	5

TABLE 2, DCR (CONT'D)

		LOW CONTRAST 2:1				MEDIUM CONTRAST (10-99):1				HIGH CONTRAST (100+):1			
		0-5 M	5-300 M	300-900 M	> 900 M	0-5 M	5-300 M	300-900 M	> 900 M	0-5 M	5-300 M	300-900 M	> 900 M
III. SIZE OF:	1. SOLUTION FEATURE	3	4	5	5	2	3	4	5	1	2	3	5
	2. MASSIVE SULFIDE DEPOSIT	3	4	5	5	2	3	4	5	1	2	3	5
	3. SALT DOME	3	4	5	5	2	3	4	5	1	2	3	5
	4. FAULT OFFSET	3	4	5	5	2	3	4	5	1	2	3	5

KEY TO RANKING

I. ACCURACY OF DEPTH

1. ± 1-5% OF DEPTH
2. ± 5-15% OF DEPTH
3. ± 15-30% OF DEPTH
4. ± > 30% OF DEPTH
5. NOT DETECTABLE

II. ACCURACY OF ANGLE

1. ± 1-5 DEGREES
2. ± 5-15 DEGREES
3. ± 15-30 DEGREES
4. ± > 30 DEGREES
5. NOT DETECTABLE

III. MINIMUM SIZE FOR DETECTION

1. TINY (1 CM - 1 M)
2. SMALL (1 M - 9 M)
3. MEDIUM (10 M - 99 M)
4. LARGE (> 100 M)
5. NOT DETECTABLE

to define vertical features is less dependent on auxiliary data. Such surveys can be effective in mapping the areal extent of anomalies.

Table 3 shows qualitatively the reliability of interpretation for a number of geologic features. The table relates reliability to both resistivity contrast and depth, showing that reliability of interpretation is usually better in cases where resistivity contrast is higher and that reliability decreases as depth increases.

5.0 COSTS

The costs of a DCR survey depend on the type of survey. A profiling survey, where electrode spacings are held constant, is less expensive per station than a sounding survey. Only one measurement is being made per station in a profiling survey, while two to ten or more are made in a sounding survey. Other factors that determine survey costs are:

a. desired depth penetration

b. type of electrode array

c. distance between stations

d. accessibility

e. terrain conditions

f. weather

Figures 7A and 7B give approximate costs per station for profiling and sounding surveys, respectively (in 1981 dollars). Interpretation costs can vary substantially, depending on how much time one wants to devote to modeling. The figures were constructed on the assumption that conditions are "average", i.e., accessibility, terrain and weather are not extreme. Tables 4A and 4B show a sample calculation used in constructing the cost curves of Figures 7A and 7B. Figure 7B and Table 4B are also based on the assumption that five measurements are made per sounding.

TABLE 3

RELIABILITY OF IDENTIFICATION OF GEOLOGIC FEATURES USING THE DCR METHOD

NOTE: 1. CONTRAST IS RESISTIVITY CONTRAST
2. SEE END OF CHART FOR KEY TO RANKING

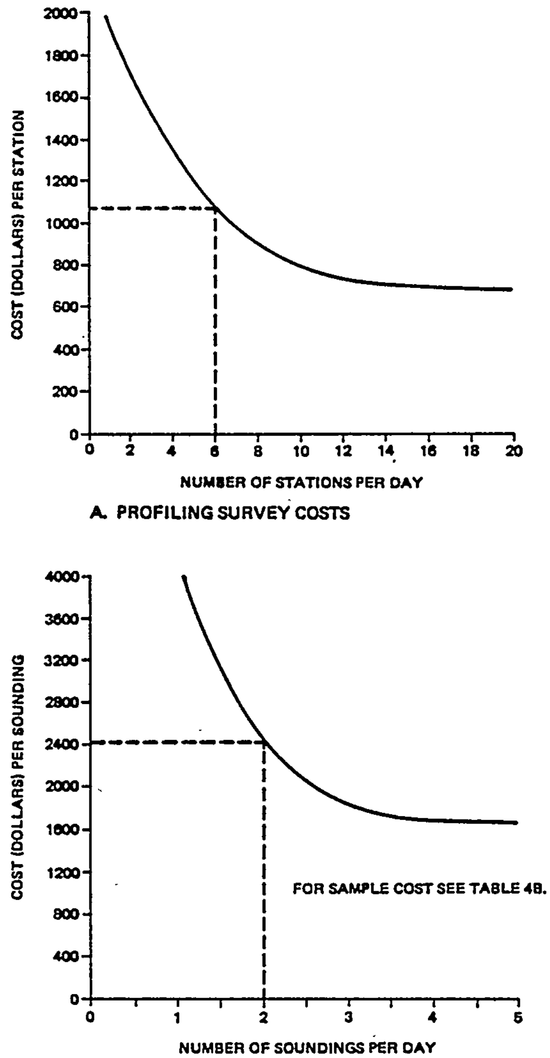
	LOW CONTRAST 2:1				MEDIUM CONTRAST (10-99):1				HIGH CONTRAST (100+):1			
	0-5 M	5-300 M	300-900 M	> 900 M	0-5 M	5-300 M	300-900 M	> 900 M	0-5 M	5-300 M	300-900 M	> 900 M
I. HORIZONTAL FEATURES												
1. BURIED EROSIONAL SURFACE	4	4	4	4	3	4	4	4	2	3	4	4
2. WATER TABLE	3	4	4	4	2	3	4	4	2	2	3	4
3. BEDROCK	3	4	4	4	2	3	4	4	2	2	3	4
4. BASEMENT	4	4	4	4	3	4	4	4	2	3	4	4
5. CONTACT	3	4	4	4	2	3	4	4	2	2	3	4
6. ANGULAR UNCONFORMITY	4	4	4	4	3	4	4	4	2	3	4	4
7. PARACONFORMITY	4	4	4	4	3	4	4	4	2	3	4	4
8. LOW-ANGLE FAULT	4	4	4	4	3	4	4	4	3	3	4	4
9. INCLINED STRATA	4	4	4	4	3	4	4	4	3	3	4	4
9a. LIMB OF ANTICLINE OR SYNCLINE	4	4	4	4	3	4	4	4	3	3	4	4
9b. MONOCLINE OR HOMOCLINE	4	4	4	4	3	4	4	4	3	3	4	4
II. VERTICAL FEATURES												
1. HIGH-ANGLE FAULT	3	4	4	4	2	3	4	4	2	2	3	4
2. FRACTURE ZONE	3	4	4	4	2	3	4	4	2	2	3	4
3. BRECCIA ZONE	3	4	4	4	2	3	4	4	2	2	3	4
4. IGNEOUS INTRUSIVE CONTACT	3	4	4	4	2	3	4	4	2	2	3	4
5. SALT DOME CONTACT	3	4	4	4	2	3	4	4	2	2	3	4
6. DIKE	3	4	4	4	2	3	4	4	2	2	3	4

TABLE 3, DCR (CONT'D)

	LOW CONTRAST 2:1				MEDIUM CONTRAST (10-99):1				HIGH CONTRAST (100+):1			
	0-5 M	5-300 M	300-900 M	> 900 M	0-5 M	5-300 M	300-900 M	> 900 M	0-5 M	5-300 M	300-900 M	> 900 M
III. OTHER FEATURES												
1. IGNEOUS INTRUSIVE BODY	3	4	4	4	2	3	4	4	2	2	3	4
2. SALT DOME	3	4	4	4	2	3	4	4	2	2	3	4
3. SOLUTION FEATURES	4	4	4	4	3	4	4	4	2	3	4	4
4. MASSIVE SULFIDE DEPOSIT	3	4	4	4	2	3	4	4	2	2	3	4
IV. COMPOSITION												
1. BEDDED OR DOMED SALT	3	4	4	4	2	3	4	4	2	2	3	4
2. SHALE	3	4	4	4	2	3	4	4	2	2	3	4
3. BASALT	3	4	4	4	2	3	4	4	2	2	3	4
4. TUFF	4	4	4	4	3	4	4	4	2	3	3	4
5. GRANITE	3	4	4	4	2	3	4	4	2	2	3	4
6. ROCK TYPE IN GENERAL	3	4	4	4	2	3	4	4	2	2	3	4

KEY TO RANKING

1. GOOD RELIABILITY (ONE OR TWO POSSIBLE INTERPRETATIONS)
2. FAIR RELIABILITY (THREE OR FOUR POSSIBLE INTERPRETATIONS)
3. POOR RELIABILITY (FIVE OR MORE POSSIBLE INTERPRETATIONS)
4. NOT IDENTIFIABLE



A. PROFILING SURVEY COSTS

B. SOUNDING SURVEY COSTS

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APPROXIMATE DCR SURVEY COSTS

6-81

FIGURE 7

Compiled by ____ / Drawn by ____ / Checked by ____ / Approved by ____ /

A. DETAILS OF PROFILING SURVEY COSTS

ASSUME SURVEY CONSISTS OF 6 AVERAGE LENGTH (l = 1 KM) PROFILING LINES OR STATIONS. TO OBTAIN THE DATA FOR 6 STATIONS IN A DAY WOULD REQUIRE 2-3 MAN CREWS WORKING A 10 HOUR DAY. THE COST PER STATION IS OUTLINED IN THE TABLE BELOW.

	COST (DOLLARS)
I. MOBILIZE - DEMOBILIZE	
A. LABOR - PROJECT (4 HRS) + TECHNICIAN (8 HRS)	460
B. OC* - FIELD SUPPLIES	240
II. FIELD WORK	
A. LABOR - 2 SENIOR TECHNICIANS (12 HRS EACH) + 4 TECHNICIANS (12 HRS EACH)	2500
B. OC - PER DIEM + VEHICAL COSTS + EQUIPMENT RENTAL + SUPPLIES	1600
III. INTERPRETATION A. LABOR - STAFF (8 HRS)	
A. LABOR - STAFF (8 HRS)	290
B. OC - NONE	0
IV. REPORT	
A. LABOR - STAFF (8 HRS) + SENIOR (2 HRS) + REPORT PERSONNEL (12 HRS)	740
B. OC - REPORT MATERIAL	110

APPROXIMATE COST PER PROFILING STATION (AT A RATE OF 6/DAY) IS $1050.

B. DETAILS OF SOUNDING SURVEY COSTS

ASSUME SURVEY CONSISTS OF 2 AVERAGE LENGTH (l = 300M) SOUNDING SURVEYS EACH CONSISTING OF 5 SEPERATE MEASUREMENTS. TO OBTAIN THE DATA FOR 2 SOUNDINGS IN A DAY REQUIRES A 3 MAN CREW WORKING A 10 HOUR DAY. THE COST PER SOUNDING IS OUTLINED IN THE TABLE BELOW.

	COST (DOLLARS)
I. MOBILIZE - DEMOBILIZE	
A. LABOR - PROJECT (4 HRS) + TECHNICIAN (8 HRS)	460
B. OC - FIELD SUPPLIES	240
II. FIELD WORK	
A. LABOR - SENIOR TECHNICIAN (12 HRS) + 2 TECHNICIANS (12 HRS EACH)	1300
B. OC - PER DIEM + VEHICAL COSTS + EQUIPMENT RENTAL + SUPPLIES	800
III. INTERPRETATION	
A. LABOR - TECHNICIAN (4 HRS) + STAFF (16 HRS) + SENIOR (4 HRS)	950
B. OC - COMPUTER PROCESSING COSTS	220
IV. REPORT	
A. LABOR - STAFF (8 HRS) + SENIOR (2 HRS) + REPORT PERSONNEL (12 HRS)	740
B. OC - REPORT MATERIAL	110

APPROXIMATE COST PER SOUNDING (AT A RATE OF 2/DAY) IS $2450.

*OC - OTHER COST INCLUDING OVERHEAD

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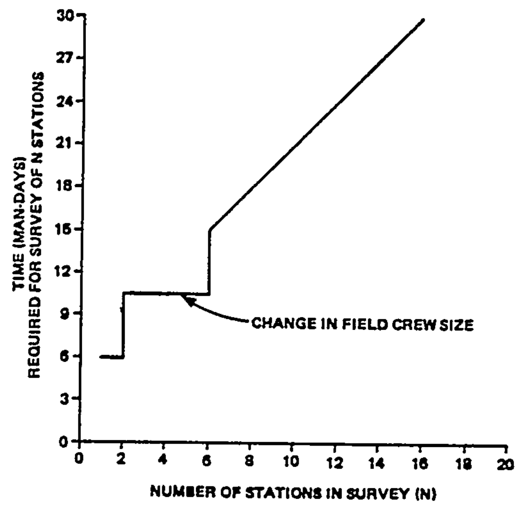
CALCULATION OF DCR SURVEY COSTS

6-81 TABLE 4

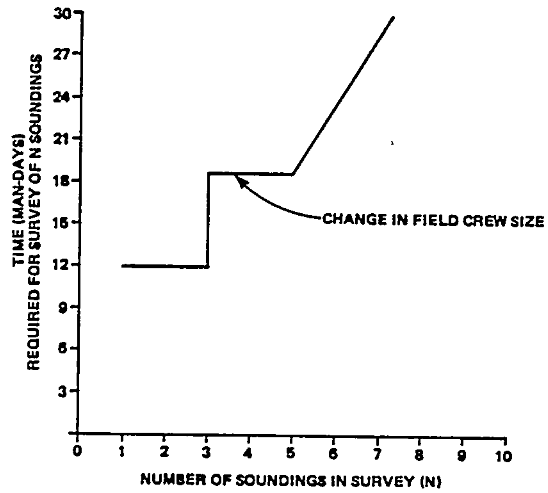
Compiled by ________ Drawn by ________ Checked by ________ Approved by ________

6.0 TIME

The time required to conduct a DCR survey depends on the same factors as costs. Figure 8A and 8B give approximate times per station for profiling and sounding surveys, respectively. The same assumptions have been made as in Section 5. Tables 5A and 5B show a sample calculation used in constructing the cost curves of Figures 8A and 8B.



A. PROFILING SURVEY TIME REQUIREMENTS



B. SOUNDING SURVEY TIME REQUIREMENTS

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APPROXIMATE DCR SURVEY
TIME REQUIREMENTS

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FIGURE 8

Compiled by ______ Drawn by ______ Checked by ______ Approved by ______

A. DETAILS OF PROFILING SURVEY TIME REQUIREMENTS

ASSUME SAME SURVEY AS DESCRIBED FOR TABLE 4A. THE TIME REQUIRED (MAN-DAYS) FOR COMPLETING THIS PROFILING SURVEY IS SHOWN IN THE TABLE BELOW.

CATEGORY	TIME (MAN-DAYS)
I. MOBILIZE - DEMOBILIZE	1.5
II. FIELD WORK	9.0
III. INTERPRETATION	1.0
IV. REPORT	3.0
APPROXIMATE TOTAL	15 MAN-DAYS

APPROXIMATE TIME REQUIRED FOR A 6 STATION PROFILE SURVEY IS 15 MAN-DAYS.

B. DETAILS OF SOUNDING SURVEY TIME REQUIREMENTS

ASSUME SAME SURVEY AS DESCRIBED FOR TABLE 4B. THE TIME REQUIRED (MAN-DAYS) FOR COMPLETING THIS SOUNDING SURVEY IS SHOWN IN THE TABLE BELOW.

CATEGORY	TIME (MAN-DAYS)
I. MOBILIZE - DEMOBILIZE	1.5
II. FIELD WORK	4.5
III. INTERPRETATION	3.0
IV. REPORT	3.0
APPROXIMATE TOTAL	12 MAN-DAYS

APPROXIMATE TIME REQUIRED FOR A 2 SOUNDING SURVEY IS 12 MAN-DAYS.

TABLE 5

CALCULATION OF DCR SURVEY TIME REQUIREMENTS

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APPENDIX B-5

MAGNETICS TECHNIQUE

By

Ertec Western, Inc.

Long Beach, California

November 1, 1981

B-5

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1.0 DESCRIPTION OF THE MAGNETICS TECHNIQUE

1.1 Physical Principle

If two magnetic poles of strength P_O and P, respectively, are separated by a distance r, the force F between them will be

$$F = \frac{1}{\mu}\frac{P_O P}{r^2}$$

The contant μ, known as the permeability depends upon the magnetic properties of the medium in which the poles are situated. The units of pole strength are defined by the specification that F is 1 dyne when two unit poles 1 centimeter apart are situated in a nonmagnetic medium such as vacuum or air (for which $\mu = 1$). If the poles are of like type, the force is repulsive; if they are unlike, it is attractive.

The magnetic field strength H, at a point is defined as:

$$H = \frac{F}{P_O} = \frac{P}{\mu r^2}$$

where P_O is a small positive test pole used to measure the field strength.

Rocks are magnetized by the earth's magnetic field. There are two types of magnetization, induced and remanent. Induced magnetization is caused by the present affect of the earth's field. The intensity of induced magnetization I, is proportional to the inducing field H, of the earth: $I = kH$. The proportionality constant k is called the susceptibility. The induced magnetic field adds vectorially to the inducing geomagnetic field and produces magnetic anomalies.

The contrast of susceptibility between geologic formations is the most significant cause of the magnetic anomalies studied in exploration. Remanent magnetization occurs in igneous rocks which have cooled below the Curie temperature in the presence of the earth's field. This thermoremanent magnetization remains even after the earth's field has changed direction, or even if it reverses polarity. Where such magnetization occurs in significant amounts it may cause a noise problem or an interpretation problem.

The magnetic effect of an extended body is in general a complicated vector integration of all the simple magnets distributed over the surface of the body. In the northern hemisphere negative poles are induced on the upper surface of the body and positive poles on the lower surface. Given the facts about a body, one can calculate its magnetic field, however the reverse process does not yield a unique answer about the body. Potential theory shows that theoretically an infinite number of pole distributions will produce the same magnetic field. Geologic constraints and knowledge from various sources are used to limit the number of interpretations. In exploration, since few details about the target body are available, one uses simple geologically plausible models to estimate the properties of the target.

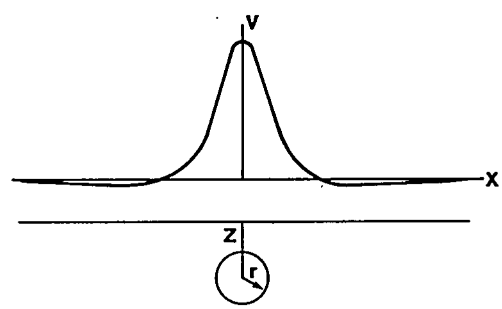
1.2 Mathematical Modeling

As examples of simple magnetic models, let us discuss the sphere, the horizontal cylinder and the fault (Nettleton, 1942). To retain simplicity, we must restrict ourselves to the vertical component of the magnetic field. In middle to northern latitudes the vertical field anomalies are at least qualitatively similar to the total field anomalies.

Sphere

A sphere model approximates a concentrated body, especially so when its dimensions are small compared to its depth. The vertical magnetic field V, due to a sphere of radius R, with intensity of magnetization I, at depth Z, is:

$$V = 8.38 \times 10^5 I \left(\frac{R}{z}\right)^3 \cdot \frac{1 - \frac{1}{2}(x/z)^2}{\left[1 + (x/z)^2\right]^{5/2}}$$



where

x is the horizontal distance from the center.

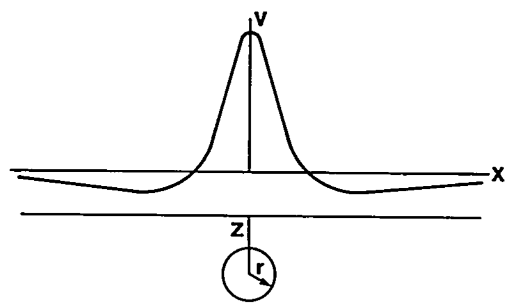
I is in cgs units and is equal to kH (in the U.S. H is about 0.6 Oersted).

The sphere field diminishes as the inverse cube of the depth, more rapidly than that of any other body.

Horizontal Cylinder

A horizontal cylinder model approximates a basement ridge, a horst, or a fold.

$$V = 6.28 \times 10^5 I \left(\frac{R}{z}\right)^2 \cdot \frac{1-(x/z)^2}{\left[1+(x/z)^2\right]^2}$$

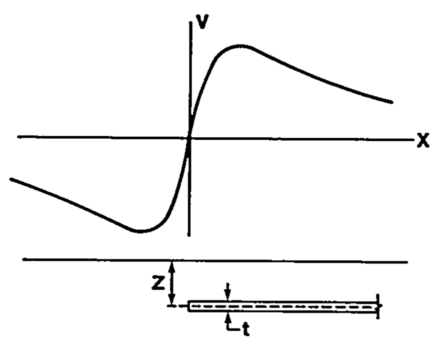


The cylinder field diminishes as the inverse square of the depth.

Fault

The vertical fault with throw t (approximated by a horizontal sheet) is expressed by:

$$V = 2 \times 10^5 \frac{It}{z} \cdot \frac{x/z}{1+(x/z)^2}$$



The fault field diminishes as the inverse of the depth.

1.3 Geologic Sources of Magnetic Anomaly

Magnetic anomalies are caused by differences of susceptibility, and the existence of structures which depart from uniform horizontal layering. Some structures which cause magnetic anomalies are faults, horsts, grabens, basement topography, dikes, sills and, if there is sufficient susceptibility constrast, sharp folds. Salt, having no magnetic minerals, can only create anomalies by its outline in the surrounding material which may be weakly susceptible sediments.

The order of susceptibilities for the host media is:

basalt	14 ± 7	(units are $x10^{-3}$ cgs)
granite	3 ± 2	
shale and sediment	$0.05 \pm$	
tuff	negligible	
salt	negligible	

1.4 Instruments

Most magnetic surveys today are performed using the proton precession magnetometer. It uses the precession frequency of protons as they realign their magnetic moments with the earth's field after being disoriented. The protons are in a liquid, water or hydrocarbon. A coil around the container is used to disorient the protons from their normal alignment by subjecting them to an alternating magnetic field. When the disturbance is removed, the coil picks up the precession signal as the protons realign themselves. They precess like a spinning top at their Larmor frequency (about 2000 Hz) for a few seconds until they are realigned. The Larmor frequency is proportional to the ambient magnetic field and serves as a measure of the field.

The more sensitive alkali vapor magnetometers are also in frequent use. They operate on a quantum mechanical effect (the Zeeman effect) having to do with the splitting of electron orbital energy levels by a magnetic field. They are called optically-pumped magnetometers because they use an alkali (cesium) vapor lamp to supply photons to boost the outer electrons of cesium atoms into more energetic orbits. They achieve a sensitivity of 0.005 gamma, as compared to about 1 gamma for the proton precession magnetometer. (Although 0.05 gamma field-survey sensitivity is claimed for the latest model proton precession magnetometer.)

2.0 THE CONTRIBUTIONS OF MAGNETICS

Airborne magnetic surveys are effective in detection and size estimation of large and deeply buried features. Ground surveys are effective in the location of small shallow bodies of large susceptibility contrast or large remanent magnetization. Ground surveys can be hindered by the masking effects of near-surface magnetization because of its proximity to the magnetometer.

Magnetic surveys are most effective for studies of basic igneous rocks because of their high susceptibility. Their effectiveness is diminished when studying acid igneous rocks and metamorphic rocks. Sedimentary rocks have low susceptibilities, and sediments generally have negligible susceptibility (Dobrin, 1976). Thus, the major contribution of magnetics lies in the mapping of basement topography and the detection of igneous intrusions. Intrabasement anomalies (due to composition change) can indicate old tectonic boundaries which may be lines of crustal weakness. Faults, dikes and sills, batholiths and stocks are geologic features for which magnetic surveys are effective. Depth to basement can be calculated from basement anomalies. If host beds are basalt the depth to them may be calculated if the surfaces are sufficiently rough to produce anomalies.

3.0 RESOLUTION

3.1 Theoretical Resolution

The description of resolution given in the report for gravity (Appendix B-1) also applies to magnetic anomalies. Magnetics may have a practical advantage in its bipolarity and the consequent plus-minus anomalies being easier to distinguish than monopolar anomalies. Also magnetic anomalies are simpler because they are generally due to one or two surfaces, whereas the gravity is often due to multiple layers.

3.2 Geologic Factors

Resolution is best for anomalies that are sharply localized and of large magnitude. The magnitude of magnetic anomalies depends on:

1. The dimensions of the anomalous body,

2. The magnetization contrast, and

3. The geometric factor.

The sharpness depends mainly on 3. The geometric parameter that has the greatest influence is depth. The ability to distinguish separate bodies strongly depends on the ratio of horizontal separation to depth (Romberg, 1958). In comparison with gravity, magnetic anomaly resolution decreases more rapidly with increasing depth.

3.3 Measurement Factors

As with gravity, there are two categories:

1. Instrument sensitivity (and noise), and

2. Sampling density.

Instrument sensitivity is about 1 gamma for proton precession magnetometers (0.05 gamma for the latest model) and about 0.005 gamma for the optically-pumped alkali vapor magnetometers.

Sampling density refers to the spacing of survey lines and measurements. The measurement spacing required to detect an anomaly of wavelength L must be no greater than 1/2 L, the Nyquist wavelength. For reconnaissance the line spacing should not be much greater than the half-width (i.e., half the width of the anomaly at half its amplitude) of the smallest anomalies of interest. For both the sphere and the horizontal cylinder, i.e., for both concentrated and long anomalies, this spacing is equal to half the depth. Line spacing wider than half the depth (from the magnetometer) can fail to detect narrower anomalies (shallower bodies).

The sampling in airborne magnetics is nonuniform. Sampling is relatively dense, but there is relatively wide separation between the lines. Along survey lines, sample spacing varies from about 20 feet to 600 feet, depending on the speed of the aircraft and the repetition rate of the magnetometer (the repetition rate must be less for higher sensitivity). The distance between survey lines may be 30 times the sample spacing. The spacing of crossing tie lines may be 5 or more times the survey line spacing. The survey lines should therefore be flown perpendicular to the magnetic strike of the region. This strike generally follows the structural trend of the crystalline or igneous rocks.

Survey flight altitudes are commonly between 750 ft to 1500 ft above the ground. This height avoids the unwanted effects of near-surface magnetic sources. For a survey plane flying at 1000 ft altitude, and a target depth of 1000 to 4000 ft, the survey line spacing should not be much greater than 1000-2500 ft.

3.4 Data Processing Factors

Computer processing of magnetic data generally requires the creation of a uniform grid of values from a non-uniform distribution of field measurements. The grid spacing affects resolution. For the best resolution, the grid spacing should equal the measurement spacing on the survey lines. The gridding process involves the use of a local averaging operator to assign values to the grid points. The sharpness of its weighting function determines the graininess of the grid representation.

The isolation of anomalies by removal of the regional magnetic trend is often accomplished by the use of various grid operators which are essentially filters. The high-pass filter response affects the resolution.

Further discrimination of anomalies is attempted by the construction of first and second derivative maps. First derivative maps display slopes, while second derivative maps display curvature, both of which are intimately related to resolution.

Mathematical continuation of the measured magnetic field downward toward the depth of the anomalous mass sharpens the anomaly, but also magnifies the noise contained in the data.

A mathematical process called "reduction to the pole" transforms the measured fields to the way they would be at the geomagnetic pole, where the field is vertical. Vertical fields are much easier to interpret since the inclination of the geomagnetic field and its interaction with the orientation of bodies needn't be considered. Vertical field maps have strong similarities to gravity maps.

References for this section are Nettleton (1971), Dobrin (1976), and Fuller (1967).

3.5 Noise Factors

The geologic noise factors are:

1. Local susceptibility inhomogeneities,
2. Regional gradients,
3. Bedrock relief, and
4. Remanence inhomogeneities.

Topographic corrections are extremely difficult due to irregular magnetization of irregular shapes. Location errors fortunately are insignificant except for irregular terrain clearance in airborne surveys. Diurnal geomagnetic field variations have to be corrected for, micropulsations and magnetic storms must be recognized and dealt with (Ward and Rogers, 1967).

4.0 RELIABILITY

4.1 Reliability of the Magnetic Method

This depends on the amount of independent evidence available concerning geologic structure and magnetization distribution. Joint gravity/magnetic analysis increases reliability.

4.2 Factors That Reduce Reliability

The lack of detailed information on susceptibilities is the main drawback.

4.3 "No Record" Situations

"No Record" situations could occur with uniform horizontal layering or non-magnetic formations.

5.0 COSTS

The cost of an aeromagnetic survey depends on the number of line-miles surveyed, the weather, the level of magnetic background noise, the location of the survey, the terrain, and other factors. All costs presented herein are in 1981 dollars.

The cost of a typical aeromagnetic survey using a twin engine aircraft with positioning by flight-path camera is about $20.00 per line mile. This includes flying, flight-path recovery, and computer processing, but not interpretation. The added cost of mobilization is, for example, $10,000 for a survey 2,000 miles distant from home base.

The line-mile cost is about evenly divided between flying and data compilation. About 1/3 of the flying cost is for salaries and the remainder for aircraft, fuel, and supplies. In the data compilation costs, about 1/3 is for salaries and the remainder for flight-path recovery, digitizing, and contour mapping.

A ground magnetic survey is usually done in conjunction with a gravity survey. In that case, the added cost of the magnetic survey is mainly the cost of the portable magnetometer and the base station magnetometer. The instrument can be operated by the gravimetrist's helper at very little extra cost. The added cost of the magnetic survey would be about $60 per day.

6.0 CRITERIA FOR MAGNETIC SURVEYS

The most important criteria are the choice of sampling pattern and the precision of the magnetometer. A magnetometer of highest sensitivity would be required to detect features in shale and salt, and even then the outlook is pessimistic because of the small susceptibility contrasts. Igneous intrusions in shale and salt would be an exception. Magnetometers of ordinary sensitivity (1 gamma) are adequate for mapping basalt and granite, but the detection of small faults requires a high-sensitivity magnetometer.

The sampling pattern should have equally-spaced survey lines perpendicular to the magnetic strike, with perpendicular tie lines which may have larger spacing, i.e., up to 5 or more times the spacing of the survey lines. A square grid is better for the finer work. If there is no perceptible magnetic strike trend, the survey lines should be oriented magnetic north-south. Survey altitudes should be as low as safety and surface magnetic noise allow, perhaps 800 ft. Survey line spacing should not be much greater than half the distance from the magnetometer to the shallowest anomalies, about 900 feet if the shallowest anomalies of interest are at 1000 foot depth.

7.0 REFERENCES

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TABLE 1

APPLICABILITY OF THE MAGNETIC METHOD TO THE IDENTIFICATION AND DEFINITION OF SUBSURFACE GEOLOGIC FEATURES

I FEATURES ASSOCIATED WITH ONE OR MORE HORIZONTAL PLANES

		RANKING 1	2	3	4
A. DEPTH TO:	1. BEDDED SALT				X
	2. SHALE				X
	3. BASALT	X			
	4. TUFF				X
	5. WATER TABLE				X
	6. BEDROCK	X			
	7. BASEMENT	X			
	8. ANGULAR UNCONFORMITY			X	
	9. PARACONFORMITY				X
	10. LOW-ANGLE FAULT			X	
B. THICKNESS OF:	1. BEDDED SALT				X
	2. SHALE				X
	3. BASALT			X	
	4. TUFF				X
	5. OVERBURDEN	X			
	6. SEDIMENTARY STRATUM IN GENERAL				X
	7. SILL			X	
C. ANGLE OF:	1. INCLINED STRATA			X	
	a. LIMB OF ANTICLINE OR SYNCLINE			X	
	b. MONOCLINE OR HOMOCLINE			X	
	2. LOW-ANGLE FAULT			X	
	3. AXIAL PLANE OF RECUMBENT FOLD				X

TABLE 1, MAGNETIC (CONT'D)

II. FEATURES ASSOCIATED WITH ONE OR MORE VERTICAL PLANES

Feature	Ranking 1	2	3	4
A. LOCATION OF:				
1. HIGH-ANGLE FAULT	X			
2. FRACTURE ZONE				X
3. BRECCIA ZONE			X	
4. IGNEOUS INTRUSIVE CONTACT	X			
5. SALT DOME CONTACT			X	
B. WIDTH OF:				
1. DIKE	X			
2. FRACTURE ZONE				X
3. BRECCIA ZONE			X	
4. SALT DOMES			X	
C. ANGLE OF:				
1. FAULT PLANE		X		
2. IGNEOUS INTRUSIVE CONTACT		X		
3. SALT DOME CONTACT				X
4. AXIAL PLANE OF NORMAL FOLD				X

III. OTHER FEATURES

Feature	Ranking 1	2	3	4
A. DEPTH TO:				
1. BURIED EROSIONAL SURFACE		X		
2. IGNEOUS INTRUSIVE BODY	X			
3. SALT DOME			X	
4. SOLUTION FEATURES				X
5. MASSIVE SULFIDE DEPOSIT		X		

TABLE 1, MAGNETIC (CONT'D)

B. DETERMINATION OF:		RANKING 1	2	3	4
	1. ROCK TYPE		X		
	a. BEDDED SALT			X	
	b. SHALE			X	
	c. BASALT	X			
	d. TUFF			X	
	e. GRANITE	X			
	2. GEOTHERMAL CONDITIONS		X		

KEY TO RANKING

1. FREQUENTLY APPLICABLE
2. OCCASIONALLY APPLICABLE
3. SELDOM APPLICABLE
4. NOT APPLICABLE

TABLE 2

DETECTABILITY OF GEOLOGIC FEATURES AND ACCURACY OF SUBSURFACE MEASUREMENTS USING THE MAGNETIC METHOD

NOTE: 1. CONTRAST IS SUSCEPTIBILITY CONTRAST
2. SEE END OF CHART FOR KEY TO RANKING

		LOW CONTRAST				MEDIUM CONTRAST				HIGH CONTRAST			
		0-5M	5-300 M	300-900M	> 900 M	0-5 M	5-300 M	300-900 M	> 900 M	0-5 M	5-300 M	300-900 M	> 900.M
I. DEPTH TO:	1. BEDDED SALT	5	5	5	5	5	5	5	5	5	5	5	5
	2. SALT DOME	5	5	5	5	5	5	5	5	5	4	4	4
	3. SHALE	5	5	5	5	5	5	5	5	5	5	5	5
	4. BASALT	4	4	4	4	4	3	3	4	4	3	3	3
	5. TUFF	5	5	5	5	5	5	5	5	5	5	5	5
	6. GRANITE	4	4	4	4	4	3	4	4	4	3	3	3
	7. BURIED EROSIONAL SURFACE	5	4	4	4	4	4	4	4	4	4	4	4
	8. WATER TABLE	5	5	5	5	5	5	5	5	5	5	5	5
	9. BEDROCK	4	4	4	4	4	3	4	4	4	3	3	3
	10. BASEMENT	4	4	4	4	4	3	4	4	4	3	3	3
	11. CONTACT	5	5	5	5	5	5	5	5	5	5	5	5
	12. ANGULAR UNCONFORMITY	4	4	4	4	5	4	4	4	5	4	4	4
	13. PARACONFORMITY	5	5	5	5	5	5	5	5	5	5	5	5
	14. LOW ANGLE FAULT	4	4	4	4	5	4	4	4	5	4	4	4
II. ANGLE OF:	1. INCLINED STRATA	4	4	4	4	4	4	4	4	4	4	4	4
	2. LIMB OF ANTICLINE OR SYNCLINE	4	4	4	4	4	4	4	4	4	4	4	4
	3. MONOCLINE OR HOMOCLINE	4	4	4	4	3	3	3	3	3	3	3	3
	4. FAULT PLANE	4	4	4	4	3	3	3	3	3	3	3	3
	5. AXIAL PLANE OF FOLD	5	5	5	5	5	5	5	5	5	5	5	5
	6. IGNEOUS INTRUSIVE CONTACT	3	3	3	4	3	3	3	3	3	3	3	3
	7. SALT DOME CONTACTS	5	5	5	5	5	5	5	5	5	5	5	5

TABLE 2, MAGNETIC (CONT'D)

	LOW CONTRAST				MEDIUM CONTRAST				HIGH CONTRAST			
	0-5 M	5-300 M	300-900 M	> 900 M	0-5 M	5-300 M	300-900 M	> 900 M	0-5 M	5-300 M	300-900 M	> 900 M
III. SIZE OF: 1. SOLUTION FEATURE	5	5	5	5	5	5	5	5	5	5	5	5
2. MASSIVE SULFIDE DEPOSIT	5	3	4	4	2	3	4	4	2	3	4	4
3. SALT DOME	5	4	4	4	5	4	4	4	5	4	4	4
4. FAULT OFFSET	5	3	3	4	2	3	3	4	2	3	3	4

KEY TO RANKING

I. ACCURACY OF DEPTH

1. ± 1-5% OF DEPTH
2. ± 5-15% OF DEPTH
3. ± 15-30% OF DEPTH
4. ± > 30% OF DEPTH
5. NOT DETECTABLE

II. ACCURACY OF ANGLE

1. ± 1-5 DEGREES
2. ± 5-15 DEGREES
3. ± 15-30 DEGREES
4. ± > 30 DEGREES
5. NOT DETECTABLE

III. MINIMUM SIZE FOR DETECTION

1. TINY (1 CM - 1 M)
2. SMALL (1 M - 9 M)
3. MEDIUM (10 M - 99 M)
4. LARGE (> 100 M)
5. NOT DETECTABLE

TABLE 3

RELIABILITY OF IDENTIFICATION OF GEOLOGIC FEATURES USING THE MAGNETIC METHOD

NOTE: 1. CONTRAST IS SUSCEPTIBILITY CONTRAST
2. SEE END OF CHART FOR KEY TO RANKING

	LOW CONTRAST				MEDIUM CONTRAST				HIGH CONTRAST			
	0-5 M	5-300 M	300-900 M	> 900 M	0-5 M	5-300 M	300-900 M	> 900 M	0-5 M	5-300 M	300-900 M	> 900 M
I. HORIZONTAL FEATURES												
1. BURIED EROSIONAL SURFACE	4	4	4	4	3	3	3	4	3	3	3	3
2. WATER TABLE	4	4	4	4	4	4	4	4	4	4	4	4
3. BEDROCK	2	2	2	2	1	1	1	1	1	1	1	1
4. BASEMENT	2	2	2	2	1	1	1	1	1	1	1	1
5. CONTACT	4	4	4	4	3	3	3	3	3	3	3	3
6. ANGULAR UNCONFORMITY	4	4	4	4	3	3	3	3	3	3	3	3
7. PARACONFORMITY	4	4	4	4	4	4	4	4	4	4	4	4
8. LOW-ANGLE FAULT	4	4	4	4	3	3	3	3	3	3	3	3
9. INCLINED STRATA	4	4	4	4	3	3	3	3	3	3	3	3
9a. LIMB OF ANTICLINE OR SYNCLINE	4	4	4	4	3	3	3	3	3	3	3	3
9b. MONOCLINE OR HOMOCLINE	4	4	4	4	3	3	3	3	3	3	3	3
II. VERTICAL FEATURES												
1. HIGH-ANGLE FAULT	2	2	2	2	1	1	1	1	1	1	1	1
2. FRACTURE ZONE	4	4	4	4	4	4	4	4	4	4	4	4
3. BRECCIA ZONE	4	4	4	4	3	3	3	4	3	3	3	3
4. IGNEOUS INTRUSIVE CONTACT	2	2	2	3	1	1	1	1	1	1	1	1
5. SALT DOME CONTACT	4	3	3	3	4	2	2	3	4	2	2	2
6. DIKE	2	2	2	3	1	1	1	1	1	1	1	1

TABLE 3, MAGNETIC (CONT'D)

	LOW CONTRAST				MEDIUM CONTRAST				HIGH CONTRAST			
	0-5 M	5-300 M	300-900 M	> 900 M	0-5 M	5-300 M	300-900 M	> 900 M	0-5 M	5-300 M	300-900 M	< 900 M
III. OTHER FEATURES												
1. IGNEOUS INTRUSIVE BODY	2	2	2	2	1	1	1	1	1	1	1	1
2. SALT DOME	4	3	3	3	4	2	2	2	4	2	2	2
3. SOLUTION FEATURES	4	4	4	4	4	4	4	4	4	4	4	4
4. MASSIVE SULFIDE DEPOSIT	2	2	2	2	1	1	1	2	1	1	1	1
IV. COMPOSITION												
1. BEDDED OR DOMED SALT	4	4	4	4	4	4	4	4	4	3	3	3
2. SHALE	4	4	4	4	4	4	4	4	4	4	4	4
3. BASALT	3	3	3	3	3	3	3	3	2	2	2	2
4. TUFF	4	4	4	4	4	4	4	4	4	4	4	4
5. GRANITE	3	3	3	3	3	3	3	3	2	2	2	2
6. ROCK TYPE IN GENERAL	3	3	3	3	3	3	3	3	2	2	2	2

KEY TO RANKING

1. GOOD RELIABILITY (ONE OR TWO POSSIBLE INTERPRETATIONS)
2. FAIR RELIABILITY (THREE OR FOUR POSSIBLE INTERPRETATIONS)
3. POOR RELIABILITY (FIVE OR MORE POSSIBLE INTERPRETATIONS)
4. NOT IDENTIFIABLE

APPENDIX B-6

SEISMIC REFLECTION TECHNIQUE

By

Ertec Western, Inc.

Long Beach, California

November 1, 1981

B-6

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1.0 DESCRIPTION OF TECHNIQUE

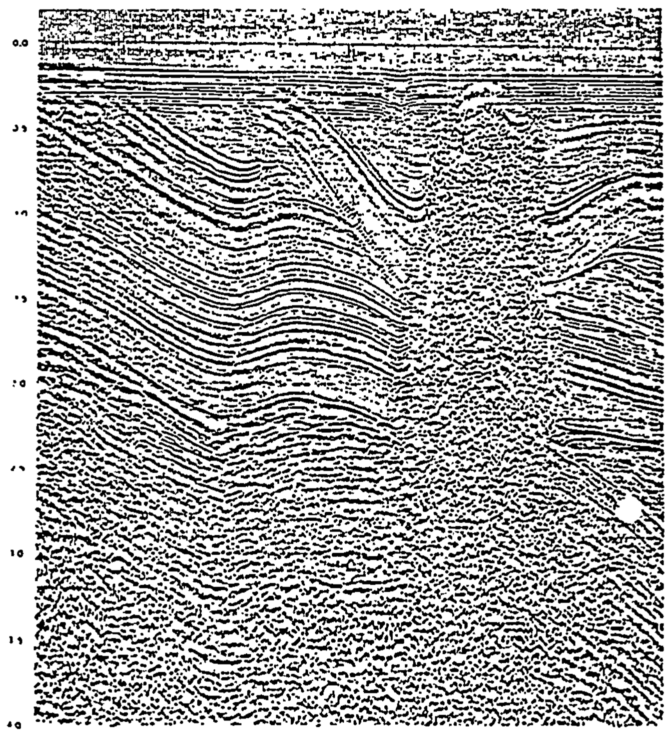
The purpose of a seismic reflection survey is to produce a sonic simulation of sub-surface geological structures (Fig. 1). This is achieved by imparting energy into the earth in the form of sound waves and measuring the time they take to return to the surface, following interactions with geological discontinuities at depth. Such discontinuities occur where rock types of varying properties are in juxtaposition due to sedimentation, faulting, folding or intrusion. The discontinuities act as partial reflectors to sound wave energy.

Seismic energy is generated at the surface either as a single pulse (dynamite explosion, weight drop) or as a controlled wavetrain (vibrator). As the energy moves away from the source, spherical divergence and friction attenuate its amplitude. The earth acts as a low pass filter, attenuating the high frequency content of the pulse or wavetrain more rapidly than the low frequency content. When it encounters a discontinuity the energy is partly reflected and partly transmitted. The ground motion caused by the arrival of the reflected component at the surface is detected by a series of equally spaced geophones laid out in a line away from the source. The information is amplified, digitally recorded on magnetic tape for later use and visually displayed on a paper record which is used for quality control.

The geophones detect noise as well as useful seismic reflection information. Noise may be either associated with the shot (surface waves, shot noise, diffractions, refractions) or independent of the survey (wind, rain, traffic). For each shot, from 12 to 96 geophone stations at intervals of 5-50 meters are used to record the reflected information. In order to improve the signal-to-noise ratio, energy from the same subsurface reflection point may be sampled and summed or stacked from successive shots, enhancing coherent seismic information relative to random ambient background noise. Similarly, several geophones may be used at each station. These can be arranged so that summing of their outputs will cause reduction of surface wave amplitude and other unwanted noise.

The geophone at each station is connected to a long multi-conductor cable, which carries the signals to the instrument platform, where they are recorded and displayed.

A seismic field crew comprising 3-10 technical personnel and a manual labor force 20-150 strong (i) plot the positions of the required seismic lines on the ground, (ii) place pegs at



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SEISMIC SECTION
DEPICTING SALT DOME

3-81

FIGURE 1

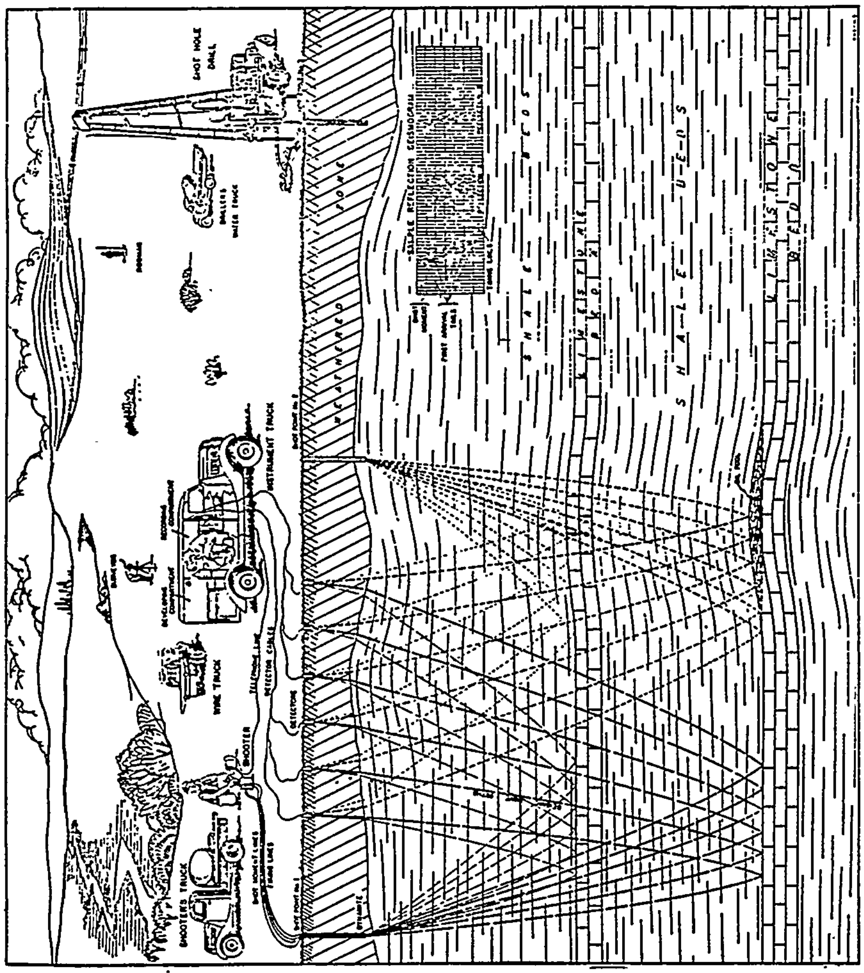
specified positions along the lines to indicate shot and geophone positions, (iii) record the grid coordinates and elevations of the pegs, (iv) drill holes (if necessary) to accommodate explosives, (v) lay cables and geophones at appropriate peg positions, (vi) fire the shots (or vibrate, thump, etc.) in the correct sequence, and (vii) record the data. A simplified field situation is shown in Figure 2, and crew structure is outlined in Figure 3.

The information from each shot is recorded digitally on tape and stacked into a seismic section during data processing which, by presenting the reflections as a function of two-way travel time, gives a first order visual impression of the subsurface. Seismic wave velocity measurements derived from the original pre-stacked data may be applied to the reflected time events, converting them to depth. On-line borehole information may allow direct correlation of the reflectors with the particular stratigraphic horizons which are good reflectors. Finally, using a grid of intersecting seismic lines/sections, contour mapping of individual horizons may be carried out, thus detailing structural highs and lows, faulting, folding, igneous and evaporite intrusion.

Using a wide variety of source types seismic reflection exploration can be carried out conveniently and safely in almost any situation. With the advent of low energy sources such as vibrators, urban exploration is possible without the safety risks involved in the use of explosives. In addition, the immediate subsurface need not be penetrated or damaged.

2.0 APPLICATION TO INFORMATION NEEDS

Seismic reflection exploration is the prime geophysical tool used in the delineation of oil-bearing structures in the earth's subsurface. Oil-trap features, such as anticlines, salt domes, faulting and stratigraphic pinch-outs, are all readily identifiable on the seismic section. In recent years, with improvements in processing techniques, it has become possible to detect the actual presence of oil and gas deposits through recognition of the very high reflection coefficients they produce. Similarly, evaporite deposits (both bedded and domed) yield very strong reflections on a section and may be accurately mapped in the deep subsurface at depths of up to 20,000 to 30,000 feet. Assessment of bedding continuity and lateral variations may be made, and



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LAYOUT OF TYPICAL LAND SEISMIC SURVEY

3-81

FIGURE 2

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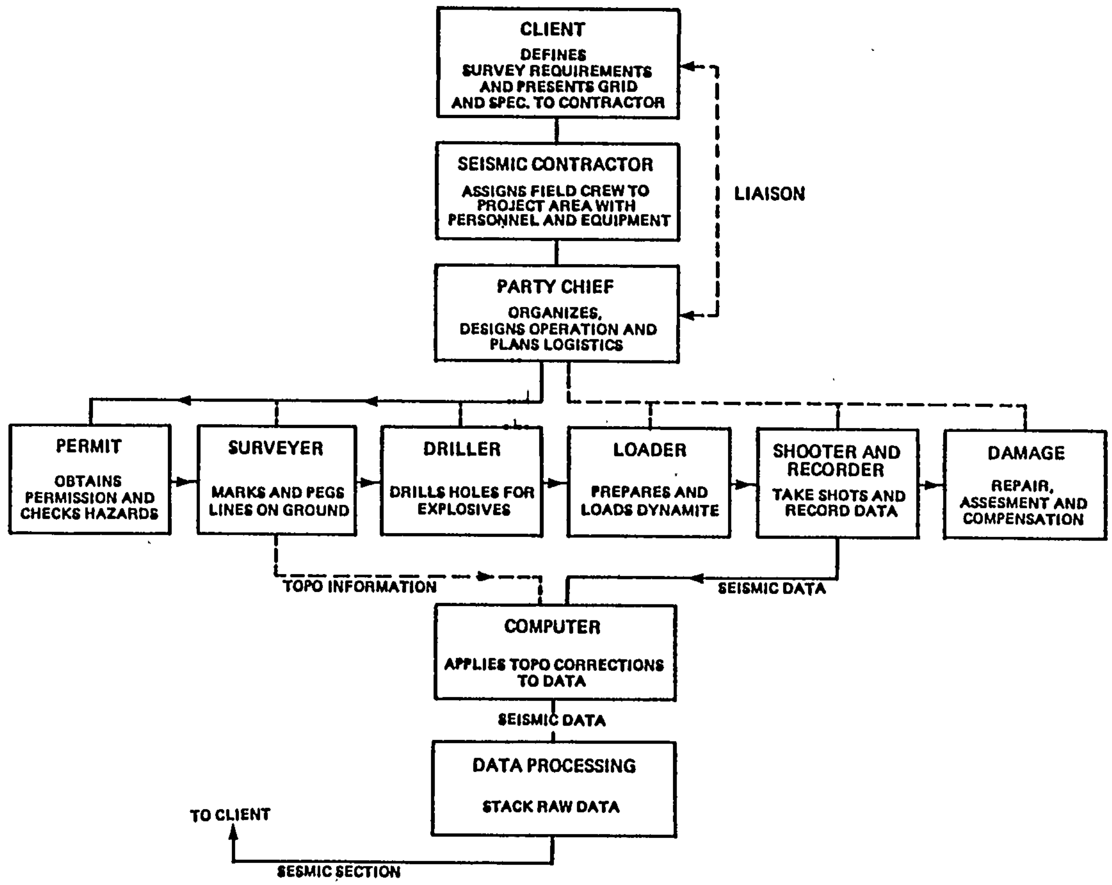
Compiled by ______ / ______ Drawn by ______ / ______ Checked by ______ / ______ Approved by ______ / ______



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ORGANIZATION OF
LAND SEISMIC SURVEY

3-81

FIGURE 3

small offset, normal faulting with 10 to 20 foot displacement at depths of 500 to 3000 feet may be detected in high resolution work.

In the absence of any other information, the method is limited to a subjective unconfirmed interpretation. However, with geological, borehole, and sonic log observations, ideally on line, reflecting horizons may be positively identified in the geological section and absolute depths applied to the data. Depending on the size of structures under investigation, seismic lines are arranged to form an intersecting grid. From this, grid time/depth contour maps may be produced for each horizon visible on the section.

In addition to a direct correlation of geological horizons with seismic reflectors, borehole velocity data may be used to create a synthetic seismogram, serving as a highly useful link between geology, depth and time.

In seismic reflection theory, the assumption is made that subsurface structural relief is gentle. In areas where this is not the case, distortion of features occurs. This may be wholly or partially removed, depending on its severity, by a process called migration. In extremely contorted areas, however, the data may be of little use. The method has its best application, therefore, in areas of thick sedimentation of low structural relief.

The applicability of the Seismic Reflection Method to the six media under consideration is as follows:

(i) Bedded Salt

All evaporite deposits are characterized by high seismic velocities. The resulting high reflection coefficients yield strong events on seismic sections. Since salt masses are fairly homogenous, with poorly defined internal structure, internal seismic expression is rare. Fault features will only be detected by their expression in the surrounding media.

(ii) Domed Salt (Fig. 1)

Salt diapirs have a highly characteristic shape which shows up well on seismic sections. Again, the high velocity of the mass causes strong reflection of energy. Steep-sided domes will yield reflections only from the top, and the flanks must be delineated by noting the termination of surrounding strata. The salt mass itself yields no internal structure. Again, faulting in the mass will only be seen if the faults are expressed in the surrounding media. Strata underlying the salt dome may appear distorted due to the velocity pull-up effect of the high velocity mass above.

(iii) Shale

Although typical reflection coefficients for shale are not as high as those at salt boundaries, reflections can be readily identified and correlated with borehole data. The structural situation may be fairly reliably mapped. In these units, internal bedding and depositional/erosional features serve to delineate faulting.

(iv) Granite

As with salt, granite intrusions into sediments may be detected by seismic reflection due to their characteristic shape and lack of a base. High density contrasts between the intrusion and overlying media yield good reflections. Internal structure is rare, and no seismic events will occur. Jointing cannot be detected, and faulting will only be expressed if it continues into the surrounding media. Once again, poor reflections will occur on the steep sides of the intrusion, but deformation in adjoining sediments and the abrupt termination of their reflections will delineate the flanks of the granitic mass.

(v) Tuff

As an extrusive rock with relatively high seismic velocity deposited within a sedimentary succession, tuff horizons may be identified and mapped. Internal layering may be visible if the tuff unit is composed of several outpourings with interbedded clastic sediments. Such internal structure may serve to delineate internal faulting.

(vi) Basalt

As with tuff, basalt (especially flood basalt) may show marked discontinuity with over- and underlying sedimentary strata. Internal structure may be visible if intra-flow clastic deposition took place. This may aid delineation of internal faulting.

3.0 RESOLUTION

The resolving power of the seismic reflection method is defined in three directions:

1. Vertical Resolution is dictated by the frequency of the seismic pulse, the fidelity of the recording equipment and the amount of noise in the system.

   a. A high frequency, sharp pulse shape will resolve much finer detail than a broad, low frequency signal. Small power sources are desirable for high initial frequency content, though penetration is affected. Since the earth acts as a lowpass filter, frequency content and, therefore, resolution are poorer with increasing depth.

   b. The recording equipment must faithfully record the shape and time of arrival of the incoming signals. Digital amplifiers of up to 84 dB dynamic range with 1-4 millisecond sampling rates are available. The sampling rate determines the upper frequency limit. High speed sampling improves resolution of the recording system. A wide dynamic range is desirable in order that both very small and very large signals be simul taneously amplified with minimal distortion.

   c. Ambient noise, which masks or distorts the seismic signal, will lower resolution. Effects such as surface waves and wind, rain and human noise may be attenuated to varying degrees by using carefully designed source and detector patterns and by filtering in the recording system.

   Data processing techniques which stack, deconvolve, filter and migrate the data, will enhance resolution by shaping the recorded wavelets into sharper pulses.

   At shallow depths in the range of 200-500 feet, using high frequency shallow penetration methods, reflector separations of 10-30 feet can be detected. In oil exploration resolution is of the order of 100-500 feet.

2. Horizontal Resolution is determined by the surface detector spacing along the line. Subsurface reflection points are spaced at half the detector interval. Any feature smaller than this in areal extent may be "missed." Typical detector spacings range from 15 feet (high resolution) to 150 feet.

3. Areal Resolution is determined by the number and spacing of seismic lines in a grid. Depending on the size of the structure under investigation and the scope of the survey, line lengths may vary from 5-50 miles, spaced 1-5 miles apart in grids covering areas from tens to thousands of square miles.

4.0 RELIABILITY

Seismic reflection exploration yields the least ambiguous information of all geophysical methods. Even so, analysis of the results is subjective and dependent on interpreter experience. Because most seismic sections look similar to a geological section, danger exists in performing direct interpretation without an appreciation of the geophysical limitations and distortions in what is a two-way time presentation. Modern seismic data are rarely interpreted without some recourse to borehole information, especially lithology and velocity logs. When this information is available close to or on a line, it removes a great deal of uncertainty in the seismic section by affording a direct time-depth correlation of individual geologic horizons.

Errors in interpretation may arise through the existence of anomalously high velocity layers near the surface, or if horizontal velocity changes occur. These serve to distort deeper data. Faulting or folding, which places high velocity rocks at the same level as low velocity rocks, may lead to a seismic expression which may be wrongly interpreted in the absence of good subsurface velocity data.

Ambiguity of interpretation increases with structural complexity, as early assumptions of horizontality bring distortions into the data.

Signal-to-noise ratio on the final section must be such that reflective horizons can be continuously identified from one side of the section to the other and, if necessary, correlated across fault zones.

Multiples which have not been removed during the processing stage may be wrongly interpreted as primary events.

The following conditions may give rise to poor seismic sections:

1. area is structurally complex.

2. surface medium offers poor geophone planting conditions.

3. poor near-surface shot medium.

4. high background noise levels.

5. poor reflective horizons at depth.

5.0 COST AND PRODUCTION RATES

Most seismic reflection work today is performed by geophysical contractors, the majority of whom specialize in seismic reflection exploration and who derive their income from contracts related to oil and gas exploration. These contracts are negotiated in four parts: (i) a mobilization fee, paid to the contractor to allow him to move his equipment into the project area; (ii) a fixed contract fee, payable from the first day of recording and including specified numbers of personnel, vehicles, instruments, cables, geophones. (iii) a consumables fee: extra contract consumables which the client has agreed to pay for; and (iv) a close-down fee, allowing the reverse of (i), which may be waived if the contract has run a specified period.

Typical contract fees (in 1981 dollars) may vary from $100,000-$600,000 per month depending on the type and size of crew (vibrator, dynamite, weight drop) the terrain (desert, urban, swamp, high/low relief), climate and access. Rates per mile of survey are typically $4,000, but may vary between $2,000-$10,000 per mile. High resolution work usually costs considerably more per mile than oil exploration work because of the small station interval.

A conventional, shot hole land seismic crew using 96 trace, 1 ms sampling equipment with a 50 mile detector spacing and 12-fold subsurface sampling may cost as follows:

Personnel (10 Hour Working Day)

1 Party Chief	$ 520.00/day
1 Deputy Party Chief/Seismologist	400.00/day
1 Computor	340.00/day
1 Senior Observer	340.00/day
1 Assistant Observer	310.00/day
1 Surveyor	330.00/day
1 Administrator	340.00/day
1 Driller	450.00/day
30 Helpers	7,020.00/day
Personnel expenses per diem	450.00/day
Total Personnel	$10,480.00/day

Technical Equipment

Recording System, Cables Geophones, Blasting Equipment	$ 2,000.00/day

Vehicles

Recording Truck	$ 100.00/day
Cable & Geophone Trucks (3)	150.00/day
Shooting Truck	50.00/day
Drill Rig	210.00/day
Surveyors Truck	35.00/day
Party Chiefs Vehicle	35.00/day
Total Vehicles:	$ 580.00/Day

Supplies

Dynamite, caps, fuel, tapes, camera paper	$ 3,500.00/day
Daily Total	$ 16,560.00

The total monthly cost is $364,320.00 per 22-day month. With a typical average shooting rate of 100 miles per month, the cost per mile is $3,650, excluding damages. For high resolution work, the monthly production rate may be as low as 40-50 miles because of the smaller detector spacing, and the cost per mile will rise accordingly.

The contract fee normally will not include data processing or interpretation. Data processing may, at extra cost, be assigned to the same contractor who performed the initial survey, or it may be carried out by an independent company. Interpretation is normally carried out by the client's own geologists and geophysicists. Depending on what is specified, data processing may cost $20-30 per 48 trace record with 4 millisecond sampling or $25-35 per 48 trace record with 2 millisecond sampling. Special processes, such as migration, are provided for an extra charge of approximately $.75 per trace.

Since cost-efficiency of a seismic survey is closely linked to production, high shooting rates are desirable, provided optimum data quality is maintained.

The production rate will depend on the following factors:

1. Detector spacing - will determine the extent of coverage obtained at each shot.

2. Number of channels in recording system: a 96-trace crew operating under the same conditions as a 48-trace crew theoretically should achieve twice the production per unit time.

3. Source type - dynamite operations are relatively slow compared to vibrator or thumper crews.

4. Multiplicity of recorded data - A higher fold of cover takes longer to shoot than single fold operation.

5. Can the instruments be truck-mounted to the line? This would be faster than a hand-carried operation.

6. Large geophone arrays will slow progress.

7. Is access good for vehicles/trucking?

8. Is climate hospitable, i.e., temperate or tropical?

9. What is the size of the grid? Will frequent non-productive camp moves be required over a large area?

10. Fairly long lines tend to yield higher production since short lines lead to more frequent location changes.

11. What is the terrain like? High/low relief, desert, swamp?

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TABLE 1

APPLICABILITY OF THE SEISMIC REFLECTION METHOD TO THE IDENTIFICATION AND DEFINITION OF SUBSURFACE GEOLOGIC FEATURES

I <u>FEATURES ASSOCIATED WITH ONE OR MORE HORIZONTAL PLANES</u>

		RANKING 1	2	3	4
A. DEPTH TO:	1. BEDDED SALT	X			
	2. SHALE	X			
	3. BASALT	X			
	4. TUFF	X			
	5. WATER TABLE			X	
	6. BEDROCK			X	
	7. BASEMENT	X			
	8. ANGULAR UNCONFORMITY	X			
	9. PARACONFORMITY				X
	10. LOW-ANGLE FAULT	X			
B. THICKNESS OF:	1. BEDDED SALT	X			
	2. SHALE	X			
	3. BASALT	X			
	4. TUFF	X			
	5. OVERBURDEN			X	
	6. SEDIMENTARY STRATUM IN GENERAL	X			
	7. SILL		X		
C. ANGLE OF:	1. INCLINED STRATA	X			
	a. LIMB OF ANTICLINE OR SYNCLINE	X			
	b. MONOCLINE OR HOMOCLINE	X			
	2. LOW-ANGLE FAULT	X			
	3. AXIAL PLANE OF RECUMBENT FOLD	X			

TABLE 1, SEISMIC REFLECTION (CONT'D)

			RANKING 1	2	3	4
II. FEATURES ASSOCIATED WITH ONE OR MORE VERTICAL PLANES						
	A. LOCATION OF:	1. HIGH-ANGLE FAULT	X			
		2. FRACTURE ZONE		X		
		3. BRECCIA ZONE		X		
		4. IGNEOUS INTRUSIVE CONTACT		X		
		5. SALT DOME CONTACT	X			
	B. WIDTH OF:	1. DIKE		X		
		2. FRACTURE ZONE		X		
		3. BRECCIA ZONE		X		
		4. SALT DOMES	X			
	C. ANGLE OF:	1. FAULT PLANE	X			
		2. IGNEOUS INTRUSIVE CONTACT		X		
		3. SALT DOME CONTACT	X			
		4. AXIAL PLANE OF NORMAL FOLD	X			
III. OTHER FEATURES						
	A. DEPTH TO:	1. BURIED EROSIONAL SURFACE		X		
		2. IGNEOUS INTRUSIVE BODY		X		
		3. SALT DOME	X			
		4. SOLUTION FEATURES				X
		5. MASSIVE SULFIDE DEPOSIT				X

TABLE 1, SEISMIC REFLECTION (CONT'D)

B. DETERMINATION OF:		RANKING 1	2	3	4
	1. ROCK TYPE				X
	a. BEDDED SALT				X
	b. SHALE				X
	c. BASALT				X
	d. TUFF				X
	e. GRANITE				X
	2. GEOTHERMAL CONDITIONS				X

KEY TO RANKING

1. FREQUENTLY APPLICABLE
2. OCCASIONALLY APPLICABLE
3. SELDOM APPLICABLE
4. NOT APPLICABLE

TABLE 2

DETECTABILITY OF GEOLOGIC FEATURES
AND ACCURACY OF SUBSURFACE MEASUREMENTS
USING THE SEISMIC REFLECTION METHOD

NOTE: 1. CONTRAST IS VELOCITY CONTRAST
2. SEE END OF CHART FOR KEY TO RANKING

		LOW CONTRAST				MEDIUM CONTRAST				HIGH CONTRAST			
		0-5M	5-300 M	300-900M	> 900 M	0-5 M	5-300 M	300-900 M	> 900 M	0-5 M	5-300 M	300-900 M	> 900 M
I. DEPTH TO:	1. BEDDED SALT	–	1	2	2	–	1	1	1	–	1	1	1
	2. SALT DOME	–	1	2	2	–	1	1	1	–	1	1	1
	3. SHALE	–	1	2	2	–	1	1	1	–	1	1	1
	4. BASALT	–	1	2	2	–	1	1	1	–	1	1	1
	5. TUFF	–	1	2	2	–	1	1	1	–	1	1	1
	6. GRANITE	–	1	2	2	–	1	1	1	–	1	1	1
	7. BURIED EROSIONAL SURFACE	–	1	2	2	–	1	1	1	–	1	1	1
	8. WATER TABLE	–	1	–	–	–	1	–	–	–	1	–	–
	9. BEDROCK	–	1	–	–	–	1	–	–	–	1	–	–
	10. BASEMENT	–	1	2	2	–	1	1	1	–	1	1	1
	11. CONTACT	–	1	2	2	–	1	1	1	–	1	1	1
	12. ANGULAR UNCONFORMITY	–	1	2	2	–	1	1	1	–	1	1	1
	13. PARACONFORMITY	–	–	–	–	–	–	–	–	–	–	–	–
	14. LOW ANGLE FAULT	–	1	2	2	–	1	1	1	–	1	1	1
II. ANGLE OF:	1. INCLINED STRATA	–	1	2	2		1	1	2		1	1	2
	2. LIMB OF ANTICLINE OR SYNCLINE	–	1	2	2		1	1	2		1	1	2
	3. MONOCLINE OR HOMOCLINE	–	1	2	2		1	1	2		1	1	2
	4. FAULT PLANE	–	1	2	2		1	1	2		1	1	2
	5. AXIAL PLANE OF FOLD	–	2	3	3		2	2	3		2	2	3
	6. IGNEOUS INTRUSIVE CONTACT	–	3	3	3		2	2	3		2	2	3
	7. SALT DOME CONTACTS	–	3	3	3		2	2	3		2	2	3

TABLE 2, SEISMIC REFLECTION (CONT'D)

	LOW CONTRAST				MEDIUM CONTRAST				HIGH CONTRAST			
	0-5 M	5-300 M	300-900 M	> 900 M	0-5 M	5-300 M	300-900 M	> 900 M	0-5 M	5-300 M	300-900 M	> 900 M
III. SIZE OF: 1. SOLUTION FEATURE		5	5	5		5	5	5		5	5	5
2. MASSIVE SULFIDE DEPOSIT		5	5	5		5	5	5		5	5	5
3. SALT DOME		3	4	4		3	4	4		3	4	4
4. FAULT OFFSET		2	3	3		2	2	3		2	2	3

KEY TO RANKING

I. ACCURACY OF DEPTH

1. ± 1-5% OF DEPTH
2. ± 5-15% OF DEPTH
3. ± 15-30% OF DEPTH
4. ± > 30% OF DEPTH
5. NOT DETECTABLE

II. ACCURACY OF ANGLE

1. ± 1-5 DEGREES
2. ± 5-15 DEGREES
3. ± 15-30 DEGREES
4. ± > 30 DEGREES
5. NOT DETECTABLE

III. MINIMUM SIZE FOR DETECTION

1. TINY (1 CM - 1 M)
2. SMALL (1 M - 9 M)
3. MEDIUM (10 M - 99 M)
4. LARGE (> 100 M)
5. NOT DETECTABLE

TABLE 3

RELIABILITY OF IDENTIFICATION OF GEOLOGIC FEATURES
USING THE SEISMIC REFLECTION METHOD

NOTE: 1. CONTRAST IS VELOCITY CONTRAST
2. SEE END OF CHART FOR KEY TO RANKING

	LOW CONTRAST				MEDIUM CONTRAST				HIGH CONTRAST			
	0-5 M	5-300 M	300-900 M	> 900 M	0-5 M	5-300 M	300-900 M	> 900 M	0-5 M	5-300 M	300-900 M	> 900 M
I. HORIZONTAL FEATURES												
1. BURIED EROSIONAL SURFACE		3	3	3		3	3	3		3	3	3
2. WATER TABLE		3	–	–		3	–	–		3	–	–
3. BEDROCK		2	–	–		2	–	–		2	–	–
4. BASEMENT		1	2	2		1	1	2		1	1	2
5. CONTACT		1	1	1		1	1	1		1	1	1
6. ANGULAR UNCONFORMITY		1	1	1		1	1	1		1	1	1
7. PARACONFORMITY		3	3	3		3	3	3		3	3	3
8. LOW-ANGLE FAULT		2	2	3		2	2	2		2	2	2
9. INCLINED STRATA		1	1	1		1	1	1		1	1	1
9a. LIMB OF ANTICLINE OR SYNCLINE		1	1	1		1	1	1		1	1	1
9b. MONOCLINE OR HOMOCLINE		1	1	2		1	1	1		1	1	1
II. VERTICAL FEATURES												
1. HIGH-ANGLE FAULT		1	1	1		1	1	1		1	1	1
2. FRACTURE ZONE		3	3	3		3	3	3		3	3	3
3. BRECCIA ZONE		3	3	3		3	3	3		3	3	3
4. IGNEOUS INTRUSIVE CONTACT		2	2	2		2	2	2		2	2	2
5. SALT DOME CONTACT		1	1	1		1	1	1		1	1	1
6. DIKE		2	2	2		2	2	2		2	2	2

TABLE 3, SEISMIC REFLECTION (CONT'D)

	LOW CONTRAST				MEDIUM CONTRAST				HIGH CONTRAST			
	0-5 M	5-300 M	300-900 M	> 900 M	0-5 M	5-300 M	300-900 M	> 900 M	0-5 M	5-300 M	300-900 M	< 900 M
III. OTHER FEATURES												
1. IGNEOUS INTRUSIVE BODY		2	2	2		2	2	2		2	2	2
2. SALT DOME	–	1	1	1	–	1	1	1	–	1	1	1
3. SOLUTION FEATURES	–	4	4	4	–	4	4	4	–	4	4	4
4. MASSIVE SULFIDE DEPOSIT	–	4	4	4	–	4	4	4	–	4	4	4
IV. COMPOSITION												
1. BEDDED OR DOMED SALT	–	4	4	4	–	4	4	4	–	4	4	4
2. SHALE	–	4	4	4	–	4	4	4	–	4	4	4
3. BASALT	–	4	4	4	–	4	4	4	–	4	4	4
4. TUFF	–	4	4	4	–	4	4	4	–	4	4	4
5. GRANITE	–	4	4	4	–	4	4	4	–	4	4	4
6. ROCK TYPE IN GENERAL	–	4	4	4	–	4	4	4	–	4	4	4

KEY TO RANKING

1. GOOD RELIABILITY (ONE OR TWO POSSIBLE INTERPRETATIONS)
2. FAIR RELIABILITY (THREE OR FOUR POSSIBLE INTERPRETATIONS)
3. POOR RELIABILITY (FIVE OR MORE POSSIBLE INTERPRETATIONS)
4. NOT IDENTIFIABLE

APPENDIX B-7

THE SEISMIC CROSSHOLE METHOD

BY

Ertec Western, Inc.

Long Beach, California

November 1, 1981

B-7

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THE SEISMIC CROSSHOLE METHOD

1.0 DESCRIPTION

All dynamic elastic moduli for earth materials, including Poisson's ratio and Young's, shear and bulk moduli, can be calculated from the density of the materials and their compressional (P) and shear (S) wave velocities. Seismic crosshole studies can be used to determine the P- and S-wave velocities, as well as the thicknesses of soil layers, down to and including the candidate host media (bedded salt, dome salt, shale, granite, tuff and basalt).

1.1 Principles

The crosshole seismic method is well-suited for determining in situ P- and S-wave velocities and layer thicknesses with depth. P-waves propagate through a material at a higher velocity than S-waves. In this method, the time taken by direct P- and S-waves to travel between points at the same depth within a soil mass is measured. Wave velocities are calculated by dividing the measured travel times into the distances across which the waves traveled.

Identification of the P- and S-waves requires an understanding of their generation and propagation. With P-waves, particle vibration is parallel to the rays comprising the wave. With S-waves, particle vibration is perpendicular to the rays. The direction of particle motion may lie in any plane perpendicular to the ray, depending mainly upon the direction of motion at the source. The behavior of the wave at a boundary depends on its plane of vibration. When a horizontally vibrating S-wave strikes a horizontal geologic discontinuity, the reflected and transmitted waves both continue as horizontally polarized vibrations. By contrast, an S-wave vibrating in the vertical plane generates reflected and transmitted P-waves, as well as vertically polarized S-waves, when it strikes a discontinuity.

Waves can be generated by explosive sources (explosives, airguns, etc.) or by mechanical sources (hammer blows, vibrators, etc.). P-waves are usually large from an explosive source and usually small from a mechanical source. The ratio of S-wave amplitude to P-wave amplitude is usually much larger from a mechanical source than from an explosive source. From an explosion, the S-wave is often difficult to recognize because the earlier arriving P-waves are of large amplitude. The S-waves from a mechanical source are usually more easily recognized because the P-waves are small. In addition, the polarity of the waves is usually known from a mechanical source, which aids in identification. The advantage of a polarized energy source is that a symmetric reversal of input energy causes an S-wave of opposite polarity to arrive at the recording station.

For most design purposes, the S-wave velocity is critical. For this reason, we recommend that mechanical energy sources be used in conventional engineering surveys.

1.2 Considerations in Repository Siting

Most crosshole work has been done at shallow depths for engineering purposes, and the most widely employed techniques in engineering studies are generally applicable to depths of only a few hundred feet. The two most popular energy sources involve striking the top of the drill stem as the source boring is being drilled or using an in-hole hammer actuated by a line to the surface. These techniques can be useful for obtaining data to support design of surface facilities for a hazardous waste repository but will be impractical for studies of the repository medium.

To obtain crosshole data within the repository medium, several survey parameters will necessarily be different from those commonly employed in engineering studies. In-hole energy sources will be required, but they must be operated electrically from the surface. They may include: magnetostrictive or crystal sources, such as are commonly used in continuous velocity loggers; vibrators of the type manufactured by Mark Products for U.S. Army Corps of Engineers, Waterways Experiment Station; or other electromechanical sources. Explosive sources can also be much more satifactory for surveys in the host media than they typically are for shallow engineering studies. The main reason for this is that borings must be farther apart in a host medium study than in an engineering study. Crosshole measurements with widely spaced borings are practical in thick, homogeneous bodies where there are no thin layers. When the borings are far apart, the time interval between the P-wave and S-wave arrivals becomes long, allowing the high amplitude P-waves to attenuate before the S-waves arrive.

Crosshole surveys at repository depths are not common. In 1964, a crosshole survey using explosive energy sources to depths in excess of 2700 feet was performed in the Tatum Salt Dome, Mississippi. Birdwell Division of Seismograph Services

Corporation has done crosshole surveys using two continuous sonic velocity logging systems (their 3-D logging system), one in each of two holes.

Because there is such limited experience in deep crosshole surveys, the remainder of this report will describe typical practice in performance of conventional engineering crosshole surveys.

1.3 Procedures

The crosshole technique is recommended for in situ measurements because it provides high measurement accuracy and, within the limits imposed by the laws of refraction, the waves travel through a particular stratum. Several factors to be considered in performing a crosshole study are (1) geological configuration of the subsurface material, (2) the depth to which the data are required for analysis, and (3) intervals at which data are to be taken.

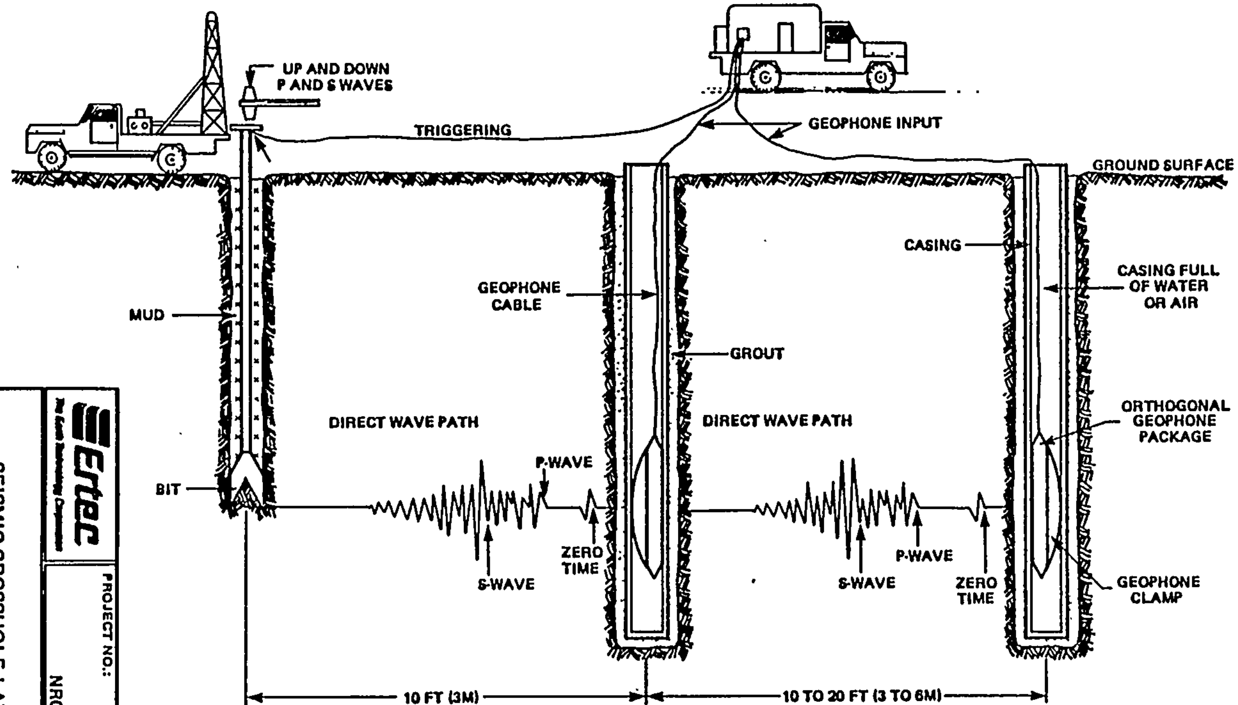
A crosshole array should consist of one energy source boring and two or more sensor borings (Figure 1). General considerations are:

1) The borings should all be in a line so that the energy from the source passes through one receiver boring on its way to the succeeding receivers. A primary benefit of the linear array is that the interval time between receivers can be used to obtain a measurement of velocity even if the instant of energy generation is not recorded. Another benefit is that it provides data that can be analyzed to evaluate whether the recorded waves are direct or refracted.

2) Borings should be spaced 10- to 20-feet (3 to 6 m) apart. This close spacing is used to increase the probability of measuring direct rather than refracted waves, which optimizes the ability to develop a unique velocity profile. The disadvantage of close spacing is that it requires high precision timing and distance measurements.

3) The sensor borings should be drilled, cased, and grouted so that they are open at least 5 feet (2 m) deeper than the specified depth of the investigation. At least one of the borings should be logged during drilling to determine soil types and layer thickness and inclination.

Compiled by ____ / ____ Drawn by ____ / ____ Checked by ____ / ____ Approved by ____ / ____



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SEISMIC CROSSHOLE LAYOUT

6-81 FIGURE 1

4) The casing should be grouted in place to insure good coupling with the surrounding soils. Back filling with sand or gravel around the casing seems to be less effective.

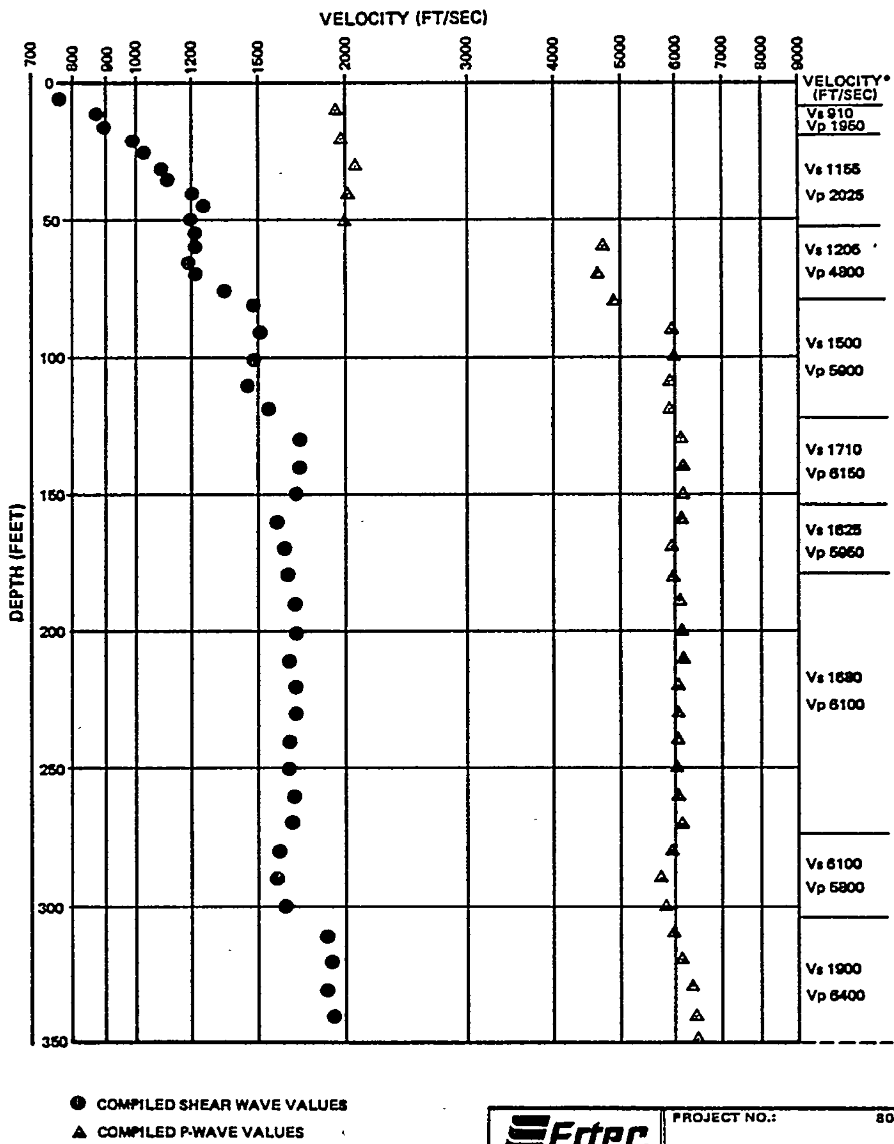
5) Casing for the sensor borings should be plastic pipe. The energy hole casing should also be plastic if a mechanical source is used. If explosives are used, the casing for the energy hole should be steel.

6) Deviations from vertical versus depth for each boring must be determined. Verticality measurements must be combined with the distance between borings at the surface to determine distances between borings at all crosshole measurement depths.

Mechanical crosshole tests can be performed with an in-hole hammer or hammer-drill stem procedure. The energy source boring can be prepared like the sensor borings before the field measurements are made if the in-hole hammer is used. It is placed at the desired depth and clamped to the casing. The hammer-drill stem method requires the drill to be used while the field measurements are made. The boring is advanced to the depth of interest and a sledge hammer is used to hit the top of the drill stem. Both methods will produce horizontally propagating, vertically polarized S-waves. The P-waves are generally more readily recorded from the hammer-drill stem method.

The recording system should have multi-channels and variable gain setting. It should have an accurate timing system and produce a permanent record. The geophones should have an appropriate directionality, sensitivity and frequency response. The geophone package should have three components; one of the geophones oriented vertically and the other two horizontally in mutually perpendicular directions. The geophone package should be equipped so that it can be clamped against the casing at any desired depth.

A time versus distance graph for each depth interval should be used to help determine apparent velocities and to analyze whether the data represents direct or refracted waves. The graphs of the timed arrivals help to identify the correct waves on the seismic records. The final results (Figure 2) are presented graphically by showing the P- and S-wave velocities determined at each depth. The depth is shown on a linear scale, and the velocities are shown on a logarithmic scale. Poisson's Ratio and shear, Young's and bulk



*INTERPRETED; VALUES SHOWN ARE WITHIN 5%.

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COMPRESSIONAL AND SHEAR WAVE VELOCITIES FROM CROSSHOLE MEASUREMENTS

6-81

FIGURE 2

Compiled by ______ / Drawn by ______ / Checked by ______ / Approved by ______ /

moduli are calculated for the various layers in the interpreted velocity profile.

2.0 APPLICABILITY

A properly performed crosshole survey will produce the most accurate P- and S-wave velocity measurements in undisturbed soil which can be made today. From the drill logs and velocity information, a detailed profile can be established relating velocities to materials. The ability to resolve layer thicknesses is a function of hole spacing, depth interval between measurements, and the velocity ratios between the layers.

Crosshole surveys measure seismic wave velocities. They are applicable to investigations of geologic features only to the degree that the feature is associated with a change in velocity and that it occurs within the confines of the boring array. Table 1 reflects this consideration.

The crosshole operations which have been described in detail in this report have been successfully applied to depths as great as 500 feet (152 m). Cost and operational considerations will require that different procedures be employed to reach substantially greater depths. Some considerations for deeper surveys are outlined in Section 1.2.

3.0 RESOLUTION

The distinguishing characteristic of the crosshole technique is its ability to measure the seismic wave velocities in individual strata in the soil column using horizontally traveling waves. The P- and S-wave velocities will be accurate if the direct distance traveled and the direct time to travel that distance are accurately established. Considering wave identification uncertainties and limits of resolution on timing on a seismic record, it is estimated that the P- and S-wave travel times typically can be measured to within one-half millisecond and one millisecond respectively, and that interval times can be measured to at least one-half these estimates. With verticality surveys of each boring, distances between holes at depth can be established to within a few inches. With these considerations, velocities obtained from crosshole studies in soils are generally expected to be accurate within about 5 to 10 percent. In this context, for purposes of resolving different layers, we would consider a change of 20 percent between adjoining layers to be a low contrast, a 50 percent change to be a medium contrast and a 100 percent change to be a high contrast. The confidence with which various layers are defined increases as their associated contrasts increase. Geologic features are detectable only insofar as they are expressed as velocity changes and occur within the limited area of the array of borings. Table 2 reflects these considerations.

4.0 RELIABILITY

The reliability of a crosshole study is controlled by the planning, field procedures, interpretation and quality control. When all elements of the survey are carefully planned to meet the objectives and each step is carried out under proper quality control, velocities can be established with high reliability within specified error limits. Table 3 rates the reliability of interpretations of geologic features using the method. This is restricted to features that can be identified based on seismic wave velocities and which are small enough to fall within the boring array.

5.0 TIME AND COST

The time and cost presented is based on a typical mechanical crosshole study to a depth of 500 feet (152 m). Such a study contains three borings (one for the energy source and two for receiving sensors). Usually, at least one of the borings will be drilled in another phase of the investigations and will be sampled thoroughly.

The time and cost figures break down into three major categories (all costs are in 1981 dollars):

1) Drilling, sampling, casing and grouting a boring typically will take about 5 or 6 days. About two days are needed for the borings that are not sampled. Costs for drilling and the soils technician are expected to be in the $20,000 to $25,000 range.

2) Mechanical crosshole field measurements and verticality surveys will take approximately 4 to 6 days and cost approximately $8,000 for technical personnel and seismic and verticality equipment.

3) Supervision, planning and interpretation will require approximately 150 hours and cost on the order of $6,000.

The weather, location, and material being drilled all influence the time and costs to perform a crosshole survey. The factor which can cause the greatest fluctuation in these parameters is the material being drilled.

TABLE 1

APPLICABILITY OF THE CROSSHOLE METHOD TO THE IDENTIFICATION AND DEFINITION OF SUBSURFACE GEOLOGIC FEATURES

I FEATURES ASSOCIATED WITH ONE OR MORE HORIZONTAL PLANES

		RANKING 1	2	3	4
A. DEPTH TO:	1. BEDDED SALT		X		
	2. SHALE		X		
	3. BASALT		X		
	4. TUFF		X		
	5. WATER TABLE	X			
	6. BEDROCK	X			
	7. BASEMENT		X		
	8. ANGULAR UNCONFORMITY				X
	9. PARACONFORMITY				X
	10. LOW-ANGLE FAULT				X
B. THICKNESS OF:	1. BEDDED SALT		X		
	2. SHALE		X		
	3. BASALT		X		
	4. TUFF		X		
	5. OVERBURDEN	X			
	6. SEDIMENTARY STRATUM IN GENERAL	X			
	7. SILL			X	
C. ANGLE OF:	1. INCLINED STRATA				X
	a. LIMB OF ANTICLINE OR SYNCLINE				X
	b. MONOCLINE OR HOMOCLINE				X
	2. LOW-ANGLE FAULT				X
	3. AXIAL PLANE OF RECUMBENT FOLD				X

TABLE 1, CROSSHOLE (CONT'D)

		RANKING 1	2	3	4
II. FEATURES ASSOCIATED WITH ONE OR MORE VERTICAL PLANES					
A. LOCATION OF:	1. HIGH-ANGLE FAULT				X
	2. FRACTURE ZONE				X
	3. BRECCIA ZONE				X
	4. IGNEOUS INTRUSIVE CONTACT				X
	5. SALT DOME CONTACT				X
B. WIDTH OF:	1. DIKE				X
	2. FRACTURE ZONE				X
	3. BRECCIA ZONE				X
	4. SALT DOMES				X
C. ANGLE OF:	1. FAULT PLANE				X
	2. IGNEOUS INTRUSIVE CONTACT				X
	3. SALT DOME CONTACT				X
	4. AXIAL PLANE OF NORMAL FOLD				X
III. OTHER FEATURES					
A. DEPTH TO:	1. BURIED EROSIONAL SURFACE				X
	2. IGNEOUS INTRUSIVE BODY				X
	3. SALT DOME				X
	4. SOLUTION FEATURES				X
	5. MASSIVE SULFIDE DEPOSIT				X

TABLE 1, CROSSHOLE (CONT'D)

B. DETERMINATION OF:		RANKING 1	2	3	4
	1. ROCK TYPE				
	a. BEDDED SALT			X	
	b. SHALE			X	
	c. BASALT			X	
	d. TUFF			X	
	e. GRANITE			X	
	2. GEOTHERMAL CONDITIONS				X

KEY TO RANKING

1. FREQUENTLY APPLICABLE
2. OCCASIONALLY APPLICABLE
3. SELDOM APPLICABLE
4. NOT APPLICABLE

TABLE 2

DETECTABILITY OF GEOLOGIC FEATURES AND ACCURACY OF SUBSURFACE MEASUREMENTS USING THE CROSSHOLE METHOD

NOTE: 1. CONTRAST IS VELOCITY CONTRAST
2. SEE END OF CHART FOR KEY TO RANKING

		LOW CONTRAST				MEDIUM CONTRAST				HIGH CONTRAST			
		0-5M	5-300 M	300-900M	> 900 M	0-5 M	5-300 M	300-900 M	> 900 M	0-5 M	5-300 M	300-900 M	> 900 M
I. DEPTH TO:	1. BEDDED SALT	3	2	2	X	2	1	1	X	1	1	1	X
	2. SALT DOME	X	X	X	X	X	X	X	X	X	X	X	X
	3. SHALE	3	2	2	X	2	1	1	X	1	1	1	X
	4. BASALT	3	2	2	X	2	1	1	X	1	1	1	X
	5. TUFF	3	2	2	X	2	1	1	X	1	1	1	X
	6. GRANITE	3	2	2	X	2	1	1	X	1	1	1	X
	7. BURIED EROSIONAL SURFACE	3	2	2	X	2	1	1	X	1	1	1	X
	8. WATER TABLE	3	2	X	X	2	1	X	X	1	1	X	X
	9. BEDROCK	3	2	2	X	2	1	1	X	1	1	1	X
	10. BASEMENT	3	2	2	X	2	1	1	X	1	1	1	X
	11. CONTACT	3	2	2	X	2	1	1	X	1	1	1	X
	12. ANGULAR UNCONFORMITY	3	2	2	X	3	2	2	X	1	1	1	X
	13. PARACONFORMITY	3	2	2	X	3	2	2	X	1	1	1	X
	14. LOW ANGLE FAULT	3	2	2	X	3	2	2	X	1	1	1	X
II. ANGLE OF:	1. INCLINED STRATA	5	5	5	X	5	5	5	X	5	5	5	X
	2. LIMB OF ANTICLINE OR SYNCLINE	5	5	5	X	5	5	5	X	5	5	5	X
	3. MONOCLINE OR HOMOCLINE	5	5	5	X	5	5	5	X	5	5	5	X
	4. FAULT PLANE	5	5	5	X	5	5	5	X	5	5	5	X
	5. AXIAL PLANE OF FOLD	5	5	5	X	5	5	5	X	5	5	5	X
	6. IGNEOUS INTRUSIVE CONTACT	5	5	5	X	5	5	5	X	5	5	5	X
	7. SALT DOME CONTACTS	5	5	5	X	5	5	5	X	5	5	5	X

TABLE 2, CROSSHOLE (CONT'D)

	LOW CONTRAST				MEDIUM CONTRAST				HIGH CONTRAST			
	0-5 M	5-300 M	300-900 M	> 900 M	0-5 M	5-300 M	300-900 M	> 900 M	0-5 M	5-300 M	300-900 M	> 900 M
III. SIZE OF: 1. SOLUTION FEATURE	5	5	5	X	5	5	5	X	5	5	5	X
2. MASSIVE SULFIDE DEPOSIT	5	5	5	X	5	5	5	X	5	5	5	X
3. SALT DOME	5	5	5	X	5	5	5	X	5	5	5	X
4. FAULT OFFSET	5	5	5	X	5	5	5	X	5	5	5	X

VELOCITY CONTRAST (RATIO OF VELOCITIES ACROSS INTERFACE)

LOW = .85
MEDIUM = .65
HIGH = .5

X: SITUATION WHICH IS GEOLOGICALLY OR GEOMETRICALLY IMPROBABLE

KEY TO RANKING

I. ACCURACY OF DEPTH

1. ± 1-5% OF DEPTH
2. ± 5-15% OF DEPTH
3. ± 15-30% OF DEPTH
4. ± > 30% OF DEPTH
5. NOT DETECTABLE

II. ACCURACY OF ANGLE

1. ± 1-5 DEGREES
2. ± 5-15 DEGREES
3. ± 15-30 DEGREES
4. ± > 30 DEGREES
5. NOT DETECTABLE

III. MINIMUM SIZE FOR DETECTION

1. TINY (1 CM - 1 M)
2. SMALL (1 M - 9 M)
3. MEDIUM (10 M - 99 M)
4. LARGE (> 100 M)
5. NOT DETECTABLE

TABLE 3

RELAIBILITY OF IDENTIFICATION OF GEOLOGIC FEATURES USING THE CROSSHOLE METHOD

NOTE: 1. CONTRAST IS VELOCITY CONTRAST
2. SEE END OF CHART FOR KEY TO RANKING

	LOW CONTRAST				MEDIUM CONTRAST				HIGH CONTRAST			
	0-5 M	5-300 M	300-900 M	> 900 M	0-5 M	5-300 M	300-900 M	> 900 M	0-5 M	5-300 M	300-900 M	> 900 M
I HORIZONTAL FEATURES												
1. BURIED EROSIONAL SURFACE	4	4	4	X	4	4	4	X	4	4	4	X
2. WATER TABLE	2	2	X	X	1	1	X	X	1	1	X	X
3. BEDROCK	3	3	3	X	2	2	2	X	1	1	1	X
4. BASEMENT	3	3	3	X	2	2	2	X	1	1	1	X
5. CONTACT	3	3	3	X	1	1	1	X	1	1	1	X
6. ANGULAR UNCONFORMITY	4	4	4	X	4	4	4	X	4	4	4	X
7. PARACONFORMITY	3	3	3	X	2	2	2	X	2	2	2	X
8. LOW-ANGLE FAULT	4	3	3	X	4	3	3	X	3	3	3	X
9. INCLINED STRATA	4	4	4	X	4	4	4	X	4	4	4	X
9a. LIMB OF ANTICLINE OR SYNCLINE	4	4	4	X	4	4	4	X	4	4	4	X
9b. MONOCLINE OR HOMOCLINE	4	4	4	X	4	4	4	X	4	4	4	X
II. VERTICAL FEATURES												
1. HIGH-ANGLE FAULT	X	X	X	X	X	X	X	X	X	X	X	X
2. FRACTURE ZONE	X	X	X	X	X	X	X	X	X	X	X	X
3. BRECCIA ZONE	X	X	X	X	X	X	X	X	X	X	X	X
4. IGNEOUS INTRUSIVE CONTACT	X	X	X	X	X	X	X	X	X	X	X	X
5. SALT DOME CONTACT	X	X	X	X	X	X	X	X	X	X	X	X
6. DIKE	X	X	X	X	X	X	X	X	X	X	X	X

TABLE 3, CROSSHOLE (CONT'D)

	LOW CONTRAST				MEDIUM CONTRAST				HIGH CONTRAST			
	0-5 M	5-300 M	300-900 M	> 900 M	0-5 M	5-300 M	300-900 M	> 900 M	0-5 M	5-300 M	300-900 M	< 900 M
III. OTHER FEATURES												
1. IGNEOUS INTRUSIVE BODY	X	X	X	X	X	X	X	X	X	X	X	X
2. SALT DOME	X	X	X	X	X	X	X	X	X	X	X	X
3. SOLUTION FEATURES	X	X	X	X	X	X	X	X	X	X	X	X
4. MASSIVE SULFIDE DEPOSIT	X	X	X	X	X	X	X	X	X	X	X	X
IV. COMPOSITION												
1. BEDDED OR DOMED SALT	3	3	3	X	3	3	3	X	2	2	2	X
2. SHALE	3	3	3	X	3	3	3	X	2	2	2	X
3. BASALT	3	3	3	X	3	3	3	X	2	2	2	X
4. TUFF	3	3	3	X	3	3	3	X	2	2	2	X
5. GRANITE	3	3	3	X	3	3	3	X	2	2	2	X
6. ROCK TYPE IN GENERAL	3	3	3	X	3	3	3	X	2	2	2	X

KEY TO RANKING

1. GOOD RELIABILITY (ONE OR TWO POSSIBLE INTERPRETATIONS)
2. FAIR RELIABILITY (THREE OR FOUR POSSIBLE INTERPRETATIONS)
3. POOR RELIABILITY (FIVE OR MORE POSSIBLE INTERPRETATIONS)
4. NOT IDENTIFIABLE

X. TECHNIQUE GENERALLY NOT APPLICABLE, OR SITUATION GEOLOGICALLY IMPROBABLE

APPENDIX B-8

MECHANICAL DOWNHOLE SEISMIC

VELOCITY SURVEY METHOD

BY

ERTEC WESTERN, INC.

LONG BEACH, CALIFORNIA

NOVEMBER 1, 1981

B-8

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1.0 DESCRIPTION

1.1 General

Mechanical downhole seismic surveys are similar in concept to uphole velocity surveys conducted in support of oil exploration. They differ primarily in the energy levels used, the depths of investigation, and in the concern for measuring shear (S) wave as well as compressional (P) wave velocities in the mechanical method. The uphole methods use explosive energy sources and record travel times to depths of several thousands of feet. The mechanical method is generally limited to only a few hundreds of feet.

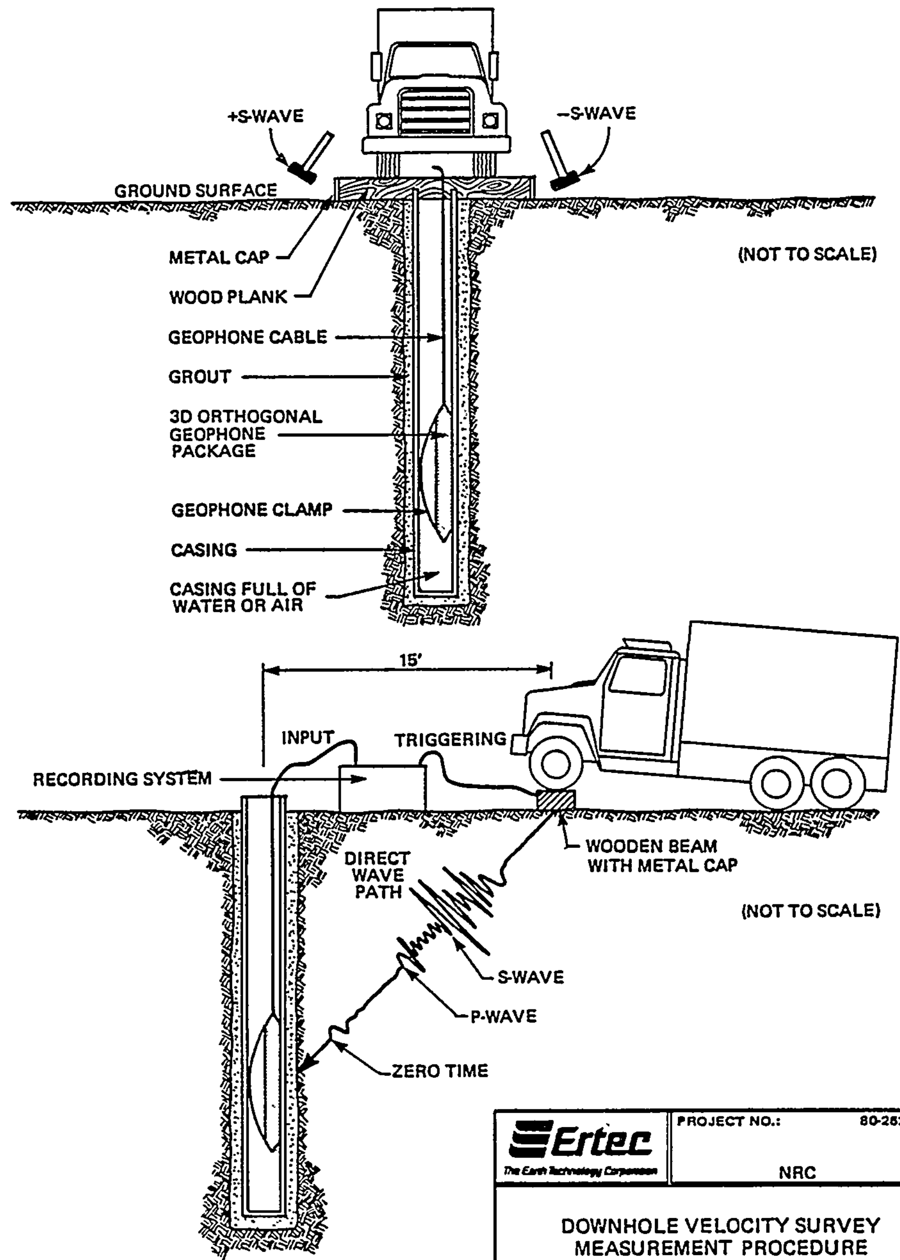
Mechanical surveys are used to determine the variation of in-situ seismic wave propagation velocities versus depth. Poisson's ratio and shear, Young's and bulk modulus for soil material can be calculated if its density, and P- and S-wave velocities are known. The primary reason for doing a downhole survey instead of a crosshole survey is that the downhole survey costs less. A crosshole study requires at least two borings (three or more are preferred), while a downhole survey requires only one boring. The velocity profile from a downhole survey is based on vertically traveling waves, so if done together with a crosshole survey, anisotropy in the materials can be determined. However, the profile obtained from a downhole survey is more generalized than that obtained from a crosshole survey.

An advantage of a downhole survey over surface refraction surveys is that lower velocity material overlain by higher velocity material can be detected.

1.2 Principles

With this method the times required for P- and S-waves to travel vertically from the surface to points within the soil mass are measured. The general concept is shown in Figure 1.

A basic principle involved in the mechanical downhole survey is the generation of a horizontally polarized S-wave at the surface and the detection of its arrival at different elevations within a borehole. Wave identification can be enhanced by reversing the direction of motion of the energy source for successive recordings. The S-waves recorded at depth will exhibit a corresponding reversal of first motion. On the other hand, the direction of first motion of compressional waves usually remains unchanged.



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DOWNHOLE VELOCITY SURVEY
MEASUREMENT PROCEDURE

6-81

FIGURE 1

A factor which can interfere with S-wave identification is that a new set of P- and S-waves is generated as the P-wave reaches each velocity interface.

1.3 Components

The key components in the mechanical downhole survey are the boring, energy source, receivers, and recording equipment.

The borings should be drilled, cased, and grouted so that it is open at least 5 feet (2 m) deeper than the specified depth of the investigation. The boring should be logged during drilling to determine soil types and layer thickness. The boring should be cased with plastic pipe. The casing should be grouted in place to insure good coupling with the surrounding soils. Back filling with sand or gravel around the casing has been found to be less effective than grout.

The source used to generate S-waves during a mechanical downhole survey is usually a wooden plank with a vehicle parked on it. The plank is placed on level ground with the center located 10 to 30 feet (3 to 9 m) from the boring and with the ends equal distance from the boring (Figure 1). The source is offset from the boring so the rays will travel over most of their paths through material that is undisturbed by drilling. The offset also avoids coupling of high levels of energy into the grout-casing column. Metal plates should be attached to the ends of the plank so that triggering time can be accurately established when the sledge hammer makes contact. This method has been used successfully to depths as great as 500 feet (152 m). For deeper investigations, it may be necessary to replace the sledge hammer and wooden plank energy source with a larger device. The P-waves are usually generated by a downward blow on a metal plate lying flat on the ground.

The recording system should have three or more channels and variable gain setting. It should have an accurate timing system and produce a permanent record. The geophones should have an appropriate directionality, sensitivity and frequency response. The geophone package should have three components; one of the geophones oriented vertically and the other two horizontally in mutually perpendicular directions. The natural frequency of the geophones should be less than one-half the frequency of the S-waves that will be recorded. The geophone package should be equipped so that it can be clamped against the casing at any desired depth.

1.4 Procedures

The geophone package is placed at a specified depth and three records (seismograms) are made. One is made from a vertical blow on the metal plate to record relatively large amplitude P-waves. The second record is made from a horizontal blow on the end of the energy source board. The third record is made from a horizontal blow on the other end of the board. The horizontal S-waves from these latter two blows will be oppositely polarized. This fact aids the interpreter in identifying them on the records. When the three records are obtained, the geophones are moved to another specified depth, and three more records are made. This procedure is repeated until records are obtained with the geophones at all the planned depths. Because of the shallow depths, the geophones are usually moved by hand, without tripods or winches.

2.0 APPLICABILITY

Mechanical downhole seismic velocity surveys are applicable for developing generalized seismic velocity surveys to depths of a few hundred feet. The velocity profiles can be useful for a variety of geotechnical engineering evaluations, especially in studies of earthquake response. Two factors restrict this method to relatively shallow (<500 feet) depths. First, the energy levels are small from the mechanical sources and second, P to S wave conversions at interfaces can hamper S-wave interpretation at greater depths. In view of the limited depths of investigation attainable with this technique, it would not be applicable to studies of the repository medium. It may be used to obtain information for design of surface structures that will be needed at the repository site.

3.0 RESOLUTION

The ability of the downhole survey to resolve the profile into discrete layers is controlled by several factors, and they are interrelated. The major factors are:

1) The contrast in velocities in adjoining layers,

2) The thickness of a velocity layer relative to the interval between travel time measurements, and

3) The precision to which wave travel times can be read.

Velocity contrasts across an interface of 20, 50 and 100 percent could be rated as low, moderate, and high. The ability to resolve thin layers, and the accuracy of determining the depth of the interface both improve as the contrast becomes greater.

A layer must be at least as thick as the interval of measurements for its velocity to be resolved. Limitations on timing resolution make it impractical to take measurements at intervals smaller than about 5 feet. For a velocity to be accurately established it should be based on several data points. Therefore, even though a thin layer may be recognized, the velocity interpreted for it may be less accurate than those measured in thicker layers.

The precision with which travel times can be measured is set by a combination of instrumentational and seismological characteristics. In reasonably good signal-to-noise conditions, P-wave travel times may be timed to within one-half millisecond and S-waves to about one millisecond. Velocities of thick homogeneous layers typically can be determined to within about 10 percent or slightly better.

4.0 RELIABILITY

The reliability of a mechanical downhole study is controlled by the planning and care exercised during the conduct of the field work and interpretation, and the quality control. When all elements of the survey are carefully planned to meet the objectives, and proper quality control procedures are followed, velocities can be established with high reliability within specified error limits. One would not normally use a downhole survey in an attempt to resolve geologic features, so, unlike other topical reports on geophysical techniques, no table of "Reliability" is included herein.

5.0 TIME AND COST

The time and cost discussion is based on a typical mechanical downhole survey to a depth of 500 feet (152 m). This survey would require one boring. In many studies, this boring will have been drilled for other purposes, and only the cost of grouting and casing is necessary for the downhole survey.

The time and cost figures break down into three major categories:

1) Drilling, sampling, casing and grouting the boring will typically require about 5 or 6 days. If no sampling is required, a boring will take about 2 days. Costs for drilling and a soils technician are expected to range between $3,000 and $12,000.

2) Mechanical downhole field measurements will require approximately 12 hours and cost about $1,500 for equipment and personnel.

3) Supervision, planning and interpretation will require on the order of 70 hours and cost about $2,600.

The weather, location and material being drilled all influence the time and costs to perform a downhole survey. The factor which can cause the greatest fluctuation in these parameters is the material being drilled.

As previously stated, the mechanical downhole method may be used to obtain information for design of surface structures at the site, but it is not applicable for characterization of the repository medium because of the repository depth. Methods employed for uphole shooting by the oil exploration industry would be applicable for determining P-wave velocities at repository depths, but costs would be on the order of 10 or more times greater than those described above.

C

APPENDIX C

BOREHOLE GEOPHYSICAL LOGGING TECHNIQUES

BY

JAMES HALLENBURG
TULSA, OKLAHOMA

November 1, 1981

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The Use of Borehole Geophysical Logging Techniques in Waste Disposal Site Characterization

In the type of project which is being considered here, it is important for the user of the techniques to specify the methods by which measurements are to be made and the amount, quality, and resolution of the data. This is in contrast to the usual practice of allowing the contractor to decide these things. This in no way implys that one is trying to "tell the contractor how to run his business", but, rather one is telling the contractor what information he needs in order to work properly. In order to do this properly the user must be familiar with the uses and capabilities of the systems.

There are a number of different borehole geophysical logging techniques available. Obviously, some are more suited to a particular task than are others. This is especially true for determining high level waste disposal useage. The major measurements can be divided into three classes: 1. Electric logging, 2. Radioactivity logging, and 3. Mechanical logging. Each of these three classes has many variations, so the user has a choice of ways to accomplish his measurement and to verify the reliability of the data. The various methods must be chosen carefully to allow calculation or determination of a specific set of geological or physical parameters. They must also be chosen so that the data may be verified. This latter is because we are working with many indirect methods and, sometimes, approximations. It is seldom we can measure the desired parameter directly.

Thus, one must decide what parameter is to be determined, how it best can be determined, and then what instruments would be best suited to make the determination. This must be done before contacting the logging contractor.

The contractor should be chosen on a number of bases.

Probably the most important point in chosing a contractor for this type of work is his willingness to cooperate in such matters as acquiring accurate data (both primary and peripheral), acquiring data peculiar to this type measurement or this project, making calibrations, documentation, and accuracy.

Secondly (and a matter with which everyone is concerned) is cost. The lowest practical cost is a major budget consideration. A low cost is expensive, however, if the data are not suitable or (more likely) erroneous. There is little difference, normally, between the cost of the best, most reliable contractor, and the cheapest one. Normally, the difference is about 10%. This is because the upper price is usually established by the biggest, most active contractor in the field.

The contractor has some fixed costs. If the bid price falls below this, the contractor has probably cut price in order to get the job. This invariably results in poor service and unsatisfactory relations. The fact that he must do this indicates that he lacks clientel. The contractor (at this writing) must pay his prober about $1500 a month salary. His capital investment will amount to another $1500 a month. Overhead and back up personnel amount to approximately another $1500 a month. Thus, a contractor who bids less than about $4500 a month is not only not going to show a profit, he will lose money. No profit incentive, especially on a long contract will result in unsatisfactory service. This practice is widespread.

Thirdly, the calibration models, techniques, and documentation used by the contractor should be examined carefully. A contractor who knows his business will be quite willing to go over these items with his client. Calibration models should be well and logically prepared. Calibration measurements should be carefully and frequently performed. The calibration data should be well documented, dated, and displayed on the log heading. Any tool using a source must have normalizing data displayed and used.

Finally, the contractor must have a good reputation for supplying service, accuracy, reliability, and aid in handling the results of his work. It is probably not a bad idea to obtain an independent evaluation and advice about this. And, he should be retained directly by the person responsible for the project, not by the driller (or other indirect means).

The logs which will result from the measurements on the project site must meet certain standards.

1. The logs must be neat and clean. Every error, smudge, and uncertainty introduces additional processing time.
2. Log headings must have all of the appropriate data filled in. This is a contractual obligation of the operator. The minimum items which must be on the log heading are
   a. Client name,
   b. Borehole identification,
   c. Date the logs were made,
   d. Other measurements made on the hole,
   e. Hole location and elevation, if available,
   f. Contractor name, prober name, truck number, office location,
   g. Logging tool type and serial number,
   h. Type system used (i.e. analog, digital, hybrid, derandomized, etc.),
   i. Types of curves run on this log,
   j. Sensor data (crystal size, type, spacings, etc.)
   k. Source type, strength and serial number (if applicable),
   l. Normalizing reading (if applicable),
   m. Date, location, and values of last calibration (if applicable),
   n. Borehole size and fluid,
   o. Mud resistivity (for electric logs and neutron logs).
   p. Driller's depth,
   q. Maximum depth logged (may be on the bottom of the log),
   r. Mud additives,
   s. Any nonroutine occurrences.

The representative of the client (Project Geologist, Project Manager, etc.) must be on hand while the logs are being run. Remember that the only reason for drilling the hole is to obtain information, and the major method is logging. He should confer with the prober before logging to be sure the prober knows what he is to do. Both the prober and the client should check the data to be sure it is complete. Both should watch during logging to be sure the logging is normal and valid.

Once the logs are run and the data complete, then processing begins. Often (especially with digital equipment) much of the processing can be done by the logging equipment. There are many options open to the client. He should find out what they are and take advantage of them.

Each curve run contributes to the total information: 1. Electric logs will indicate depositional processes, vertical permeability features, fluid content and type, correlation features, and structure. 2. Radioactivity logs will show sand and clay content, lithogical details, mechanical details, correlation details, alteration features, and fluid content and type. 3. Mechanical logs will show lithological features, fluid content and type, construction and mining considerations.

The greatest value of these logs, however, is when they are used in concert. A resistivity, SP log, and a gross count gamma ray log can show depositional history, especially that due to hydraulic phenomena. A density and neutron porosity log can determine, quantitatively the detailed lithology or mineralogical composition, the fluid type and content of a formation. Fluid and pore space determinations can also be made with the electric logs. Similiar results with several methods will verify the data. The neutron porosity, density, and acoustic logs can supply lithological detail about the site. All of the logs, when used with surface geophysical methods can supply detailed, wide area information concerning the vertical and horizontal distribution of geological features. Many of the logs, especially the electric logs can supply detail about formation fluids when used with surface geochemical methods.

With respect to Table 1 of Exhibit A (Specific Work Instruction, Information Needs for Site Characterization, Technique Studies), the following techniques can be used for the specific items addressed 10 CFR 60.122(a)(9):

(i) The pattern, distribution and origin of fractures and other discontinuities in the host rock and surrounding confining units may be determined by several logging techniques. These are important considerations in the petroleum business and the mineral business is beginning to realize their importance, also.

The high resolution dipmeter is a fine method for locating fractures and their distribution. Discontinuities can also be detected with this tool. It gives the best results when used in sediments. It may, however be used to a large degree in hard-rock environments (this is because it uses a focussed resistivity system). It should be used with the conventional electric logs, such as the SP and the focussed resistivity measurements. The gross count gamma ray measurement will add information about clay contents and fluid channeling. Lithology determination can be added.

(ii) Potential hydraulic pathways can best be detected in sediments by the gross count gamma ray curve in combination with a resistivity curve. The gamma ray spectrograph can help locate existing fluid pathways by their uranium content. Fault-plane communication possibilities can be detected with the high resolution dipmeter. Neutron and acoustic measurements are excellent for use in hard-rock environments. Secondary porosity (i.e. fracturing, vugular porosity, etc. can often be detected by a combination of the acoustic-derived porosity compared to the neutron or density derived porosity.

(iii) In situ determination of geomechanical properties can be determined by the density, acoustic, and electronic cone penetrometer methods. The ECP is best for pore pressure determinations. Ambient stress conditions, perhaps could be detected and measured by determining the elastic properties with the acoustic and density systems.

(iv) Bulk hydrogiologic properties can be partially determined by a combination of GCGR, neutron, density, and resistivity measurements. The GCGR will pin-point the quantity and quality of clays, the neutron and density measurements will determine fluid types and amounts. The gamma ray spectrograph can give a better assessment of the clay amount. The density and resistivity systems can determine lithology and fluid character.

(v) Geochemical conditions are difficult to determine with wireline logs. The SP curve can determine effective total dissolved solid content (assuming NaCl). Specific ion measurements may be of some use. Resistivity measurements can aid the SP determinations of salinity. The SP can indicate redox trends.

(vi) Response to thermal loading is possible beyond present analytical methods, at this time.

10 CFR 60.122(b) Potentially adverse natural conditions

(i) Extreme bedrock incision can best be detected by combining surface methods, such as resistivity and high resolution seismology with downhole resistivity in several boreholes. In all probability, the focussed resistivity methods, especially the 7 electrode focussed resistivity, would be best because of their deep investigation.

(ii) Dissolution can be detected (but not always specifically) by any of the porosity tools. By comparing the porosity derived from one of the nonresistivity methods with that derived from the resistivity value, the cementation constant of Archies relation may help indicate dissolution resulting in nongranular porosity. The gamma ray spectrograph can help detect calcite cementation because uranium is rejected from the crystal structure during deposition.

(iii) Structural deformation can be specifically determined with the high resolution dipmeter. Standard measurements, such as the GR-electric logs should accompany it.

(iv) Near field of Quaternery faulting is difficult to detect with borehole logs because of the relatively shallow depth of investigation of most of them. When the absence of faulting indicated by a wire-line log is accompanied by the indication of the presence of a fault by surface methods, the suspicion of faulting should be present, at least. Faulting can be detected when intersected by the borehole by the SP, Resistivity, GCGR, and High Resolution Dipmeter logs.

(v) High seismicity is probably one place where a long history of cooperation between seismographic explorers and wire-line operators will pay off. Geophones to run on logging lines and the techniques to handle them and the data exist in the major petroleum logging companies and the seismographic firms.

(vi) Igneous activity can often be detected by comparing temperature measurements with those of locations somewhat distant. Unusual temperature gradients (high) often indicate igneous activity.

(vii) Temperature gradients are measured routinely with oil-field logging equipment. In the case of an absolute gradient measurement, it may be desirable to case the borehole with inexpensive pipe and allow the thermal disturbance due to drilling, to dissipate. An alternative would be to bury sensors in the hole and make measurements after some time had elapsed. This is often done because the sensors are inexpensive.

10 CFR 60.122(b) Potentially adverse natural conditions, Hydrologic

(i) The potential for significant changes in hydrologic conditions would depend upon locating possible conduits or simple, very porous conditions with the GR and electric logs and assessing the potential for change from wide-area surface measurements and mapping.

(ii) Since the electric log, combined with the GCGR is an indicator of deposition from flowing water, this might be useable in the near surface sediments.

(iii) Natural impoundments (potential) can usually be detected with the high resolution dipmeter if the impoundment, such as a fault or a dike is intersected by the borehole. A combination of surface and downhole methods is valuable.

(iv) The same comments as iii apply here.

Potentially adverse natural conditions, Geochemical

(i) Low retardation should be related to a low cation exchange capacity (CEC) of the clays. This will be reflected by the effect upon the SP curve (deflection more nearly that of a sand?), upon the resistivity curve (higher resistivity), upon the gross count gamma ray curve (less retention of uranium ions; lower radioactivity) and the identification of possible clay types by the GR spectrometer. Also affected will be the neutron porosity measurement, because of the lower bound water content.

10 CF R 50.122(c) Favorable Conditions

1) Candidate Area

(i) Demonstratable stability since the beginning of the Quaternary will be demonstrated by a uniform, nearly horizontal stratification of sediments and an absence of any faulting or other structure. This can be demonstrated by almost any of the curves, but especially by the SP and resistivity. The high resolution dipmeter would be needed, in addition, to show a uniform, shallow dip and a lack of faults.

(ii) Host rock and confining units provide:

a. Long ground water residence times and long flow path rates: These may be indicated by low permeability and porosity. Flow rates can be indicated by the neutron porosity tool.
b. Inactive groundwater circulation is difficult to assess with logs: Both this, and the previous item (a) can be confirmed by injection in a nearby hole of radioactive tracer material, or an exotic ion type. Both can be detected upon entry into the observation hole vicinity. Of the two, the radioactive tracer is easier to perform.
c. Geochemical conditions resulting in low solubility of radionuclides and lack of complexing agents: If a clay is considered a complexing agent, the SP, gamma ray and resistivity measurements will indicate its presence and amount. A gamma ray spectrograph can help identify the type of clay. The SP

curve can indicate the relative state of oxidation of the formation. E_H electrodes can make redox measurements after a stabilizing time has elapsed (5 to 60 days).

2). Volume of Rock:

(i) Favorable conditions above the zone being examined can be determined by detecting the presence and amounts of shales, using the GCGR or the GR spectrograph. The detection of the lack of porosity will accomplish the same thing. This may be measured with any of the porosity methods or combinations (in crossplot of any two of them. Favorable lithology determinations can be made by using the litho-density measurement or the M-N crossplot. Formation competancy measurements will need a combination of the acoustic P-wave and S-wave travel time and density measurements.

(ii) Geologic framework permitting effective sealing, evacuation of stable subsurface openings, and emplacement of waste would be indicated by several logs in combination. Resistivity, SP, GCGR combination would indicate favorable formation types, sequences, and the presence of voids, openings, or porosity. This should be verified by the density, neutron, and acoustic measurement combinations. Mud resistivity monitoring is very sensitive to the presence of massive evaporites, such as halite. Gamma measurements can confirm potassium evaporite presence; resistivity will do the same for halite or other sodium evaporites. These last, too are offered as contract services. The SP and the neutron tools, with resistivity and density can identify calcium and magnesium minerals. Acoustic measurements will aid any of these. Openings and cavities can be detected with the caliper, resistivity, acoustic, density systems, the high resolution dipmeter and with the borehole televiewer.

(iii) Groundwater flow is difficult to detect, except as noted previously.

a. Host rock with very low water content: Low water content can be indicated very sensitively by the neutron porosity methods, especially in combination with the density. The relative amounts of water, rock, and gas can be determined.

b. Circulation is difficult to detect, except for low porosity indicating low permeability. Intrusion can be seen by the electric logs if the intruding water contrasts in resistivity with the native water.

c. The upward flow probability can be assessed by the gamma ray, resistivity, density, neutron, and acoustic curves.

d. Hydraulic gradients are difficult to measure.

e. Horizontal or downward hydraulic gradients are difficult to meausre.

f. Groundwater residence times cannot be measured with present wireline techniques.

(iv) The geomechanical properties can be measured quite accurately with a combination acoustic (pressure and shear wave velocities) and density measurements. The resistivity, gamma ray, and neutron measurements will allow a good lithologic assement.

(v) Population density does not apply.

(vi) Meterological considerations do not apply.

(vii) Climate change considerations do not apply.

Table 2. Examples of Important Site Parameters Provided in 10CFR60 Technical Support Document.

1.0 Geologic Framework

1.1 Conditions

Geometry can be determined with multiple boreholes and resistivity, GCGR measurements. Included with geometry is depth to host rock, tectonic framework, and distribution and extent of resources. Temperature and differential temperature measurements can determine the geothermal gradient in as much detail as desired. Boreholes may have to stabilize, however over a period of days to weeks. The lateral extent of any stratigraphic features can be determined with a high enough frequency of boreholes. It is probably best to use a combination of surface and down-hole measurements for any or all of these determinations.

1.2 Processes

Measurements of the extent, magnitude and rate of surficial geologic processes can usually be better done by surface measurements in combination with wireline measurements. Wireline logs can be used for depth and detailed parameter control. SP, GCGR and resistivity can identify depositional mechanism. Tectonic processes can be determined with focussed resistivity, density, neutron, acoustic, and gamma ray measurements. These can greatly be enhanced with the high resolution dipmeter. These comments will apply equally well to dissolutioning, uplift, and subsidence. The GCGR and SP are the primary measurements for dissolutioning and the HRD for uplift and subsidence.

1.3 Events

The extent and magnitude of volcanism can be determined with temperature and acoustic measurements. The extent and magnitude of faulting can be determined with the HRD and acoustic measurements. The rate and likelihood of either is not likely to be determined from downhole measurements, without extensive study. My knowledge of earthquake characteristics is not extensive enough to comment on them.

2.0 Geomechanical Framework

2.1 The mechanical conditions listed here can all be determined or estimated with a combination of acoustic pressure and shear wave velocity and density measurements. Acoustic P and S waves tend to be reflected by horizontal and vertical fractures at different rates. Fractures tend to be ignored in the acoustic porosity calculation. The HRD should be included and GCGR and focussed resistivity measurements would be desirable.

2.2 Thermomechanical Properties

If the borehole is allowed to return to thermal equilibrium after drilling, thermal conductivity, alteration properties (some), specific heat, and density can be determined with temperature, differential temperature, gamma ray, resistivity and density measurements. It is possible that temperature profiling can be used to determine specific heat, conduction and convection characteristics. Coring may be needed for expansion coeffecients and the ECP for pore water pressures.

3.0 Groundwater system

3.1 Flow framework

Flow is difficult to detect with most logging methods. Radioactive tracer or exotic ion tracer methods can be used. The neutron tool can also be used to determine flow, but it is not very sensitive nor accurate. The SP curve is very sensitive to electrofiltration potentials. This, plus one of the tracer methods can be used with a mapping technique to determine the location of recharge and discharge. A surface resistivity measurement would aid, greatly.

The depth to the water table can be determined closely with the resistivity and SP measurements. A single point resistivity is usually good enough for this. Density and neutron readings will confirm the location.

It is difficult to detect permeability with logging methods. Thus, the difference between aquifers and aquicludes can only be inferred by porosity and clay content calculations from the neutron, density, resistivity, and gamma ray measurements.

Aquifer capacities can be determined closely with multiple borehole and/or surface resistivity measurements and a combination of GCGR, SP, and focussed resistivity logs. Porosity determinations should be confirmed with the density, neutron, or acoustic travel time logs.

Direction, velocity, travel times, and gradients are difficult to determine. Tracer logs may help.

3.2 Flow Properties

Interstitial flow can be inferred from porosity measurements (resistivity, density, neutron, acoustic) and the permeability indication of the SP curve. Resistivity measurements (focussed or IL) with Archie's relationship and an independent porosity measurement will identify the porosity type. Fracture flow can be inferred from the presence of extensive fracturing indicated by the HRD, and by comparing porosity measurements made with the acoustic system and density (or neutron) measurements.

Permeability is difficult to measure in situ. It can be inferred from porosity determinations. In general, empirical methods are the most reliable. The relations take the form of

$$K = a\phi^b$$

where K is the permeability and a and b are empirical

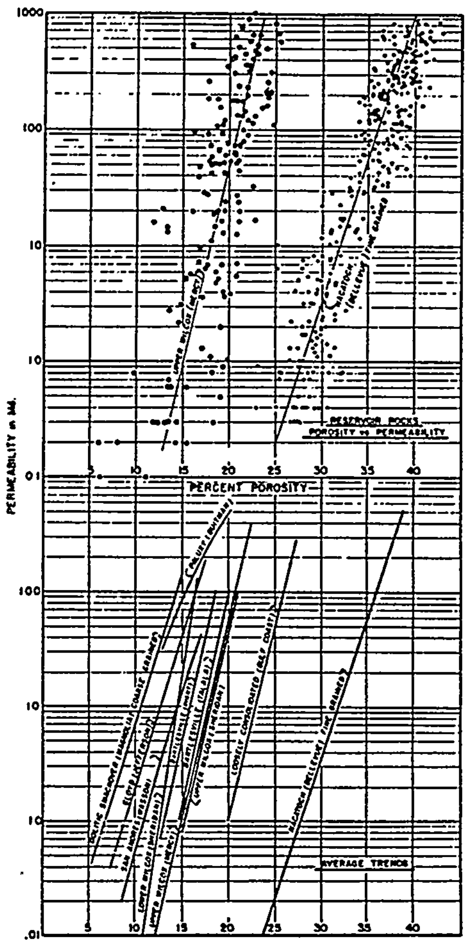


Fig. 1-5a. Average relation between porosity and permeability. From G. E. Archie, "Electrical Resistivity—An Aid in Core Analysis Interpretation," *Bull. Am. Assoc. Petroleum Geol.*, Vol. 31, No. 2 (1947).

coefficients and ϕ is the fractional, dispersed porosity, corrected for clay content. Groundwater age and dispersivity cannot, to my knowledge be determined from logs.

4.0 Geochemical System

4.1 Rock properties can be determined with log combinations: Mineralogy and petrology can be determined with the density, neutron-acoustic combination, aided with the GCGR, SP, and Lithodensity logs. The neutron activation and gamma ray spectrograph measurements are excellent for mineralogy. There are several forms of these last in commercial use at this time. Alteration processes can be inferred from the detection of some of the products with the gamma ray, SP, and resistivity measurements. The density, neutron, and acoustic measurements can help. Retardation properties are related to the alteration properties (very often) and can be detected in the same way.

Organic content can be detected with the GCGR and/or the GR spectrograph. The C/O log will help detect organic materials.

4.2 Nuclide properties

Concentrations of the gamma emitters can be determined with the GCGR and GR spectrograph. Beta and alpha emitter concentrations must be detected from core studies.

Stabilities cannot be determined from logs, except as inferred from the radioactive nuclide identification from the spectral gamma ray logs.

Solubilities of some compounds can be inferred from SP and redox measurements.

Reactions and complexing identification are beyond logging methods, for the most part.

4.3 Groundwater chemistry

Oxidation/reduction potential can be inferred from the SP curve and measured (after the borehole equilibriates) with the redox systems.

The same comments hold for pH.

Ionic strength and distribution are measured with the SP curve. Inorganic and organic composition can be determined with neutron activation and gamma ray spectrograph techniques.

Hydrologic evolution is a new field in logging. Detection of depositional rates caused by different flow rates can be detected with a combination GCGR, SP, and R. Several formats of the HRD presentation are valuable.

Finally, the responses of the various borehole geophysical methods are characteristic for the several classes of materials considered: Bedded salt may be determined by a sharp drop of R_m when the salt is drilled into. The salt itself, has a high resistivity so the R_t/R_m ratio will be very high and demand a focussed resistivity method. The gamma activity will depend upon the type of salt. The stratigraphic indications of the resistivity curve and the acoustic curve will identify the bedded layers. The acoustic velocity as well as the density will be characteristic of the type salt. The HRD will help identify the bedded features.

Domed salt can be detected in much the same way as bedded salt, except that structural features, as indicated by the HRD and stratigraphic features indicated by the GCGR and focussed resistivity will be different.

Shale is one of the components most interesting to mineral and petroleum explorationists. The GCGR can be used to calculate the fractional volume of shale with a reasonable accuracy. The GR spectrograph, using the thorium indication is better. The SP is especially sensitive to shale. A density, acoustic travel time crossplot or an M, N(density, neutron, acoustic travel time) crossplot can separate the relative component amounts of shale. The GR spectrograph must be used for shale or clay determinations in arkosic or uraniferous sands.

Granites have characteristic densities, acoustic travel times, and neutron cross sections. Resistivities and gamma activities are high. A density, acoustic travel time crossplot is definitive. The R-ϕ crossplot is excellent for arkosic sand evaluation.

Tuff will have much the same character to logging methods as sands. The gamma activity, however, is often low reflecting a low potassium and uranium content. Porosity determinations will show the amount and type of fluid filling the material. Porosities may be low. Densities may be variable. Use the neutron porosity and focussed resistivity to determine porosity. The R, ϕ crossplot will help identify the tuff and discriminate it from a sand. Dresser Atlas uses a K - R crossplot to show low potassium content, and a C/O ratio - K crossplot to show low carbon, low potassium content.

Basalt has a characteristic density range(usually above 3.0 g/cc) and acoustic travel time. The neutron cross section will further help identify the material.

Resistance

Resistance measurements can be made with any of the devices described (except for the Induction Log). Resistance is the measured voltage of the electode, divided by the current used to obtain it:

$$r = \frac{E}{I}$$

Resistance is a function, also of the length and cross sectional area of the material and the resistivity, R:

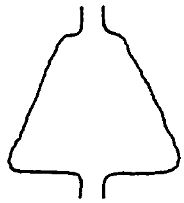
$$r = R\frac{L}{A}$$

Resistance measurements can be used in many nonquantitative ways. The relative deflections from one formation to another can be used to discriminate between sands and clays or shales. With care, high resistivity zones such as limestones, highly cemented sandstones, may be found. Determinations of stratigraphy represent a very important use of this curve type.

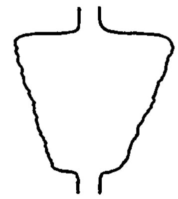
Patterns and signatures are sidely used for cross-section determination and other types of correlation. This probably represents 80% of the use of the curve.

Resistances of dielectric materials, such as quartz, are affected by the grain sizes. Thus, very fine grain sizes (silt) show reductions of resistivity which may be correlated with grain sizes and sorting. thus, the indications can be correlated with fluid flow rate at the time of deposition. This effect is further enhanced by the appearance of clay. The curve should be used with the SP and gamma ray curves for this.

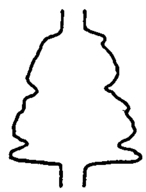
SP and RESISTIVITY CURVE SHAPES AS INDICATORS OF DEPOSITIONAL ENVIRONMENT



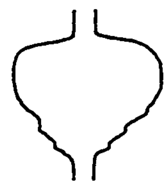
BEACH SAND – TRANSGRESSIVE



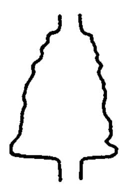
BEACH SAND – REGRESSIVE



VALLEY FILL SAND

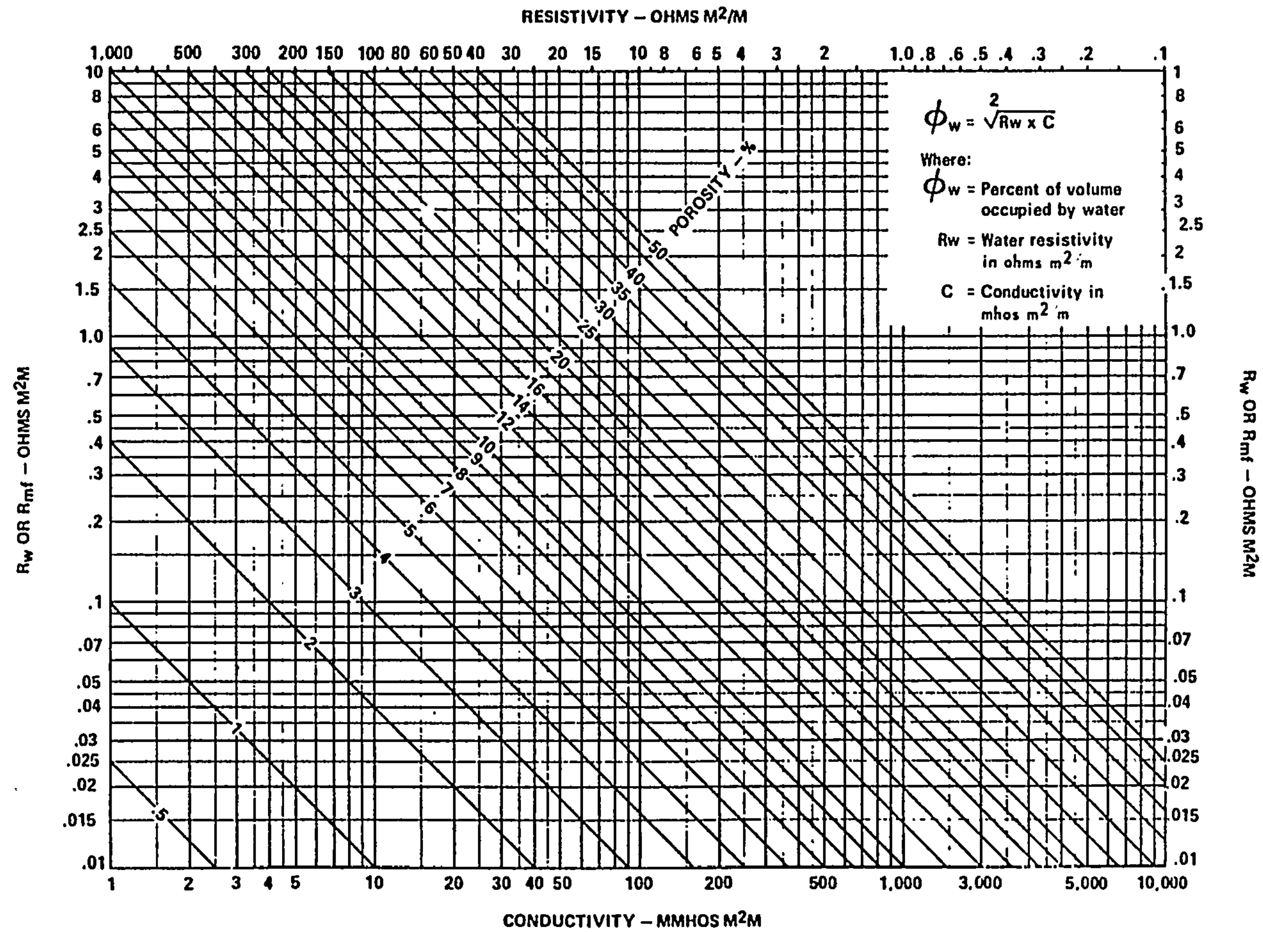


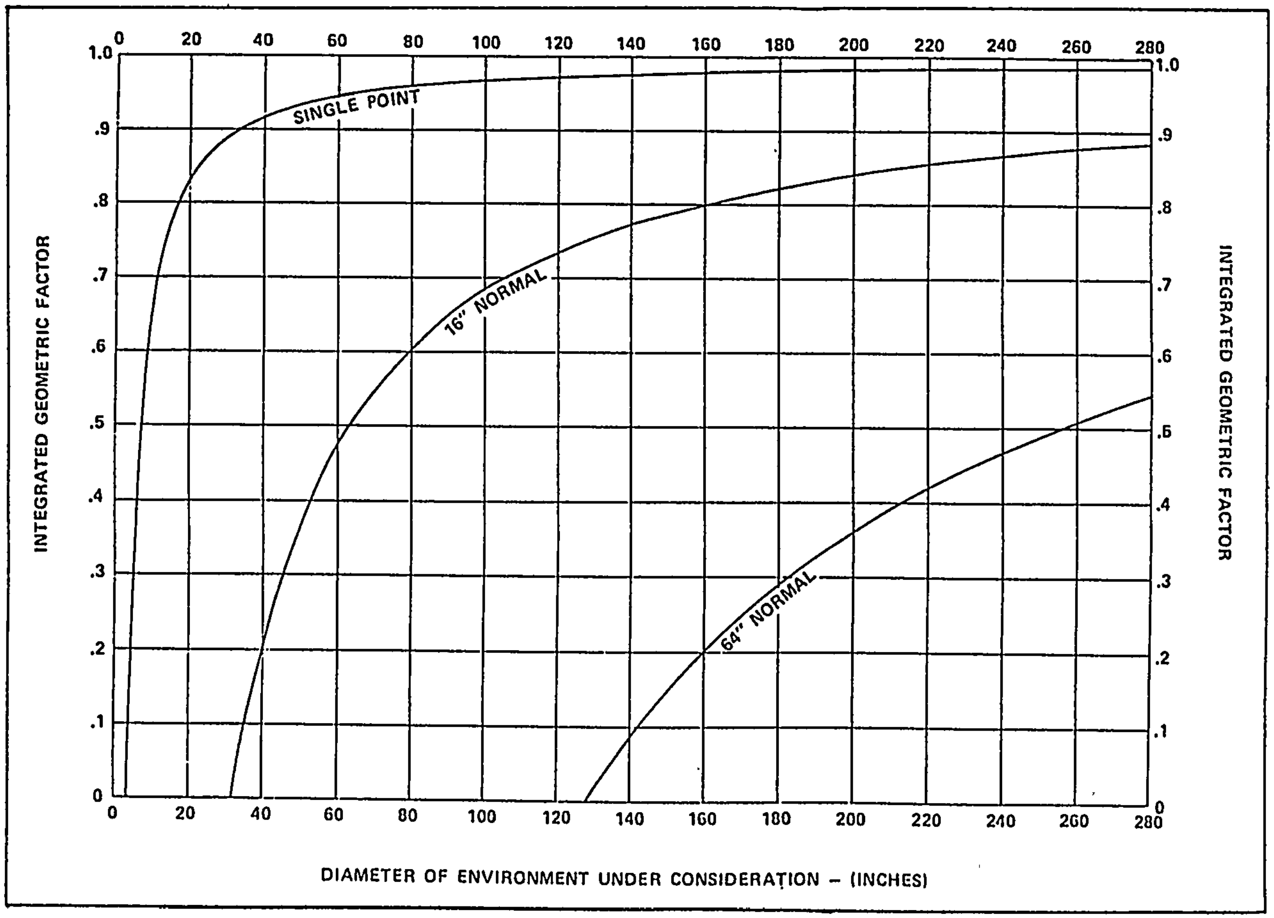
BAR SAND



TURBIDITY SAND

WATER FILLED POROSITY–RESISTIVITY RELATIONSHIPS




INTEGRATED GEOMETRIC FACTOR
SINGLE POINT
16" NORMAL
64" NORMAL
DIAMETER OF ENVIRONMENT UNDER CONSIDERATION – (INCHES)
0 20 40 60 80 100 120 140 160 180 200 220 240 260 280
0 .1 .2 .3 .4 .5 .6 .7 .8 .9 1.0

Resistivity

Resistivity is a basic characteristic of any material. If resistivity can be determined, the material may be identified.

Resistivity, R, is the measured resistance, r, times a geometrical constant, K:

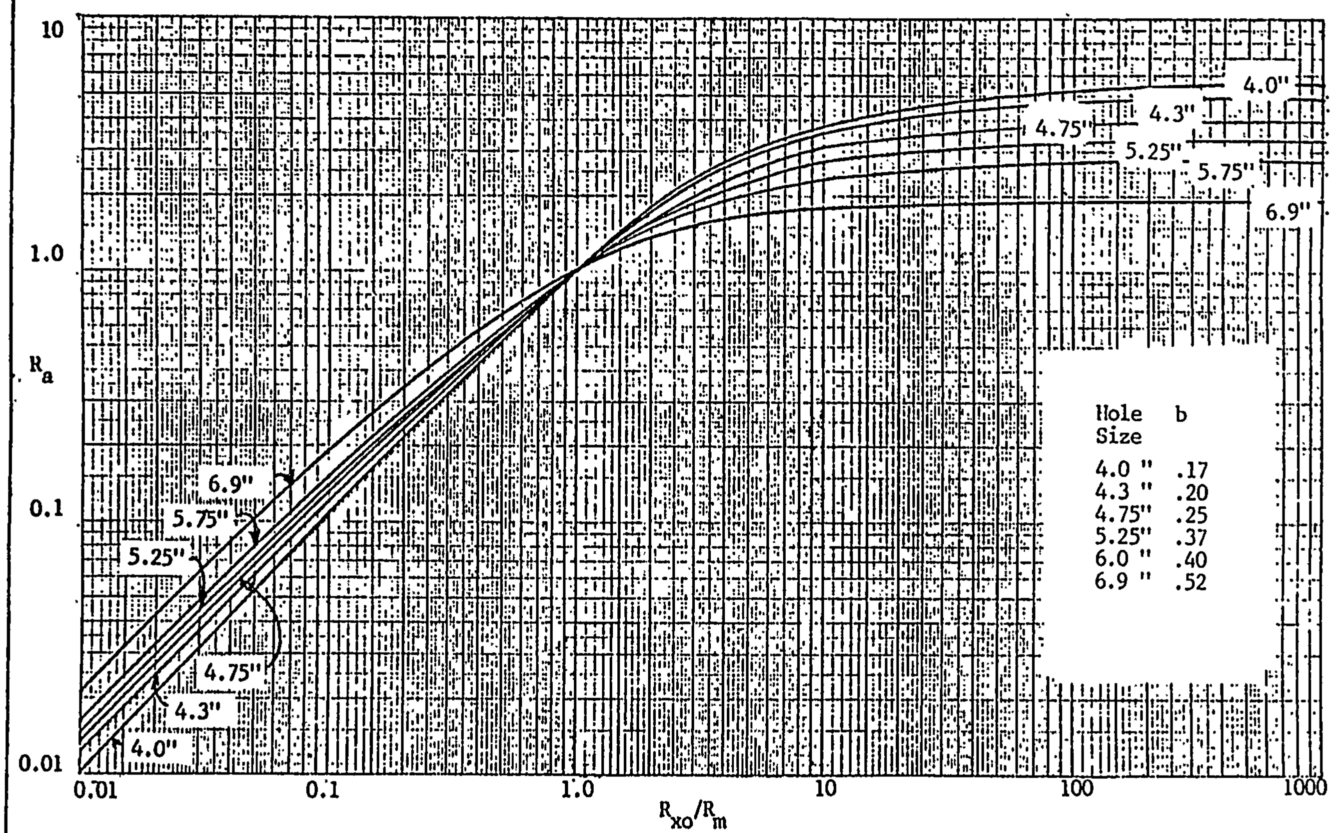
$$R = K r$$

In a porous medium the ratio of the measured resistivity to the resistivity of the water filling the medium is the Formation Resistivity Factor:

$$\frac{R_{measured}}{R_{fluid}} = F = \frac{R_{xo}}{R_{mf}} = \frac{R_o}{R_w} = \frac{a}{\phi^m}$$

Thus R_{xo} (the flushed zone resistivity) may be determined by measurement with a single point resistivity device, a short normal resistivity device, a shallow focussed log, a micro focussed log. R_o (the resistivity of a water-saturated, undisturbed zone) may be determined with an induction log, a deep focussed resistivity device. R_{mf} (the resistivity of the liquid portion or filtrate of the mud) may be determined from a surface mud sample. R_w (the native formation water resistivity) may be determined from the SP curve, and ϕ may be determined from a neutron, density, or acoustic device. m is the "cementation" constant and will vary from 1.5 for totally unconsolidated sand to 2.2 for porous carbonate. a is the "tortuosity" factor. Its value will depend upon m. Thus, any suitable combination may be used to solve for any one parameter of the above relations.

Resistivity is mostly a measure of the characteristics of the interstitial or pore volume and the fluids filling it. This is because the ratio of conductivities of the pore fluids (if they are water) to the rock material are usually extremely high ($>10^8$). The exceptions are (commonly) clay or shale for the solid material and liquid hydrocarbon or gas in the pore space.



Single Point Resistivity Departure and Hole Size Correction

Class: Electric Logging
Method: Single Point, Single Point Resistivity
Measures: Resistance/Resistivity: R_{xo}, Shallow
Characteristics: Unfocussed, shallow, used in low R_{xo}/R_m environments (<5). Usually used without calibration. Never used in Petroleum logging. Severely affected by borehole size and salinity. Needs a water-base mud.

Usually, the value of the resistance, r is measured. Most mineral logging contractors have not determined the conversion constant, K for their device. The relationship to determine resistivity, R is

$$R = K r$$

where K is

$$K = 4\pi L \frac{1}{\ln_e \frac{2L}{d}}$$

where L and d are the length and diameter respectively of the electrode. Use the accompaning departure curve set to determine R_{xo} from the single point resistivity.

Uses: Excellent correlation curve, good for high detail. Can be used to calculate R_{xo}. Has limited use as a lithology curve.

Peripheral Data Needed: R_m, R_{mf}, borehole diameter, electrode dimensions.

Advantages: Symmetrical, sensitive, detailed, simple.

Disadvantages: Not useable quantitatively above $R_{xo}/R_m = 5$ (where it has a poor resolution and a non linear response). It is very sensitive to hole diameter and mud salinity. Usually used without R_m and without peripheral data. Often confused by contractors by other than a true single point resistivity.

Suppliers: Most mineral logging contractors.

Trade names: None

Other names: Point electorde resistivity.

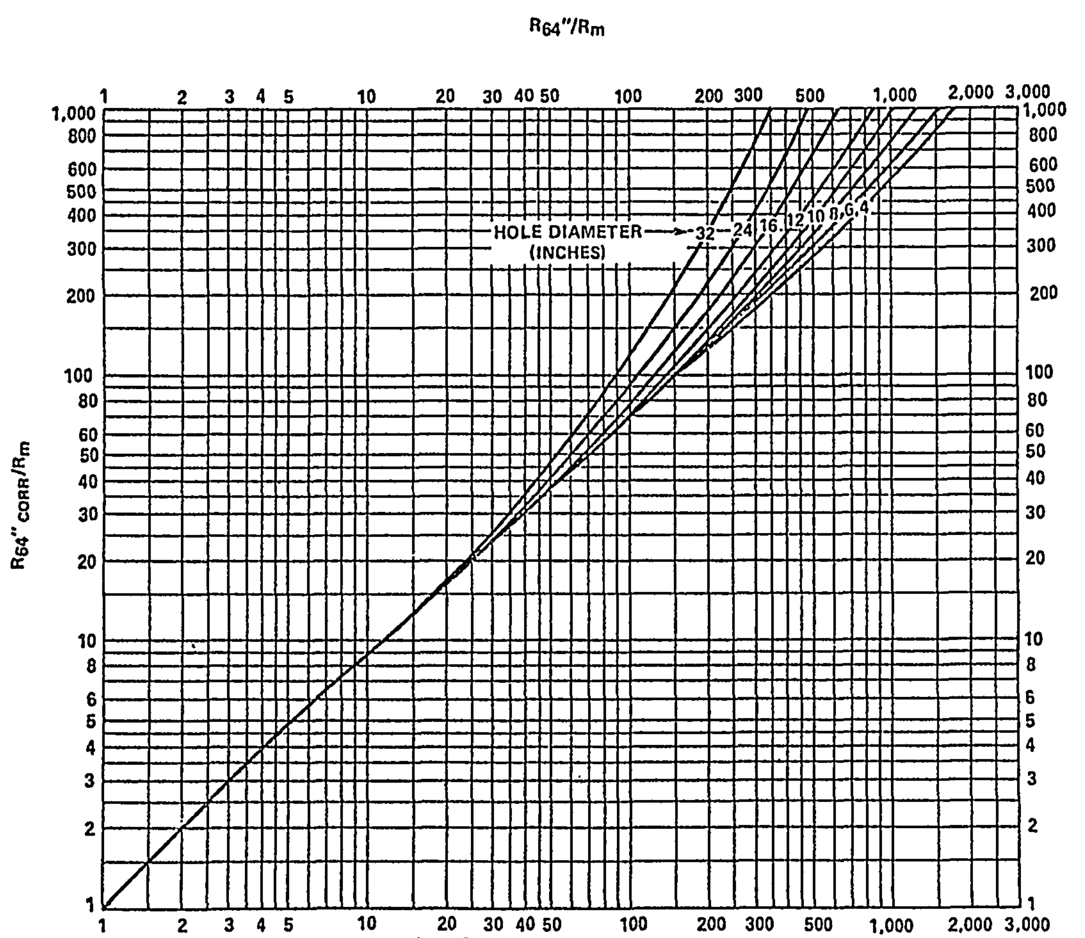


Figure 5.26 Borehole Correction for 64" Normal

Courtesy GEARHART OWENS INDUSTRIES, INC.

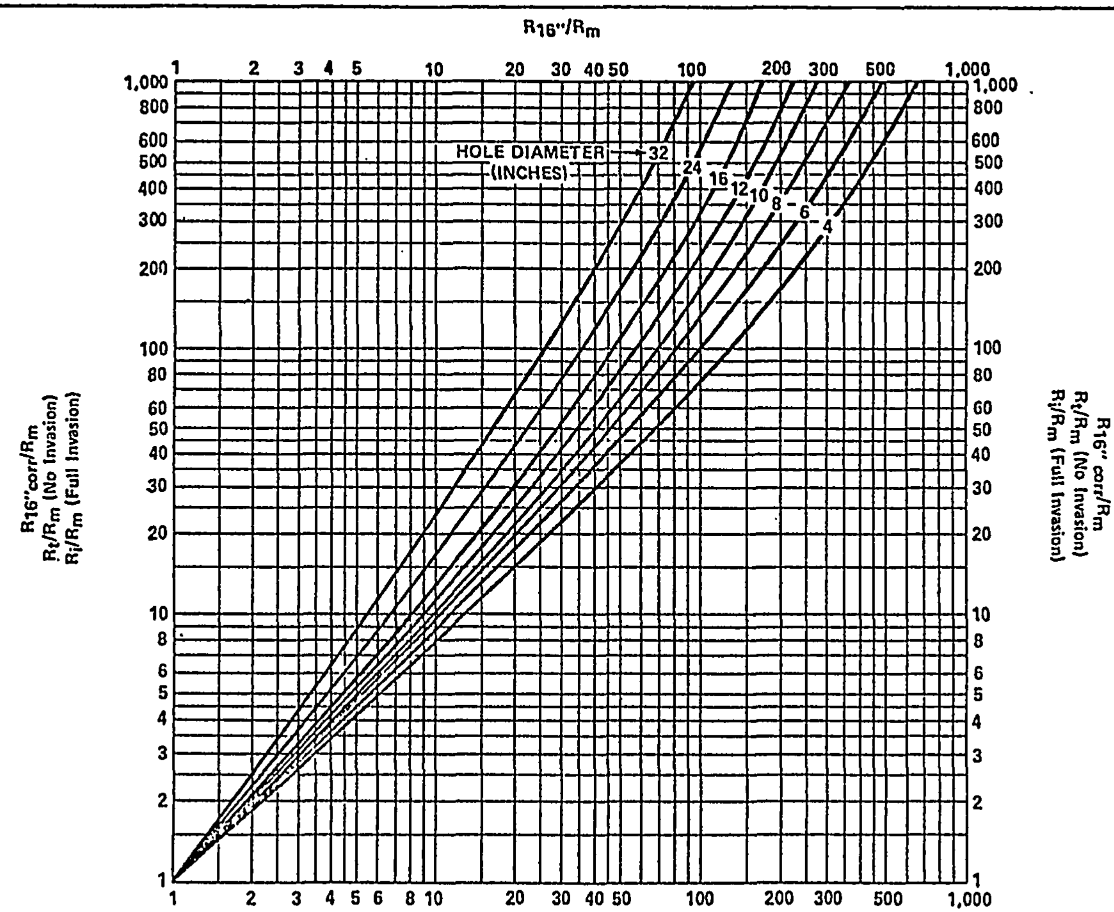


Figure 5.25 16" Normal Departure Curves from the Formation Evaluation Handbook, Courtesy GEARHART OWENS INDUSTRIES, INC.

Method: Normal, N.

Measures, Resistivity: R_{xo}, R invaded zone

Characteristics: Unfocussed, shallow to deep, used in low R_{xo}/R_m environments (<10). Strongly influenced by borehole and invaded zones. Sensitivity, depth of examination, and resolution depend upon spacing. Commonly used in petroleum logging.

Uses: Fair correlation curve, spacing (thus depth and resolution) can be easily changed for examining any particular zone. Used to calculate R_{xo} and determine sand/shale lithology. Correlation curve with IL, acoustic, GR, etc. Needs R_m, should have R_{mf}. Calculate R_{xo}.

Peripheral data needed: R_m, R_{mf} borehole diameter, array spacing.

Advantages: All of those of Single Point Flexible. Well documented common.

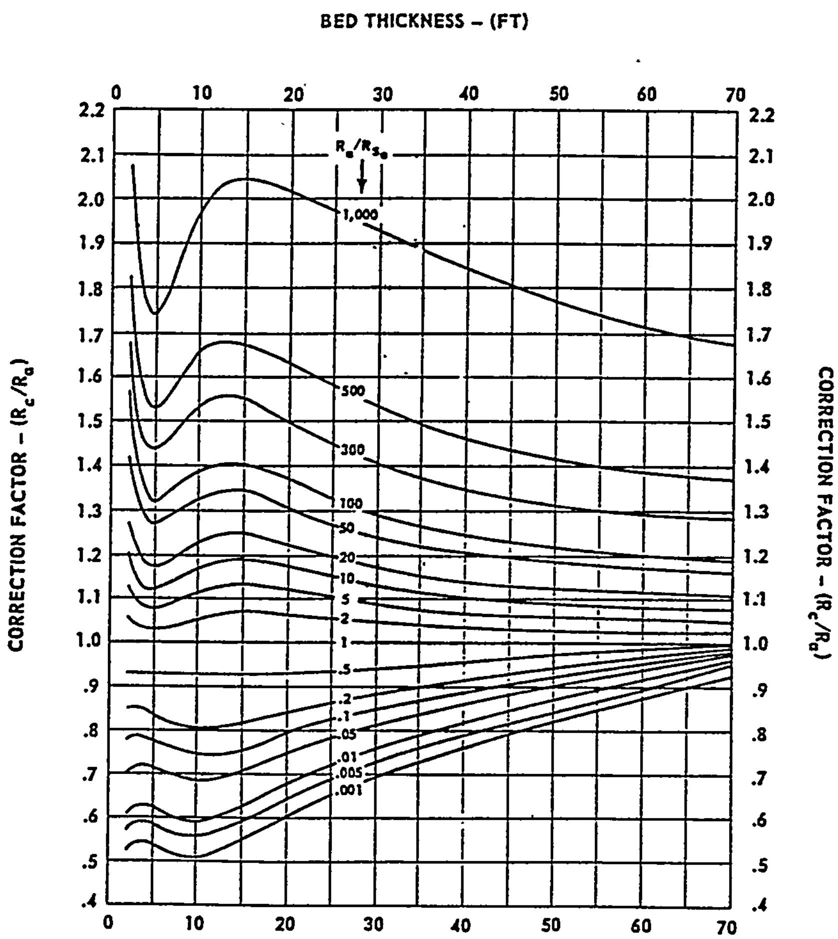
Disadvantages: Not useable at high R_{xo}/R_m ratios. Limit depends on spacing. Severe bed boundary and thin bed effects.

Suppliers: Most oil-field contractors. This may be a "limited availability" device with some. Some mineral logging contractors

Trade names: None

Other names: Short normal, long normal, electric log, pole-pole resistivity.

GUARD LOG CORRECTION FOR ADJACENT BED EFFECTS



Figure

Method: Focussed Resistivity, LL.

Measures: Resistivity: R_{xo}, R invaded, R_t R_o. Medium to deep.

Characteristics: Focussed response which may be shallow to deep. Geometry is controlled electronically. Used in high R/R_m environments (in some cases up to 5000). Minimizes borehole and invaded zone effects, if so designed. May limit the use of other systems in its vicinity. High detail, excellent in high R. Retains very high resolution with some types.

Uses: Excellent for determining R_{xo} or R_t.The exact use may be determined by design. Excellent in saline muds and/or high resistivity formations. Retains high resolution (which can be determined by design). Commonly used in both petroleum and mineral logging (mineral use, however usually does not include recording of R_m, or R_{mf} unless demanded). Curves and other data for the use of these devices must be obtained from the contracter supplying the service.

Peripheral data needed: Spacing, R_m, R_{mf}.

Advantages: Has all of the advantages of single point. Is almost insensitive to changes in borehole diameter. It has a minimum sensitivity to R_m. It may be designed for shallow or deep investigation. Can have exceptionally high resolution. Adaptable to sidewall methods. Excellent in high R_t/R_m environments.

Disadvantages: Complex circuit. Difficult to measure SP near 3 electrode device. Seven and eight electrode devices limited to oilfield tools and have poorer resolution than mineral tools.

Suppliers: BPB Instruments
Century Geophysical
Dresser Atlas
GO

Suppliers (continued)
Schlumberger Well Services
Welex

Trade names: Focussed Log

Other names: Guarded resistivity log.

Method: Induction Log, IL.

Measures: Conductivity, reciprocated to R_o, R_t (usually), deep.

Characteristics: Can be focussed to a specific zone. Almost independent of borehole fluid. Does not need conductive mud. Best in low R_t/R_m environment.

Uses: Originally designed for R_t in oil-filled holes. Used for R_t with minimum R_{xo} interference. Information for the use of these devices and the curve evaluation must be obtained from the contractor supplying the device.

Peripheral data needed: R_m, Borehole diameter, spacings, mud quality.

Advantages: Minimizes R_{xo} and borehole interference. As a first approximation, log value can be used as R_t. Can be used in air or oil-filled holes.

Disadvantages: Very complex, large size (3 3/4" diameter), available from oil field contractors only. Not reliable in high R_t/R_m zones and in deep invasion.

Suppliers: BPB Instruments
Dresser-Atlas
GO
Schlumberger Well Services
Welex

Trade names: Induction Log

Other names: None.

Method: MicroLog, ML

Measures: R_{xo}, mud cake presence, very shallow.

Characteristics: Very short spacings (1" & 2"), sidewall tool, independent of borehole diameter. Unfocussed, Highly detailed.

Uses: Detect permeability, measure R_{xo}, R_m, R_{mc}, R_{mf} spacings. Data for the use of these devices and curves can be found in any logging interpretation handbook. These are available from the contractors listed below.

Advantages: Minimizes borehole effects, measures R_{xo} in shallow invasion. High detail.

Disadvantages: Sensitive to hole wall conditions. Available only from oil-field contractors. Needs R_{mc} and R_{mf} values. Useable only where R_{xo}/R_{mc} is between 0.1 to 10.

Suppliers: Dresser Atlas
GO
Schlumberger Well Services
Welex

Trade names: Minilog
Micro Electric Log
Micro Log
Contact Log

Other names: Side wall resistivity

Method: Micro guard log, MLL

Measures: R_{xo}, shallow to medium

Characteristics: Very high resolution, sidewall tool, unaffected by borehole conditions, focussed device, depth of penetration easily controlled by design.

Uses: Determine R_{xo}

Peripheral data needed: R_m, R_{mf}, R_{mc} mud quality.

Advantages: Depth of penetration determined by design. Minimizes effect of R_{mc}. High detail, symmetrical.

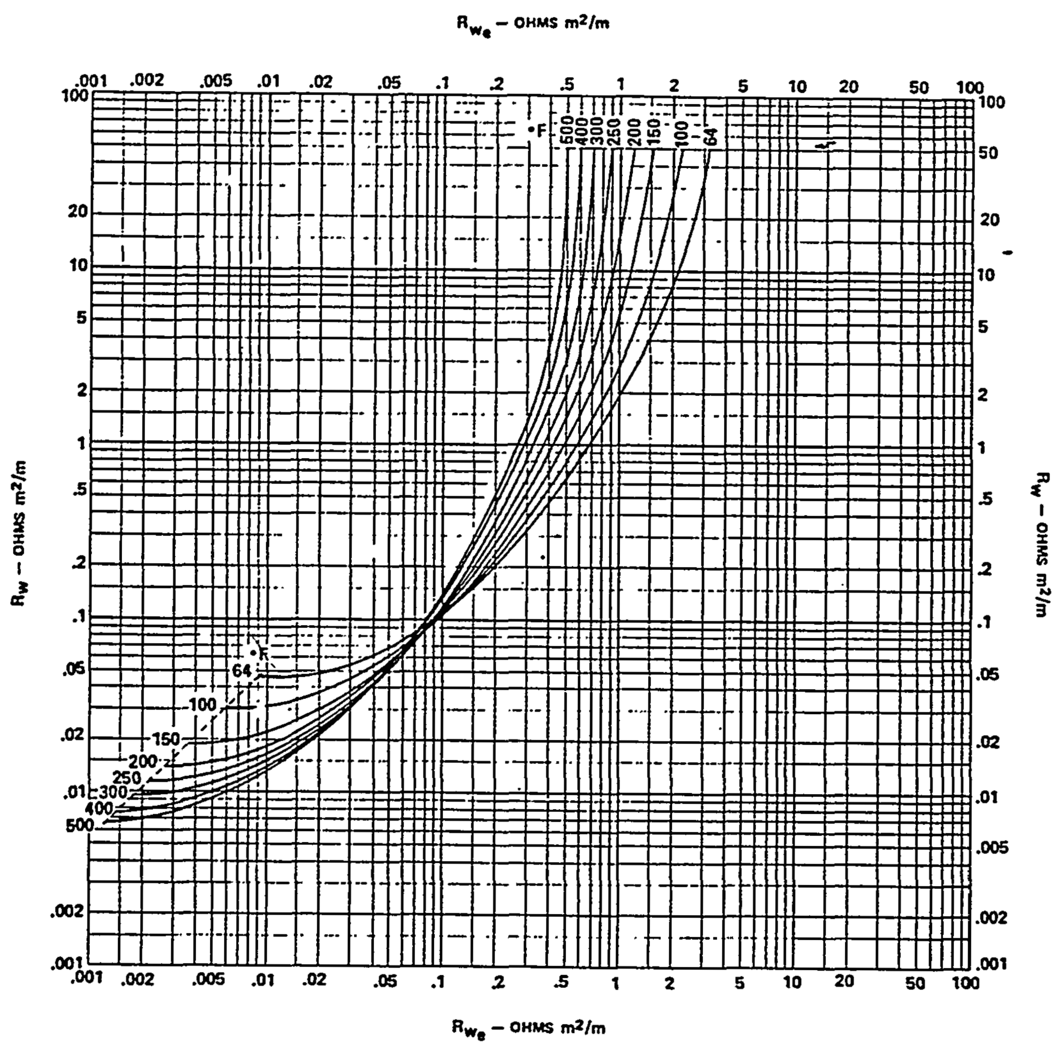
Disadvantages: Complex, sidewall, large diameter, available only from oil-field contractors.

Suppliers: Dresser Atlas
GO
Schlumberger Well Services
Welex

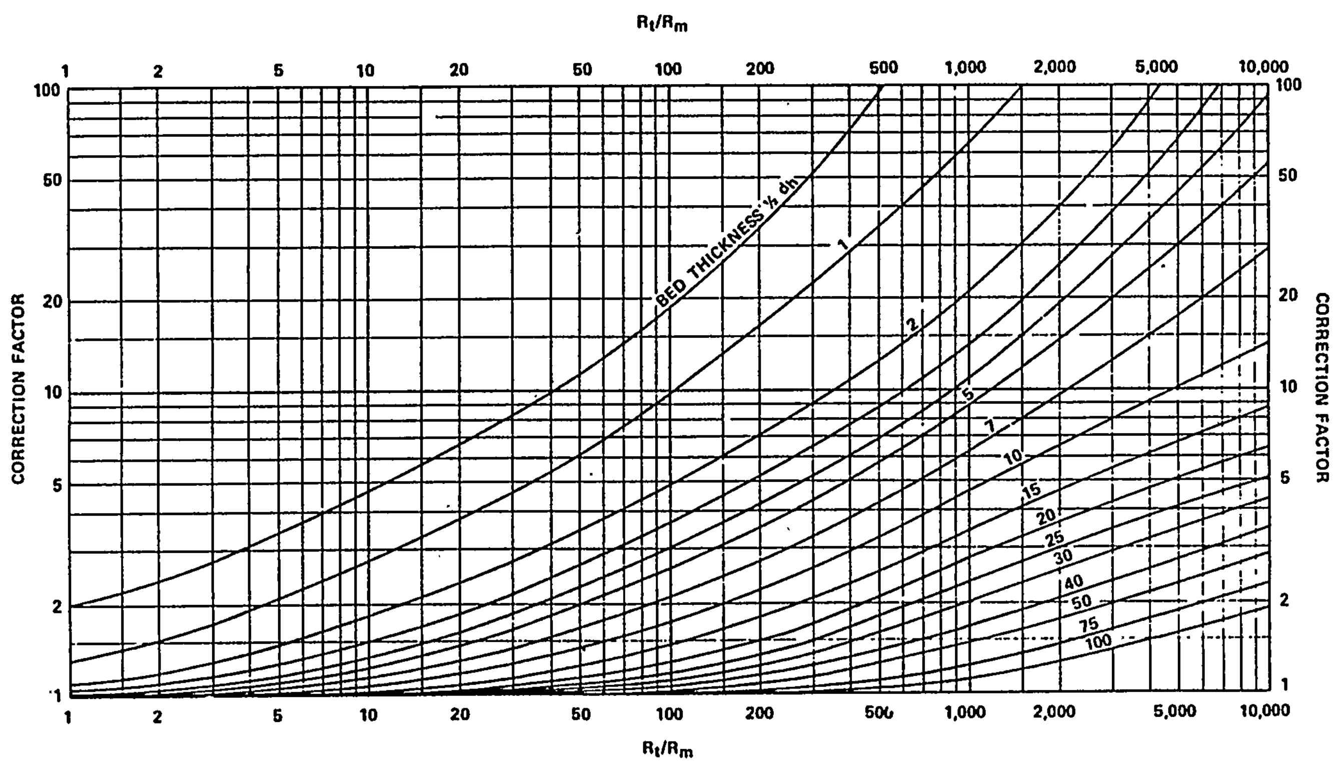
Trade names: Micro Laterolog
MicrolateroLog
Fo Rxo Log

Other names: Microfocussed log

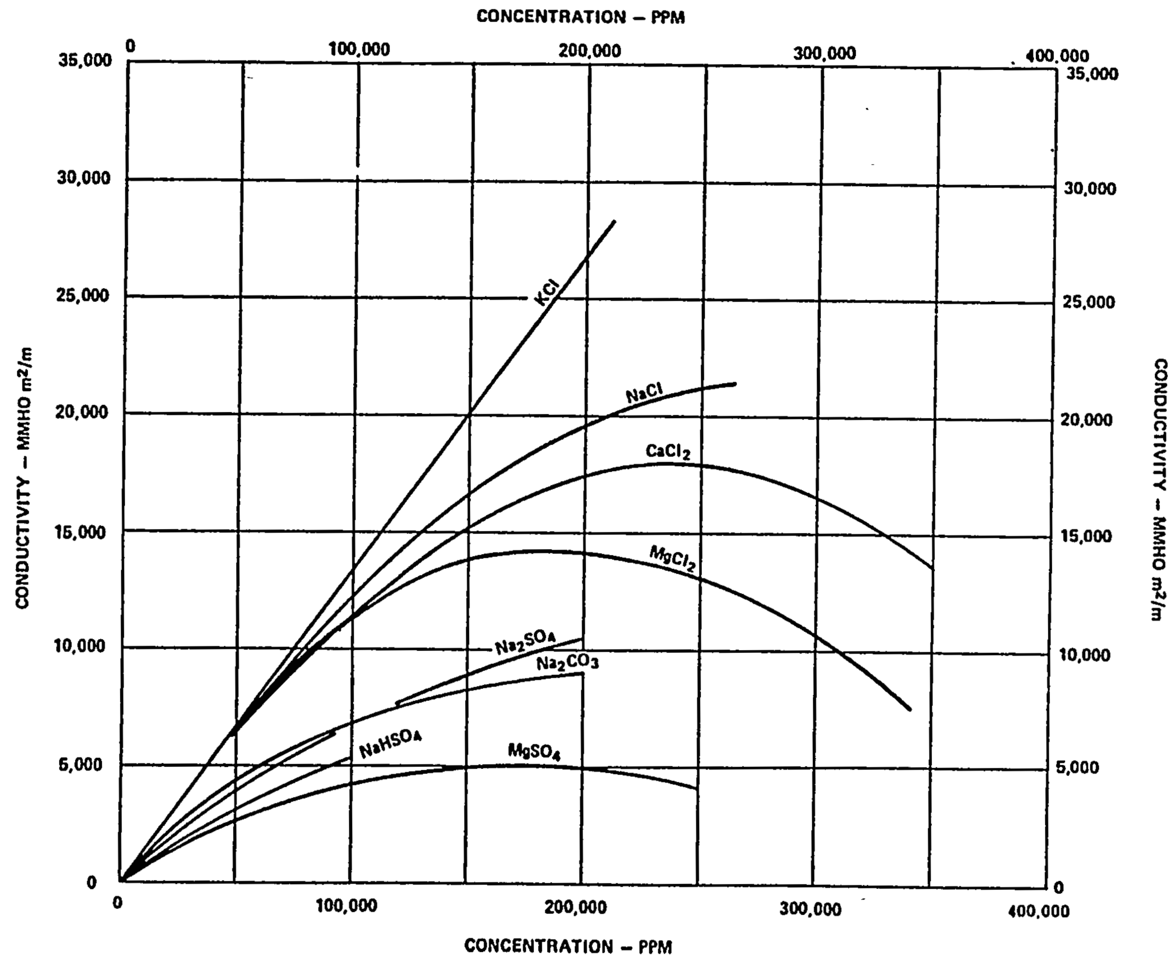
R_w VERSUS R_{we} AT VARIOUS TEMPERATURES



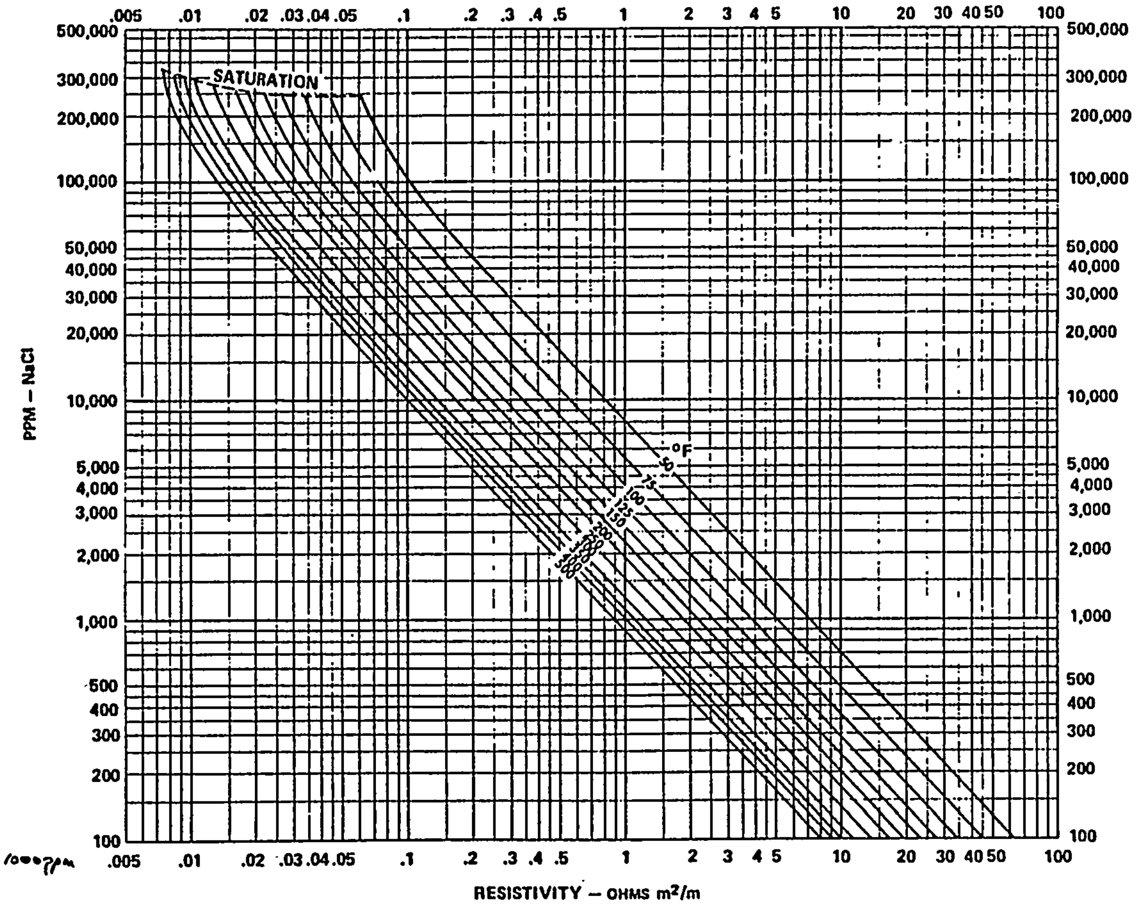
SP CORRECTION FOR BED THICKNESS



CONDUCTIVITY VERSUS CONCENTRATION FOR VARIOUS SALT SOLUTIONS AT 18°C

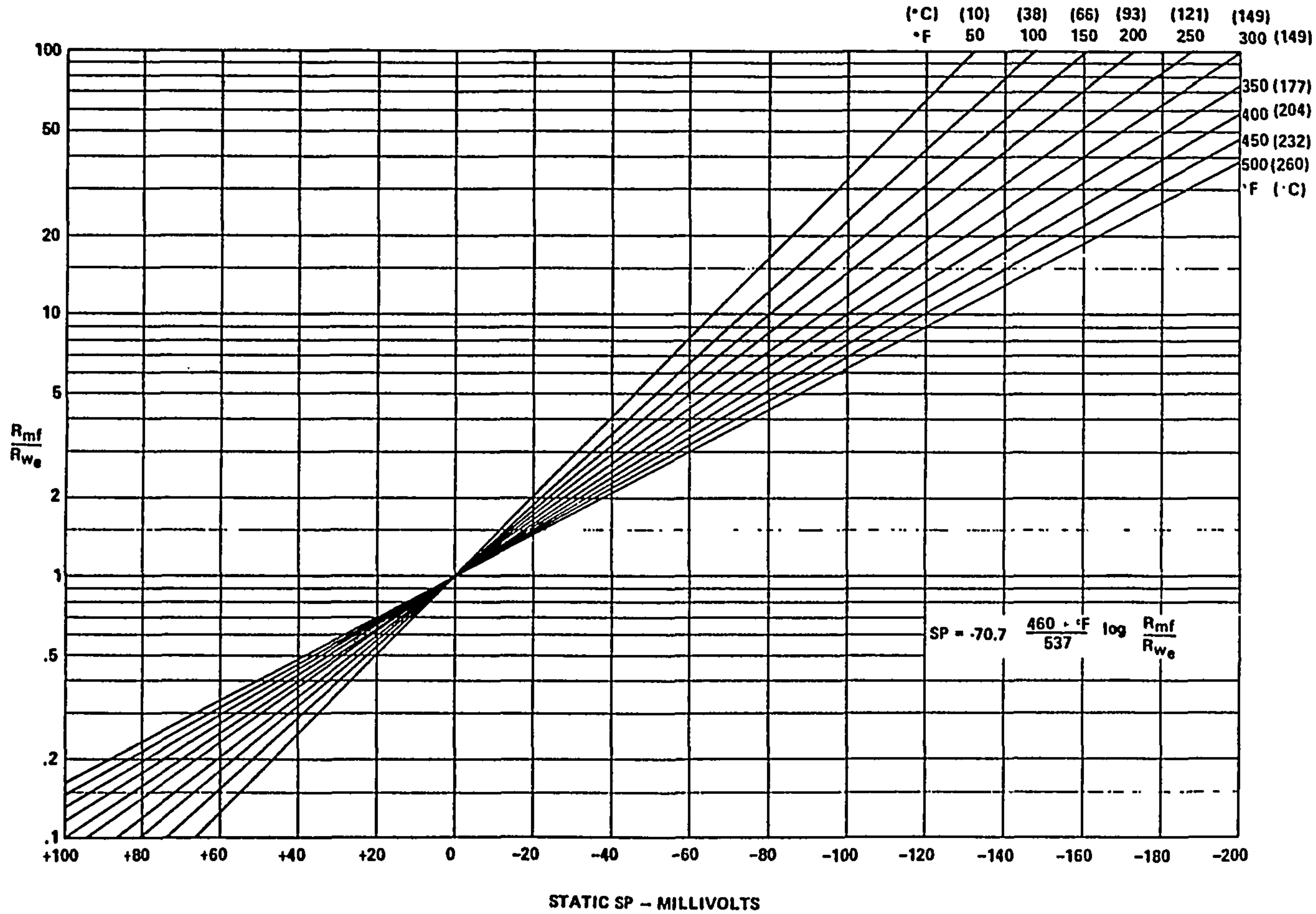


RESISTIVITY VERSUS TEMPERATURE – NaCl SOLUTIONS



mg/ml = 1000 ppm

EQUIVALENT FORMATION WATER RESISTIVITY FROM SSP



Spontaneous Potentials

The spontaneous potential (SP) measurement is used to locate sands and differentiate between sands and shales or clays.

The SP measurement is the potential drop in the borehole due to a flow of electrical current in the mud column. The flow of current is caused by potentials due to differences of ion concentrations across the R_{mf}/R_w interface (difussion potential) plus concentration difference potentials across the sand/shale interface and the shale/mud interface, usually caused by absorption (Nernst potential). The SP is the potential opposite the sand compared to that opposite the shale (or clay). Thus, the deflection of the SP curve opposite a sand or other permeable zone, with respect to the shale potential (distance from the shale line) is a measure of the ratio R_{mf}/R_w:

$$E_{DA} = K \ \mathrm{lof}_{10} \frac{R_{mf}}{R_{we}}$$

where R_{we} is the effective formation water resistivity, assuming only sodium chloride in dilute solution.

The SP deflection can be negative, zero or positive, depending upon the ratio of R_{mf}/R_{we}.

R_{we} must be corrected (empirically) to R_w. If the ion types are known, the correction can be made rigorously.

Fluid movement into or out of the borehole is also detected by the SP curve. Its value, E_H is

$$E_F = \frac{\xi R \zeta}{4 \pi \mu} \Delta P$$

where ξ is the dielectric constant of the fluid, ζ is the zeta potential, μ is the viscosity, and ΔP is the differential pressure. This is also known as the Helmholz potential or the streaming potential.

Class: Electric Logging

Method: Spontaneous Potential

Measures: Unbalanced ion distributions, R_w, E_{ox}, E_F.

Characteristics: Voltage measurements. Measures IR drop in the borehole due to flow of current caused by differences in formation and/or interface potentials. Deflection can be positive, zero, or negative opposite a permeable zone, depending upon ratio of R_{mf}/R_w. If R_{mf}/R_w is less than 1, then SP is positive. If they are the same, SP is zero. If R_{mf}/R_w is greater than 1, SP is negative. SP deflection will not be present if there is no permeability.

Uses: It is used to calculate the value of the formation water resistivity:

$$E_{DA} = K \log_{10} \frac{R_{mf}}{R_{we}}$$

where K is a conversion constant and is equal to -70.7 millivolts for a clean sand, R_{mf} is the filtrate resistivity and R_{we} is the effective formation water resistivity (assuming a dilute solution of NaCl). Data for the use of this curve can be obtained from any contractor.

Peripheral data needed: R_m, R_{mf}, ion type, temperature

Advantages: Simple curcuitry. Good sand/shale log. Unaffected by radioactivity.

Disadvantages: Complex signal. Not well understood. Easy to run incorrectly. Affected by presence of clay or shale. Cannot run in a cased hole. Affected by ion types (activity and mobility).

Suppliers: All

Trade names: None

Other names: Self potential, natural potential.

ULSEL, Ultra Long Spacing Electric Log

The ULSEL method may have some application in site evaluation. It is a method for making electrical resistivity measurements to a great depth (horizontally) from the borehole. Detection of salt domes at distances of 1800 to 2500 feet from the borehole have been made.

The ULSEL method uses long spacing (up to 5000') normal resistivity measurements. Typical spacings are 75, 150, 600, 1000 feet for the current to measure electrode. The theoretical response of the systems, in the absence of any lateral anisotropy is calculated and compared with the actual response. A layered model with up to 200 layers is used.

The ULSEL method requires a relatively deep environment and borehole. It may, however, have a special use.

Reference: ULSEL
Runge, R. J. "Ultra Long Spacing Electric Log (ULSeL)" 10th Annual SPWLA Symposium Proceedings, paper H, 1969.

Radioactivity Logging.

All radioactivity logging systems are effective lithology indicators and can be used for stratigraphic determinations. When used quantitatively they can be used to identify lithologic features accurately, such as natural radioactivity, characteristic gamma emission energy, specific gravity or density, porosity, neutron capture cross-section, activation emission energy, water content, chemical composition, and many others. Further, to a great extent they can be used in open or cased holes, liquid or gas filled.

The fractional volume of shale, V_{sh} in a shaly sand or a sandy shale or clay is

$$V_{sh} = \frac{\gamma - \gamma_s}{\gamma_{sh} - \gamma_s}$$

where γ is the gross count gamma ray reading in the zone of interest. This determination is more accurate if the thorium curve (^{208}Tl) is used.

The mineral grade, G affecting any curve is

$$G\,T = K\,A\,F$$

the area under the curve, A is

$$A = w \sum_{i=1}^{n} N_i$$

and the correction factor, F is

$$F = F_c\,F_w \ldots$$

There are other, more sophisticated methods available. You are referred to the list of reference material under gamma ray techniques and deconvolution (inverse filtering) techniques.

These grade determination methods will work with any of the radioactivity curves.

The density system is not very effective through casing because of its sensitivity to material near it. However, it can be used in that fashion.

The density systems are excellent for porosity and other fractional volume determinations. The bulk density, ρ_b is

$$\rho_b = V_a\rho_a + V_c\rho_c + V_d\rho_d + \cdots$$

where V is the fractional volume of a component, ρ is the density, and a, c, d, etc are components.

Neutron porosity systems are used for porosity determinations. The response over the normal porosity range is

$$N_n = c\, e^{-\phi_a f}$$

where c and f are constants determined by the borehole diameter, salinity, source strength, tool type, and formation rock type and ϕ_a is the apparent porosity or hydrogen index.

The value of ϕ_a will include the clay content of the formation, becuase of the high water and chlorine content of the clay. Therefore, a correction must be made:

$$\phi = \phi_a - V_{sh}\, \phi_{sk}$$

where ϕ_{sk} is the apparent neutron derived porosity in a shale.

The neutron tools can usually be used in the presence of high gamma radiation (except for the gamma detection, $n-\gamma$ devices). The $n-\gamma$ devices and the density ($\gamma-\gamma$) devices may be used in the presence of high gamma radiation if precautions are taken. There are several possibilities:

1. The gamma radiation can be determined with a separate gamma ray detector. Then a conversion factor can be applied and the result subtracted from the density or neutron counting rate:

$$N = N_a - K_1\, \gamma$$

2. The density or neutron tool may be run twice, first without a source and then with one:

$$N = N_2 - N_1$$

3. A dual spacing tool may be used, assuming that the same gamma flux is affecting each detector:

$$N = N_1 - K_2N_2$$

N, in this case, is still a function of porosity or density. Any tool using a source must be normalized to compensate for source strength differences and tool sensitivity differences and changes:

$$N = \frac{C_s}{C_d} N_a$$

where C_s is the counting rate under standard conditions (i.e. in a model or a tank of water) at the time of primary calibration, C_d is the counting rate in the same environment at the time of logging and N_a is the uncorrected counting rate at the time of logging.

All of the radioactive tools are excellent ones for crossplotting purposes. This will be covered separately.

Class: Radioactivity Logging

Method: Gross Count Gamma Ray

Measures: Total gamma ray emmission

Characteristics: An excellent open or cased hole log. It is easy to combine with other types of instrumentation. Sensitive to a wide range of natural gamma ray energies. The petroleum type systems are sensitive but not calibrated. The mineral type are less sensitive but are usually calibrated.

Uses: Used as a correlation curve for depth control and identification of lithologic features. It is commonly used to evaluate the amount of shale or clay in sedimentary sequences. It is an excellent curve to use for some types of lithology identification. In a calibrated form, it is used to calculate equivalent uranium grade. In construction,it is used to identify clays and shales (opposed to sands and limestones). When it is properly used, it often can identify specific shale members of formations.

Periperal data needed: Detector size and type, date of calibration, type of circuitry used (digital or analog), standard or check reading, and mineral or petroleum type log.

Advantages: Circuitry well developed and available in many forms. The curves and measurements are well understood. The service is readily available. It may be used in open or cased holes, liquid or gas filled.

Disadvantages: The mineral and petroleum types of instruments are not directly interchangeable. The instrument response depends largely upon the detector characteristics. There are fundamental differences betweem the digital and analog systems which are largely ignored. There are many poor operators in the contracting business.

Suppliers: All logging contractors

Trade names: None

Other names: None

Class: Radioactivity

Method: Gamma gamma Density.

Measures: Formation bulk density;

Characteristics: Calibrated measurements are quite accurate. There are many forms of the tool available. Calibration techniques are complex, expensive.

Uses: Used for lithology identification in sediments and hard rock. It is a fine measurement for advanced techniques, such as cross-plotting and simultaneous equation methods. It is a specific identifier of coal. Porosity-density relation is $\rho_b = \phi\rho_f + (1 - \phi)\rho_m$.

Peripheral data needed: Type of tool used, type and strength of source used, normalization data(such as standard counting rate and a check counting rate). Must have a caliper.

Advantages: Probably capable of better accuracy than any other logging method. Available widely.

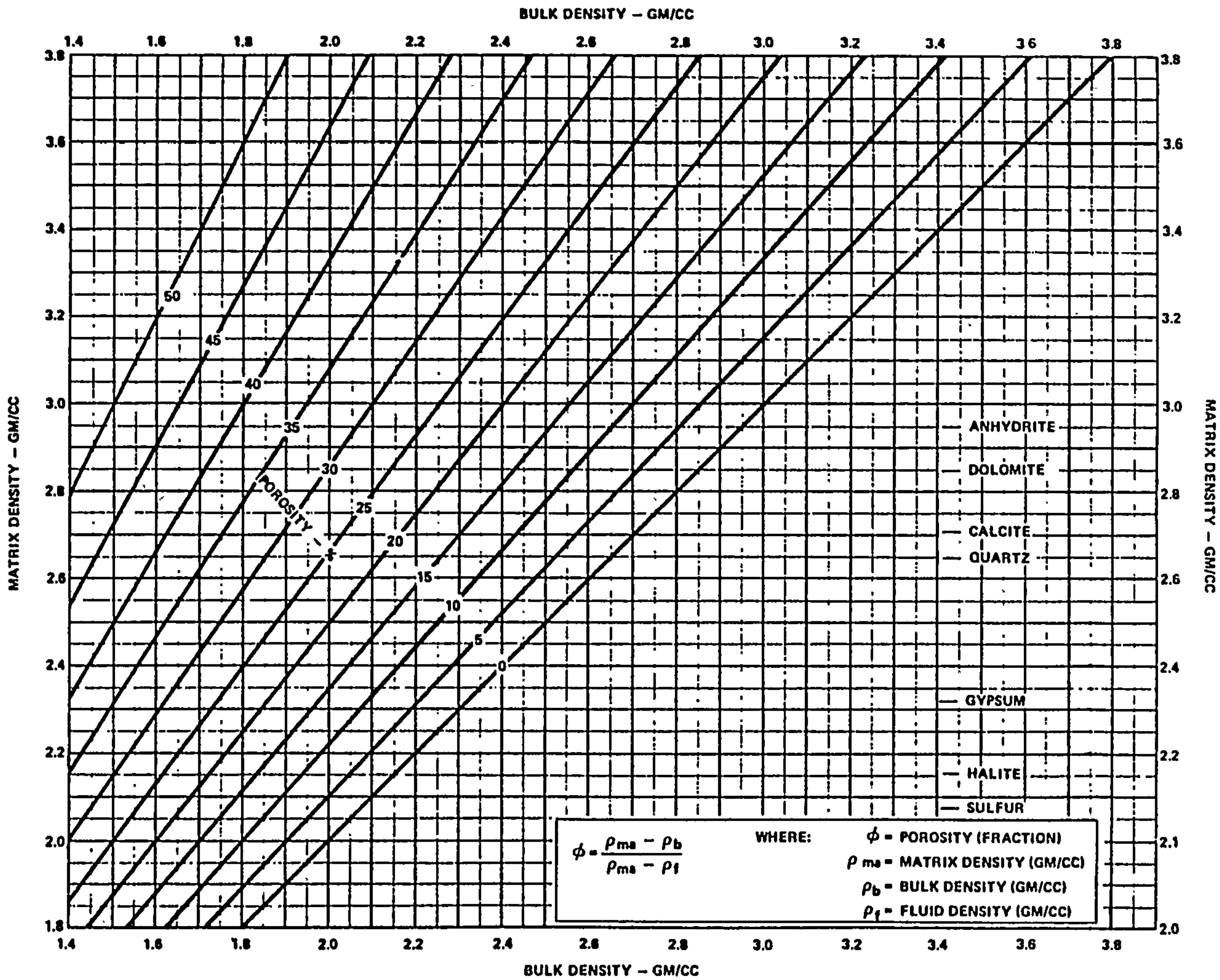
Disadvantages: Complex. Requires a radioactive (gamma) source. Several forms available. Difficult to use in high radiation environments without special techniques. Often it is not very well calibrated. Normalizing techniques are often neglected resulting in large errors.

Forms available: Omnidirectional is used for qualitative evaluation of coal depth and thickness. Sidewall, single-spacing tool is used for mineral location, evaluation, density, porosity and lithology as a short spacing tool (6 to 12 inches). Subject to standoff and rugosity problems. Sensitive to natural gamma radiation. Dual spacing sidewall tool: Compensates for borehole wall problems of the single spacing tool. Can be used in high radiation environments with special techniques. Litho-Density Tool: Special adaptation of the compensated system to measure high energies for density and lower energies for lithology.

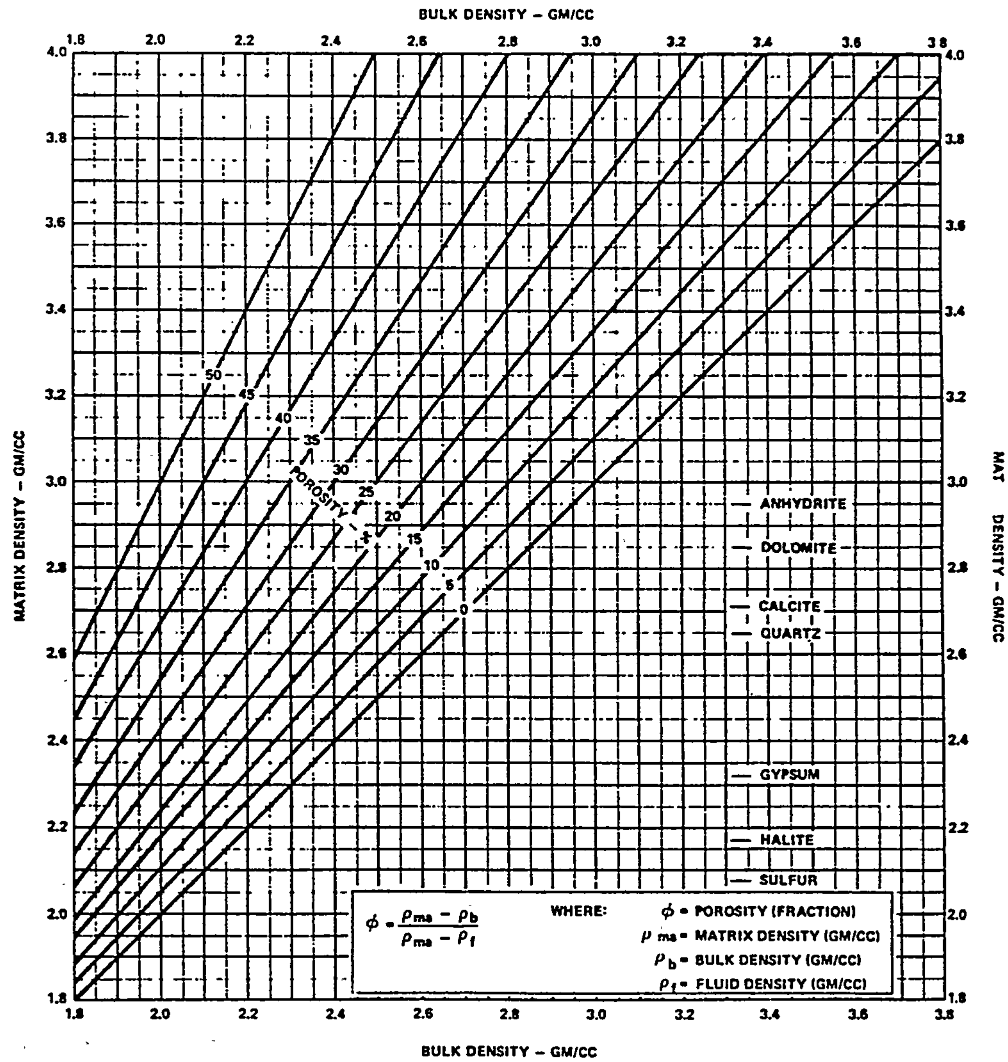
Suppliers: All major logging contractors

Trade names: Densilog

Other names: None


BULK DENSITY – GM/CC
MATRIX DENSITY – GM/CC
POROSITY – %
0
5
10
15
20
25
30
35
40
45
50
ANHYDRITE
DOLOMITE
CALCITE
QUARTZ
GYPSUM
HALITE
SULFUR
$\phi = \frac{\rho_{ma} - \rho_b}{\rho_{ma} - \rho_f}$
WHERE:
ϕ = POROSITY (FRACTION)
ρ_{ma} = MATRIX DENSITY (GM/CC)
ρ_b = BULK DENSITY (GM/CC)
ρ_f = FLUID DENSITY (GM/CC)
(CHART "b")

CALCULATION OF POROSITY FROM BULK DENSITY (WATER FILLED HOLES, $\rho_f = 1.0$)



(CHART "o")

Class: Radioactivity

Method: Neutron Porosity

Measures: Porosity, hydrogen content

Characteristics: Slightly sensitive to neutron capture cross-section. Sensitive to hydrogen content. Several forms available.

Uses: This tool is used primarily to measure the hydrogen content (porosity) of sedimentary formations. It is an excellent one to use with other tools for advanced techniques, such as cross-plotting. In hard rock environments it can be used as a capture cross-section (Σ) tool. Excellent cased hole and air-filled hole tool.

Peripheral data needed: Hole diameter, fluid type, type of detection used. Response curves must be obtained from the contractor supplying the service.

Advantages: Can be used in place of resistivity measurements. Will operate well in a cased or open hole and in any hole fluid.

Disadvantages: Complex. Requires a radioactive (neutron) source. Normalizing and correction techniques often neglected with resulting large errors. Calibration is complex. Operation and response often not well understood. Mineral tools are often not calibrated for empty or saline holes.

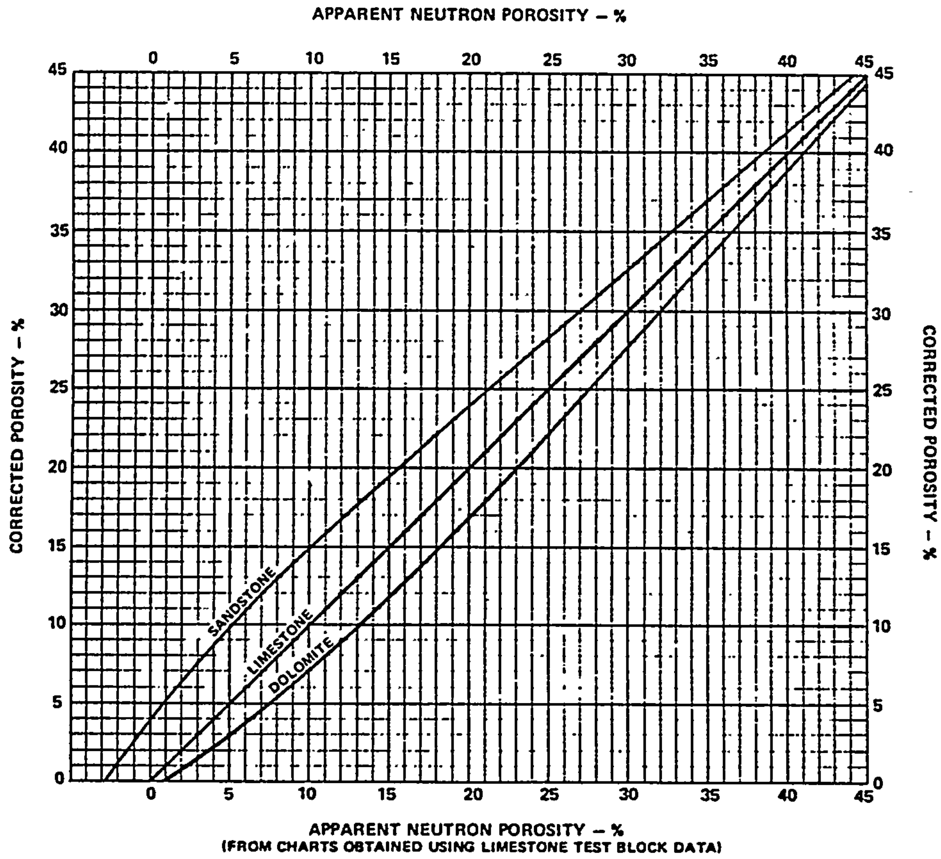
Forms available: Single spacing, omnidirectional tool good for porosity determinations. Hole size, hole fluid, salinity and shale corrections must be made. Used for lithology determinations, in combination. Dual spacing tool is independent of hole size. Sidewall tool can use lower counting rate techniques. Detection may be of epithermal neutrons (good but low counting rates), thermal (higher counting rates but chemistry sensitive), thermal/eqithermal(simple and a good compromise), gamma (chemistry and natural gamma sensitive).

Suppliers: All logging contractors

Trade names: Compensated neutron
Linear porosity neutron
Epithermal Sidewall neutron
Sidewall Neutron Porosity
CNL
SNP

Other names: None

ESTIMATED NEUTRON CORRECTION
FOR FORMATION CHEMISTRY EFFECTS
(NEUTRON–NEUTRON LOGGING,
WATER FILLED HOLES)



Class: Radioactive

Merhod: Neutron activation

Measures: Element content

Characteristics: Limited supply. May use an isotopic or electronic source of neutrons. Expensive and complex but very sensitive to some elements.

Uses: Detecting trace elements. Variations can detect uranium or thorium directly. Many forms measure ratios: C/O, Ca/Si. Sulfur content measured in coals and oils. Interpretation data must be obtained from the contractor supplying the serive.

Peripheral data needed: Standard logs.

Advantages: Measures many things directly and accurately.

Disadvantages: Needs a strong source. Expensive and complex. In short supply. Many techniques are experimental and not well documented.

Suppliers: Century Geophysical (uranium only)
Dresser Atlas
PGT
Schlumberger Well Services (Hydrocarbon only)

Trade names: DFN
Carbon/Oxygen Ratio Log
Calcium/Silicon Ratio Log
Dual Detector Lifetime Log
Lifetime Log
Thermal Decay Time Log
TDT

Other names: None

Class: Radioactive

Method: Gamma Ray Spectroscopy

Measures: Radioactive element emission of gamma rays or reaction resulting in a capture gamma ray.

Characteristics: Limited supply and complex. Two types are generally available; a sodium-iodide detector, 3 channel system, and a multi channel germanium detector system.

Uses: Used to determine the element emitting radioactivity and amount. Used to correct for radioactive contamination (i.e. thorium in uranium deposits), allows more accurate evaluation of low level radiation, can identify specific types of clays, valuable for some depositional history problems.

Peripheral data needed: Standard Logs.

Advantages: Performs a measurement which is unique. Gamma transport is relatively simple.

Disadvantages: Expensive and complex in some forms. Many techniques still experimental.

Suppliers: Century Geophysical Corp.
Dresser Atlas
PGT
Schlumberger Well Services

Trade names: KUT Log
SpectraLog
Natural Gamma Ray Spectroscopy

Other names: None.

Class: Mechanical Methods

Method: Borehole Deviation

Measures: Deviation of borehole from vertical.

Characteristics: Usually measures the direction of the earth's magnetic field and gravitational gield. Inertial devices are available to measure with reference to a fixed position in space. These devices are sensitive to the frequency at which measurements are made. If measurements are spaced too far apart, severe inaccuracies may enter. Several data reduction devices are available.

Uses: These devices are used primarily to detect deviations and direction of deviation from vertical. The purposes are location of the bottom of the hole, location of a mineral body, true depth, true thickness, contractual obligations, legal obligations. The contractor will reduce the data upon completion of the measurement.

Advantages: The continuous readout instruments are exceptionally fine instruments and quite accurate. Small diameters. Inertial devices are independent of magnetic fields.

Disadvantages: Magnetic types cannot be used in steel pipe or near magnetic ore bodies. Inertial types are expensive and not as accurate as magnetic types. Photographic types are slow and subject to errors.

Suppliers: All logging contractors

Trade names: Deviometer
Drift Log

Ptjer names: Directional log
Drift log
Deviation log

Class: Mechanical Methods

Method: Caliper

Measures: Hole wall condition, borehole diameter.

Characteristics: Usually have one or more arms which contact the wall of the hole. Circuitry and mechanisms are often simple.

Uses: A primitive, single arm caliper is indispensible for density logging to locate rough, caved, or swelled hole zones and mudcake. A three-armed caliper is used to detect caved zones and measure hole diameter for cementing purposes and for correction purposes for gamma ray, neutron, and resistivity logs. A four-armed caliper will measure the shape as well as diameter of the borehole. Multiple armed calipers (6 or 12 independent arms) are used for large holes, such as vent-shafts.

Suppliers: All logging contractors

Trade names: None

Other names: None

Class: Mechanical Methods

Method: Sample taker

Measures: Takes a small sample of the formation or fluid of the formation.

Characteristics: There are versions of this method for both wireline and drillpipe. All take a small sample (1 cc to 1000 cc) of either the formation at the wall of the borehole or the fluid within the formation.

Uses: This class of tool in primarily used to obtain samples for double checking or where cores have not been taken.

Advantages: Usually saves drilling another hole.

Disadvantages: Small sample size, usually disturbed by borehole fluids.

Forms available: Wireline sample takers are usually the percussive type using hollow, retrievable bullets. Drillpipe samplers are usually the gouge type. Fluid samplers fire a bullet, trailing a hose, into the formation.

Suppliers: All oil-field contractors
Goodwell Logging

Trade names: None

Other names: None

Acoustic Logging Methods

The acoustic logging methods are excellent for determining mechanical properties of formation material. Studies have indicated that wireline, borehole acoustic measurements to determine the elastic properties of sedimentary formations may be more reliable than studies on cores. This is because of the possibility of mechanical damage to the cores during removal and the possibility of lost sections.

The moduli which can be determined with the acoustic and density tools are:

1. Poisson's ratio, the ratio of transverse contraction to elongation of a sample under tension or compression, P is

$$P = \frac{\frac{1}{2}\left(\frac{V_P}{V_s}\right)^2 - 1}{\left(\frac{V_P}{V_s}\right)^2 - 1}$$

where V_P and V_s are the pressure wave and shear wave velocity respectively.

2. Youngs Modulus, E, the modulus of compression,

$$F/A = \frac{(E\ e)}{L_o}$$

where F is the applied force, A the cross sectional area, e the elongation, and L_o the original length.

$$E = 2\mu(1 + P)$$

3. The shear modulus, μ is the modulus of change of shape with transverse force:

$$(F/A) = \mu\,\Theta$$

where Θ is the shear angle.

4. The bulk modulus, B is the modulus of change of volume with external force:

$$\Delta P = B \frac{\Delta \text{ volume}}{\text{volume}_o}$$

where P is the change of external force.

$$B = \rho V_P^2 \quad - 4/3\ V_s^2$$

The pressure wave travel time, ΔT can be used to determine porosity through Wyllie's Time Averaging equation:

$$\Delta T = \Delta T_f \phi + \Delta T_m (1 - \phi)$$

Newer studies (Raymer, et al) have suggested refinements to Wyllie's relation:

1. In the range) to 37%

$$V_1 = (1 - \phi)^2 \quad V_m + \phi V_f$$

$$\Delta T_1 = \frac{10^6}{V_1}$$

where Δ T and V are the measured travel time and velocity respectively of the pressure wave, ρ is the density, m and f are the rock matrix and fluid respectively, and ϕ is the fractional porosity.

2. In the 37% to 47% porosity range

$$\Delta T = \frac{0.47 - \phi}{0,1} \Delta T_1 + \frac{\phi - 0.37}{0.1} \Delta T_2$$

3. In the 46% to 100% range:

$$\Delta T_2 = \left(\frac{\rho \phi \Delta T_f}{\rho_f} + \frac{(1 - \phi)\ \Delta \cdot T_m}{\rho_m} \right)^{\frac{1}{2}}$$

In porosities greater than 50% the material often acts lide a liquid with solid particles in suspension (i.e. a clay). In this case

$$\frac{1}{\rho V^2} = \frac{\phi}{\rho_f V_f^2} + \frac{1 - \phi}{\rho_m V_m^2}$$

and

$$B = \phi B_f + (1 - \phi) B_m$$

The acoustic measurements are excellent for lithology identification and for cross plotting.

Class: Mechanical Methods

Method: Acoustic Measurements

Measures: Porosity, Elastic parameters

Characteristics: Uses high frequency mechanical pulses. Needs a liquid-filled borehole.

Uses: Used as a porosity measuring tool. Excellent for cross-plotting to determine lithology. Used with density to reliably calculate elastic moduli and Poisson's ratio of formations. Extensive use in construction industry. Used to detect secondary porosity. Porosity, ϕ may be determined from the travel time, ΔT

$$T = T_f\phi + (1 - \phi)\ \Delta T_m$$

Peripheral data needed: Mud type, associated curve (i.e. neutron, density, resistivity).

Advantages: Adequate sample size and minimal sample damage compared to cores. Accurate and reliable. Several formats available.

Disadvantages: Needs a liquid-filled borehole. Information is sometimes difficult to extract, especially with some formats. Most velocity and travel time data have been developed for high overburden pressures (deep holes). Availability limited to oilwell contractors, at this time.

Forms available: Cement bond tool is a simple, one transmitter, one receiver tool which makes no attempt at compensation. It is useful for qualitative purposes and for evaluating cemented casing. The two receiver tool compensates for the travel trhough the borehole. It is an excellent porosity tool. Can be used for more sophisticated purposes with appropriate readout equipment. Borehole compensated are independent of position within the borehole. Sidewall tools eliminate borehole effects entirely.

Suppliers: All oil-field contractors
Century Geophysical Corp.

Trade names: Sonic Log
Acoustilog
BHC Sonic

Other names: Acoustic signature
Amplitude Logging
BHC Acoustilog
Variable Density Log
Acoustic velocity log
Acoustic travel time log
Cement Bond log

Crossplotting and Simultaneous Equation Techniques

Of the more useful techniques for reducing the data from the borehole logs, there are two which merit special mention. These are the crossplotting techniques and the simultaneous equation techniques. In reality one is the graphical form of the other. While the general form can be described and followed, the specific information must be obtained from the particular situation being examined and the final form of the solution tailored to the situation.

If two or more measurements are made of the same formation members in the same borehole, the measurements may be compared point-by-point to enhance the observation of the parameter being examined. In the crossplotting method this is done graphically.

To proceed with the crossplotting technique, one chooses two (for example) curves which show variations, to different degrees, with the parameter to be examined. If for example, we wished to examine shale content, the gamma ray measurement and the resistivity measurement would be two good choices. This is because both systems respond to the clay or shale content of a sand-shale sequence. The gamma ray system (especially if the thallium -208 or thorium response is used) responds linearly to the clay content. It may be plotted from the X axis. The resistivity curve responds exponentially to the clay (or shale) content. It may be plotted from the Y axis. The two measurements are then set up on a sheet of graph paper. Usually this is a 10 x 10 divisions per inch, linear grid paper. Values at each borehole depth (after any needed depth corrections are made) are selected from the curves and plotted. Groupings will be noted. These will be groupings of sand and shale values.

A grid may be set up on the above crossplot to identify the pure shale values of gamma radiation and resistivity for the zone. Similiarly, the points of pure sand and pure water may be identified. The values of two phase mixtures (i.e. sand and water or sand and shale) may be calculated or estimated and scaled off on a line connecting the two appropriate pure values. Mixture values from the logs may then be evaluated. The accompanying illustrations show commonly used examples of these.

A crossplot need not be restricted to two measurements. The Litho-porosity (or M-N) crossplot uses the density, neutron-derived porosity, and P-wave acoustic travel time

$$M = \frac{\Delta T_f - \Delta T}{\rho_b - \rho_f} \times 0.01$$

$$N = \frac{\phi Nf - \phi N}{\rho_b - \rho_f}$$

where ΔT is the measured travel time in the zone of interest, ΔT_f is the travel time in the formation fluid (i.e. interstitial water). ρ_b and ρ_f are the bulk density (measured in the zone of interest) and the fluid density respectively, and ϕ_N and ϕ_{Nf} are the neutron derived apparent porosity values in the zone of interest and in the formation fluid respectively. This particular combination of values is essentially independent of primary porosity. Thus, lithological changes are more apparent.

It is also possible to plot the frequency of occurance for each pair of values. This so called frequency plot can place a high degree of emphasis upon often occurring measurements. The frequency of occurance is commonly shown as a numbered value for each plotted point.

These crossplotting methods are graphical solutions to a series of simultaneous equations. The problem can be examined in this way, too. If we wish to determine the relative amounts of sand, shale, and water in a zone, for example, we will need 3 equations to represent the conditions in that zone. We may assume that those three components are all that are in that zone. Thus

$$1 = V_s + V_{sh} + V_f$$

where V is the fractional volume of the sand, shale and fluid respectively. If there is a density measurement available, then

$$\rho = \rho_s V_s = \rho_{sh} V_{sh} + \rho_f V_f$$

where ρ is the density of the zone of interest and the subscripted values the densities of the three pure components. If a gamma ray curve is available, the value of V_{sh} may be determined:

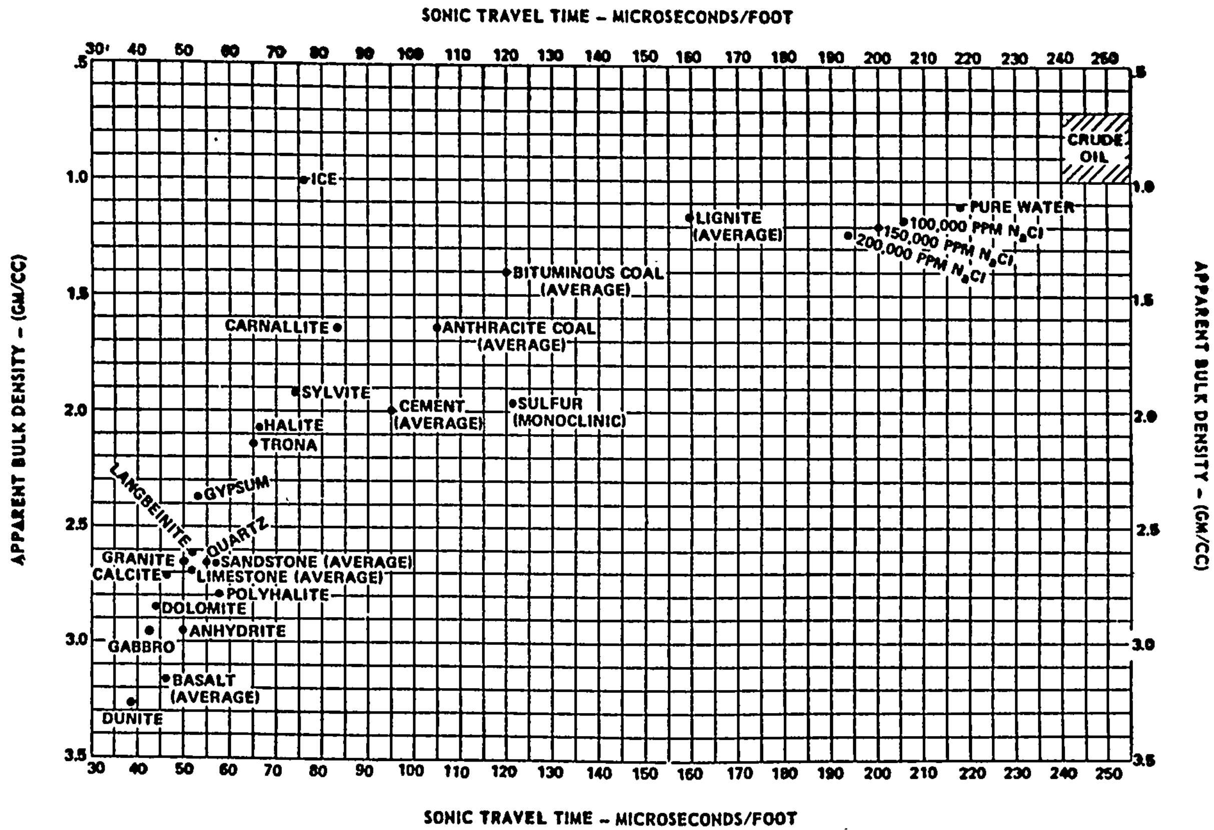
$$V_{sh} = \frac{\gamma - \gamma_s}{\gamma_{sh} - \gamma_s}$$

where γ is the gamma ray reading (or the thorium/thallium -208 reading).

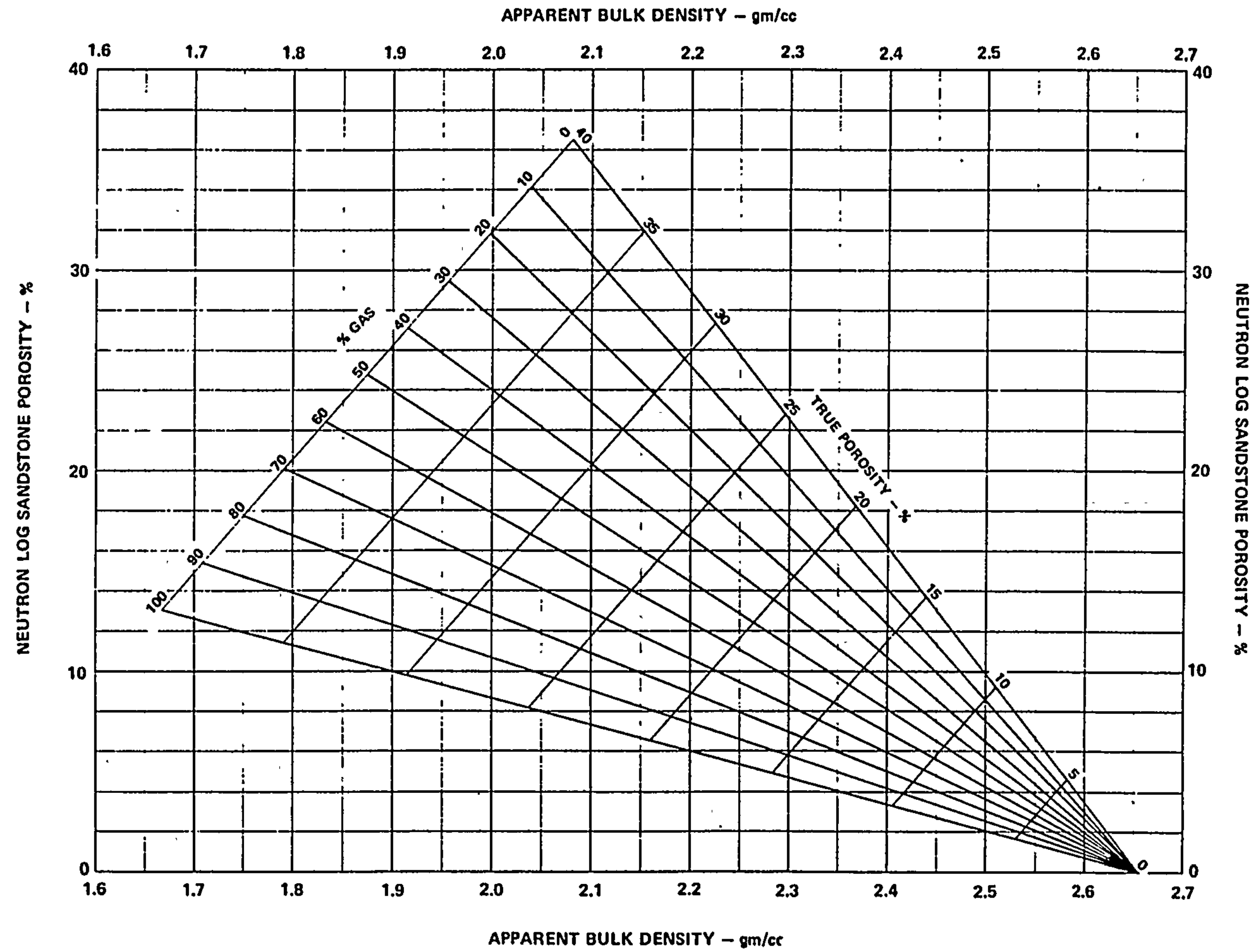
Both of these methods lend themselves quite well to computer processing.

SONIC - DENSITY CROSS PLOT (LITHOLOGY)

Density Log Calibration to Z/A=0.5)

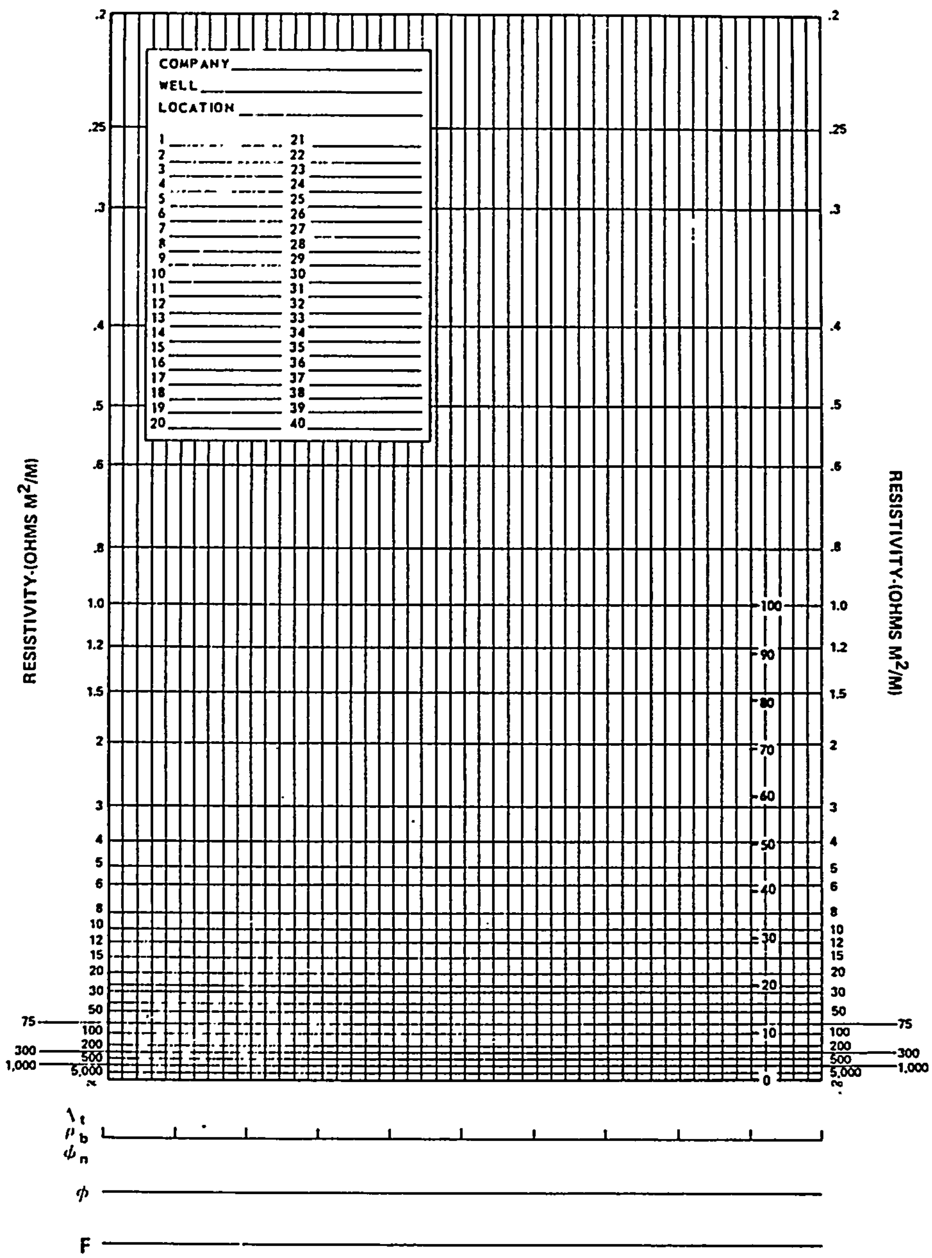


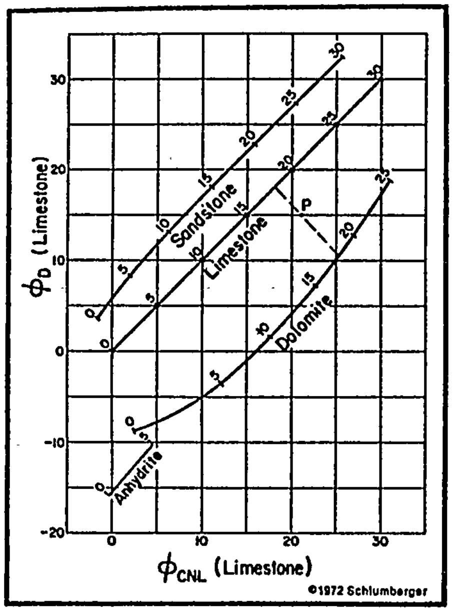
GAS DETECTION AND POROSITY DETERMINATION IN SANDS FROM DENSITY – NEUTRON LOG CROSS PLOTTING



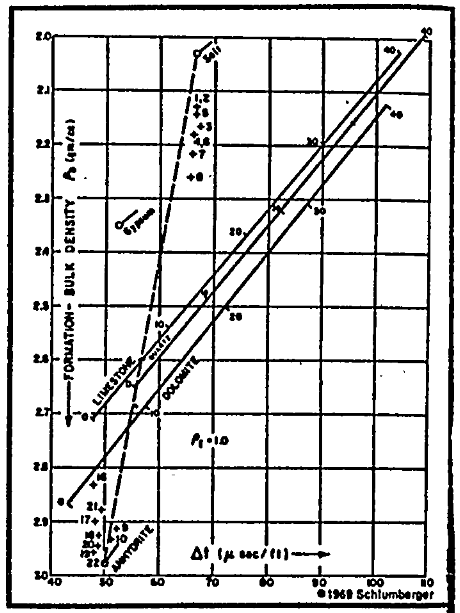
RESISTIVITY VS Δ_t, ρ_b, ϕ_n or ϕ

CONSOLIDATED SANDS ($F = \phi^{-2.0}$)



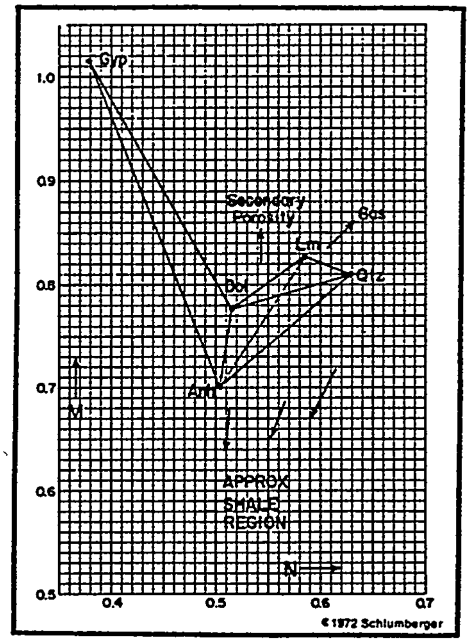


— *Porosity and lithology determination from FDC Density and CNL Neutron logs in water-filled holes.*



— *Porosity and lithology determination from FDC Density and Sonic Logs.*

Courtesy of Schlumberger Well Services, Inc.



—M-N plot showing points for several minerals. (N is calculated using SNP Neutron log). Arrows show direction of shifts caused by shale, gas, and secondary porosity.

Courtesy of Schlumberger Well Services, Inc.

Magnetic Logging Methods

There are several magnetic logging methods available::

1) the induction log (magnetic resistivity or conductivity measurements),
2) magnetic field intensity,
3) magnetic field direction,
4) magnetic permeability,
5) magnetic susceptibility.

Of these, the induction log is the only one which is run on a large scale commercially. The magnetic field direction measurements and, thus, magnetic field intensity measurements are used commercially in borehole deviation measurements. The rest are used as specialty measurements, usually by an in-house group for a commercial establishment, or for a government agency (U.S.G.S., D.O.E.).

The induction log has been covered under electric logging methods. It has the advantages that electrical conductivity may be measured with a relative independence from the borehole fluid and that locallization of the response zone is effective.

Magnetic field intensity and susceptibility measurements are used mostly for evaluation of mineralization of various kinds. As mineralization often occurs in fault zones and fractures, due to the transport of pregnant solutions, the methods may have some promise in site evaluation. However, the lack of commercial services and literature is a severe handicap.

The methods, except for the induction log and hole deviation devices seem to offer no great usefulness at the present time. In the future this picture may change.

Electromagnetic "Radar" Logging

Electromagnetic logging, sometimes called "radar" logging and electromagnetic Propagation Time (EPT) logging, uses high frequency electromagnetic waves or pulses to observe effects due to differences of electrical permittivity and magnetic permeability of materials.

A signal may be transmitted as a pulse or a continuous wave. Frequencies are usually high; on the order of 15 MH_z to 2 (or more) GH_z. The signal attenuation or propagation time is measured.

Reflected power, P_s at the receiver is

$$P_s = P_T R^2 (\frac{G}{2\omega t})^2 \ 10^{-\alpha t/10}$$

where P_T is the transmitted power, G is the antenna gain, $\omega = 2$ f, f is the frequency, t is the two-way travel time (in microseconds), and α is the attenuation factor.

The attenuation factor is

$$\alpha = \omega\{\frac{\mu\varepsilon}{2} (1 + 1/\omega^2\rho^2\varepsilon^2)^{\frac{1}{2}} - 1 \}^{\frac{1}{2}}$$

where

$\mu = \mu_o = 4\pi \times 10^{-7}$ henry/meter, magnetic permeability
$\varepsilon = K\varepsilon_o = K/(36\pi \times 10\ )$ farad/meter, electrical permittivity
$\omega = 2\pi f$, frequency in Hertz
$\rho =$ RF loss resistivity in ohmmeters
$K =$ dielectric constant.

The attenuation is a function of frequency:

$$\frac{2.65}{f} \approx \text{constant} = L$$

The value of L is in dB per gigahertz-meter. It will range from about 3 in granite, 7 to 8 in coal and limestone, 16 to 18 in gypsum, quartz and schist, 22 and above for wet rocks, 50 - 200 for wet clays (Cook 1975).

The velocity of propagation is v_P,

$$v_P = \frac{1}{(\mu^* \varepsilon^*)^{\frac{1}{2}}}$$

where μ^* and ε^* are the complex magnetic permeability and electrical permittivity respectively (Stewart and Unterberger 1976).

The oil-field tool (EPT) makes use of the high dielectric constant of water (≃80) compared to petroleum (≃2) and rock materials (≃6). It uses a frequency of 1.1 GH_Z as a continuous wave. At this frequency it is virtually independent of water salinity.

The electromagnetic propagation techniques have been used to locate tunnels, map volcanic tructure, map salt domes, and discriminate between oil and water. Surface, hole-tohole, and wireline techniques have been used.

It would appear, at first examination, that the oil-field type tool would not be too useful in site evaluation because of its shallow penetration (≃2"). The lower frequency methods hold more promise, however.

Class: Electric Logging

Method: Electromagnetic Propagation

Measures: Water content, contrasts in electrical and/or magnetic properties.

Characteristics: A relatively untried technique, but one which is promising. A wide range of characteristics, such as penetration, sensitivity to salinity, and component measurement are available.

Uses: It is used to locate electrical and/or magnetic discontinuities, such as contrasts in magnetic permeability or dieletric content.

Advantages: Can be made to penetrate deeply (several hundred feet). It has a fair resolution (½ a wave length). It can be independent of water salinity. It is sensitive to water, compared to other materials by an order of magneture.

Disadvantages: The technique is relatively untired. The oil-field version is very shallow investigation. The tools are usually built and run on a one-of-a-kind basis.

Suppliers: Schlumberger Well Services

Trade name: EPT

Borehole Gravity Measurement

Borehole gravity measurement is an accurate method of determining the average bulk density of a large sample of earth. The measurement differs in two major respects from the gamma gamma density measurement:

1. the gravity measurement is a direct, absolute measurement (thus, it requires no calibration), and
2. the sample size and the resolution are quite different. The gravity measurement, when measuring the density of a 100 foot thick zone has a radius of measurement of about 500 feet for 90% of its signal. (T. H. McCulloh, et al, 1968.) This is a sample volume of more than 7.8×10^{10} cubic feet. The gamma gamma density tool has a depth of investigation of 4 to 9 inches for 50% of its measurement or 20 to 42 inches for 90% of its measurement. The measured interval is 10 to 20 inches long. Thus, the measured volume for 90% of its signal is approximately 0.4 to 1.5 cubic feet. The resolution of detail is inversely proportional to the volumetric examination.

The determination of density, ρ_b with the borehole gravimeter is

$$\rho_b = 3.686 - 39.185\ (\Delta g/\Delta Z)$$

where Δg is the difference in gravity readings at two different stations (in milligals) and ΔZ is the distance between the two stations (in feet).

The gravity measurement is valuable in that it can detect anomalous density values, and thus, structural changes at a distance from the borehole. It is used to locate porous zones behind reef structures, salt domes and faults not intersected by the borehole, and anomalous large bodies (i.e. mineral bodies, coal, caves) which are a distance from the borehole. In this use, it is usually used with and compared to the gamma gamma density readings.

The gravity measurement must be corrected for several things and the measurement of the depth and depth interval is critical. The corrections needed (Rasmussen, 1973) are for

1. Tide
2. Drift
3. Borehole (usually small to negligible)
4. Terrain
5. Subsurface structure
6. Hole deviation.

Measurements are made discontinuously.

Class: Mechanical

Method: Borehole gravity

Measures: Gravity acceleration, bulk density

Characteristics: Needs no calibration, examines a large sample. Measurements are discontinuous. Features remote from the borehole can be sensed.

Uses: Used to detect structural and stratigraphic features beyond the distance range of other logging tools.

Peripheral data needed: Gamma gamma density log, other porosity devices.

Advantages: Has a great radius of investigation. Virtually unaffected by borehole conditions. Extremely accurate (gravity measurement to $\pm$.005 milligals).

Disadvantages: Low resolution. Many corrections needed. Tools are large (≈4" diameter). Measurements are slow and exacting.

Suppliers: LaCosta and Romberg, Edcon.

Trade names: none

Cost Comparisons of the Various Contractors and Services.

The actual cost of each of the measurements described will depend upon many factors. A sample for comparison is included. In general, the mineral logging systems are less expensive by a factor of about 2 to 6. However, a smaller choice of options is available from the mineral logging contractor. The mineral logging tools are designed for small hole (<5" diameter) operation. The measurements and detector characteristics may be designed for different parameters or a different range of parameters than petroleum-oriented logging equipment. Finally, in general, except for the gamma ray measurements, calibrations and peripheral data are generally more complete with petroleum oreinted contractor's services.

With the above things in mind, we will assume that logging services are desired at a site 100 miles from the service company office, in a sand-shale sequence, to bottom in a massive salt-dome. The borehole is 1000 feet deep and is 6 inches diameter, uncased. The following primary logs are desired: Gross count gamma ray, KUT gamma ray spectrograph, focussed resistivity, spontaneous potential, density, neutron. Secondary logs are the borehole deviation and high resolution dipmeter. Three contractors will be considered: Century Geophysical, Schlumberger, and Dresser-Atlas. These are representative of mineral logging contractors, high cost petroleum and lower cost petroleum contractors, respectively. Price schedules for several contractors are enclosed. A standard digital system will be used. Gearhart and Welex have similiar prices to Dresser-Atlas. They may be 10% to 20% lower, but not all tools are available. Digital processing may not be available with Welex.

Milage 200 miles RT. Century	.50/mi	$ 100
Daily rate	500/day	500
9050A tool: GCGR, Single point	.12/ft	
Neutron	.07/ft	
Deviation	.07/ft	260
9030A tool: GCGR, DEnsity, focussed R	.18/ft	180
HRD tool: Not available		
KUT tool:	.23/ft	230
Tape Cartridge	$17/cartridge	17
1 extra log	$2.00 + .01/ft	12
Transcription to 9 track	4.00 + .15/ft	154
Cost of Dresser Atlas HRD		2385
TOTAL w/o HRD		$1453
TOTAL w/HRD		$3838

Milage 200 miles RT, Dresser Atlas		$ 210
Service Charge		620
Induction Electric log, Gamma Ray, Depth charge 680 min.		680
	Logging charge	580
Densilog/Caliper/Gamma Ray, Depth charge		660
	Logging charge	580
Compensated Neutron/Gamma, Depth charge		660
	Logging charge	580
4 Arm High Resolution Diplog		700
Directional Survey		520
Basic Information tape	$165 + .03/ft	195
1 extra log		140
TOTAL		$6125

Cost Comparisons of the Various Contractors and Services Page 2

Milage 200 miles RT,	Schlumberger	$1160
Induction-Electric Log	Depth Charge	700
	Operations Charge	620
Formation Density	Depth Charge	680
	Operations Charge	620
Gamma Ray	Depth Charge	180
	Operations Charge	160
Compensated Neutron	Depth Charge	680
	Operations Charge	620
Gamma Spectrograph	Depth Charge	680
	Operations Charge	620
High Resolution Dipmeter	Depth Charge	720
	Operations Charge	2330
Library Tape		840
TOTAL		$10,610

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APPENDIX

LIST OF SYMBOLS, ABBREVIATIONS, AND SUBSCRIPTS:

Symbols

T	Acoustic travel time
γ	Gamma Ray or gamma ray reading
ϕ	Fractional porosity
ξ	Dielectric constant
ρ	Density
Σ	Thermal neutron capture cross-section
Σ	Mathematical; summation
μ	viscosity
μ	mass absorption coefficient
V	fractional volume
γ	zeta potential

Abbreviations

A	Area
d	diameter
E	Voltage or electrical potential
F	Correction factor
G	Grade percent
GCGR	Gross count gamma ray
GR	Gamma ray
HRD	High resolution dipmeter
i	incremental values
IL	Induction Log
K	Conversion factor
L	Length meters
LL	Laterolog, focussed resistivity log
LS	Limestone
n	recorded counting rate
n	neutron
N	corrected counting rate
N	Normal resistivity measurement
r	Electrical resistance, ohms
R	Electrical resistivity, ohmmeters
SP	Spontaneous potential
T	Thickness
w	Width

Subscripts (if not noted) and coefficients

a	Tortuosity coefficients
a	Apparent
b	Bulk
w	Equivalent
f	Fluid
m	Cementation coefficient
m	Mud
m	Matrix
Mc	Mudcake
mf	Mud filtrate
o	Original or undisturbed
o	Containing no hydrocarbon or gas
s	Sand
sh	shale
t	True, as measured but corrected
w	Water, formation water
xo	The totally flushed zone near the borehole.

SOLUBILITY OF GEOLOGIC MATERIALS

Material	GMS/100cc Cold Water	GMS/100cc Hot Water
Lead Pb	i*	i
Uraninite UO_2	i	i
Cinnabar HgS	0.000001(18°C)	N/A
Iron Fe	i	i
Galena PbS	0.000086(18°C)	N/A
Chalcocite Cu_2S	10^{-14}	N/A
Hematite Fe_2O_3	i	i
Magnetite Fe_3O_4	i	i
Pyrite FeS_2	0.00049	N/A
Zircon $ZrSiO_4$	i	i
Stibnite Sb_2S_3	0.000175(18°C)	N/A
Barite $BaSO_4$	0.000222(18°C)	0.000336(50°C)
Chromite $FeCr_2O_4$	i	i
Rutile TiO_2	i	i
Corundum Al_2O_3	0.000098(20°C)	N/A
Rhodocrosite $MnCO_3$	0.00265 (20°C)	N/A
Sphalerite ZnS	0.0007 (18°C)	N/A
Siderite Fe_2CO_3	0.0067 (25°C)	N/A
Limonite $2Fe_2O_3.3H_2O$	i	i
Magnesite $MgCO_3$	0.0106	N/A
Anhydrite $CaSO_4$	0.209 (30°C)	0.1619 (100°C)
Aragonite $CaCO_3$	0.200153(25°C)	0.00190(75°C)
Dolomite $CaMg(CO_3)_2$	0.032 (18°C)	N/A
Calcite $CaCO_3$	0.0014 (25°C)	0.0018 (75°C)
Aluminum Al	i	i
Quartz SiO_2	i	i
Kieserite $MgSO_4.H_2O$	N/A	68.4 (100°C)
Gypsum $CaSO_4.2H_2O$	0.241	0.222 (100°C)
Graphite C	i	i
Halite NaCl	35.6 (0°C)	39.8 (100°C)
Nahcolite $NaHCO_3$	6.9 (0°C)	16.4 (60°C)
Trona $Na_2CO_3HNaCO_3.2H_2O$	13.0 (0°C)	42.0 (100°C)
Sulphur, orthorhombic (below 95.4°C)	i	i
Potash $K_2CO_32H_2O$	110.5 (20°C)	155.7 (100°C)
Sylvite KCl	28.0 (0°C)	56.0 (100°C)
Carnallite $KMgCl_3.6H_2O$	64.5 (19°C)	N/A

(*i = insoluble)

POTASSIUM CONTENT OF VARIOUS FORMATION MATERIALS

MATERIAL	POTASSIUM CONTENT BY WEIGHT (%)	
	(Average)	(Range)
Sylvite	54	
Potash	44.9	
Langbeinite	20	
Microcline	16	
Kainite	15.1	
Carnallite	14.1	
Orthoclase	14	
Polyhalite	12.9	
Muscovite	9.8	
Biotite	8.7	
Illite	5.2	3.51-8.31
Arkose (sandstone)	4.6	4.4-5.1
Synite	4.53	
Glauconite	4.5	3.2-5.8
Granite	4.0	2.0-6.0
Norite	3.3	
Granodiorite	2.90	
Shale	2.7	1.6-9.0
Igneous rock	2.6	
Graywacke (sandstone)	1.8	1.2-2.1
Diorite	1.66	
Basalt	1.3	
Sandstone	1.1	0-5.1
Gabbro	.87	
Diabase	.75	
Kaolinite	.63	0-1.49
Limestone	.27	0-0.71
Montmorillonite	.22	0-.60
Orthoquartzite (sandstone)	.08	0-0.12
Dolomite	.07	03-0.1
Dunite	.04	
Sea Water	.035	

This table is presented to show the effects of formation potassium content on gamma ray response. About 0.012% of all natural potassium is radioactive (i.e., K-40) giving off a 1.5mev gamma ray upon disintegration. Approximately 20% of the gamma ray emissions from shale are caused by the isotope K-40. The remaining radiation from shales is generally caused by uranium and thorium series elements.

The average sandstone contains about 12% feldspar. Even orthoquartzite sands may contain 10% feldspar. "Although any kind of feldspar may be present the acid feldspars, particularly potash-bearing (orthoclase) varieties are most common" (Pettijohn).

A number of sandstones from California have been reported to contain an average of 50% feldspar.

(Continued on Page 219)

FORMATION AND MINERALS RESISTIVITY CATALOG

FORMATION/MINERAL	RESISTIVITY-OHMS M^2/M (At STP Unless Otherwise Stated)
sulphur	10^9-10^{16} (1.9 . 10^{15}@20 C, 9.5 . 10^9@115 C)
petroleum	10^9-10^{16}
biotite	10^{14}-10^{15}
sylvite	10^{14}-10^{15}
mica	10^{14}<
halite – (common salt)	10^4-10^{14}<
quartz	10^{12}-10^{14}
muscovite	10^{11}-10^{12}
calcite	10^7-10^{12}
cinnabar	10^6-10^{10}
sheelite	10^6-10^{10}
anhydrite	10^4-10^{10}
limonite	10^6-10^8
sphalerite	10^5-10^7
anthracite coal	10^{-3}-5 (Most below 1 ohm m^2/m)
bauxite	10^2-10^6
hematite	2.1×10^{-3} - 1×10^6
bituminous coal	10-10^6
basalt	8×10^2-10^5
gabbro	8×10^2-10^5
diabase	8×10^2-10^4
gneiss	10^2-10^4
"sub-bituminous coal"	10^2-10^4
dolomite	1-7×10^3
limestone ("dense")	80-6×10^3
lignite	4×10^3
conglomerates	up to 3,000
siderite	10-1,000
sand	up to 1,000
slate	up to 1,000
marl	up to 600
siltstone	up to 300
peat	10-300
argillite	1-300
braunite	.01-100
ilmenite	.01-100
marcasite	.01-100
shale	up to 15
pyrolusite	1-10
chalcopyrite	.001-.1
"sulfides"	.001-.1
pyrite	.0001-.1
magnetite	.0001-.01
bornite	.000001-.01
galena	.00001-.001
pyrrhotite	.00001-.0001
graphite	.000001-.0001
native metals	less than .000001

*The resistivity of most bedded formations will vary with the direction of measurement.

HYDROGEN CONTENT OF VARIOUS SUBSTANCES

Substance	Hydrogen Atoms x10^{23} per cc	Hydrogen Index*
Pure water		
60°F, 14.7psi	.669	1
200°F, 7,000psi	.667	1
Salt water, 200,000ppm NaCl		
60°F, 14.7psi	.614	.92
200°F, 7,000psi	.602	.90
Methane CH_4		
60 F, 14.7psi	.0010	.0015
200°F, 7,000psi	.329	.49
Ethane C_2H_6		
60°F, 14.7psi	.0015	.0023
200°F, 7,000psi	.493	.74
Average natural gas		
60°F, 14.7psi	.0011	.0017
200°F, 7,000psi	.363	.54
N-pentane C_5H_{12}		
68°F, 14.7psi	.627	.94
200°F, 7,000psi	.604	.90
N-hexane C_6H_{14}		
68°F, 14.7psi	.645	.96
200°F, 7,000psi	.615	.92
N-heptane C_7H_{16}		
68°F, 14.7psi	.658	.99
200°F, 7,000psi	.632	.95
N-octane C_8H_{18}		
68°F, 14.7psi	.667	1.00
200°F, 7,000psi	.639	.96
N-nonane C_9H_{20}		
68°F, 14.7psi	.675	1.01
200°F, 7,000psi	.645	.97
N-decane $C_{10}H_{22}$		
68°F, 14.7psi	.680	1.02
200°F, 7,000psi	.653	.98
N-undecane $C_{11}H_{24}$		
68°F, 14.7psi	.684	1.02
200°F, 7,000psi	.662	.99
Bituminous coal .8424 (C) .0555 (H)	.442	.66
Carnallite	.419	.63
Limonite	.369	.55
Cement	about .334	about .50
Kernite	.337	.50
Gypsum	.325	.49
Kainite	.309	.46
Trona	.284	.42
Potash	.282	.42

Substance	Hydrogen Atoms x 10^{23} per cc	Hydrogen Index*
Muscovite	.089	.13
Illite	.059	.09
Biotite	.041	.06

*Based on fresh water (under equal pressure and temperature in the case of fluids). The Hydrogen Index is the equivalent Neutron porosity.

Remarks: The number of hydrogen atoms per cubic centimeter of a substance may be determined as follows:

1) Determine the molecular weight of the substance
2) Divide the molecular weight by the density
3) Divide Avogadro's Number (6.025×10^{23}) by the above quotient
4) Multiply the above quotient by the number of hydrogen atoms per molecule of the substance

The density variation for "crude oils" with temperature and pressure used above was estimated from charts published by D.L. Katz and M. Muskat (see references).

**Gypsum is probably not found where formation temperatures exceed about 140°F (60°C)

DENSITIES, Z/A RATIOS, AND THERMAL NEUTRON CAPTURE CROSS SECTIONS PER UNIT VOLUME OF GEOLOGIC MATERIALS

(DENSITY AT ROOM TEMPERATURE AND ONE ATMOSPHERE PRESSURE UNLESS OTHERWISE STATED)

Material	Z/A Ratio	Matrix Density G/CC	Apparent* Density G/CC	** Σ Material (Capture Units)
Lead Pb	.3953	11.34	8.97	5.61
Uraninite UO_2	.4000	8.25 (6.5-10.8)	6.60	49.69
Cinnabar HgS	.4143	8.1 (8.0-8.2)	6.71	7,981.16
Iron Fe	.4687	7.87	7.38	214.90
Galena PbS	.4093	7.5 (7.4-7.6)	6.14	12.47
Wulfenite $PbMoO_4$	.4187	6.9 (6.7-7.0)	5.78	32.50
Arsenopyrite FeAsS	.4605	6.1 (5.9-6.2)	5.62	165.22
Cobaltite CoAsS	.4517	6.1 (6.0-6.3)	5.51	936.73
Chalcocite Cu_2S	.4610	5.65 (5.5-5.8)	5.21	173.56
Hematite Fe_2O_3	.4787	5.26 (4.9-5.3)	5.04	100.47
Magnetite Fe_3O_4	.4774	5.18 (4.97-5.18)	4.95	112.10
Bornite Cu_5FeS_4	.4643	5.15 (4.8-5.4)	4.78	145.63
Pyrite FeS_2	.4850	5.06 (4.95-5.17)	4.91	89.06
Ilmanite $FeTiO_3$	.4757	4.75 (4.5-5.0)	4.52	158.23
Zircon $ArSiO_4$	.4691	4.69 (4.2-4.86)	4.40	5.42
Stibnite Sb_2S_3	.4436	4.57 (4.52-4.62)	4.05	17.82
Pyrrhotite Fe_5S_6	.4812	4.55 (4.58-4.64)	4.40	90.52
Barite $BaSO_4$	.4454	4.45 (4.30-4.60)	3.96	19.40
Chromite $FeCr_2O_4$	.4753	4.45 (4.30-4.60)	4.23	102.20
Rutile TiO_2	.4756	4.20 (4.15-4.25)	3.80	202.75
Chalcopyrite $CuFeS_2$	.4751	4.2 (4.1-4.3)	3.99	80.95
Corundum Al_2O_3	.4904	4.02 (3.95-4.10	3.94	11.04
Carnotite $K_2O.2UO_3.V_2O_5.2H_2O$	.4350	4+	3.48+	56.21
Rhodocrosite $MnCO_3$	.4793	4.0 (3.5-4.0)	3.84	278.93
Sphalerite ZnS	.4720	4.0 (3.9-4.1)	3.78	38.33
Siderite Fe_2CO_3	.4797	3.88 (3.0-3.88)	3.72	68.81
Limonite $2Fe_2O_3.3H_2O$	.4897	3.8 (3.51-4.0)	3.72	74.10
Dunite (4 Samples)	.4978	3.3 (3.24-3.74)	3.29	17.03
Olivine $(Mg,Fe)_2SiO_4$	.4892	3.3 (3.27-3.37)	3.23	31.74
Magnesite $MgCO_3$	.4992	3.1 (3.0-3.2)	3.1	1.48
Norite (11 Samples)	.4970	2.984 (2.720-3.020)	2.97	12.88
Diabase (6 Samples)	.4954	2.98 (2.96-3.05)	2.95	17.12
Gabbro (27 Samples)	.4938	2.976 (2.850-3.120)	2.94	21.47
Anhydrite $CaSO_4$	.4995	2.95 (2.89-3.05)	2.95	12.30
Aragonite $CaCO_3$	.4995	2.94 (2.85-2.94)	2.94	8.12
Muscovite $KAl_2(AlSi_3)O_{10}(OH)_2$	.4966	2.93 (2.76-3.1)	2.91	17.30
Biotite $H_2K(Mg,Fe)_3Al(SiO_4)_3$	.4900	2.90 (2.65-3.1)	2.84	25.20
Dolomite $CaMg(CO_3)_2$	.4994	2.85 (2.80-2.99)	2.85	4.78
Illite $KAl_5Si_7O_{20}(OH)_4$	.4954	2.84 (2.60-3.0)	2.81	39.90
Diorite (13 Samples)	.4964	2.839 (2.721-2.960)	2.82	14.33
Langbeinite $K_2Mg_2(SO_4)_3$	.4961	2.83	2.61	78.87
Polyhalite $2CaSO_4.MgSO_4.K_2SO_4.2H_2O$	.5013	2.78	2.79	21.00
Synite (24 Samples)	.4971	2.757 (2.630-2.899)	2.74	16.43
Granodiorite (11 Samples)	.4963	2.716 (2.668-2.785)	2.696	11.33
Chlorite $(Mg,Al,Fe)_{12}(Si,Al)_8O_{20}(OH)_{16}$	.5056	2.71 (2.60-3.22)	2.74	17.56
Calcite $CaCO_3$	.4996	2.71 (2.71-2.72)	2.71	7.48
Aluminum Al	.4818	2.70	2.60	13.99

*Based on tool calibration using a Z/A ratio of 0.5. **Capture Units in 10^{21} Barns/cm^3

Material	Z/A Ratio	Matrix Density G/CC	Apparent* Density G/CC	** Σ Material (Capture Units)
Plagioclase feldspar $xNaAlSi_2O_8 \cdot yCaAl_2Si_2O_8$	.4925	2.69 (2.62-2.76)	2.65	6.99
Limestone (Av. of 345 Samples)	.5000	2.69 (2.66-2.74)	2.69	8.72
Granite (155 Samples)	.4969	2.667 (2.516-2.809)	2.65	11.62
Quartz SiO_2	.4993	2.65 (2.65-2.66)	2.65	4.36
Sandstone (Av. of 12 Samples)	.4990	2.655 (2.59-2.84)	2.655	8.66
Kaolinite $(OH)_8Al_4Si_4O_{10}$	.5103	2.63 (2.40-2.68)	2.68	13.06
Albite $NaAlSi_3O_8$	.4885	2.62 (2.61-2.65)	2.56	6.77
Orthoclase feldspar $KAlSi_3O_8$	.4958	2.57 (2.55-2.63)	2.55	16.00
Kieserite $MgSO_4.H_2O$	.4724	2.57	2.43	12.77
Concrete		2.35 (1.98-2.35)		
Montmorillonite $(OH)_4Si_8Al_4O_{20}.nH_2O$ (n=1)	.5009	2.35 (2.00-3.00)	2.35	8.10
Gypsum $CaSO_4.2H_2O$	.5111	2.32 (2.30-2.35)	2.37	19.40
Glauconite KMg (FeAl) $(SiO_3)_6.3H_2O$	.4998	2.30 (2.20-2.80)	2.30	16.80
Graphite C	.4995	2.22 (2.09-2.23)	2.22	0.38
Serpentine $Mg_3Si_2O_5(OH)_4$	.5062	2.20	2.23	8.80
Halite NaCl	.4799	2.16 (2.135-2.165)	2.07	752.36
Nahcolite $NaHCO_3$	.4905	2.20	2.16	
Kainite $MgSO_4.KCl.3H_2O$	.5140	2.13 (2.1-2.13)	2.19	196.13
Trona $Na_2CO_3HNaCO_3.2H_2O$	.5043	2.125 (2.11-2.15)	2.14	16.21
Sulphur, orthorhombic (below 95.4°C)	.4990	2.07 (2.05-2.09)	2.07	19.06
Potash $K_2CO_32H_2O$	.5049	2.04	2.06	39.70
Sylvite KCl	.4829	1.99 (1.97-1.99)	1.92	570.68
Cement (32 Samples)		1.99		about 13
Sulphur, monoclinic (above 95.5°C at 1 atm; above 150°C at 19,000 psi) S	.4990	1.96	1.96	18.05
Kernite $Na_2B_4O_7.4H_2O$	.5026	1.91	1.92	12,793.69
Carnallite $KMgCl_3.6H_2O$	.5095	1.61 (1.60-1.61)	1.64	370.92
Anthracite coal .9350(C) .0281(H) .0097(N) .0272(O)	.5134	1.60 (1.32-1.80)	1.64	1.08
Bituminous coal .8424(C) .0555(H) .0152(N) .0869(O)	.5201	1.35 (1.15-1.7)	1.40	1.54
Lignite		1.10 (.5-1.5)	1.16	
Water (300,000 ppm NaCl)	.5325	1.219	1.298	146.22
(250,000 ppm NaCl)	.5363	1.1825	1.268	122.55
(200,000 ppm NaCl)	.5401	1.146	1.238	100.08
(150,000 ppm NaCl)	.5438	1.109	1.206	78.75
(100,000 ppm NaCl)	.5476	1.073	1.175	58.69
(50,000 ppm NaCl)	.5513	1.0365	1.143	39.02
(30,000 ppm NaCl)	.5528	1.022	1.130	32.56
(Pure Water)	.5551	1.00	1.11	22.08
NaCl solution density at STP≅1 + (.00000073 x ppm)				
Oil $n(CH_2)$, 10° API, STP	.5703	1.00	1.14	28.02
30° API, STP		.88	1.00	25.89
40° API, STP		.85	.97	24.22
50° API, STP		.78	.85	22.23
(C_8H_{18}), 70° API, STP	.5778	.70	.81	22.12
N-pentane C_5H_{12},STP	.5823	.626	.733	20.80
200°F, 7,000 psi		.603	.702	20.02
N-hexane C_6H_{14}. STP	.5803	.659	.765	21.38
200°F, 7,000 psi		.628	.739	20.37
N-heptane C_7H_{16}, STP	.5778	.684	.790	21.80

*Based on tool calibration using a Z/A ratio of 0.5. **Capture Units in 10^{21} Barns/cm^3

Material	Z/A Ratio	Matrix Density G/CC	Apparent * Density G/CC	** Σ Material (Capture Units)
200°F, 7,000 psi		.657	.759	20.84
N-octane C_8H_{18}, STP	.5778	.703	.812	22.12
200°F, 7,000 psi		.673	.778	21.12
N-nonane C_9H_{20}, STP	.5768	.718	.828	22.37
200°F, 7,000 psi		.686	.791	21.37
N-decane $C_{10}H_{22}$, STP	.5763	.730	.841	22.55
200°F, 7,000 psi		.701	.808	21.65
N-undecane $C_{11}H_{24}$, STP	.5759	.740	.852	22.71
200°F, 7,000 psi		.713	.821	21.87
Methane CH_4, STP	.5703	.000677	.00076	0.028
200°F, 7,000 psi		.2189	.2497	10.88
Ethane C_2H_6, STP	.5986	.001269	.00015	0.051
200°F, 7,000 psi		.4104	.4913	16.34
Propane C_3H_8, STP	.5896	.00186	.0022	0.067
N-butane C_4H_{10}, STP	.5850	.00246	.0029	0.085
Helium He, STP	.4997	.00017	.00017	0.0000
Carbon dioxide CO_2, STP	.4999	.001858	.001857	0.0001
Nitrogen N_2, STP	.4998	.001182	.001185	0.004
Oxygen O_2, STP	.5000	.001350	.001350	0.00001
Hydrogen sulphide H_2S, STP	.5281	.001438	.001519	0.029
Air (dry) (N-78%, O-21%, A-1%)	.4997	.001224	.001223	
Argon A,STP	.4859	.001688	.00144	0.017
Average natural gas, STP	.5735	.0007726	.000886	
200°F, 7,000 psi		.252	.289	
Hydrogen H	.9921	.00009		
Oxygen O	.5000	.001429		
Nitrogen N	.4998	.00125		
Carbon C	.4995	3.52		
Calcium Ca	.4990	1.5		
Sulfur S	.4990	2.07		
Silicon Si	.4985	2.4		
Magnesium Mg	.4975	1.74	1.73	
Potassium K	.4859	.86		
Phosphorous P	.4845	1.83		
Aluminum Al	.4818	2.70	2.60	
Sodium Na	.4804	.97		
Chlorine Cl	.4795	:0032		
Nickel Ni	.4769	8.90		
Iron Fe	.4687	7.86		
Boron B	.4625	2.45		
Chromium Cr	.4614	7.1		
Titanium Ti	.4593	4.5		
Zinc Zn	.4589	7.14		
Manganese Mn	.4568	7.4		
Copper Cu	.4564	8.92		
Vanadium V	.4514	5.96		
Cobalt Co	.4432	8.9		
Arsenic As	.4405	5.7		
Zirconium Zr	.4385	6.4		
Bromine Br	.4380	3.12		
Strontium Sr	.4336	2.6		
Tin Sb	.4312	7.2		
Molybdenum Mo	.4159	10.2		
Barium Ba	.4077	3.5		
Mercury Hg	.3988	13.56		

**Capture Units in 10^{21} Barns/cm^3

Material	Z/A Ratio	Matrix Density G/CC
Lead Pb	.3953	11.34
Uranium U	.3865	18.7
Water H_2O	.5551	1.0
Carbon dioxide CO_2	.4999	
Calcium carbonate $CaCO_3$	.4996	
Calcium sulfate $CaSO_4$	.4995	
Calcium Oxide CaO	.4993	
Silicon oxide SiO_2	.4993	
Magnesium oxide MgO	.4985	
Aluminum oxide Al_2O_3	.4904	
Phosphorous oxide P_2O_5	.4935	
Boron oxide B_2O_3	.4884	
Potassium oxide K_2O	.4883	
Sulfur trioxide SO_3	.4874	
Sodium oxide Na_2O	.4855	
Hematite Fe_2O_3	.4787	
Magnetite Fe_3O_4	.4766	
Iron oxide FeO	.4757	
Titanium oxide TiO_2	.4756	
Titanium oxide TiO	.4695	
Manganese oxide MnO	.4652	
Zirconium oxide ZrO_2	.4555	
Strontium oxide SrO	.4439	
Barium oxide BaO	.4173	

*Based on tool calibration using a Z/A ratio of 0.5.

Many of the minerals listed are most often found in nature to be impure.

The values listed are minus photoelectric effects, which may become significant when elements heavier than sodium are present within the volume under investigation. The calculation of Z/A effects in formations rich in heavy atoms is mainly academic because here the Z/A effects become unimportant compared to those of photoelectric absorption. Present-day density log interpretation techniques are not designed for the accurate determination of bulk density in many heavy mineral-rich formations.

Many rich ore deposits contain only 1% to 1-1/2% of the mineral to be extracted. The sought after mineral therefore may not contribute significantly to the bulk density of the ore.

To determine the neutron capture cross section (Σ) of a substance:

1) Determine the molecular weight of the substance.
2) Divide the molecular weight of the substance by its density.
3) Divide Avogadro's Number (6.025×10^{23}) by the above quotient (yields molecules per cm^3).
4) Multiply the number of atoms of each element present per cm^3 by the thermal neutron capture cross section (in barns) for the element.
5) Sum the capture cross section contributions for each element as determined from Step #4 above to determine the capture cross section (in barns x $10^{21}/cm^3$) for the substance.

D-1

APPENDIX D-1

DRILLING AND CORING METHODS
FOR
PRECHARACTERIZATION STUDIES

by

Earth Sciences Company
Houston, Texas

October, 1981

EVALUATION OF SOURCES

For

DRILLING OF BOREHOLES

For

GEOLOGIC AND GEOPHYSICAL EVALUATIONS

OCTOBER 14, 1981

EVALUATION OF SOURCES

FOR

DRILLING OF BOREHOLES

GEOLOGIC AND GEOPHYSICAL EVALUATIONS

October 14, 1981

INTRODUCTION

There are three potential sources of equipment and personnel available to accomplish geologic and geophysical evaluations relevant to site selection for high level nuclear waste isolation. The petroleum, mining and water well drilling industries offer varied approaches and inherant limitations to accomplish the desired end results.

The petroleum industry employs drilling equipment capable of borehole depths to 40,000 feet, with relative limitations on depth borehole and/or core sizes ranging from 2 3/4 inches to in excess of 30 feet. Fluids available for drilling include various liquid systems, fresh water, salt water, oil, oil emulsions, asphalt, and combinations of liquids, air, natural gas and foams. Direct circulation is normally employed in the petroleum industry. A large variety of fluids handling and controlling equipment is available as required to meet drilling conditions anticipated or encountered. Coring equipment is available in a relatively wide range of sizes and types designed for various media and borehole conditions. A very wide range of drilling bits for borehole drilling without coring is available. Overall the petroleum industry could provide the best end results and geographical coverage for drilling and coring for the program.

The mining industry employs portable drilling equipment capable of borehole and corehole depths to about eight thousand feet maximum. Borehole sizes range from 1-1/2 inches to 4-3/4 inches utilizing drill rods and slim hole drill pipe. Core diameters range from 1/2 inch to 2-1/8 inches. The types of circulation systems include dry drilling, mud and air. The mud systems utilized are similar to those used in the petroleum industry, though the equipment normally found on these rigs is not suited to coring below about 2,500 feet, with the exception of one type of continuously coring rig styled the Concor Rig. Limited availability and high maintenance costs on these units make them rather impractical for this project.

The water well drilling industry normally employs reverse circulation of drilling fluids eliminating the use of core equipment, which requires direct circulation. Reverse circulation water well rigs could be employed for drilling boreholes to about 2,000 feet for geophysical logging and cased hole insitu testing only. Water well rigs normally are not equipped with sufficient pump capacity to effectively drill below 2,000 feet with 6-3/4 inch borehole size maximum. Shallower tests can be drilled with up to 17-1/2 inch borehole sizes. The depth and hole size limitations would seriously effect use of water well drilling equipment for this project although this equipment is generally available throughout the Continental United States.

PARAMETERS:

An overview of the available drilling technology is herein considered according to the requirements of the project. There are certain parameters and/or assumptions that must necessarily be established in order to make proper comparative analyses of equipment and drilling services required to accomplish the objectives of the project. These parameters and/or assumptions are based upon directive requirements of past and current studies for the Office of Nuclear Waste Isolation and the Texas Bureau of Economic Geology as follows:

A. Assumption that same or similar requirements by ONWI and state agencies will be the same.

B. Parameter of repository overburden of 2500 feet, minimum, i.e. 2500 foot coring/drilling depth.

C. Assumption that all drilling sites will be accessible to equipment from any source.

D. Parameter of required borehole size of 8-3/4 inches to be equal regardless of drilling equipment source for complete geophysical logging purposes, that is that petroleum, mining or water well equipment must be capable of drilling or coring a hole large enough to accomodate logging.

E. Parameter that all boreholes are to be of sufficient diameter (7-7/8 inch) to accomodate 5½ inch diameter casing and ample cement sheath so that extended insitu hydrologic testing can be performed.

F. Assumption that all drill sites will be onshore Continental United States.

GUIDELINES FOR ANALYSES:

This study is made for each medium included as potential respository formations. The comparisons of equipment and services by sources is made for each medium with cost comparisons and effectiveness ratings for the sources being the result of the analyses.

Each of the three sources of equipment and services is included principally to show cost comparisons under the initial assumption that all three sources could meet the above parameters.

GENERAL NOTES:

A. EQUIPMENT AND SERVICES DISTRIBUTION

1. PETROLEUM INDUSTRY

Equipment and support services are currently active in every sedimentary basin in the Continental United States, and in overthrust belts of the Appalachian, Ouachita and Rocky Mountain systems. This distribution puts the petroleum industry within practical operating distance of all areas with the possible exception of the far northeast portion of New England. Apparently no petroleum rigs are in operation east of the Adirondack Mountains of New York.

2. MINING INDUSTRY

Equipment and support services are currently active in all hard-rock mining districts of the United States. With the exception of coring equipment in the Wyoming-Dakotas Coal Region, Southeastern Oklahoma, East Texas and the Four Corners district of the Rocky Mountains, few mining industry core rigs are operating in sedimentary basins. The hard rock mining districts of the Rocky Mountains, the Western Sierras and the Appalachians support the bulk of this industry's equipment and services.

3. WATER WELL INDUSTRY

There are water well drilling rigs available throughout the United States. The various areas support water well drilling rigs whose capabilities are regulated to the depths of potable water. This results in a wide range of rig sizes from the 200 foot or less to 2000 foot depth ratings. Most available rigs are relatively self supporting insofar as ancillary services, flexibility and special equipment is concerned. Therefore, modifications available for coring and special requirements are very limited. The rigs with capabilities to the 2,000 foot range are located in the sedimentary basins of East Texas, West Texas, New Mexico, Arizona and portions of the Michigan Basin and the Mississippi Embayment.

B. AVAILABILITY OF RIGS - COMPARATIVE TIME FRAME

1. PETROLEUM INDUSTRY

The energy development situation throughout the United States has created a shortage of readily available rigs. Current waiting time for rigs to contract ranges from three to eighteen months, dependent upon the areas of activity.

2. MINING INDUSTRY

Increased minerals exploration activity has created somewhat of a shortfall in rig availability in the active areas. Contract rigs are generally available within six weeks to six months of desired dates. Most of the rigs in this industry are utilized under relatively long term exploration contracts, but these contracts are not all in effect in the same time frames. Therefore, dependent upon areas, rigs generally become available within reasonable waiting periods.

3. WATER WELL INDUSTRY

This industry experiences a rather uniform usage rate in comparison to the other sources. Generally these rigs are available on a few days to, at most, a few weeks notice.

COMPARISONS OF EQUIPMENT AND SERVICES

This comparison assumes that all three sources are capable of accomplishing the end results as specified under PARAMETERS above although in actuality only petroleum industry sources are capable of fulfilling all parameters. The objective of this section of the study is to provide comparative costs and ratings.

The items noted herein and their respective ratings are generalized experience and observed rateings of normally equipped standarized rig packages from each source.

"Availability" reflects both time frame for contract and geographic proximity to sites for each medium.

"Equipment Efficiency" reflects the normally equipped rig package as found in each source with reference to the desired end result as defined under PARAMETERS above.

"Drilling Fluid Control" refers to standard equipment and normal source industry requirements when providing the various required functions to meet the PARAMETERS as aboved described.

"Blowout Prevention" refers to equipment range ratings generally available from each source industry.

"High Tech Capabilities" refer to developed or developing equipment, materials and techniques available from each source industry and its specific support group to accomplish all requirements described under PARAMETERS above.

"Overall Effectiveness" is comparative with reference to achieving the desired end results as described in PARAMETERS above.

"Rating", again assuming that the sources profess capability to accomplish the defined end results, places the sources in their respective order of overall capability to do the job in a specific medium.

Rating 1 places the source industry as most capable for the specific medium. Rating 2 indicates probable capability to accomplish the desired end result but at higher cost. Rating 3 indicates probable inability to accomplish the desired end results.

Considering the above definitions the following comparisons are made for the various media assuming that the PARAMETERS, above, are to be met.

A. BEDDED SALT

Bedded salts occur in evaporite basins at depths from the surface to below the 2,500 foot overburden required. Due to the nature of the sedimentary section and specifically the salt beds two major drilling (coring) problems occur. The ability to recover significant cores without extraneous fluid contamination and drilling solids buildup in the fluid systems are the most usual problems encountered. Both problems are controlled by use of proper mud systems and physical equipment on the rigs. The salt sections must be cored with salt saturated mud systems and good solids removal equipment must be employed.

The following table represents a comparison of the three sources of equipment as it would apply to coring or drilling of bedded salt, as related to typical equipment used in normal operations.

ITEM	PETROLEUM	MINING	WATER WELL
Availability	Good	Poor	Good
Equipment Efficiency	Excellent	Fair	Poor
Drilling Fluid Control	Excellent	Fair	Poor
Blowout Prevention	Excellent	Poor	Poor
Depth Capabilities	Excellent	Fair	Poor
High Tech Capability	Excellent	Excellent	Fair
Estimated Core Rate	120 ft/d	80 ft/d	60 ft/d
Estimated Drill Rate	300 ft/d	160 ft/d	200 ft/d
Est. Cost - Coring	$134.40/ft.	$150.00/ft.	$133.33/ft.
Est. Cost - Drilling	$ 53.33/ft.	$ 75.00/ft.	$ 40.00/ft.
Overall Effectiveness	Excellent	Fair	Poor
Rating	1	2	3

B. DOMED SALT

Domed salt occurs in sedimentary basins of the Gulf Coast of the United States. They are generally classified as piercement and non-piercement domes. With few exceptions, moderate to severe faulting is associated with the domes and usually severe formation dips occur over and around the salt bodies. These geological factors give rise to two of the three more common drilling problems associated with drilling mud, coring salt domes, pressure abnormalities leading to flowage of formation solids and crooked hole problems. The third common problem is satisfactory core recovery in the salt section. Drilling fluid property control utilizing a salt saturated mud system and good solids removal equipment will control the formation flow and core recovery problems. The crooked hole problem is normally controlled by proper downhole tool assemblies and reduction of penetration rates.

The following table represents a comparison of the three sources of equipment as it would apply to coring or drilling of salt domes, as related to typical equipment used in normal operations.

ITEM	PETROLEUM	MINING	WATER WELL
Availability	Good	Poor	Good
Equipment Efficiency	Excellent	Fair	Poor
Drilling Fluid Control	Excellent	Fair	Poor
Blowout Prevention	Excellent	Poor	Poor
Depth Capabilities	Excellent	Fair	Poor
High Tech Capability	Excellent	Excellent	Poor
Estimated Core Rate	120 ft/d	80 ft/d	60 ft/d
Estimated Drill Rate	500 ft/d	200 ft/d	200 ft/d
Est. Cost - Coring	$134.40/ft.	$150.00/ft.	$133.33/ft.
Est. Cost - Drilling	$32.00/ft	$60.00/ft.	$40.00/ft
Overall Effectiveness	Excellent	Fair	Poor
Rating	1	2	3

C. SHALE

Shale occurs in sedimentary basins throughout the Continenal United States. It is usually found in bedded form, but does occur in the Gulf Coast Region in the form of piercement and non-piercement diapirs similar to salt domes. Drilling problems encountered in bedded shales are generally limited to hole stability, but in diapric shales abnormal pressures are usually encountered and contemporaneous faulting is often associated with these features. Drilling fluid property control and good solids removal equipment will contral the problems associated with drilling and coring of shales.

The following table represents a comparison of the three sources of equipment as it would apply to coring or drilling of shales, as related to typical equipment used in normal operations.

ITEM	PETROLEUM	MINING	WATER WELL
Availability	Good	Poor	Good
Equipment Efficiency	Excellent	Fair	Poor
Drilling Fluid Control	Excellent	Fair	Poor
Blowout Prevention	Excellent	Poor	Poor
Depth Capabilities	Excellent	Fair	Poor
High Tech Capability	Excellent	Excellent	Poor
Estimated Core Rate	120 ft/d	80 ft/d	60 ft/d
Estimated Drill Rate	500 ft/d	200 ft/d	200 ft/d
Est. Cost - Coring	$134.40/ft.	$150.00/ft.	$133.33/ft.
Est. Cost - Drilling	$32.00/ft	$60.00/ft.	$40.00/ft
Overall Effectiveness	Excellent	Fair	Poor
Rating	1	2	3

D. GRANITE

Granite rock occurs in the cores of most mountain systems in the Continental United States. These areas generally are within reasonable logistical range of petroleum industry sources and have currently active mining industry drilling rigs in operation. Though there are water well drilling rigs in these areas, they normally are incapable of drilling hard rock and are used in alluvial formations on or near basement rocks. Water well industry sources are not considered capable of drilling granites due to the physical size and nature of the equipment.

The drilling and coring problems encountered in drilling granite are mostly in the area of equipment and availability and cost effectiveness due to extreme bit and core barrel wear. Drilling of boreholes in granite can be accelerated by utilizing air and/or air-foam fluid systems.

The following table represents a comparison of the three sources of equipment as it would apply to coring or drilling of granite, as related to typical equipment used in normal operations.

ITEM	PETROLEUM	MINING	WATER WELL
Availability	Fair	Excellent	Good
Equipment Efficiency	Excellent	Excellent	Poor
Drilling Fluid Control	Excellent	Excellent	Poor
Blowout Prevention	N/A	N/A	N/A
Depth Capabilities	Excellent	Excellent	Poor
High Tech Capabilities	Excellent	Excellent	Poor
Estimated Core Rate	40 ft/d	45 ft/d	--
Est. Drill Rate - Mud	100 ft/d	100 ft/d	--
Est. Drill Rate - Air	200 ft/d	200 ft/d	--
Est. Cost - Coring	$842.75/ft.	$709.41/ft.	--
Est. Cost - Drlg Mud	$400.00/ft.	$266.67/ft.	--
Est. Cost - Drlg Air	$100.00/ft.	$66.67/ft.	--
Overall Effectiveness	Good	Excellent	N/A
Rating	2	1	N/A

E. TUFF

Tuff occurs in numerous areas of the Continental United States, in or near ancient and recent volcanic regions. Tuff beds are generally flat and homogeneous, uniform in character and thickness, but not relatively widespread. For the purposes of this analysis, the tuff to be drilled is considered to be vitric ash or pure tuff, as opposed to other types, thus the drilling conditions are considered to be the most severe that would be encountered in tuffaceous rocks.

Drilling problems in tuff are similar to that in granites, with the additional problem of core recovery due to jamming of core barrels. Drilling will be comparable in time and cost to granites.

The following table represents a comparison of the three sources of equipment as it would apply to coring or drilling of tuffs, as related to typical equipment used in normal operations.

ITEM	PETROLEUM	MINING	WATER WELL
Availability	Fair	Excellent	Good
Equipment Efficiency	Excellent	Excellent	Poor
Drilling Fluid Control	Excellent	Excellent	Poor
Blowout Prevention	Excellent	Excellent	Poor
Depth Capabilities	Excellent	Excellent	Poor
High Tech Capabilities	Excellent	Excellent	Poor
Estimated Core Rate	40 ft/d	45 ft/d	15 ft/d
Est. Drill Rate - Mud	100 ft/d	100 ft/d	30 ft/d
Est. Drill Rate - Air	200 ft/d	200 ft/d	60 ft/d
Est. Cost - Coring	$602.75/ft.	$562.75/ft.	$533.32/ft.
Est. Cost - Drilling Mud	$160.00/ft.	$120.00/ft.	$266.67/ft.
Est. Cost - Drilling Air	$ 80.00/ft.	$ 60.00/ft.	$ 66.67/ft.
Overall Effectiveness	Good	Excellent	Poor
Rating	2	1	3

F. BASALT

Both recent and ancient basalts occur in numeraous areas of the Continental United States in historical igneous regions. Basalt flows are generally flat and homogeneous, most often uniform in character and thickness. Basalts are notoriously vacuous, fractured and associated with faulting, in part. Due to the nature of the rock and its local distribution patterns, a number of drilling problems are to be expected. The hardness and abrasiveness contribute to excessive bit and core barrel wear, the cavernous and fractured nature of the rock masses lead to loss of circulation of drilling fluids and crooked hole problems. These problems require close control of drilling fluid systems, special downhole drilling tool assemblies and reduced rates of penetration.

The following table represents a comparison of the three souces of equipment as it would apply to coring or drilling of basaltic formations, as related to typical equipment used in normal operations.

ITEM	PETROLEUM	MINING	WATER WELL
Availability	Good	Good	Good
Equipment Efficiency	Excellent	Excellent	Poor
Drilling Fluid Control	Excellent	Good	Poor
Blowout Prevention	Excellent	Poor	Poor
Depth Capabilities	Excellent	Excellent	Poor
High Tech Capabilities	Excellent	Excellent	Poor
Estimated Core Rate	40 ft/d	45 ft/d	15 ft/d
Est. Drill Rate - Mud	80 ft/d	80 ft/d	25 ft/d
Est. Drill Rate - Air	160 ft/d	160 ft/d	50 ft/d
Est. Cost - Coring	$602.75/ft.	$562.75/ft.	$533.32/ft.
Est. Cost - Drilling Mud	$200.00/ft.	$150.00/ft.	$320.00/ft.
Est. Cost - Drilling Air	$100.00/ft.	$ 75.00/ft.	$160.00/ft.
Overall Effectiveness	Good	Excellent	Poor
Rating	2	1	3

VARIATIONS IN EQUIPMENT USAGE

Considering the fact that portions of site characterization programs may deviate from the PARAMETERS cited above, the source industries may have different applications in which their respective capabilities would vary from the above COMPARISONS OF EQUIPMENT AND SERVICES.

Where specific normal usage of a source industry is applicable, such as mining industry core drill for slim hole coring, over all effectiveness and commensurate costs are appreciably changed with regard to each specific application.

In order to categorize these specific applications by medium it is necessary to rate each industry as to its best suited capabilities and availabilities.

A. PETROLEUM INDUSTRY

This source industry has best applications in bedded salt, salt domes and shale media. Petroleum industry rigs are normally equipped with tools, ancillary equipment and support services capable of drilling or coring required overburden and potential repository media. This source is not best suited to slim hole drilling or coring in comparison to the mining industry sources, but has the capability of slim hole drilling or coring in any media. For cost comparison the following factors can be applied to petroleum industry sources for each medium cited above in COMPARISONS OF EQUIPMENT AND SERVICES.

1. Bedded Salt

   a. .Estimated Cost - Coring 1.0 X $134.40/ft = $134.40/ft.

b. Estimated Cost - Drilling 0.75 X $53.33/ft = $ 40.00/ft.

2. Domed Salt

a. Estimated Cost - Coring 1.0 X $134.40/ft = $134.40/ft.
b. Estimated Cost - Drilling 0.75 X $53.33/ft = 40.00/ft.

3. Shale

a. Estimated Cost - Coring 1.0 X $134.40/ft = $134.40/ft.
b. Estimated Cost - Drilling 0.75 X $32.00/ft = 24.00/ft.

4. Granite

a. Estimated Cost - Coring 1.0 X $842.75/ft = $842.75/ft.
b. Estimated Cost - Drilling 1.0 X $400.00/ft = 400.00/ft.

5. Tuff

a. Estimated Cost - Coring 1.0 X $602.75/ft = $602.75/ft.
b. Estimated Cost - Drilling 0.8 X $160.00/ft = 128.00/ft.

6. Basalt

a. Estimated Cost - Coring 1.0 X $602.75/ft = $602.75/ft.
b. Estimated Cost - Drilling 1.0 X $200.00/ft = 200.00/ft.

NOTE: above figures apply to drilling with mud only as air coring/drilling with petroleum industry equipment presents excess hazards and costs.

B. MINING INDUSTRY

This source industry has best application in granite, tuff and basalt media. It is best suited to slim hole coring and drilling. For cost comparison the following factors can be applied to mining industry sources for each medium cited above in COMPARISONS OF EQUIPMENT AND SERVICES.

1. Bedded Salt

a. Estimated cost - Coring 1.0 X $150.00/ft = $150.00/ft.
b. Estimated Cost - Drilling 0.8 X $75.00/ft = 60.00/ft.

2. Domed Salt

a. Estimated Cost - Coring 1.0 X $160.00/ft = $160.00/ft.
b. Estimated Cost - Drilling 0.8 X $75.00/ft = 75.00/ft.

3. Shale

a. Estimated Cost - Coring 1.0 X $150.00/ft = $150.00/ft.

b. Estimated Cost - Drilling 0.8 X $60.00/ft. = 48.00/ft.

4. Granite

a. Estimated Cost - Coring 0.5 X $709.41/ft = $354.70/ft.
b. Estimated Cost - Drilling 1.0 X $266.67/ft = 106.67/ft.

5. Tuff

a. Estimated Cost - Coring 0.5 X 562.75/ft. = $281.37/ft.
b. Estimated Cost - Drilling 0.5 X $120.00/ft = 60.00/ft.

6. Basalt

a. Estimated Cost of Coring 0.5 X $562.75/ft = $281.37/ft.
b. Estimated Cost - Drilling 0.4 X $150.00/ft = 60.00/ft.

NOTE: Above figures apply to drilling with mud only as air coring/drilling increases cost except in limited specific areas.

C. WATER WELL INDUSTRY

This source industry does not lend itself to any slim hole drilling or coring due to the equipment generally available, therefore, is not considered herein applicable to this work.

The water well industry is best suited to nominal hole size drilling (6 3/4 inch to 17½ inch borehole) to depths of 2,000 feet. Holes drilled with this industry source can be geophysically logged and cased for hydrologic testing. It is best suited to sedimentary sections and when utilized for drilling any such section of overburden above any of the proposed host media the following cost can be applied to all such drilling cost.

Above all host media in sediments - Estimated cost = $40.00/ft.

It is readily seen that the Petroleum Industry source is most cost effective in deep, large borehole drilling and coring, and in slim hole drilling and coring in bedded salt, domed salt and shale. The Mining Industry source is most cost effective in slim hole drilling and coring in granite, tuff and basalt. The Water Well Industry source is best suited to shallow overburden drilling in sedimentary formations.

EQUIPMENT REQUIREMENTS

Equipment necessary to drill into potential repository zones below 2,500 feet is dependent upon end result requirements such as core size geophysical log suites, and necessity to case and hydrologically test various formations penetrated.

Assuming the requirements of setting and cementing 5½ inch casing after drilling and/or coring and 8 3/4 inch borehole for 2,500 feet to 4,500 feet depth, the following basic equipment would be required.

Drawworks	Nominal horsepower rating - 300 HP
Mast	Hook load capacity - 140,000 lb (minimum)
Substructure	Set back capacity - 110,000 lb (optional)
Mud Pump (Main)	275 HP Triplex or equivalent duplex
Mud Pump (Standby)	275 HP Triplex or equivalent duplex
Traveling Equipment	Compatible with mast and drawworks
Rotary Table	17½ inch
Mud Handling Equipment	Steel shale, circulating and suction pits - 350 BBL minimum Mud premix pit and pump Changing pump with Triplex mud pumps 2000 BBL water storage tank Double or tandem high speed deck type shale shaker Desander
Electric Power Plant	145 KW minimum
Drill Pipe	4½", 15.50#/ft, Grade E (4,000')
Drill Collars	6 1/8" X hole or equivalent weight (12)
Full complement of tools and handling equipment	
Blowout Preventers	Double stack and blind rams - 5000 psi W.P.

Assuming that the holes are not to be cased and that core sites less than 4½ inch diameter are the desired end results, slim hole core rigs capable of coring NC or NX holes could be utilized.

A Longyear 44 or equivalent rig could be used for this type operation set up approximately as follows:

Hoist	60 HP minimum
Pull Down	30,000 lb
Mast	30' height
Mud Pump (Main)	35 GPM rating at 500 psi. Duplex or Triplex
Mud Pump (Standby)	35 GPM rating at 500 psi. Duplex or Triplex
Mud Tank	150 BBL capacity
Shale Shaker	Tandem high speed deck type
Electric Power Plant	55 KW minimum
Drill Rod	4,000' type N
Full complement of tools and handling equipment.	

NOTE: Blowout control equipment must be adapted to N-Rod drilling if possible for use of this equipment in most areas.

PERSONNEL REQUIREMENTS

Fully controlled coring in large boreholes will require the following personnel. These requirements are based on experience on continuous coring to 4,000 to 5,000 feet in West Texas. These would be required regardless of rig source or target medium.

Description	Number of Persons	Combined Time On Site Hrs/d
Site Drilling Engineer	2	24
Site Geologist	2	12-24 (as needed)
Mud Engineer	1	12-24 (as needed)
Coring Engineer	2	24
Mud Logger	2	24
Core Handling Assistants	2	12-24 (as needed)
Site Supervisor-Liaison	2	24
Ancillary Personnel-on call		
Fishing Supervisor	1	as needed
Trucker -Flatbed & tank	2	as needed
Welder	1	as needed
Cementing Engineer	1	as needed
Cementing crews & service	1	as needed
Open Hole Squeeze Specialist	1	as needed
Drill Stem Tester	1	as needed
Drill Pipe Inspection Crew	1	as needed

GENERAL COMMENTS

Mobilization costs applied herein on a footage basis include rig-up, rig-down, trucking and personnel mobilization costs (including per diem fees and expenses). Mobilization rates on the rig, exclusive of personnel, are based upon an average move of 100 miles one way at a cost of $17,250. Additional costs calculated on a footage basis are personnel mobilization costs of $680 per day for personnel required in drilling operations and $2,720 per day for personnel required in coring operations.

Rig mobilization costs are averages of the three sources relative to estimated geographic distribution and availability. For the purposes of this study it is impractical to attempt to define specific mobilization costs applied to each medium and source due to the extreme variability of these costs. It should be noted that the rig mobilization costs are more regulated by number of truck loads, loading and unloading time and rig-up and rig-down time than by move distances.

Costs attributed to bit wear and related services in both coring and drilling operations are for all practical purposes in direct proportion to hole size and are based herein upon current pricing.

Air drilling is herein included because in some areas it can be most effective with regard to increased penetration rates. Boreholes can be drilled to in excess of 10,000 feet depth with air although coring with air has specific limitations in that some cooling fluids should be in the system. Costs of air compressors and boosters are based upon current prices from rental compressor services in West Texas.

Costs and time estimates for the various sources are as shown above are based upon current rates, best average estimates for each source in their typical applications with costs of modifications to accomplish desired end results added.

Costs for casing and cementing will be universally applicable for all sources and media. Although casing and cementing costs are not included in the analyses the following estimates are made for casing and cementing surface and production strings.

9 5/8" surface casing (650')	$19.00/ft.
Cement and services - surface	$2750.00
5½" production casing (3,500')	$8.00/ft.
Cement and services - production	$4,800.00

All cost estimates are in 1981 dollars and reflect rates and fees as of October, 1981.

CONCLUSION

From this analyses it appears that in order to accomplish full hole coring of sufficient diameter to accomodate hydrologic testing through casing after coring is completed to at least 2,500' depth petroleum industry source drilling equipment is best suited in all media.

Special coring applications without the hydrologic testing requirement, with typical bore sizes would best be accomplished by equipment from mining industry sources, although major modifications would be required in sedimentary basis.

The water well industry could provide equipment for drilling boreholes and setting casing above 2,000' depth for overburden hydrologic testing. It is recommended that this source not be utilized in coring operations due to reverse circulation technique normally used on water well drilling rigs.

Care must be taken regardless of source that the rigs have blowout prevention equipment in those area where occurrences of oil, hydrocarbon gas, hydrogen sulfides, nitrogen or carbon dioxide are possible.

Selection of rigs should be based upon desired end results which will regulate borehole/corehole size and depth to be drilled.

George E. Payne, Jr.
Registerd Professional Engineer
No. 26824

D-2

APPENDIX D-2

SUBSURFACE DRILLING METHODS

FOR SITE CHARACTERIZATION

BY

ERTEC ROCKY MOUNTAIN, INC.

DENVER, COLORADO

NOVEMBER 1, 1981

ESTIMATE OF DRILLING COSTS

IN

SELECT ROCK TYPES

This study was undertaken to identify drilling rates and associated costs in granite, basalt, shale, tuff, bedded salt and dome salt. Both percussive and core drilling procedures were analyzed, and all drilling was assumed to be from previously prepared underground stations.

Published references were reviewed, particularly those of the U.S. Bureau of Mines, to identify drilling rates which could be expected in the various media. Additionally, drilling foremen and engineers were contacted who were presumed to have current knowledge on penetration rates and drilling conditions in the given rock types. Specifically these included staff members at such public works projects as the Nevada Test Site and the Basalt Waste Isolation Project.

It was rather quickly determined in this study that empirical data on drilling rates can vary by a factor of two or more for similar rock types, depending on such diverse factors as equipment employed, fluid pressure, rock competency, the driller's experience, and so forth. Because of this, an effort was made to identify both a range and average penetration rate for the rock under consideration. Distinctions between the rock types became fuzzy upon comparison of the ranges in penetration rates. Thus granite and basalt exhibit similar resistances to drilling, as do shale and tuff, and the two types of salt formations. Any practical differences in drilling salt, for example, could be attributable almost soley to the presence of impurities like shale or anhydrite stringers (more likely in the bedded variety).

Equipment manufacturers were contacted to ascertain purchase prices of typical units employed in underground drilling. Material and supply costs and labor requirements were determined and added to depreciation charges to arrive at direct operating costs. These charges have been displayed on a dollar/hour basis; conversion to cost/foot drilled then requires simple division by the appropriate penetration rate.

Tables 1A and 1B identify the basic operating information for both percussion and core drills. Three types of percussion drills were analyzed ranging from a small hand-held jackleg to the self-mobilized track drill. It will be noticed that only the track drill is considered for the drilling of salt; discussions with personnel knowledgeable in salt mining confirmed that salt penetration rates are so high a non-mobile percussive drill is simply not practical.

Figures given for penetration rates are those which would be experienced in an actual working situation on a day-in/day-out basis. As such they are somewhat less than might be attained under short-term, controlled conditions. Thus a drilling efficiency of 67 percent has been factored into the percussive penetration rates, and a 50 percent drilling efficiency has been used to determine expected core penetration rates. Core drilling time as a percentage of total shift time is inherently lower than for percussive drilling because of the need to remove and handle core, grease the rods, and so forth. The 50 percent efficiency factor assumes a ring drilling setup where several holes can be completed from a single station. If either the skid-mounted or column-mounted machines had to be moved between individual holes, a further reduction in hourly penetration rates (to approximately two thirds the value shown in Table 1) would be in order.

Table 2 illustrates both capital and direct operating costs for running the equipment suite directly related to drilling. Allocated charges for men and material transportation to the working place, for example, have not been included, nor have supervisory and administrative charges, interest, taxes, and insurance. A contractor's profit, which would appear as a cost to the project owner, similarly has not been determined. Taken as a group these items could easily add 50 to 100 percent to the direct hourly operating figures.

Bit and steel costs have been identified by rock type on Table 2 based on their average lives and current unit costs. For clarity, however, only the values for granite and basalt are totaled in either the columns of rows. Labor costs are assumed at $16.00/man-hour inclusive of fringe benefits. A crew of two is required for the track drill and core drills. The final column in Table 2 provides total direct operating costs by equipment type and drilling method employed.

It will be noticed that for percussive drilling the compressors have all been sized at about double the required capacity. This is because in actual practice it is common to run multiple drills off the same air source. Thus, full utilization of compressor capacity (a doubling in this case) could be achieved with less than a doubling in costs. As an example, the jackleg setup for granite and basalt is estimated to cost $33.28 per hour for a single drill. With two drills serviced from the same compressor, total operating costs would be approximately $54.24 per hour or $27.12 per hour per drill, a decrease of nearly 19 percent.

Table 3 is the culmination of the operating and costing information showing direct drilling costs expressed on a dollar per foot basis. There are remarkable similarities as to costs for percussion drilling in a given rock type. A reflection of larger hourly operating charges for the larger machines is offset almost totally by correspondingly higher assumed average penetration rates. Similar but less striking comparisons are noted for the core drills.

The cost figures developed in this analysis are based on "typical" conditions and are intended only to illustrate general ranges which can be expected. These costs are for comparison of various theoretical sites and conditions and should not be indiscriminately applied to site specific cases without proper modifications. The number of materials involved and their wide range of physical characteristics is too great to permit other than preliminary or guiding estimates of drilling costs.

TABLE 1A
DRILL CHARACTERISTICS

DRILL TYPE	Hole Size (inches)	Air Consumption CFM @ 90-100 psi	Typical Hole Depth	Remarks
Percussion Drills				
Jackleg, hand held	1 1/4	85	to 10 ft.,	
	1 3/4	90	20 ft max.	
	2 1/4	105		
Drifter, column mounted	1 1/2	155	12-15 ft.	
	2 1/2	245	50 ft. max.	
	3 1/2	350		
Track Drill or Jumbo	2	365	15-40 ft.	
	3 1/2	750	200 ft. max.	
	5	1,050		
Core Drills				
Longyear EHS 38			"HQ" Rods to 1,200 ft. "NQ" Rods to 1,900 ft. "BQ" Rods to 2,400 ft.	Largest underground drill made by Longyear; skid mounted, 50 hp electric motor; requires 15 hp air driven pump with 250 CFM nominal air consumption
Longyear 65			"A" wireline to 500 ft.	Air driven, column mounted, screw feed unit; typical air consumption 250 CFM with 450 max; requires air driven pump using nominal 150 CFM

TABLE 1B
DRILL PENETRATION RATES

DRILL TYPE	Material Type	Expected Penetration Rate ft/hr.* Range	Average	Bit Life/Steel Life ft** Range	Average
Percussion Drills					
Jackleg, hand held	Granite & Basalt	2- 16	8	0-400/0-300	200/1,500
1 3/4 in. hole	Shale & Tuff	12- 28	20	400-800/3,000-6,000	600/4,500
Drifter, 2 1/2 in. hole	Granite & Basalt	4- 30	15	0-600/0-3,000	300/500
	Shale & Tuff	20- 60	40	600-1,200/3,000-6,000	900/4,500
Track Drill or Jumbo	Granite & Basalt	8- 50	25	100-900/0-3,000	500/1,500
3 1/2 in. hole	Shale & Tuff	30-100	65	800-2,000/3,000-6,000	1,400/4,500
Track Drill or Jumbo 2 in. hole	Salt	400-500	450	4,000+/30,000+	4,000/30,000
Core Drills					
Longyear EHS 38	Granite & Basalt	2- 4	3	50-100/15,000+	75/15,000
"NX" Core (2 1/8")	Shale & Tuff	4- 8	6	200-300/25,000+	250/25,000
	Salt	10- 15	12	700-800/50,000+	750/50,000
Longyear 65	Granite & Basalt	2- 4	3	50-100/15,000+	75/15,000
"BX" Core (1 5/8")	Shale & Tuff	3- 5	4	200-300/25,000+	250/25,000
	Salt	5- 8	6	700-800/50,000+	750/50,000

* Penetration rates for percussion drills at 67 percent efficiency and core drills at 50 percent efficiency as might be expected in ring drilling from 1 set-up. Additional moves would lower rate.

** Bit and steel life are related not only to a material's toughness, but also to its abrasive quality and to drilling machine characteristics.

TABLE 2

DRILLING COSTS*

(Mid 1981 Dollars)

Item		Capital Cost $	Life Hrs	Depreciation Charges $/hr	Fuel & Lube $/hr	Machine Repairs $/hr	Bits & Steel $/hr ***	Total Materials & Supplies $/hr	Operating Labor $/hr **	Maintenance Labor $/hr	Total Labor $/hr	Grand Total Operating Cost $/hr
Jackleg:	Joy 275 compressor	33,500	9,600	3.49	3.35	4.52	-	7.87	0.80	0.96	1.76	13.12
	Joy AL 60 drill with 48" leg	3,200	3,600	0.89	0.04	1.20	2.08 G, B	3.32	15.20	0.40	15.60	19.81
							1.80 S, T	3.04				
	Hose, fittings, misc.	1,000	4,200	0.24	-	0.11	-	0.11	-	-	-	0.35
	TOTAL	37,700		4.62				11.30			17.36	33.28
Drifter:	Gardner-Denver 1000 compressor	98,500	12,800	7.69	13.79	11.81	-	25.60	0.80	3.95	4.75	38.04
	Gardner-Denver DH 123 drill w/feed	17,000	3,600	4.72	0.17	6.37	4.65 G, B	11.19	15.20	2.13	17.33	33.24
							4.40 S, T	10.94				
	Hose, fittings, misc.	1,500	4,200	0.36	-	0.17	-	0.17	-	-	-	0.53
	TOTAL	117,000		12.77				36.96			22.08	71.81
Track Drill:	Gardner-Denver 2000 stationary comp.	84,000	12,800	6.56	21.84	7.56	-	29.40	0.80	2.52	3.32	39.28
	Gardner-Denver ATD 3100B air track	63,000	9,600	6.56	0.63	16.54	8.50 G, B	25.67	31.20	5.51	36.71	68.94
							7.15 S, T	24.32				
							13.50 Salt	30.67				
	Hose, fittings, misc.	2,000	4,200	0.48	-	0.22	-	0.22	-	-	-	0.70
	TOTAL	149,000		13.60				55.29			40.03	108.92
Core Drill:	Joy 275 compressor	33,500	9,600	3.49	3.35	4.52	-	7.87	0.80	0.96	1.76	13.12
	Longyear EHS 38 drill with pump	55,600	11,200	4.96	2.78	14.49	19.90 G, B	37.27	31.20	4.86	36.06	78.29
							6.00 S, T	23.37				
							2.02 Salt	19.39				
	Hose, fittings, misc.	2,000	4,200	0.48	-	0.22	-	0.22	-	-	-	0.70
	TOTAL	91,100		8.93				45.36			37.82	92.11
Core Drill:	Gardner-Denver 1000 compressors	98,500	12,800	7.69	13.79	11.81	-	25.60	0.80	3.95	4.75	38.04
	Longyear 65 drill with pump	16,500	11,200	1.47	0.33	2.72	16.40 G, B	19.45	31.20	0.91	32.11	53.03
							4.98 S, T	8.00				
							1.67 Salt	4.72				
	Hose, fittings, misc.	2,000	4,200	0.48	-	0.22	-	0.22	-	-	-	0.70
	TOTAL	117,000		9.64				45.27			36.86	91.77

* Direct operating costs only; does not include provision for supervisory and administrative charges, interest, taxes, insurance or storage.

** Labor rates assumed to be $16/hour including fringe benefits.

*** Granite = G, Basalt = B, Shale = S, Tuff

TABLE 3

DIRECT DRILLING COSTS

$/ft.

(Mid 1981 Dollars)

Drill Type	Granite, Basalt		Shale, Tuff		Salt	
	Range	Average	Range	Average	Range	Average
Jackleg	2.08 - 16.54	4.14	1.18 - 2.75	1.65		
Drifter	2.39 - 17.95	4.79	1.19 - 3.58	1.79		
Track Drill	2.18 - 13.61	4.36	1.08 - 3.59	1.65	0.23 - 0.28	0.25
Core Drill EHS 38	23.02 - 46.05	30.70	9.78 - 19.55	13.03	4.95 - 7.42	6.18
Core Drill 65	22.94 - 45.88	30.59	16.06 - 26.77	20.08	9.63 - 15.40	12.84

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APPENDIX E-1

GEOMECHNICAL/THERMOMECHNICAL TECHNIQUES FOR PRECHARACTERIZATION STUDIES

BY

TERRA TEK, INC.

SALT LAKE CITY, UTAH

November 1, 1981

INFORMATION NEEDS FOR SITE CHARACTERIZATION

Topical Report

PRE-SITE CHARACTERIZATION

Suggested Methods For Measuring

The Geomechanical And Thermal Properties

Of Rock Masses

Submitted to:

ERTEC Inc.,
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TR 81-33
April 1981

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INTRODUCTION

This document presents an overview of the various existing rock mechanics tests, which are implemented in both the laboratory and field environments, to assess the adequacy of a given rock type in a specific location as a potential host medium for the construction of a repository to be used for the long term storage of high level nuclear wastes. The emphasis of the document is on those specific tests which are thought to be pertinent to the characterization of a repository site. That is, the tests described herein, when taken as a whole, comprise that sequence of investigations which form a logical program of exploration and testing, both laboratory and field, to determine specific properties of the geological materials and conditions at a particular site which are relevant to the storage of high level wastes in a subsurface repository. The tests and procedures described in this document fall in the broad category of rock mechanics and they pertain to those specific parameters of a rock mass which are used to describe or calculate the response of a rock mass when subjected to mechanical and thermal loading. The document is limited in the sense that it does not cover the broad spectrum of site investigation techniques and the numerous geomechanical investigations which are so intricately interwoven throughout the complex exercise of site characterization. Rather, Ertec has chosen to identify eight technical disciplines and examine these individually. These disciplines are:

1) remote sensing
2) surface mapping
3) seismologic studies
4) geophysical exploration
5) drilling and logging
6) hydrologic studies

7) geochemical studies

8) geomechanical/thermal studies

This document only covers the subject of geomechanical/thermal studies, but it cannot be emphasized too strongly how much the discipline of geomechanical/thermal studies depends upon measurements which should rightfully be described in the context of one of the seven other disciplines. Because of this strong interdependence, reference is made in this document, where appropriate, to tests and measurements which should, strictly speaking, be described in the context of one of the other technical disciplines; this is done solely to insure completeness.

This document is the first of two documents examining the geomechanical and thermomechanical properties of rock masses which can be measured and observed, and which are pertinent to the characterization of sites to assess their adequacy for the construction of subsurface repositories for the storage of high level wastes. As the first document, its emphasis is primarily on those techniques which would be performed prior to actual site characterization; the emphasis is, therefore, on the gross elimination of sites from further consideration while minimizing the costs incurred in reaching this goal. The second document, which will be submitted at a later date, will concentrate specifically on the actual characterization of specific sites. Both documents follow an outline based upon the relative effort to be expended in the field exploration program:

1) No drilling at a site; data from surface based exploration only.

2) Data available from drilling done prior to siting study, in addition to (1).

3) Drilling and appropriate logging performed during the siting study, in addition to (1) and (2).

The test methods selected for presentation in this document are based primarily upon those test methods suggested by the International Society for Rock Mechanics (ISRM) as being adequate for complete classification and characterization; a second set of test categories, the Engineering, Design Tests, are more applicable to intensive studies undertaken during site specific characterization and will be discussed in detail in the second document of this study. The modifications to the proposed suite of tests suggested by the ISRM are primarily in the areas pertaining to the thermal response characteristics of rock. The proposed ISRM test sequences together with the modifications to characterize thermal properties are presented in Table 3.

Examination of Table 1 illustrates once again the interrelationship of the various characterization and how fruitless it would be to attempt to characterize the geotechnical and thermomechanical aspects of a particular site on the basis of rock mechanics tests alone. For the purpose of this study, certain tests, as indicated by an asterisk* in Table 1, do not specifically apply to site characterization for high level waste storage, or should be covered in another technical discipline. Other tests, indicated by a double asterisk** in the table are assumed to be adequately covered in the documents covering other technical disciplines. Engineering design tests that could be performed in situ,*** in surface exposures, mines, etc., prior to specific site characterization, will be described in the second document. The discussions contained within this document also specifically address the points specified in the 10CFR60 Draft Technical Criteria (Table 2) and the 10CFR60 Technical Support Document (Table 3).

TABLE 1

Category I: CLASSIFICATION AND CHARACTERIZATION

Rock material (laboratory tests)

(1) Density, water content, porosity, absorption.

(2) Strength and deformability in uniaxial compression; point load strength.

(3) Anisotropy indices.

(4) Hardness, abrasiveness, attrition,*drillability.*

(5) Permeability.

(6) Swelling and slake-durability.

(7) Sound velocity; pulse and resonance.

(8) Micro-petrographic descriptions.*

Rock mass (field observations)

(9) Joint systems; orientation, spacing, openness, roughness, geometry, filling and alteration.

(10) Core recovery, rock quality designation and fracture spacing.

(11) Seismic tests for mapping and as a rock quality index.

(12) Geophysical logging of boreholes.**

Category II: ENGINEERING DESIGN TESTS

Laboratory

(1) Determination of strength envelope and elastic properties (triaxial, uniaxial compression and tensile tests).

(2) Shear strength of joints and planes of weakness.

(3) Time-dependent and plastic properties.

In-Situ (surface exposure rock cuttings, mines, etc.)

(4) Deformability tests of jointed rock.

(5) Direct shear tests of joints.

(6) Field permeability, ground-water pressure and flow monitoring; water sampling.**

(7) Rock stress determination.

TABLE 2

SUMMARY OF PERTINENT GEOMECHANICAL/THERMAL

INFORMATION NEEDS EXTRACTED FROM DRAFT TECHNICAL CRITERIA

Investigations Required for Site Characterization:

10CFR 60.122(a) (9):

(i) Pattern, distribution and origin of fractures and other discontinuities in the host rock and surrounding confining units.

(iii) In situ determination of bulk geomechanical properties, pore pressures, and ambient stress conditions.

(vi) In situ determination of response to thermal loading.

(2) Volume of Rock

(ii) Geologic framework permitting effective sealing, excavation of stable subsurface openings, and emplacement of waste.

(iv) Geomechanical properties that provide stability for construction and operation under the anticipated thermal and other conditions.

TABLE 3

EXAMPLES OF IMPORTANT GEOMECHANICAL/THERMAL

SITE PARAMETERS PROVIDED IN 10CFR60 TECHNICAL SUPPORT DOCUMENT

2.0 Geomechanical Framework

2.1 Mechanical Conditions

Distribution of heterogeneities and discontinuities (fractures, faults)
Quality of rock conditions
Stress conditions
Strength
Moduli
Plasticity

2.2 Thermomechanical Properties

Thermal conductivity
Expansion coefficients
Thermal alteration properties
Specific heat
Density
Conduction and convection characteristics
Pore water pressures

SURFACE BASED EXPLORATION (NO DRILLING)

The level of site characterization through geomechanical and thermal-mechanical parameter evaluation is admittedly minimal but the amount of effort expended at this stage can lead to the construction of a strong data base upon which decisions affecting later stages of exploration and evaluation can be based. The discussion which follows is predicated on the assumption that, for the most part, the lithology and conditions which are exposed at the surface are indicative of conditions at depth.

IN SITU STRESS STATE.

a) Applicability: A knowledge of the state of stress which exists in the earths' crust at the lithologic horizon under consideration for repository construction is an invaluable input parameter for design studies. The in situ stress state affects the selection of excavation dimensions and, more importantly, knowledge of the ratio of horizontal in situ stresses and their relative orientation must be considered in selecting the orientation of the repository. If the repository is oriented optimally with respect to the stress field, spalling of rock from the excavation is minimized and the stress field tends to close joints or discontinuities. The reverse is true for an unfavorably oriented excavation. An unfavorable orientation of the stress field can also lead to rock mass shearing on joints and discontinuities. In actual practice, there is typically some compromise between orientation with respect to stress and jointing directions.

b) Procedure: During surface based exploration,there is no opportunity to measure the in situ stress field directly, but its approximate magnitude can be estimated from examination of published data (e.g. Zoback and Zoback, 1980) based upon other stress measurements in the region, focal plane solutions for earthquake events and geologic evidence. More importantly, the orientation of the horizontal stress field can be estimated reliably from this same data base supplemented by a knowledge of present day tectonic plate motions.

c) Cost: The cost of such a study, which can actually be performed from the office, is minimal, requiring an expenditure of perhaps
upon the reference material available to the investigator.

d) Exceptions: The validity of such a study is dependent upon the uniformity of the geology in the area under investigation. The mechanism of emplacement of dome salts in particular would suggest that regional stress states are probably not indicative of site conditions. There is also reason to expect variations of up to 100%in the estimated stress magnitudes as a function of the compliance properties of various lithologic beds within a sequence.

UNCONFINED COMPRESSIVE STRENGTH.

a) Applicability: Unconfined compressive strength has long been used as a characterization parameter for rock, primarily due to the ease with which it can be measured. It is primarily used as input to numerous formulae for excavation design and for correlation. Through the use of unconfined compressive strength, it is possible to estimate the value of Young's modulus for the rock to an accuracy of 25% dependent upon the type of rock. For some sedimentary rocks the error is much higher, perhaps as much as several hundred percent.

b) Procedure: In the preliminary stages of site characterizations, compressive strength can be estimated in the field with one of two pieces of portable equipment. The first of these measures the tensile strength by crushing an irregular lump of the rock material (or a piece of core) between two spherical platens, in a point bad test apparatus. The specimens should have a length to shortest diameter ratio of 1.5 to one, and 25 specimens with a mass difference of less than 2% should be used. They are crushed parallel to the long axis and perpendicular to any laminations. A size effect correction must be applied. A second technique utilizes a portable hardness measuring device such as a Schmidt hammer. In this test, a dynamic load is applied to the specimen and a rebound value is measured. This test requires a relatively flat surface. The results of both of these test techniques correlate well with uniaxial compressive strength. The use of the Schmidt hammer requires a knowledge of the density of the rock for accurate results.

c) Cost: Each test or set of tests of this type takes only a few minutes time; the major expenditure is for the equipment. The portable testing machine can be constructed or purchased for approximatley $2000. A Schmidt hammer can be purchased for approximately $250.

d) Exception: The tests are known to be valid for most rock types; Schmidt hammer techniques do not work well on either very hard or very soft rocks.

DESCRIPTION OF DISCONTINUITIES.

a) Applicability: The majority of rock masses, particularly those within a few hundred meters of the surface, behave as discontinua, with discontinuities largely determining the mechanical behavior of the rock mass. It is therefore essential that both the structure of a rock mass and the nature of its discontinuities be carefully described as a supplement to the lithologic description of the rock mass. Those parameters which can be used in some type of stability analysis should be quantified wherever possible. For the case of excavation stability and estimation of support requirements, the description will supply primarily indirect information since a direct analysis of stability has yet to be devised. However, a careful description of the structure of the rock mass and the nature of its discontinuities can be of inestimable value for extrapolating experience of support to new rock mass environments. Descriptions should be sufficiently detailed so that they can form the basis of a functional classification of the rock mass.

b) Procedure: A quantitative description of the structure of the rock mass is accomplished through the measurement or observation of the following ten parameters of the discontinuities.

1) Orientation - the attitude of a discontinuity in space. Described by the dip direction (azimuth) and the dip of the line of steepest inclination in the plane of the discontinuity. Controls possibility of unstable conditions or excessive deformation. Measurements are made with a pocket transit or a protractor relative to a line of known attitude and with an inclinometer.

2) Spacing - the perpendicular distance between adjacent discontinuities. Normally referes to the mean or modal spacing of each particular set of joints. Controls the size of individual blocks. Measured with a ruler or tape.

3) Persistence - discontinuity trace length as observed in an exposure. May give a crude estimate of the areal extent or penetration length of a discontinuity. Important to fluid flow and general behavior. Measured with a tape.

4) Roughness - inherent surface roughness and waviness relative to the mean plane of a discontinuity. Both roughness and waviness contribute to the shear strength of the rock mass. Measured with a profilometer or, on a larger scale, a compass or protractor.

5) Wall strength - equivalent compressive strength of the adjacent walls of a discontinuity; may be lower than intact rock strength due to weathering or alteration. An important component of rock mass shear strength if discontinuity walls are in contact. Measured with a Schmidt hammer.

6) Aperture - perpendicular distance between adjacent walls of a discontinuity in which the intervening space is air or water filled. Important indicator of previous shear displacement. Measured with a ruler or a feeler guage.

7) Filling - material that separates the adjacent walls of a discontinuity and is usually composed of weathered material from the parent rock, but can be a later deposit such as quartz or calcite. Material type can strengthen the joint, or have weakening, time dependent properties. Qualitatively described.

8) Seepage - water flow and free moisture visible in discontinuity. Indicative of local hydraulic gradient. Qualitatively described, but if outflow is observed it should be quantitatively described.

9) Number of sets - the number of sets comprising the intersecting joint system; the mass may be further divided by individual discontinuities. Dominates mechanical behavior of mass. Quantitative observation.

10) Block size - rock block dimensions resulting from the mutual orientation of intersecting joint sets and the spacing of the individual sets. Individual discontinuities may further influence the block size and shape. Combination

of block size and discontinuity shear strength determine rock mass behavior. Calculated from spacing and orientation data.

All of the required measurements and calculations are easily made to within the accuracy required for the task at hand. It is noted that the types of measurements required are easily accomplished during routine geologic mapping if personnel are adequately trained.

c) Cost: The cost of the program is difficult to estimate since it is strongly dependent upon the areal extent of the region being mapped and the number of outcrops which can be mapped. It is unlikely that more than one man-month of effort would be required in any event. All necessary equipment, excluding a Schmidt hammer can be purchased for less than $1000.

d) Exceptions: The usefulness of an investigation of this nature at this early stage of characterization is totally dependent upon how representative the surface is of conditions at the proposed repository depth. In particular, at the surface, discontinuitites tend to be more open with more highly weathered surfaces; filling is typically absent, and roughness can be diminished. The techniques described apply to all rock types but the structure of dome salts is typically not expressed at the surface.

DRILLING PRIOR TO SITING STUDY

The existance of previously drilled holes in a potential siting area can provide much useful data for site characterization, provided a rational core logging program was undertaken at the time of drilling and that core is available. Most of the characterization tests described in this section would, in all likelihood, have been performed during the original logging program.

ROCK QUALITY DESIGNATION (RQD)

a) Applicability: The RQD is a measure of fracture frequency and is basically a modified core recovery measurement procedure. There is a demonstrated relationship between the numerical values of the RQD and the general quality of the rock for engineering purposes. It provides the means to qualitatively describe the rock as being very poor, poor, fair, good, or excellent for engineering purposes. RQD correlates with the ratio of field and lab measured sonic velocities, and there is a fair correlation between RQD and the reduction in rock mass modulus as compared to that of intact specimens. RQD is also an input parameter in several support requirement calculation schemes.

b) Procedure: RQD is calculated by measuring all pieces of core longer than 4 inches (10 cm) in the total core run [usually 10 feet (3m)] and comparing this to the total length of the core run. RQD is expressed as a percentage; if RQD is greater than 90%, the rock is excellent; between 75% and 90%, it is good; between 50% and 75%, it is fair; between 25% and 50%, it is poor, and if less than 25%, the rock is very poor. Drilling induced fractures are not counted and all that is required for the measurement of RQD is a tape.

c) Cost: Since core recovery is measured during drilling, little, if any, additional cost is incurred by the measurement of RQD.

d) Exceptions: The RQD concept is valid for all rock types.

POROSITY/DENSITY

a) Applicability: The presence of pore space in the fabric of a rock material decreases its strength and increases its deformability. A knowledge of porosity, the ratio of the pore or void volume to the total volume, is required if characterization descriptions are to be indicative of mechanical performance of the rock mass. Porosity is also the single most important factor of intact rock affecting permeability. Density of a rock mass is used primarily for correlation but it does function as an input parameter to other studies such as sonic velocity or Schmidt hammer. The two parameters are discussed together because they are typically determined in a single test.

b) Procedure: A representative sample for testing should be comprised of several rock lumps, each an order of magnitude larger than the largest grain or pore size. Although there are several techniques available to measure porosity and the related properties, only the mercury displacement technique is universally applicable. It can be used with irregularly shaped specimens and it is the only test which can be used if the rock material is liable to swell or disintegrate if immersed in water.

The volume of specimen is determined by mercury displacement and the water content (described later) determined. The bulk density of the specimen is calculated as the dry weight of material divided by its volume. Next, the sample is pulverized with no particles exceeding 150 mm and the grain density determined by a standard pycnometer or volumetric flask technique. This technique requires four weight measurements: the weight of the volumetric flask; the weight of the volumetric flask when full of water (at constant temperature conditions; the weight of grain material; and, the weight of the flask, water, and grain material. From these measurements, on calculates the grain density; knowing the grain density and the bulk density of the specimen, one is able to calculate the porosity.

c) Cost: The cost of a mercury displacement porosity determination is approximately $50. Other techniques can be less expensive but cannot be used with very friable material or with material which is liable to swelling or disintegration if immersed in water.

d) Exceptions: The test procedure is probably accurate to one or two percent except in those cases where fissures are present, in which case the results can be erratic unless a large sample or a sample smaller than the fissure spacing is used.

WATER CONTENT

a) Applicability: The water content is a measure of the amount of water in the pore space of a rock and is an important characterization parameter. Rock strengths, sonic velocities, and water flow characteristics are strongly affected by water content. Saturation is closely related to water content and expresses that percentage of the maximum possible water content. The most commonly encountered definition of water content is based upon the ratio of the weight of water to the weight of the dry material.

b) Procedure: A ten lump sample with each lump having a mass of at least 50g, or dimensions ten times that of the largest grain, whichever is larger, is selected, weighed, dried in an oven to constant mass at 105°C., cooled in a desicator and weighed again. The water content is defined as the weight of water divided by the weight of solid material, expressed as a percentage. The saturation is defined as the volume of the water divided by the volume of the pore space (calculated from porosity). A knowledge of grain density along with the porosity allows one to calculate the moisture content at 100% saturation.

c) Cost: The cost of a water content determination is typically of the order of $10. Water contents are routinely determined with most other tests.

d) Exceptions: Care must be taken to insure that the moisture content of the core in situ is preserved to within 1% of in situ conditions by encasing the sample in wax immediately as it comes from the core tube. Porous rocks will probably become saturated by the drilling fluid. Correction must be made if the pore fluid is other than water. It is unlikely that anything would be gained by running this test on samples which had been stored for some time.

ABSORPTION

a) Applicability: An absorption test is intended to measure the void index of a rock specimen which is an indicator of whether or not the pore space is interconnected. The most important parameters of a rock mass influenced by interconnected pore space are the permeability and pore pressure.

b) Procedure: A representative batch of ten rock lumps is selected such that the mass of each sample exceeds 50g or its minimum dimension exceeds ten times the grain dimension. The batch is dried in a desicator for 24 hours and the mass of the batch is determined. The batch is replaced in a container and water is added until each batch is fully immersed; the container is agitated and left to stand for a period of one hour. The batch is removed and weighed; the void index is calculated as the ratio of the weight of water gained to the dry weight of the batch. The result is probably accurate to within 1% or 2%.

c) Cost: An absorption test costs approximately $50.

d) Exceptions: As with porosity, the absorption test would be unreliable in fractured or fissured rock. Shale or salt samples would have to be tested with a fluid other than water; care would have to be taken to ensure that the fluid viscosity and surface tension characteristics matched those of water. The short time duration of the test makes it unlikely that it would be a meaningful parametric test for tight rock.

SWELLING AND SLAKE DURABILITY

a) Applicability: An abundant class of rock materials, notably those with high clay content, are prone to swelling, weakening or disintegration when exposed to short term weathering processes of a wetting and drying nature. Special tests are necessary to predict this aspect of mechanical performance. These tests are index tests; they are best used in classifying and comparing one rock with another. The swelling strain index should not, for example, be taken as the actual swelling strain that would develop in situ, even under similar conditions of loading and of water content.

These tests simulate natural wetting and drying processes. Other types of test are better suited to estimating resistance to such weathering agencies as frost, salt crystallization or attrition.

Where possible undisturbed rock specimens should be tested, since rock fabric has an important effect on the other properties to be measured. Where the sample is too weak or too broken to allow preparation of undisturbed specimens, as is usually the case with joint-filling materials for example, the swelling tests may be carried out on remolded specimens. Remolding should be according to standard procedures for soil compaction.

These tests are commonly required for classification or characterization of the softer rock materials. They may also be used, however, for characterization of harder rocks where the rock condition, its advanced state of weathering for example, indicates that they are appropriate.

Rocks that disintegrate during the tests should be further characterized using soil classification tests such as determination of the liquid and plastic limits, the grain size distribution, or the content and type of clay minerals present.

The swelling pressure index is intended to be a measure of the pressure necessary to constrain an undisturbed rock specimen at constant volume when it is immersed in water. Modifications of the swelling pressure tests, the swelling strain index tests are similar in nature to the swelling pressure index test, but not as well suited to the testing of less durable rocks.

The slake-durability test is intended to assess the resistance offered by a rock sample to weakening and disintegration when subjected to two standard cycles of drying and wetting.

b) Procedure: A standard soil consolidometer forms the basic test apparatus to measure swelling pressure index; a device capable of loading the specimen and porous plates are also required. The sample should be maintained at a moisture content of within 1% of in situ conditions. The sample is placed in a consolidometer with a small axial force. The specimen is flooded with water and the force is adjusted to maintain zero specimen swell (to within 0.01mm) throughout the test. Swelling force is recorded until it reaches a constant level or passes a peak. The swelling pressure index is defined as the average stress in the sample at peak conditions.

In a slake-durability test, a sample of ten rock lumps, each with a mass of 40-60g, is placed in a clean drum and dried to a constant mass at 105°C. and the mass recorded. The drum is then mounted in a trough and coupled to a motor. The trough is filled with water to a prescribed level and the drum rotated for 200 revolutions in 10 minutes to an accuracy of 0.5 minutes. The drum is removed from the trough and the drum plus retained portion of the sample dried to constant mass at 105°C. The mass of the drum plus retained portion of the sample is recorded after cooling. The above steps are repeated and the mass of the drum plus retained portion of the sample is recorded. The slake-durability index (second cycle) is calculated as the percentage ratio of final to initial dry sample weights.

c) Cost: The cost of a swelling pressure index test could be low ($100) for a rapidly reacting specimen or could easily approach $1000 for slowly reacting specimens. Slake-durability tests would cost approximately $250.

d) Exceptions: There would be little knowledge gained by running the tests on samples which had been stored for long periods of time with exposure to humidity, since those rocks which would react to these tests would probably have experienced complete degradation.

SONIC VELOCITY

a) Applicability: Sonic velocity measurements are performed on laboratory samples of rock for several reasons. If density of the rock is known, elastic modulii can be calculated from velocity data; Poisson's ratio can also be calculated from sonic velocity data. It must be emphasized that the calculated modulii are dynamic and not directly applicable to elastic calculations, but, nevertheless, they are invaluable for correlation purposes. When utilized with field obtained velocity data, there is a very good correlation between the square of the ratio of the field and lab measured velocities and the ratio of in situ and sonic modulii.

b) Procedure: There are numerous techniques for determining sonic velocity; only one technique, the pulse technique, will be described here, primarily due to its ease of interpretation and ease of adaptability to use within pressure/temperature chambers. The method is for the determination of velocities of compressional (dilatational, longitudinal, P-) and shear (rotational, transverse, S-) waves in rock specimens of effectively infinite extent compared to the wave length of the pulse used. The condition of infinite extent is satisfied if the average grain size is less than the wave length of the pulse, which is less than the minimum specimen dimension. Rectangular blocks, cylindrical cores or even spheres (for determination of elastic symmetry of anisotropic rocks) are recommended to be not less than 10 times the wavelength. The travel distance of the pulse through the rock shall be at least 10 times the average grain size. The test is run with a receiver/transmitter pair positioned on opposite faces of the specimen. The velocities of either P or S waves are calculated from the measured travel time and distance between transmitter and receiver. With this data, it is a simple matter to calculate elastic modulii.

c) Cost: The cost of a sonic velocity test ranges from about $50 at completely ambient conditions, to about $500 when run under conditions of temperature and pressure.

d) Exceptions: The technique gives erratic results in fissured rock; in fact this is the basis of nondestructive test techniques for industrial applications. The sound velocity of a rock specimen can be very sensitive to the mineralogic composition of the specimen; it is very common for bedded or foliated rocks to exhibit an anisotropy in the sound velocities corresponding to the bedding or foliation directions. This anisotropy, if present, should be investigated and the results reported, perhaps as a ratio of velocities defining a velocity anisotropy index.

UNIAXIAL COMPRESSIVE STRENGTH AND DEFORMABILITY

a) Applicability: The uniaxial unconfined compressive strength test is used primarily for strength classification and characterization of intact rock; it provides an estimate of the relative strength characteristics of rock types. The uniaxial compressive strength is used as an input parameter for several underground excavation design schemes. The deformability properties of a rock sample, described by Young's modulus and Poisson's ratio are determined from the stress-strain behavior of the rock sample. This data is also used for classification and characterization purposes. Furthermore, the uniaxial compressive strength together with the ratio of Young's modulus to compressive strength allows for more detailed classification. A rock sample is described by its strength and this modulus ratio; for example: moderate strength/high modulus ratio.

b) Procedure: A testing machine capable of applying axial load at a designated rate through properly designated platens is used for the test. It is supplemented by suitable displacement measuring and recording devices such that axial and diametral displacement can be measured to an accuracy of 0.002mm during the test. Load on the specimen is applied continuously at a constant stress rate such that failure will occur within 5 to 10 minutes of loading. The maximum load on the specimen is recorded and the uniaxial compressive strength is calculated by dividing this load by the original cross-sectional area of the specimen. It is advisable to test at least five specimens to insure the quality of the results. Axial strain is calculated as the ratio of change in specimen length to original length; likewise the diametral strain is calculated. Young's Modulus is defined as the ratio of the axial stress change to the axial strain produced by this change and may be reported as a tangent, secant or average value. Poisson's ratio is the ratio of diametral strain to the axial strain or by the ratio of the slopes of the axial stress-strain and diametral stress-strain curves.

c) Cost: The cost of a uniaxial compression strength test including deformation measurements is approximately $250. The strength data alone can be obtained for less than $50.

d) Exceptions: Moisture can have a significant effect on both the strength and deformability of the test specimen. If possible, in situ moisture conditions should be preserved until the time of the test; if this is not possible, it should be noted. Also the presence of fractures can lead to erratic results.

PERMEABILITY

a) Applicability: Permeability is a measure of the ease with which fluids can flow through a rock sample. It is closely related to porosity and is, in light of the need for containment in high level waste storage schemes, perhaps the single most important rock property. Classical permeability tests involve establishing steady state flow conditions through the sample; the permeability coefficient is the ratio of the flow rate through the sample normalized with respect to the area to the hydraulic gradient across the sample. For rocks which are of interest for high level waste storage, the permeability coefficient is desirably low, and steady state flow tests do not produce satisfactory results. For these rock types, a transient or pulse testing technique must be adopted. In this type of test, reservoirs of known volume are brought to equilibrium on either side of the rock sample;one of the reservoirs is given a pressure pulse and the pressure decay as a function of time is observed. The permeability coefficient is determined from the slope of the pressure decay versus time curve.

b) Procedure: Permeability tests, especially tests on tight rock, are not standardized, but all testing techniques are quite similar. Basically, the equipment consists of a cell which encapsulates the specimen and supplementary equipment for measuring flow, pressure, and time. The accuracy of the steady state tests is good for porous rocks, in all likelihood, into the millidarcy range. The transient tests, on the other hand, are capable of measuring permeabilities well into the nanodarcy range.

c) Cost: The cost of a steady state flow test probably does not exceed $250, depending upon the equipment set up. Pulse tests, on the other hand, can exceed $1000 per test.

d) Exceptions: If the rock material is soluble in water such as would be the case for salt, or if the material is sensitive to water, such as would be the case for shales, special testing fluids must be used. This special attention can increase the cost of the test by approximately 25% to 50%. The test results are also extremely sensitive to the presence of fractures even on a micro-scale. Special attention must be given to the condition of such rocks so that the reported values of permeability coefficient are truly those desired.

TRIAXIAL COMPRESSION

a) Applicability: The triaxial compression test is probably more of an engineering test than a classification or characterization test. Its primary use is to measure the strength of rock specimens under confined conditions, thus more closely approximating the conditions which would exist at a repository. The test provides the values necessary to determine the rock strength envelope, the corresponding internal friction angle, and the apparent cohesion value, which are subsequently utilized in design calculations. However, in light of the requirements of a high level waste storage scheme, it is probably realistic to consider rock strength parameters for classification purposes.

The triaxial compression test apparatus is ideally suited for making numerous other measurements while the rock is actually being loaded. Among these are: permeability, pore pressure, sound velocity, temperature, thermal conductivity, thermal diffusivity, and thermal expansion. The triaxial test also permits control of temperature and pressure parameters, thus allowing an investigation of the effects of pressure and temperature on the above listed parameters, as well as modulus and strength data.

The strength behavior of confined rock specimens, and rock masses for that matter, is sensitive to the effects of temperature. Increasing the temperature of rock tends to make it behave more ductiley, and exhibit a decrease in the ultimate strength behavior.

b) Procedure: The procedure for triaxial testing is similar to that for uniaxial testing, except that a triaxial confining cell and a device for generating confining pressure are required. The triaxial cell is typically cylindrical and a confining pressure is applied equally around the jacketed sample. The confining pressure must be maintained and recorded to within 2% of the desired value. Deformation measurements are made as in the uniaxial test, and corresponding values of peak strength, Young's modulus, and

Poisson's ratio can be calculated. If the test machine is servo-controlled, values of ultimate or residual strength can usually be observed.

A minimum of five samples per rock type are tested in addition to the unconfined strength data. The confining pressures and corresponding strength data are plotted according to one of several techniques. The simplest and possibly most useful of these techniques involves the use of the Mohr's circle for each of the individual stress states. The primary advantage of this technique is that pore pressure effects, if they have been measured, can be incorporated in the strength data. To use the Mohr circle approach, the peak or ultimate strength and the confining pressure data for each of the sample tests are plotted, as circles, in a shear stress/normal stress space. The diameter of these circles increases with an increase in confining pressure and decreases with an increase in pore pressure. A line tangent to these circles is drawn with the resulting slope and intercept of this failure envelope representing intact friction angle and intact rock cohesion respectively.

c) Cost: A complete series of room temperature triaxial tests required to describe the failure envelope could be performed for approximately $2000 to $3000, provided that no additional measurements such as permeability or sonic velocity are required. A complete suite of tests investigating parametric variation as a function of either confining pressure or temperature resulting in the generation of failure envelopes as a function of temperature could easily exceed $10,000.

d) Exceptions: The basic apparatus and test sequence is the same for all rock types, but pore fluids for saturation or permeability testing could affect the outcome of the results for salts or shales, and appropriate steps must be taken.

THERMAL CONDUCTIVITY

a) Applicability: Thermal conductivity is a measure of the ease with which heat flows through a body under a temperature gradient. Although not normally thought to be a classification or characterization parameter of a rock mass, the special needs of high level waste storage schemes make it imperative that thermal properties be studied. The generation of heat by an emplaced waste cannister must be conducted from the cannister or severe thermal degradation of the rock will occur.

b) Procedure: Thermal conductivity can be measured in simulated temperature-pressure environment by the transient line heat source ("needle-probe") method. A heater approximating the behavior of an ideal line heat source is placed along the longitudinal axis of the test sample. A thermocouple is attached to the heater at the mid-sample location. The entire probe assembly is then "potted" in place with a mixture of ceramic cement and powdered copper to minimize the contact resistance between the probe and the sample. Ceramic insulators are used to minimize heat loss from the ends of the test sample. The overall internal heater length should be chosen to give a heater length to heater diameter ratio greater than 30. It has been shown that a L/D ratio of 30 is minimum for an acceptable approximation of an infinite line source in this type of test. Power, in the form of carefully monitored voltage and current, is applied to the probe heater (for periods less than one minute) while the test sample exterior is maintained at the desired temperature and pressure. Sample conductivity determines the probe heater temperature rise. The exterior temperature of the sample does not change; a sample of finite dimension can behave (as the theory requires) as though it were infinite in size. Thermal conductivity for the material is calculated from the internal heater temperature history and the power input. The techniques typically utilized involve core-matching of predicted and observed behavior or plotting temperature at a point as a function of logarithm of time. The slope of this curve is equal within a constant to the ratio of the power dissipated per unit length and the condutivity.

Due to the absence of thermal conductivity standards over a large range, accuracy definition is uncertain. It is estimated that thermal conductivity values are accurate to within $\pm 5\%$

c) Cost: A typical thermal conductivity test consisting of four data points at different temperatures but run at ambient pressure conditions, would cost approximately $1000. If the test were run at elevated pressures, the same four points would cost approximately $2000.

d) Exceptions: Thermal conductivity of various material types is known to be a function of the temperature and pressure at which the measurement is made. Complete characterization of the conductivity of a material would therefore require rather extensive testing. It is suggested that for pre-characterization purposes, conductivity at ambient conditions adequately classifies the material.

There are two other closely related thermal properties of materials which will probably be considered during the design stages of repositories. The specific heat is a measure of a material's ability to retain heat. For most rock-like materials, the specific heat is very nearly a constant but in any event can be calculated to a high degree of accuracy if the mineralogic composition is known, since it is a mass related phenomena. The other property of interest is the diffusivity, which is the ratio of a material's ability to conduct heat to its ability to retain heat. Diffusivity can be determined experimentally, but it is a much simpler matter to calculate it once specific heat, density, and conductivity are known.

DRILLING PERFORMED DURING THE STUDY

All of the tests which can be used for characterization and classification, with the exception of two borehole tests to be described in this section, have already been described. Provided that the core quality had not degraded, the tests performed on core from previously drilled boreholes would be valid. The important point to note is that tests performed on core obtained during a pre-characterization study, providing that the core was properly stored, will provide data which is characteristic of the in situ properties. There is no guarantee, however, that core tests performed on core which was obtained in a previous study would be representative of the in situ conditions of interest. It is important to obtain data that is indicative of in situ conditions if the characterization is to be meaningful; it may, therefore, be more logical to concentrate laboratory testing for characterization purposes in this phase of site exploration. This is certainly the case for those rock types which are most sensitive to degradation.

BOREHOLE MODULUS TESTS

a) Applicability: Two types of borehole test are available for estimating the rock mass modulus: the Goodman jack and the CSM cell. In the case of the Goodman jack, hydraulic rams are used to force curved (90° arcs, 1.5 inches radius) steel platens against opposite segments of the borehole wall. Loads can be directed, thereby allowing anisotropic modulii to be recorded. In contrast, the CSM cell loads the borehole walls by pressurizing an adiprene membrane over the complete 360° surface of the borehole. The cell is calibrated to determine the volumetric stiffness of the fluid lines. Modulus determination depends on measurement of volume change. High sensitivity is required when high modulus rocks are to be characterized. Both techniques can be applied to a wide range of rock types, i.e. from shale to granite. At present, CSM cells are designed to operate in 38mm (EX) holes, and Goodman jacks in 76mm (NX) holes.

b) Procedure: The CSM cell is calibrated in a large aluminum block in the laboratory, so that the change in borehole volume at a given measuring point can be separated from the volume change of the system; i.e. the fluid lines, transducer membrane, etc. Pressure-volume curves are obtained at each measuring point down the given borehole. The rock modulus is calculated from the measured modulus of rigidity and Poisson's ratio. Analysis indicates that the radial and tangental stresses 40mm from the borehole wall are only 10% of those at the wall. The presence or absence of joints in the 165mm long test section should be recorded from borecore logging to aid in the interpretation of results.

The test procedure for using the Goodman jack is straightforward. However, derivation of rock modulii from the force-deformation measurements is complicated, due to the probability of slight mismatch between the borehole and platen radii. The assumed half angle of contact (45°) which is critical for determining the modulus can therefore vary with pressure. The maximum value of 45° which gives a lower-bound to the modulus is seldom achieved in practice. Several methods have been proposed for improving the interpretation.

c) Cost: It is difficult to totally separate the cost of borehole modulus from all other drilling operations since there is a fair amount of overlap of personnel. Approximately two man-weeks of personnel effort would be required for a borehole modulus test and the equipment rental for a 1000' hole would be less than $5000. The CSM cell would probably be less expensive than the Goodman jack, but it is not commercially available, so prices have been estimated.

d) Exceptions: The CSM cell cannot be used at distances from the borehole collar exceeding about 50-100 meters, due to the problem of system stiffness masking rock response. Its use is therefore limited to near-surface characterization, unless mines or exploratory shafts are available.

IN SITU STRESS STATE

a) Applicability: The stability of rock openings, especially those with appreciable spans is largely determined by the state of initial stresses in the rock in combination with the joint properties. Stress data is useful for comparison to the strength properties of the rock mass: this aspect is probably most significant in weak rock. The stress data can also be used to estimate the maximum shear stress in the rock mass which is of particular importance if the mass is jointed. If the opportunity is presented during a drilling program, the magnitude and orientation of the in situ stress state can be measured in a borehole by any one of numerous techniques. However, most of those techniques involve overcoring of an EX (1.5") diameter hole, which has an emplaced stress gage, with a six inch diameter coring bit. With the exception of measurements made by the two techniques described in this section, successful measurements are rarely made at depths greater than about 100 ft from the surface. Repository design requires knowledge of the stress field at greater depths; the discussion which follows is predicated on the assumption that stress measurements have to be made at a depth of 1000 ft. The overcoring technique developed by the Swedish State Power Board has been used at this depth, but this is certainly approaching the limits of this device. Hydraulic fracturing, on the other hand, is routinely utilized at these depths, and, in fact, depths of 10,000 ft pose no problems for the method.

b) Procedure: The described overcoring method is useable at depths approaching 1000 ft for several reasons: wireline gage setting techniques are utilized thus eliminating the need for stringing electrical cable inside drill pipe; the overcoring is accomplsihed by NX (3 in) over EX (1.5 in) and, the development of a remotely triggered device for gluing strain gages to the wall of the well bore. In use a borehole with a diameter of 76 mm is drilled to the desired depth. The last core is broken perpendicular to the borehole axis. The small bore with a diameter of 36 mm is centered exactly on the bottom of the larger bore and drilled for about 400 mm. By means of the small core, it can be judged whether the rock is without joints and is of a suitable quality for measurement. Also, undulations or an otherwise unsuitable quality of the bore wall can be judged with the help of the core. If the conditions are not fulfilled, the 76 mm bore must be continued and the above procedure repeated. The bore must be thoroughly washed (about 30 minutes at 2 MPa overpressure in a hole 300 m in depth) before the small core is hoisted, in order that all rock flour from the drilling may be removed. While the probe is hanging over the borehole, the acryl glue is mixed;

the glue pot is filled, and the rosettes are submerged in the glue. Then the probe is lowered into the borehole, rather quickly at first (it is braked by the water in the hole) and very carefully for the last few metres. Finally, the glue pot and the strain-gage carrier are inserted into the small hole.

When the correct position for cementing (this position is adjustable) is reached, two pinpoints touch the bottom of the large bore. The mechanism is triggered off and the weight in the probe pushes the glue pot downwards and liberates the tongues of the gage carrier. Next, the downwards-moving, central cone presses the tongues against the bore wall. During the hardening of the cement (about 2 hours), there is time to heat the compass electrically, so that the fluid, a soft wax is melted and the compass needle can adjust itself. There is also time for the fluid to freeze again. At the end of the hardening time, the nine strain gages are measured for the first time. A correction must be made for the reduced sensitivity of the gages because of the non-negligible resistance of the long wires. For measurements at depths exceeding 300 m, it is best to use special measuring circuits, in which case the measurements will become independent of the resistance of the wires.

At the start of the upward movement, the gage carrier is unhitched and the wires cut off. The carrier is left in the borehole with the gages. By overcoring with the 76 mm bit, a de-stressed, hollow core with the gages is obtained. As soon as this core has been hoisted, the wires of the gages are connected again to those of the probe. The gages of the now relaxed core are measured again, using exactly the same wiring as previously in the borehole. During this second measurement, the core must be carefully kept at the same temperature as it was in the borehole. In order to observe any creep and the influence of any intruding water, the measurements are continued for about two hours. Including local drilling and a hardening time of 2 to 3 hours, one measurement at a depth of about 200 m requires about 5 hours, if no complications occur. Two points close to each other can thus be measured during a long working day.

Finally, the magnitudes and directions of the three principal stresses of the stress tensor can be calculated for the core from the measurement data, essentially according to the formulae of Leeman and Hayes. In most cases, the rock material is not quite isotropic but more or less orthotropic as regards its modulus of elasticity and Poisson's ratio. The simplest approximation, however, is to use mean values of the elastic constants in the calculations, as if the material was isotropic.

At greater borehole depth it may be necessary to introduce a correction for the additional stresses caused by the water column above the measuring point, stresses which are unloaded while the core is being hoisted. These additional stresses around the borehole, and the resulting strains in the direction of every strain guage can be calculated according to the theory of elasticity.

The technique of stress determination by small scale hydraulic fracturing techniques is well documented and has, in fact, historically been the only method available to obtain data at depths greater one hundred meters. The method is based upon an exact elastic solution to a stress distribution problem and involves pressurizing a section of a borehole and increasing fluid pressure until the rock breaks.

The implication of the uncertainties in the magnitude and even the physical meaning of the breakdown pressure, and the degree of uncertainty associated with the value of the rock tensile strength, is that large errors may be introduced in the magnitudes of in situ stress determined by classical hydraulic fracturing theory. It has been suggested, in fact, that hydraulic fracturing should only be used to determine the magnitude of the minimum principal stress and its orientation. However, from a pressure-time record based upon re-opening pressures, it is possible to calculate, with a fair degree of accuracy, perhaps to within 10%, minimum horizontal stress; the maximum horizontal stress cannot be measured as accurately but can be estimated within bounds of approximately 30% based upon results of comparisons of hydraulic fracturing measurements to overcoring measurements.

The technique of hydraulic fracturing for stress determination involves lowering a straddle packer, consisting of a mandrel connecting two inflatable packers and a carrier for down-hole pressure monitoring equipment, down the borehole to the required depth. The inflatable packers are inflated and the region between them is then opened to the surface in the drill pipe. Surface pumps are used to pressur· the interval between the packers. A pressure-time record is recorded and it typically exhibits the recognizable characteristics of breakdown,propagation and shut-in. The shut-in response is a manifestation of the equilibrium between the fluid pressure in the fracture and the minimum horizontal stress. The fracture can be shown to propagate in a direction normal to the minimum stress direction. The minimum horizontal stress is thus directly measurable. The maximum horizontal stress is calculated from elastic analysis of stresses around a wellbore. The wellbore is assumed parallel to a principal stress direction, in this case, vertical.

The orientation of the hydraulically induced fractures is determined by wrapping an inflatable packer with soft rubber, going back down the borehole to the depth of testing and inflating the packer. The soft rubber extrudes into the fracture; upon deflating the packer, a negative image of the fracture is obtained. The packer and thus the fracture are oriented by means of a downhole compass; the orientation of the fracture defines the orientation of the stress field because the fracture always propagates in a direction perpendicular to the minimum principal stress.

c) Cost: The costs of a stress determination program is extremely difficult to estimate due to the large number of interacting variables. Typical costs of personnel and equipment for the overcoring method would be in the $40,000 to $60,000 range per hole, exclusive of rig costs. The hydraulic fracturing technique is slightly more expensive, in the $50,000 to $70,000 range per hole, including service company costs, but again, excluding rig time.

d) Exceptions: The overcoring technique would be difficult, if not impossible, to perform in a borehole in poor quality rock. The hydraulic fracturing technique introduces a fracture in the rock mass; the fracture has small areal extent but it nevertheless could be a cause for concern of breaching the integrity of the repository. Some thought probably must be given to pressure grouting after a test of this nature.

APPENDIX E-2
GEOMECHANICAL/THERMAL TECHNIQUES
FOR
SITE CHARACTERIZATION STUDIES

E-2

By
Terra Tek, Inc.
Salt Lake City, Utah

November 1, 1981

INFORMATION NEEDS FOR SITE CHARACTERIZATION

Topical Report

SITE CHARACTERIZATION TECHNIQUES

Suggested Methods for Measuring the
Geomechanical and Thermal Properties
of Rockmasses

Submitted to:

ERTEC Inc.
3777 Long Beach Boulevard
Long Beach, CA. 90807

TR 81-68
July, 1981

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1. OBJECTIVE

The objective of this topical report is the description and evaluation of suitable techniques for measuring the geomechanical and thermal properties of a potential repository site. Techniques applicable to site selection studies, using surface mapping, drill core analysis, and drill hole testing were summarized in a previous topical report (TR 81-33, April, 1981). In the present report, site access is assumed, but testing methods would be pre-construction in nature. A test room at the bottom of the first access shaft is the assumed test scenario.

The statement of work requires that the jointed media: granite, tuff, basalt and shale; and the plastic media: domed salt and bedded salt, are all considered as potential repository host rocks. Test techniques, applicability, costs and time will vary accordingly. Test techniques are to be described and documented so that NRC staff can assess the adequacy of exploration and test results likely to be presented in a site characterization report.

2. SCOPE

Surface mapping and drilling surrounding a potential site will have provided only a crude picture of the detailed geological structure, due to the limitations of near-vertical drilling. Horizontal access from a drilling adit and test room at the base of an exploratory shaft at, for example, 1000 meters depth, will allow improved exploration and sampling from a representative area of the potential repository. Many of the pre-characterization tests described in the first topical report will need to be performed in greater detail. These will include the following tests and characterization parameters:

A. Measurements during shaft and test room excavation, and from drill core.

1. point load tests 2. Schmidt hammer tests	estimation of unconfined compression strength during core logging
3. discontinuity description tests: (ISRM, 1978)	(i) orientation (ii) spacing (iii) persistence (iv) roughness (v) wall strength (vi) aperture (vii) filling (viii) seepage (ix) number of joint sets (x) block size
4. RQD	

B. Measurements on prepared laboratory samples:

5. porosity/density
6. water content
7. absorption
8. swelling and slake durability
9. sonic velocity
10. unconfined compression strength
11. E modulus of deformation; Poisson's ratio
12. triaxial compression strength
13. permeability
14. thermal conductivity, specific heat, diffusivity
15. coefficient of thermal expansion

(items 9–15: ambient and as a function of temperature)

16. borehole modulus (Goodman jack, CSM cell)
17. in situ stress measurement by overcoring (modified Leeman, USBM, CSIRO, etc.)

The present topical report will address the larger scale tests that can be used for site characterization. Particular emphasis will be placed on test methods that incorporate a representative volume of rock mass, such that jointing (in jointed media) and inhogomeneities (in salt) are sampled.

Full scale heater arrays and time-scaled heater tests as performed at Stripa and Climax will not be described, as these are considdred to be primarily engineering design tests. Experimentation with heater levels and canister design will determine suitable waste distribution patterns within the repository as a whole. Emphasis would be directed towards the avoidance of thermally induced decrepitation and retrievability problems (Cook, 1978).

Thermo-mechanical rockmass properties can, of course, be estimated from heater experiments of this type, if displacements and rock stresses are monitored (Chan et al, 1980a). However, experience has shown that the complex and poorly defined boundary conditions are major drawbacks. More reliable thermo-mechanical data are obtained at reduced cost from large block or cylinder loading tests, in which stresses, loading rates and temperatures can be controlled independently.

3. KEY PARAMETERS FOR CHARACTERIZATION

According to the theory of linear thermo-elasticity, thermally induced displacements are determined by the coefficient of thermal expansion (α) and are weakly affected by Poisson's ratio (ν). Displacements are independent of the value of Young's modulus from one constant value to another (Timoshenko and Goodier, 1951). Thermally induced stresses are linearly proportional to the product of Young's modulus and (α), and weakly dependent on ν (Chan et al 1980b).

The lower deformation modulus (E) of a jointed rockmass, and its non-linearity as compared to that of an intact laboratory sample, means that both the thermally induced compressive stress components within the heated zone, and the thermally induced tensile components outside the heated zone, are likely to be less than calculated from the results of laboratory tests (Cook, 1978).

According to experiences from Stripa, the displacments calculated using laboratory values agree better with field data than is the case for stresses. However, it is important to measure and use temperature dependent values of α, E, ν and thermal conductivity (k). The temperature dependence of (α) has the most significant effect on displacments (Chan et al 1980b). Clearly the value of thermal conductivity will also be important, as this determines the temperature level, thereby influencing (α) and (E).

A key component of the thermal and stress dependence of (α) and (E) on the scale of the rock mass, is the compliance of joints. Both the normal and shear stiffnesses (K_n and K_s) of joints are stress dependent, and recent results of a heated block test (Voegele et al 1981) suggest that K_n may also be temperature dependent. It is known from extensive documentation that K_s is size dependent (Barton 1981). Large-scale testing is therefore a top priority for determining representative values of α, E and K_s.

Numerical modelling of the rockmass response to the thermal pulse will also be dependent on the correct measurement or constitutive modelling of shear strength-displacement and dilation paths. Even small magnitudes of joint dilation caused by limited shearing will cause potentially serious increases in joint permeability (Maini, 1971, Barton, 1981). Methods will therefore be needed for quantitatively characterizing joint roughness at large scale, so that dilation and permeability can be correctly coupled. Fortunately, a rough joint which has the potential for exhibiting greatest permeability-dilation coupling, will also be the most stable from the point of view of tunnel integrity.

While this topical report is directed chiefly towards geomechanical and thermal properties, and not towards hydrologic properties, it must be emphasized that changes in hydrologic properties are chiefly a result of geomechanical (and thermal) properties. Since this aspect is unlikely to be addressed in detail in hydrologic documents, suitable test methods will be described here.

Repositories sited in rocks prone to stress and temperature-induced creep (i.e. dome salt, bedded salt and the weaker shale rocks) will need to be characterized with particular care. It is known that too-rapid loading or unloading of salt causes dilation and lattice damage. Slow, careful excavation and slow loading rates over a long test period (with and without slow temperature coupling) will provide the most relevant primary creep coefficients for simulating repository scale behavior. Brine migration towards the heat source also needs special characterization methods.

4. HYDROTHERMOMECHANICAL (HTM) IN SITU BLOCK TESTS

4.1 DESCRIPTION

4.1.1 Test Parameters

As the name implies, this is a comprehensive in situ test designed to provide quantitative characterization of

- E (modulus of deformation)
- K_n (joint normal stiffness) — ν (Poisson's ratio)
- α (coefficient of thermal expansion)
- k (thermal conductivity)
- K_j (joint permeability)

Each of the above parameters is determined as an independent function of stress and temperature, and as a function of coupled stress and temperature. The block test facility should also be used for cross-hole sonic velocity and acoustic emission monitoring. Since these two tests will be described in other topical reports, they will not be treated here.

4.1.2 Precedence

By way of a footnote, it should be mentioned that one HTM block test has been performed at this time. However, the success of the test (for granitic gneiss) indicates that it is likely to become a standard method for repository site characterization. This was also the reason why the test was funded by ONWI. A second test is in the early stages of devel-

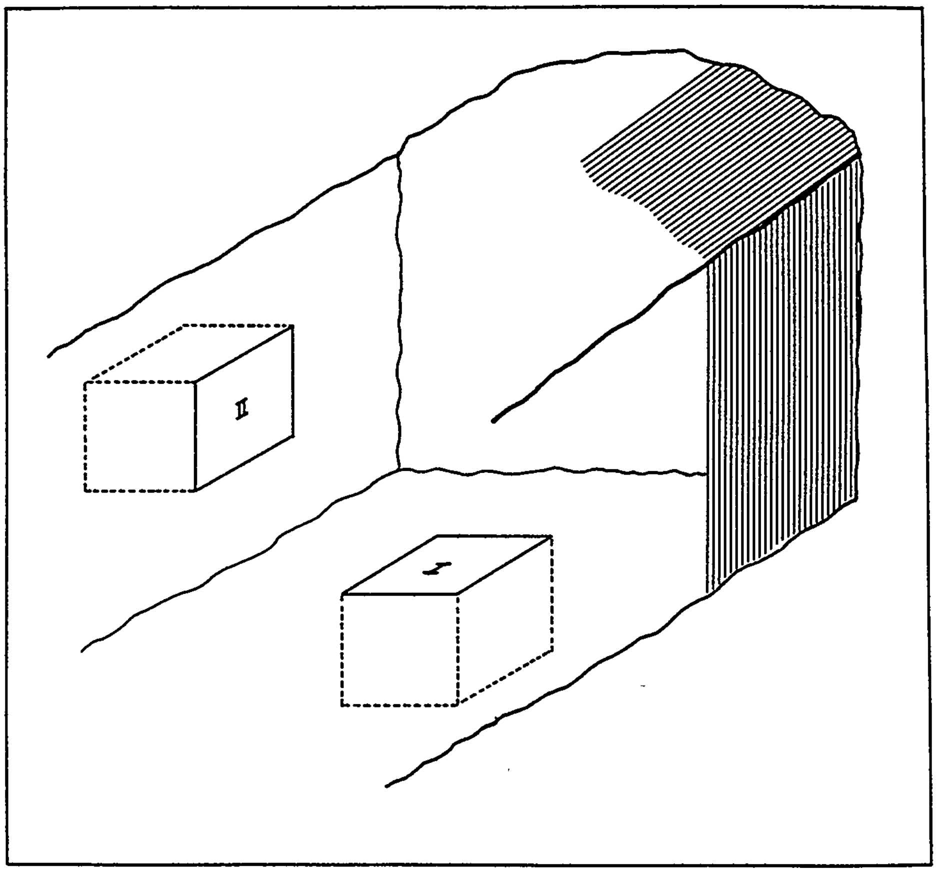


Figure 1. The HTM block test should be performed on a representative block of jointed rock, located in the floor or walls of a 10m span test room.

opment in jointed basalt (Rockwell-Hanford Reservation, Washington) and a third is now under active planning for characterization of jointed tuff (Sandia-Yucca Mountain, Nevada).

4.1.3 Block Location

The block test can be performed in the floor or walls of a test room (Figure 1). Smooth-wall blasting is a prerequisite. Test room dimensions of ca. 10m are recommended for best thermal parameter data. The block itself should be at least $8m^3$ in volume, i.e. at least 2 meters on a side. The block should be located, as far as practicable, in the center of the floor or wall in a representative body of the jointed media.

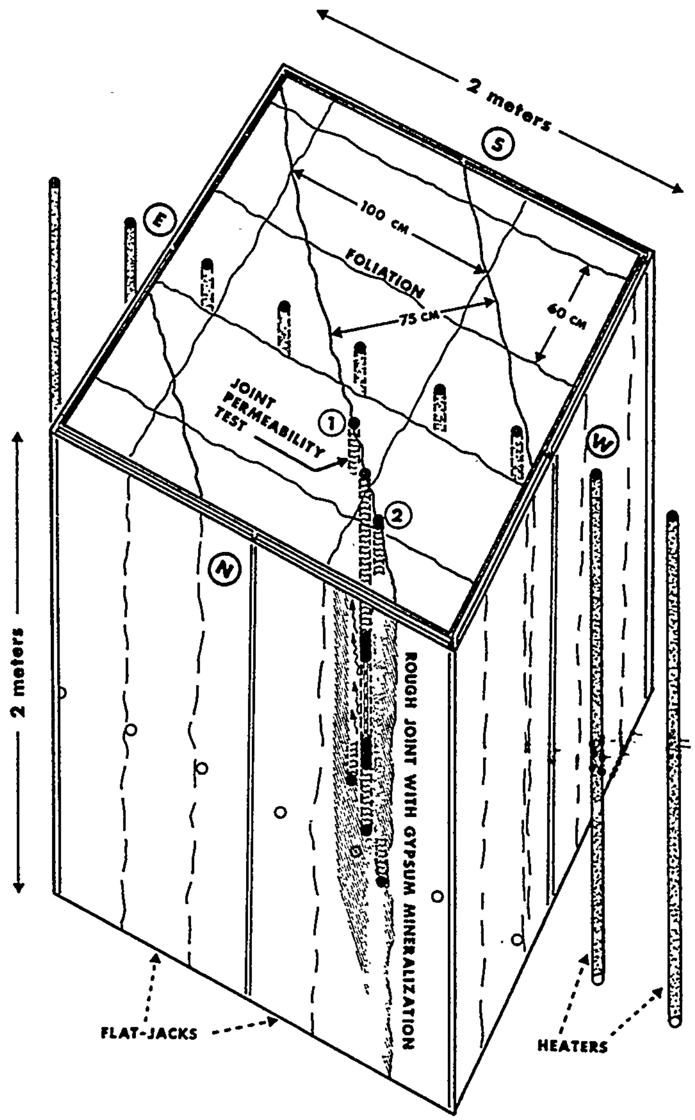
4.1.4 Joint Sampling

In view of the presumed importance of vertical or steeply dipping jointing to the hydrologic integrity of a repository, these joints in particular should be carefully sampled by appropriate location of the block. (Horizontal drilling from the test room in at least two directions should determine the joint-sampling priorities.) A schematic example of the jointing sampled in Terra Tek's HTM block test in granitic gneiss (CSM experimental mine, Colorado) is shown in Figure 2. The optimum orientation of the block will be corner to corner (diagonal) sampling of the top-priority joint set. This will allow both normal and shear stress to be applied, by appropriate flatjack loading.

4.1.5 Slot Drilling

Core drilling of over-lapping holes using a drill guide in the harder rocks (granite, basalt, tuff), and broaching of the web between closely spaced holes in the softer rocks (shale) are recommended. Drill core should be carefully oriented and logged (applies to primary holes only). If block side dimensions of 2 meters are chosen, then slot depths of at least 2.5 meters are recommended. Flatjacks should be grouted in place

Figure 2. Schematic block diagram showing the relationship of the average joint structure to the flatjacks and the line of borehole heaters in Terra Tek's HTM block test of granitic gneiss.



upon completion of each slot, to reduce disturbance to the rock mass to a minimum. It is recommended that fine sand is used to fill the lower 0.5m of each slot, before grouting the flatjacks in place. This technique will reduce the stiffening effect of the intact base of the block.

4.1.6 Flatjack Loading

An $8m^3$ block will require $16m^2$ of flatjacks to load the four sides released by slot drilling. For convenience of handling, flatjacks of 2 x 1 meters size are recommended. After suitable greasing or coating with double "Teflon"(PTFE) sheeting, the flatjacks should be placed in pairs, centrally opposite pairs will be equally stressed using a hydraulic system similar to that sketched in Figure 3.

4.1.7 Heating

The central line of heaters shown in Figure 2 extended to a depth of 4 meters. Quite well defined and predictable temperature gradients were recorded by numerous thermocouples distributed throughout the block. Heater power outputs of 500 watts or 1000 watts per borehole applied for a period of approximately 1 month are capable of heating an $8m^3$ block to the desired maximum temperature. However, there are certain disadvantages to this relatively inexpensive single-plane heating method. Since temperatures vary in planes perpendicular to the heater plane, interpretation of some test results depends on extrapolation and empirical approximation procedures.

A more expensive but reliable method would be achieved with guard heaters outside the block. Two parallel rows of heaters, extending in length to at least twice block dimensions, with insulation of an extensive area of the floor of the test adit is recommended. This would enable the block to be raised to a more or less constant temperature. The central heater array could be used at lower power levels to establish a gradient

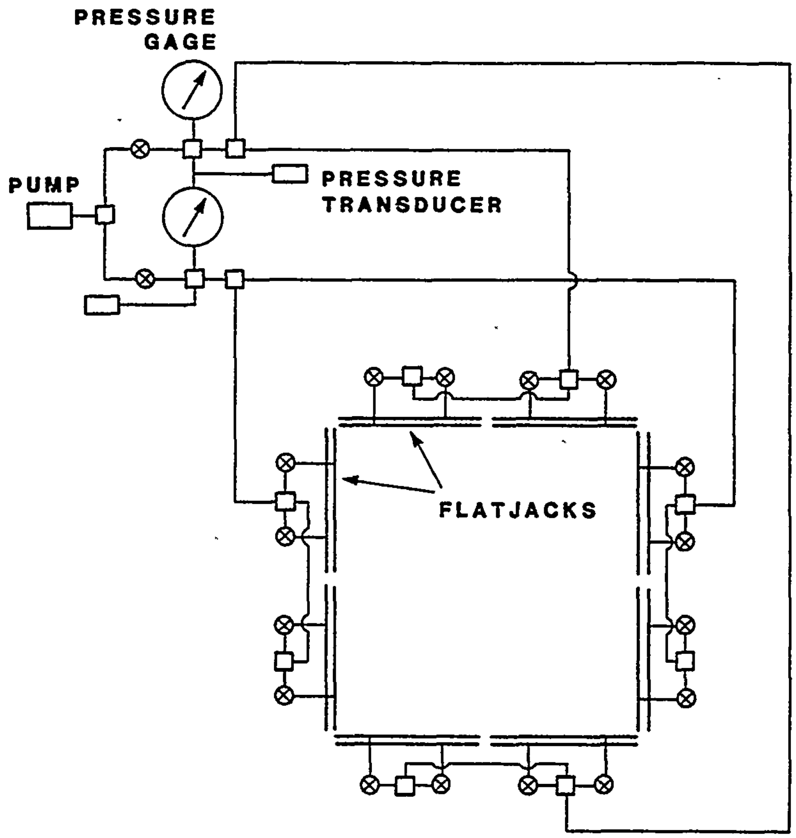


Figure 3. Schematic of a suitable flatjack loading system. The flatjacks are paired to reduce the chance of loss of loading through rupture.

which would allow calculation of conductivity at a variety of temperatures (and pressures). One single central heater could in fact replace the line of heaters to reduce costs.

4.1.8 Testing Matrix

The test matrix will depend on the repository depth. Ideally, stress levels up to 20 MPa should be applied, with instrument scanning (or manual reading) at intervals of 5 MPa (or less) during loading and unloading. Three equal biaxial load cycles at ambient temperature are recommended first, to ensure that joint disturbance caused by slot drilling (and previous blasting) is eradicated. Joint closure tends to be more pronounced on first loading, and artificially low deformation moduli will be recorded.

Figure 4 illustrates an appropriate test matrix for the initial equal biaxial (zero shear stress) loading. The most relevant performance data will probably be obtained in the 10-20 MPa, 60-100°C ranges. Stress cycling with constant temperature (paths 3, 5 and 7) and temperature cycling with constant stress (path 8) will provide data for constitutive modelling. Since coupled stress and temperature increase and decrease are relevant to the thermomechanical cycle to be experienced by the repository, validation of models against paths 4,6&9 should be an important goal.

Following the unloading/cooling path 9, it is recommended that uniaxial (shear) loading is initiated. Due to the strong path dependency and hysteresis involved with shearing, it is recommended that loading and unloading along path 9 is followed. As illustrated in Figure 5, activation of a N-S pair of jacks will cause shearing in one direction. Reversal, also along path 9, would be achieved by activating the E-W pair of jacks.

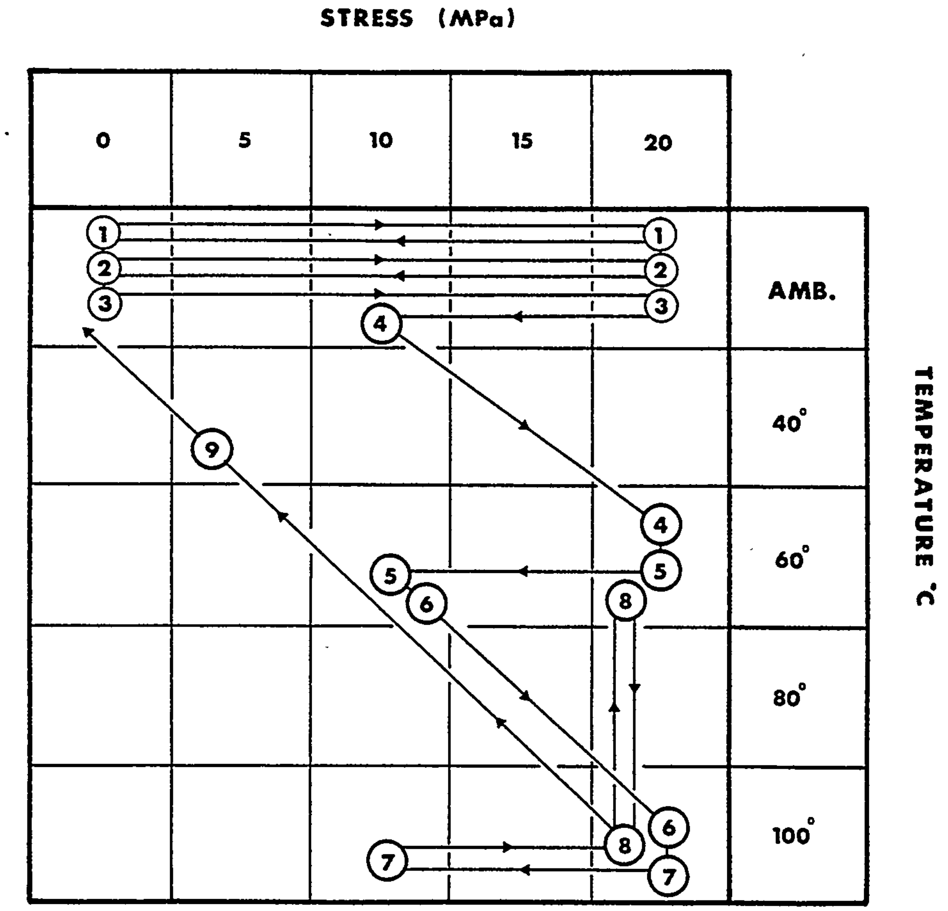


Figure 4. A suggested thermo-mechanical test matrix for simulation of heating and cooling, and stress increase and reduction effects. This test matrix shows a suitable primary equal biaxial loading sequence, which should be followed by uniaxial (shear) loading and unloading.

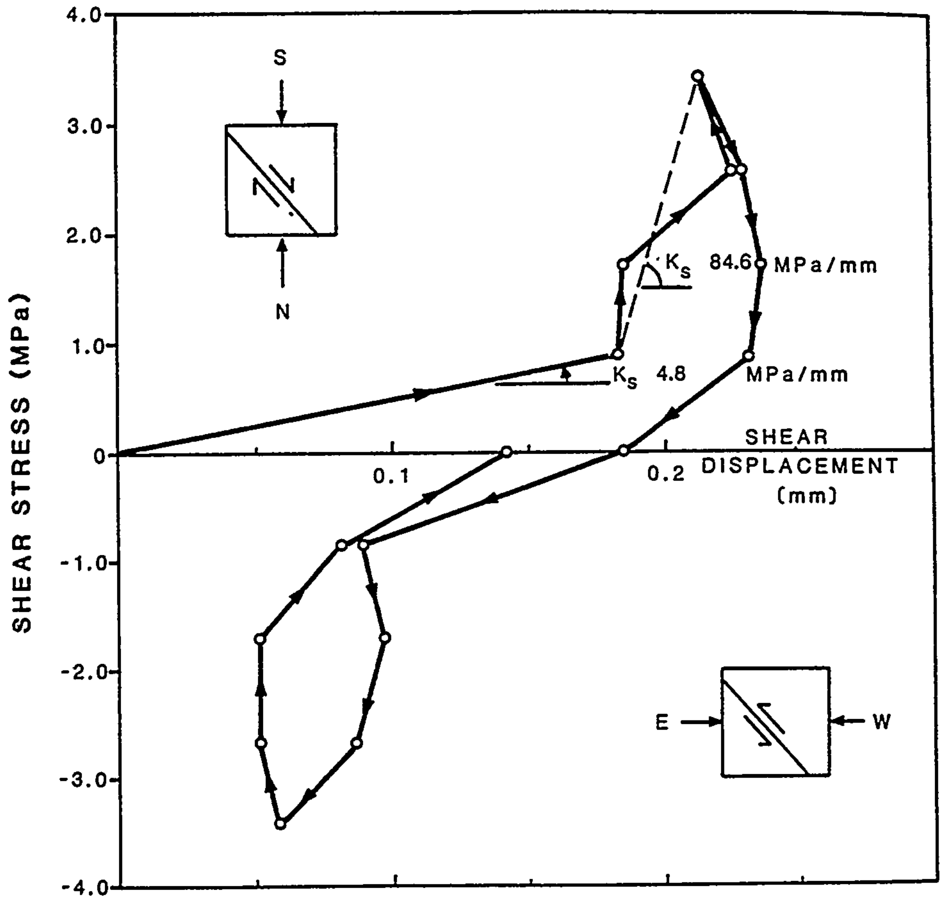


Figure 5. Example of joint shearing and reversal caused by N-S and E-W uniaxial loading, from Terra Tek's HTM block test.

4.1.9 Instrumentation

Due to the large area-thickness ratio of the flatjacks, the block boundary stresses will be accurately known from the pressure gauges and transducers coupled to these flatjacks (Figure 3). These principal stresses will be resolved into normal and shear components along the relevant joints, for the case of the uniaxial load cycles just described.

In general, stresses will be controlled, and the stress distribution can be calculated from elastic analysis using the known boundary stresses. However, strains and displacements will need to be monitored with a specific instrumentation program. The directional deformation of the whole block, and the individual deformation of prominent joints intersecting the block will be required, for all the stress-temperature cycles.

Surface measurements of strains and displacements can be readily accomplished using a combination of horizontal strain indicator (HSI) gauges (LVDT's), and Whittemore (manual dial gauge) readings. Gauges located across the slot boundaries of the block can be used to monitor the width of the crack which forms in the grout above each flatjack. An elastic solution (Figure 6) can be used to derive values of the block deformation modulus. Gauges located across individual joints can be used to monitor joint apertures and joint normal stiffness. Since a gauge length of 25cm (10 in.) between measurement posts is usually involved, the deformation of 25cm of intact rock (or rock and grout) needs to be subtracted to obtain crack or joint displacements. Reliable, directional values of the E modulus represented in each gauge length are required. As illustrated in Figure 7, stress-strain data measured in situ tends not to be linear due to the influence of microcracks and minor jointing. Selection of appropriate E moduli therefore involves some uncertainties.

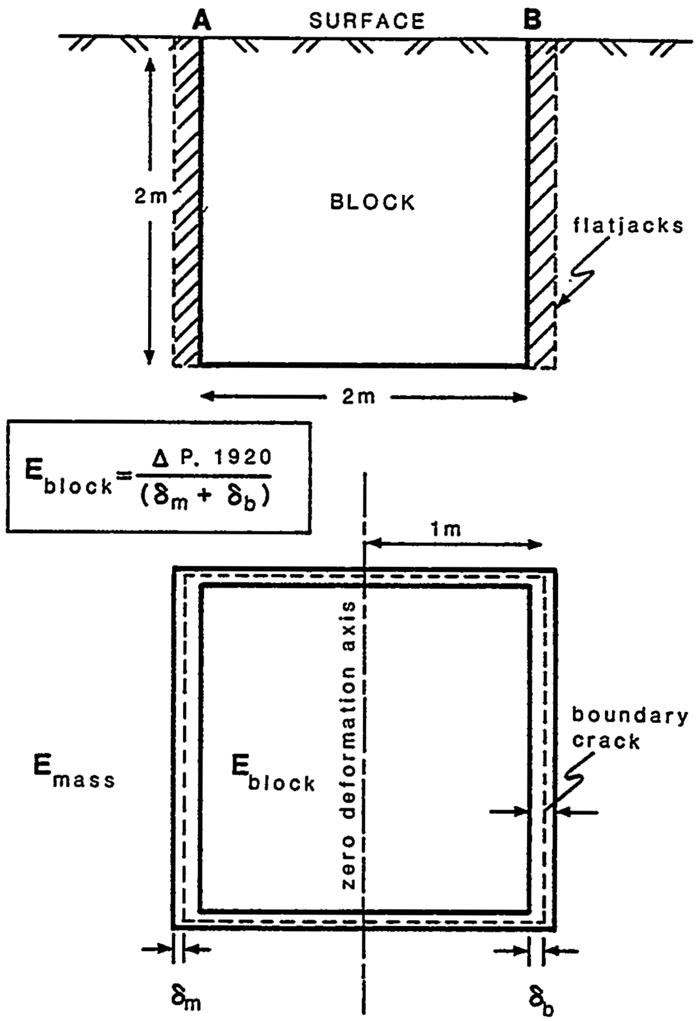


Figure 6. Derivation of the block deformation modulus from the boundary crack aperture changes, from elastic solution of Davis and Poulos (1970). For derivation, see Terra Tek, 1981 (ONWI Contract E512-04700).

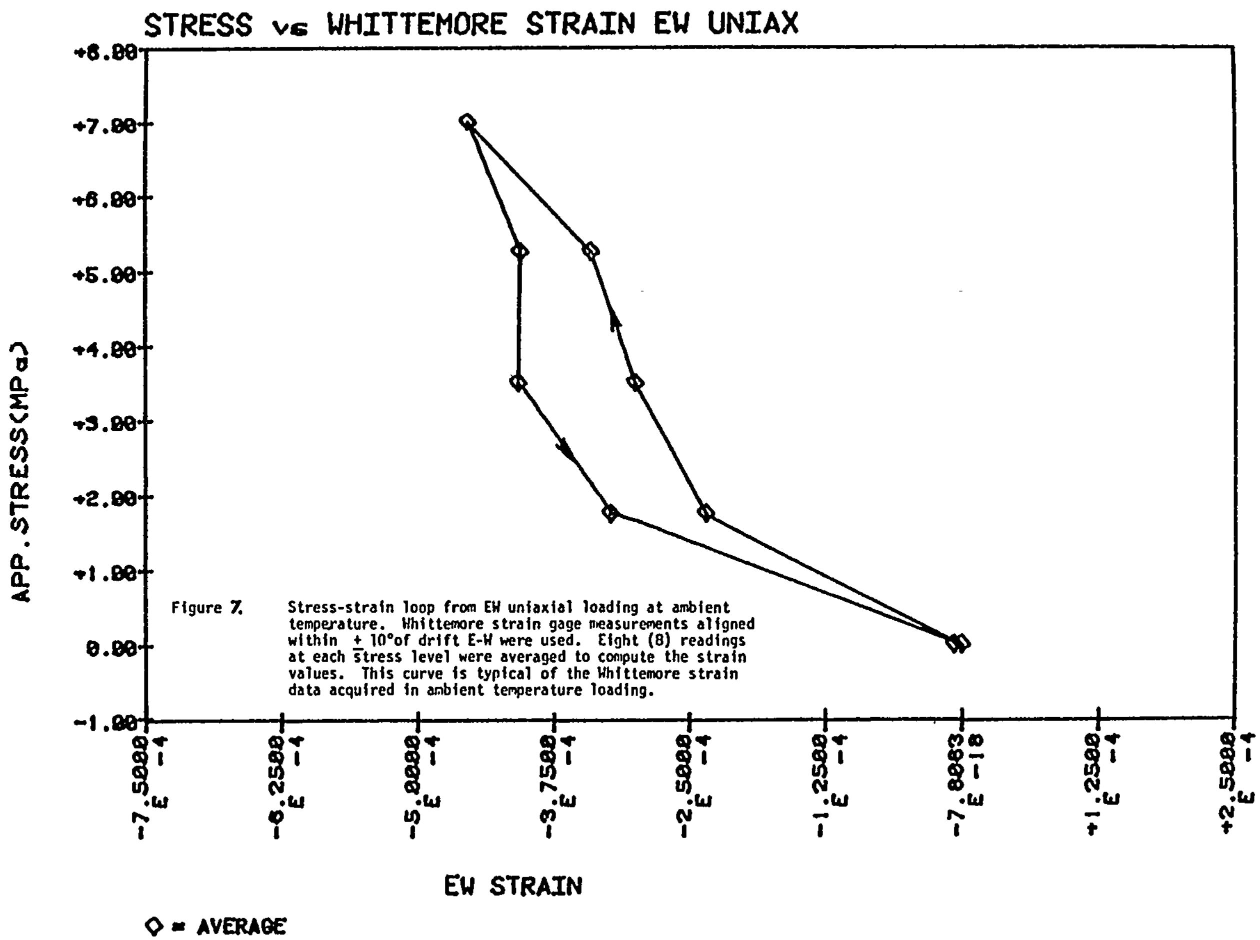


Figure 7. Stress-strain loop from EW uniaxial loading at ambient temperature. Whittemore strain gage measurements aligned within ± 10° of drift E-W were used. Eight (8) readings at each stress level were averaged to compute the strain values. This curve is typical of the Whittemore strain data acquired in ambient temperature loading.

Subsurface strain and deformation data can be obtained from multiple position borehole extensometers (MPBX's). Installation of vertical MPBX's in holes within the block poses few problems, so reliable values of Poisson's ratio should be obtained. A useful method of monitoring joint aperture changes within the block is to drill coaxially down individual joint planes and locate borehole deformation gauges across the joints.

The measurement which causes considerable problems is the horizontal strain and deformation within the block. Several approaches are possible. Sub floor-level access from an adjacent drift and from a floor recess in the same test drift would allow horizontal drilling through the block from two perpendicular directions. Modified MPBX gauges could be located within the block after slot drilling. This would allow direct calculation of deformation moduli. An indirect method requiring elastic theory for interpretation (as in Figure 6) would be the use of flatjack deformeters. Strain-gauged cantilevers installed inside the flatjacks would allow sub-surface boundary crack apertures to be monitored. However, calibration of instrumented flatjacks of $2m^2$ size at realistic stress and temperature levels would be an expensive operation.

Alternative solutions, which are presently being tested in rockmasses, consist of optical down-hole methods. Photo voltaic and interferometer techniques can, in principle, be used to detect lateral sub-surface strain, when installed in adjacent boreholes. However, the quadrant detectors and reflectors required in these two methods might be adversely affected by high temperatures.

4.1.10 Joint Permeability

During site selection and site characterization studies, estimates of the variation in aperture (e) for the different joint sets intersected by drill holes could be back-calculated from flow tests, using closely spaced double-packers coupled with a method for accurately locating the packers across joints. With wider-spaced packers, estimates of (e) could be based on the statistical method proposed by Snow (1968), which provides a useful estimate of the mean conducting aperture (e), and also the mean spacing of the water conducting joints (S), assuming the rock mass can be idealized by a cubic network of water-conducting joints.

In each case, the estimated apertures will reflect the effective normal stress levels operating across the joints at the various test levels. Care will need to be taken to pump at very low excess pressures, so as not to reduce this stress level and cause opening of the joints, close to the borehole walls. Since it would be difficult to monitor such changes in aperture, the borehole pump-in test should essentially be an investigation of "fixed" apertures, with a degree of built-in uncertainty.

The HTM block test is essential for investigating how the above "baseline" conducting apertures change as a result of changes in the total normal stress, shear stress and temperature, or coupling of all three. In Terra Tek's HTM block test, the diagonal joint intersecting the block (Figure 2) showed variations in conducting aperture from 60μm to 9μm in response to stress and temperature perturbations of no more than 7 MPa and 60°C. This variation represents a potential 45-fold increase in transport time for an equally stressed and heated region.

At least two of the steeply dipping or vertical joints intersecting the block should be drilled with three coaxial, parallel holes spaced at about 0.25 - 0.5m, or as determined by joint spacing. The central hole of each trio is used for injection from between straddle packers, and the two outer holes for monitoring flow rate. The core recovered

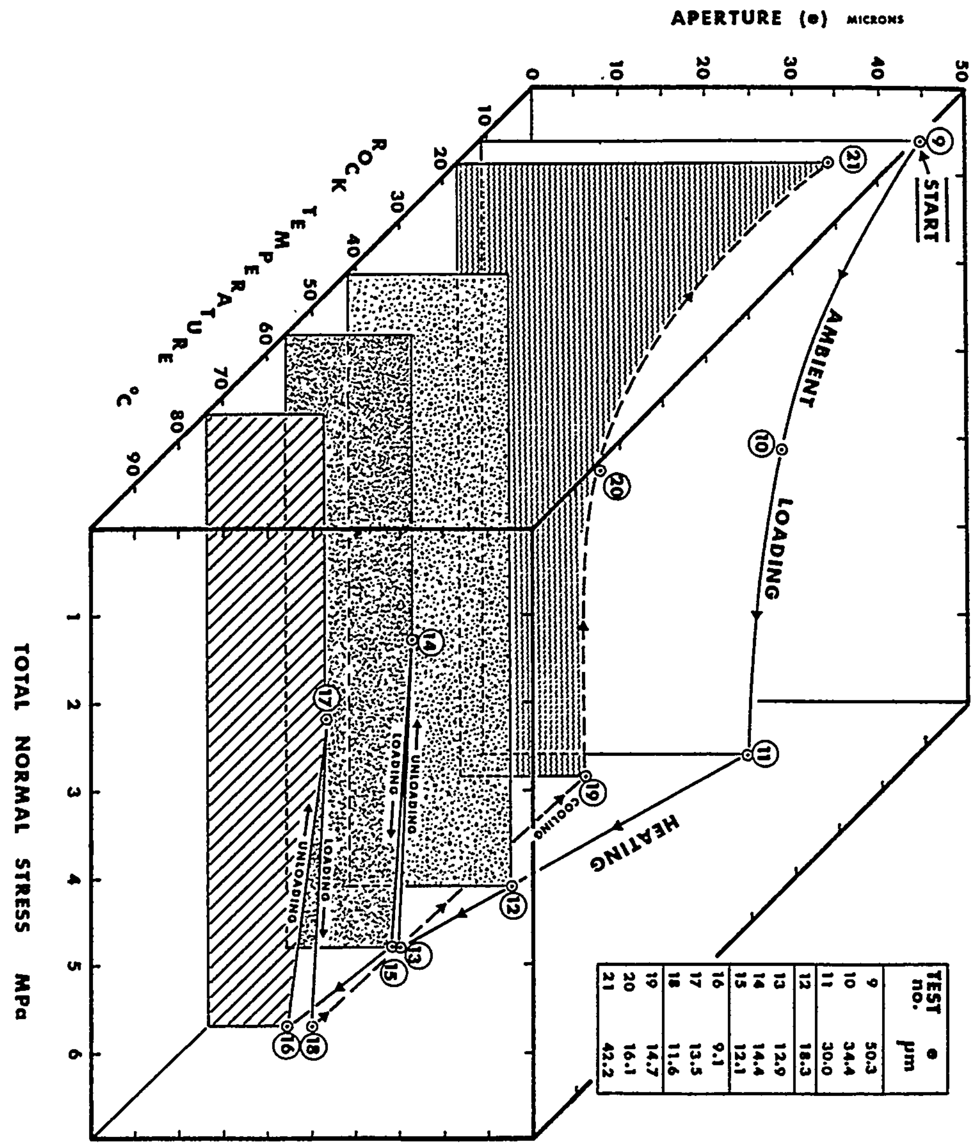


Figure 8. Biaxial loading at elevated rock temperatures facilitates hydrothermo-mechanical coupling causing dramatic reductions in flow aperture (Voegele et al. 1981).

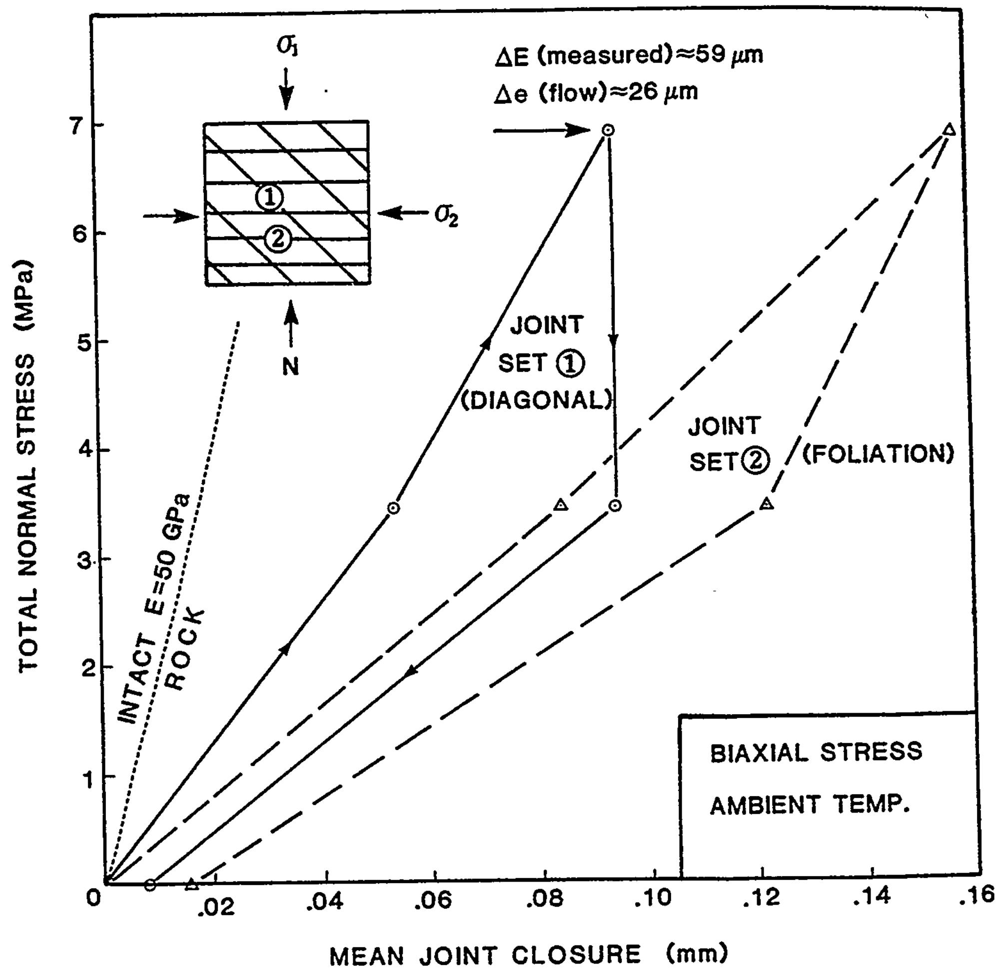


Figure 9. Example of joint normal stiffness measurements from Terra Tek's (1981) HTM block test. Measured changes in joint aperture (ΔE) exceed the changes in conducting aperture (Δe).

from these holes should be carefully examined to check if the joint passes outside the holes. The packers should be spaced at about 0.25 - 0.5m, or as determined by joint spacing. In general, linear (as opposed to radial) flow should be aimed for, with no secondary joint intersections in the test section. This will simplify interpretation. Interpretation of flow test results under both normal and shear stress using the well-known "cubic flow" law is illustrated by Voegele et al. (1981). The potentially positive result of thermomechanical coupling illustrated in Figure 8 demonstrates the importance of this test option. A key feature of the test results, discussed in detail by Voegele et al. (1981) is the different magnitudes of the real apertures and conducting apertures. This is illustrated in Figure 9.

4.1.11 Data Acquisition System

Data acquisition requirements will vary with the number of automatic readout instruments installed. Borehole joint-deformation gauges, MPBX instruments, horizontal surface strain indicators, flatjack pressures, thermocouples are scanned automatically, using back-up systems for data storage. A data logger operated from a video console terminal can be used to scan all channels at specified intervals (stress levels, temperature levels, time intervals) and perform data reduction operations.

Manual measurements such as Whittemore gauge lengths, water injection pressures, water flow rates, etc. will be recorded on special forms, ready for subsequent punching and data reduction. Spot validation of data using hand calculations should not be neglected.

Experience from Terra Tek's HTM block test indicate that a minimum of three technical personnel are required to run the facility during test phases. Unless servo-control is utilized, the test facility should be manned daily on a caretaker basis, so that temperatures and flatjack pressures are coordinated as planned in the relevant test matrix.

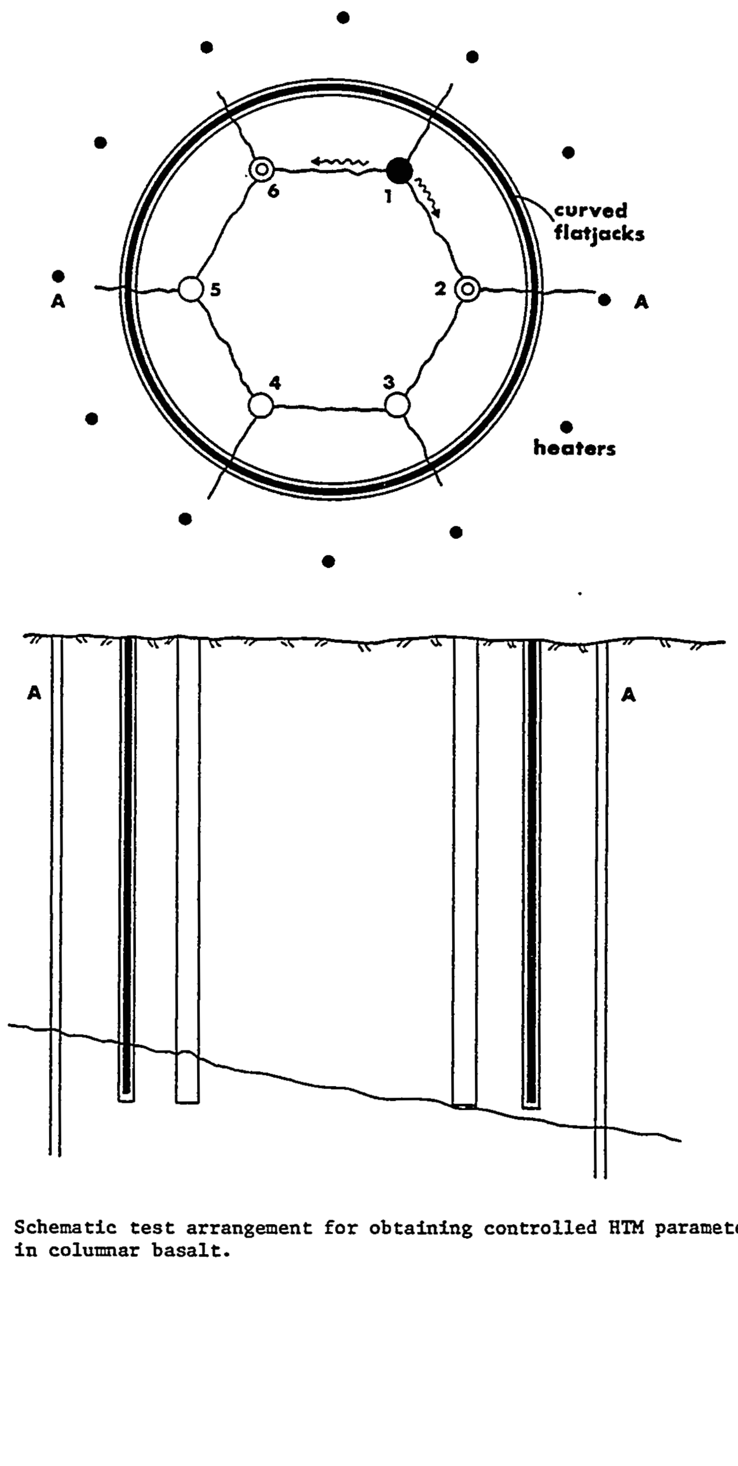


Figure 10. Schematic test arrangement for obtaining controlled HTM parameters in columnar basalt.

4.2 APPLICATION

The HTM in situ block test is applicable to jointed media (granite, basalt, tuff and shale). The test methods summarized in the preceeding pages could be applied directly to jointed blocks of granite, tuff and competent shale. However, the unique columnar jointing of basalt flows poses problems in interpretation and testing, since a given uniaxial compressive stress across a vertical plane in the block will tend to close some of the vertical joint planes and open others.

Permeability testing at elevated temperature and stress (not at present planned in the Rockwell-Hanford block test) will be difficult to execute and particularly difficult to interpret due to the stress anomaly mentioned above.

Fundamental flow-stress-temperature characterization in columnar basalt could be approached using cylindrical blocks (Figure 10). Representative basalt columns would be "over-cored" with large diameter "Calyx" core barrels, and loaded radially with curved flatjacks. A ring of guard heaters round the outside of the cylindrical block would be used to vary temperature. Six boreholes drilled down the lines of intersection of the six vertical joint planes would be flow tested in turn to characterize the adjacent joint planes.

An equivalent test arrangement for obtaining the thermomechanical creep properties of dome salt and bedded salt is described later in this report.

4.3 RESOLUTION AND RELIABILITY

Chief among factors influencing the resolution and reliability of the HTM data is the influence of the joint structure sampled within the block boundaries. A single block will never contain a truly representative sample of the repository rockmass as a whole. The cost and time involved in conducting a comprehensive HTM test as described obviously limits the number likely to be performed in a given characterization study, perhaps to no more than two tests per repository. Rockmass classification schemes described later need to be used to extrapolate some of the measured data to other parts of the repository to reduce costs and to improve reliability.

A second factor which influences the resolution and reliability is the fundamentally non-linear behavior of rockmasses, caused mainly by strongly non-linear joint response. Marked hysteresis will usually be observed in the early load cycles, due to the stress changes associated with test room excavation and slot drilling.

Examples of hysteresis are shown in Figure 9. This ambient temperature biaxial stress test was only the second loading cycle to which the particular block was subjected. On the fourth loading cycle (Figure 7) a typical stress-strain loop almost closed on unloading. However, the non-linearity is strongly in evidence. Utilization of single values for a parameter such as deformation modulus in numerical models, even under ambient conditions, is an unrealistic oversimplification.

It would not serve any useful purpose to list the instrument resolution magnitudes involved in measuring a given parameter, when some of the parameters are known to vary by several hundred percent depending on stress path, temperature, or number of joints sampled in a given instrument measurement space. The resolution available in standard instrumentation is not the source of reduced reliability for the parameters measured in an HTM block test. The inherent rockmass variability is the chief source of reduced reliability.

Consequently, detailed characteriztion of the jointing and any lithology changes within the block will be most important for improving the interpretation of measured data. The goal for improving reliability will be the adaptation of measured block and joint response into numerical models. Test block performance must first be predictable, before the measured response can be extrapolated for the repository as a whole.

4.4 COST AND TIME

The only HTM block test completed to date took approximately 1½ years from start date to final report. The extreme strength contrast of the particular granitic gneiss due to pervasive quartz lenses caused considerable delays in slot drilling, which was initially by percussive drilling - a technique used successfully in granite and quartz diorite. An extensive instrument evaluation program also increased the time schedule.

Costs and time will obviously vary with the size of test matrix. It is probably reasonable to estimate a final cost in the range $600,000 - $800,000 and a time schedule of 9 - 15 months. A test in granite or tuff would probably be close to the lower of the above ranges, while extensively jointed basalt and less than competent shale would be nearer the higher values. Smaller scale cylindrical tests for basalt (Figure 10) would be cheaper alternatives, but would need to be performed in several locations, in view of the reduced scale of sampling.

5. JOINT CHARACTERIZATION TESTS

5.1 DESCRIPTION

5.1.1 Test Parameters

Recent advances in joint characterization techniques and careful studies of joint size-strength effects (Bandis, 1980) make it possible to extrapolate the results of simple in situ tests to predict a number of important rockmass properties required in numerical modelling of near-field repository response. The joint characterization tests to be described enable full-scale values of the following parameters to be estimated:

$\tau - \delta$ (shear strength-displacement behavior of joints)

K_s (shear stiffness)

d_n (joint dilation)

$K_j - d_n$ (joint permeability - dilation coupling)

5.1.2 Recognition of Scale Effects

Individual joints intersecting a rockmass are responsible for a variety of size effects. Several of these will have been characterized and quantified in the HTM block test. However, due to the intact base (or side) of these blocks, shear displacements are limited during the uniaxial load cycles. A test method is needed which allows for larger shear displacements to be investigated, and which can be used to quantify the effect of size on shear strength, dilation and joint permeability. The size effect is caused by roughness effects. As sample size is increased, asperities of larger size and flatter inclination are found to control behavior. The net result is lower shear strength, lower shear stiffness, and reduced dilation, as joint size is increased. These components are illustrated in Figure 11.

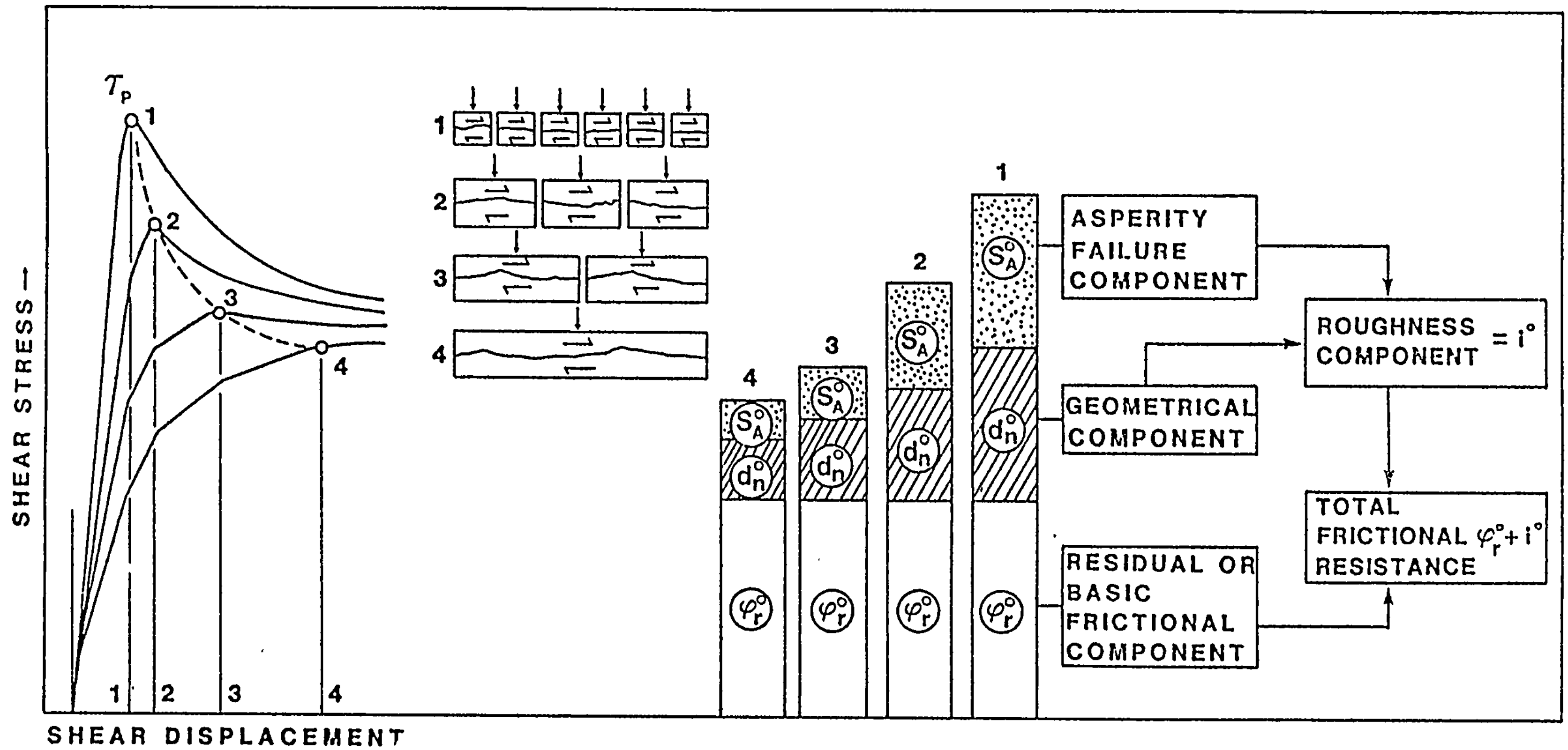
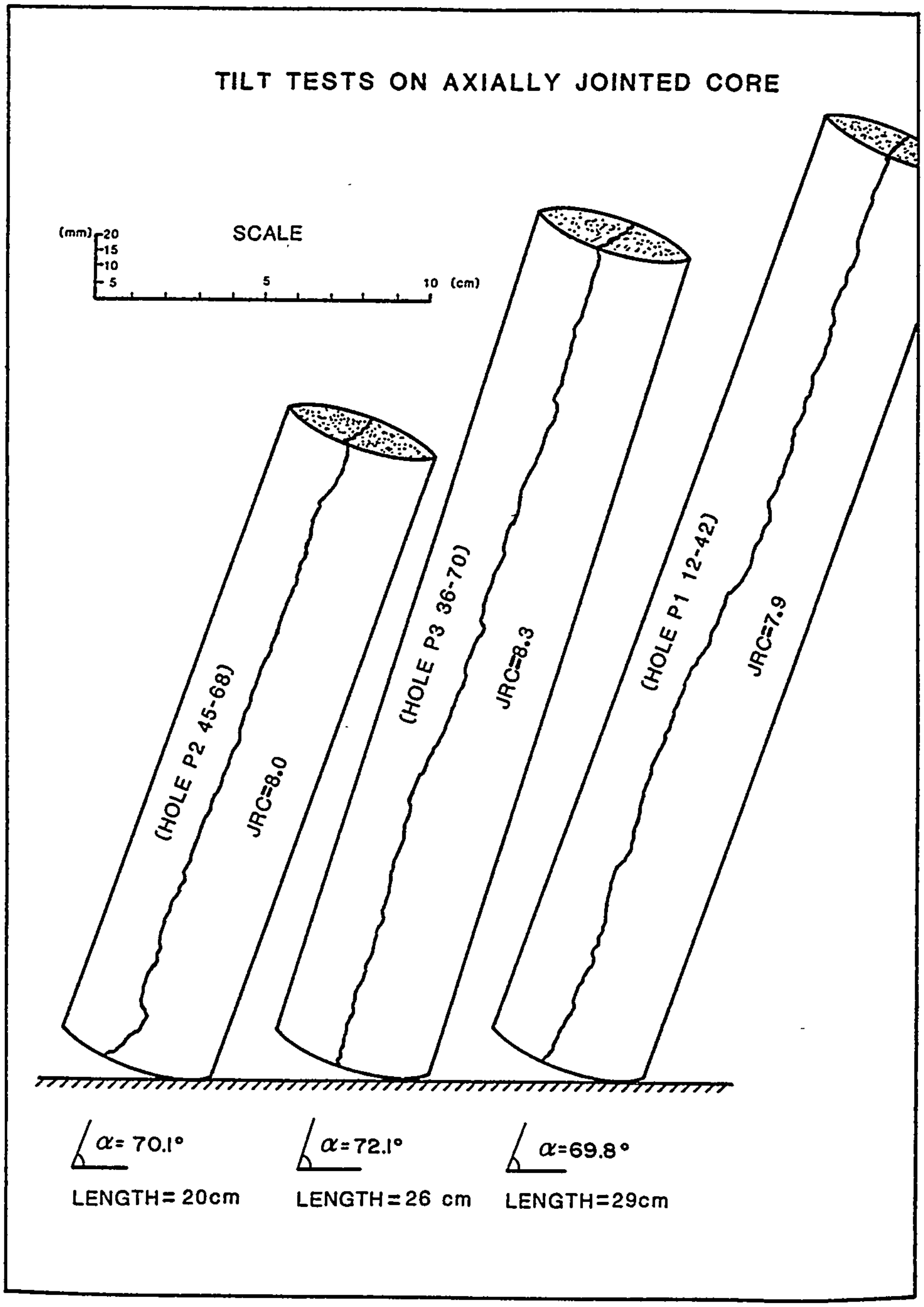


Figure 11 Joint sample-size affects the shear strength, the shear stiffness and the dilation that accompanies shear, after Bandis et al. (1981). Reprinted with permission from Pergamon Press, Ltd.

Figure 12. Characterization of joint roughness from self-weight tilt testing of axially jointed drillcore.



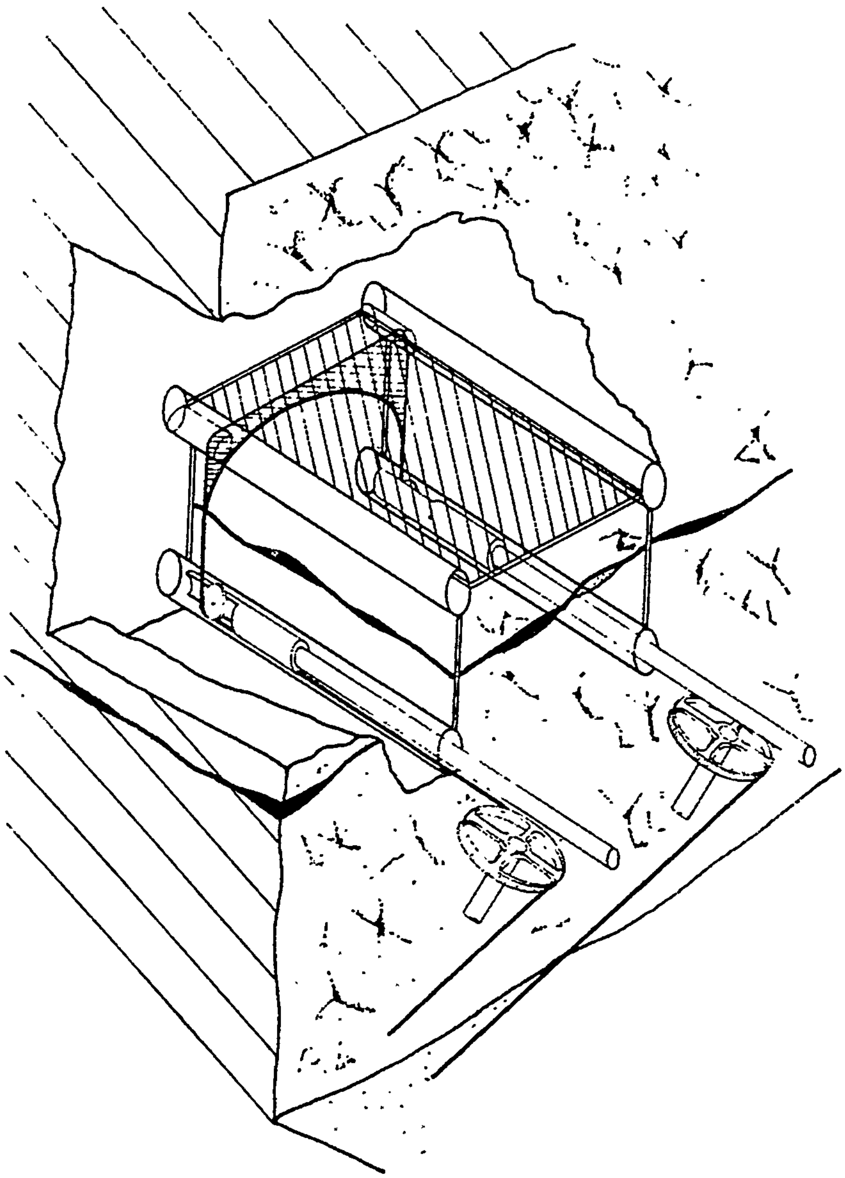


Figure 13. A method for extracting jointed blocks of rock from the walls or floor of a test adit, after Londe (1972).

5.1.3 Self-Weight Sliding Tests

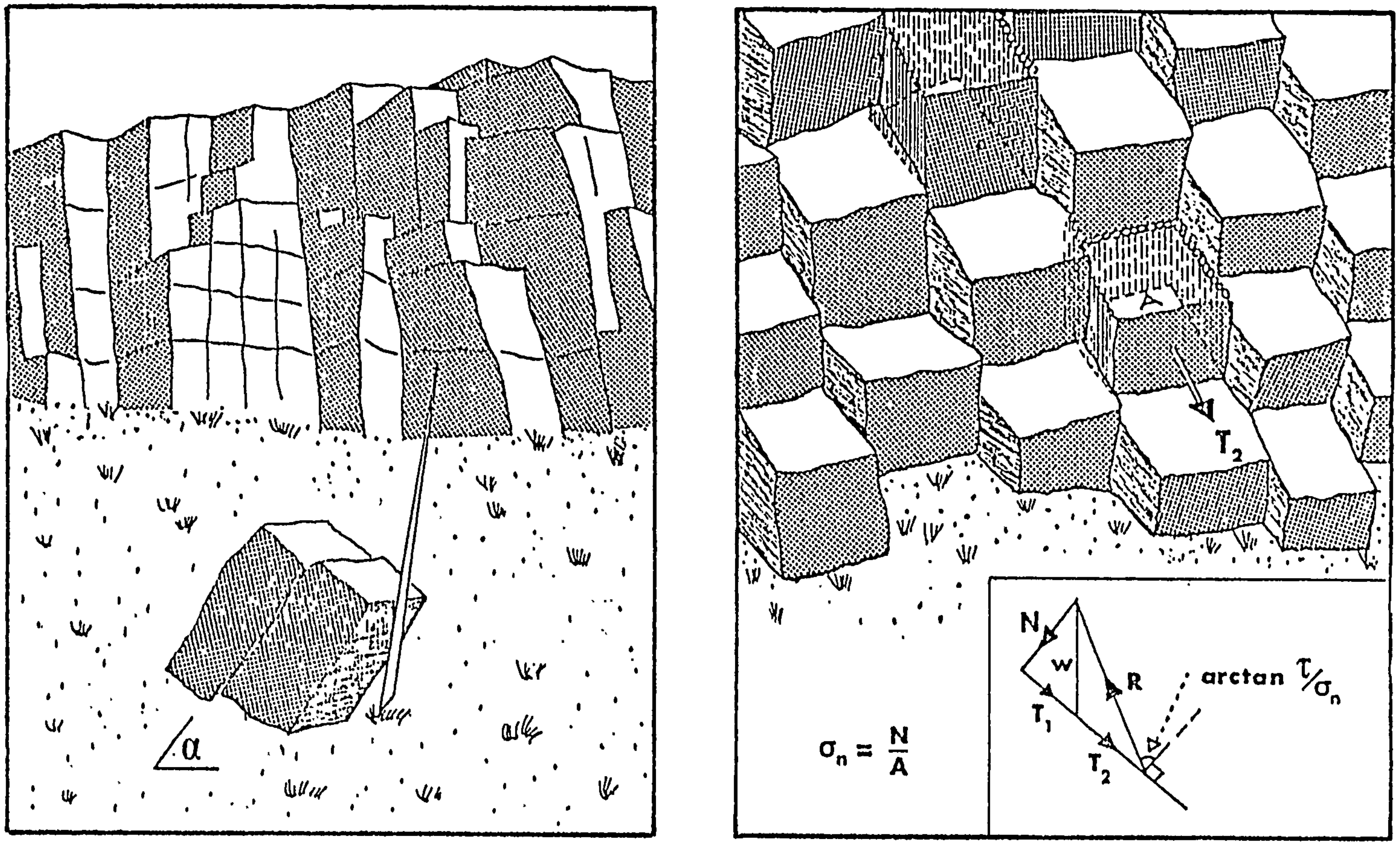
The tests to be described can be performed on coaxially drilled joint specimens (Figure 12), or on jointed blocks sawn from the walls or floor of the test adit, using the wire-saw method described by Londe (1972). The sliding tests can be performed by tilting the jointed specimens until sliding occurs at angle $\alpha°$ (= arctan τ/σ_{no}', where τ = shear stress, σ_{no}' effective normal stress) or by pull-testing larger blocks in their undisturbed location; and measuring the force required with a dynamometer. Tilt-tests and pull-tests for rock slope characterization are shown schematically in Figure 14.

Back-analysis of these tests provides estimates of the peak value of the joint roughness coefficient (JRC), which varies from 0 (for completely smooth surfaces) to about 20 (for exceptionally rough surfaces). For a given joint, values of JRC will be smaller with increasing size of sample. It is important to try to measure JRC on jointed blocks of natural size, if size corrections (Bandis et al. 1981) are to be avoided.

5.1.4 Schmidt Hammer Rebound Tests

This test for estimating unconfined compression strength was referred to in the first topical report (TR 81-33, April, 1981). For joint characterization purposes, the rebound hammer is applied directly to joint surfaces. (In near surface characterization, joint walls may be weathered or mineralized, thereby generating lower rebound values than on the unweathered rock.)

The effective compressive strength of the joint walls is estimated from the strength-rebound-density chart developed by Miller (1965). Experimental details of the testing of rock joints using this method are given by Barton and Choubey (1977). The value obtained is termed the joint wall compression strength (JCS). Joints exposed in the walls



TILT TEST PULL TEST

Figure 14 Tilt-testing or pull-testing of jointed blocks of natural size should provide scale-free values of the joint roughness coefficient (JRC), after Barton and Bandis (1980) Reprinted with permission from Pergamon Press, Ltd.

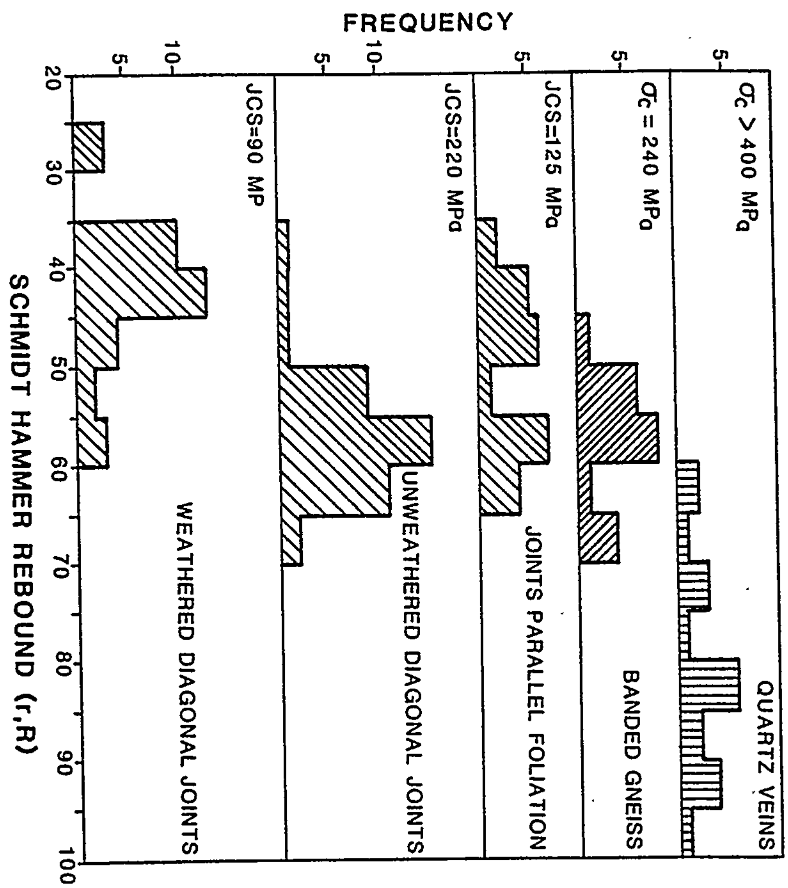


Figure 15. Estimates of joint wall compression strengths (JCS) and unconfined compression strength (σ_c) obtained from numerous Schmidt hammer tests in the CSM test adit, where Terra Tek's HTM in situ block test was performed (Terra Tek, 1981).

and roof of the test room and joins sampled in extracted blocks should be characterized in this way to indicate the strength contrast of the different joint sets. An example is shown in Figure 15.

5.1.5 Basic or Residual Friction Angle

In near surface characterization, where jointwalls are frequently weathered or mineralized, the minimum or residual friction angle (ϕ_r) is often some degrees lower than the basic friction angle (ϕ_b) of the unweathered rock. Methods of estimating ϕ_r using the Schmidt hammer are described by Barton and Choubey (1977).

At repository depth, the minimum friction angle of a planar rock surface (i.e. a joint without any roughness or asperities) can be measured from simple tilt tests on core pieces (Figure 16). Depending on mineralogy, values will generally lie in the range of 25° - 35°.

5.1.6 Estimation of Joint Behavior Under Shear Stress

Extensive direct shear testing of rock joints and replicas of rock joints has established a sound basis for describing the peak friction angle (ϕ') of a rock joint using the index parameters JRC, JCS and ϕ_b just described (see Barton and Choubey, 1977, Bandis et al. 1981):

$$\phi' = \phi_b + i = \phi_b + \text{JRC} \cdot \log\left(\frac{\text{JCS}}{\sigma_n'}\right)$$

where σ_n' = effective normal stress

This empirical equation accounts for the crushing of asperities under high-stress shearing, and accounts for the over-riding of asperities (dilation) under low-stress shearing. The lower value (ϕ_r) is substituted for (ϕ_b) if joints are weathered.

Methods have been developed for extrapolating values of JRC and JCS to the scale of the rockmass, and for describing shear stress-displacement, dilation, and joint permeability behavior as a function of block-size and shear displacement. Since a detailed description of these methods is

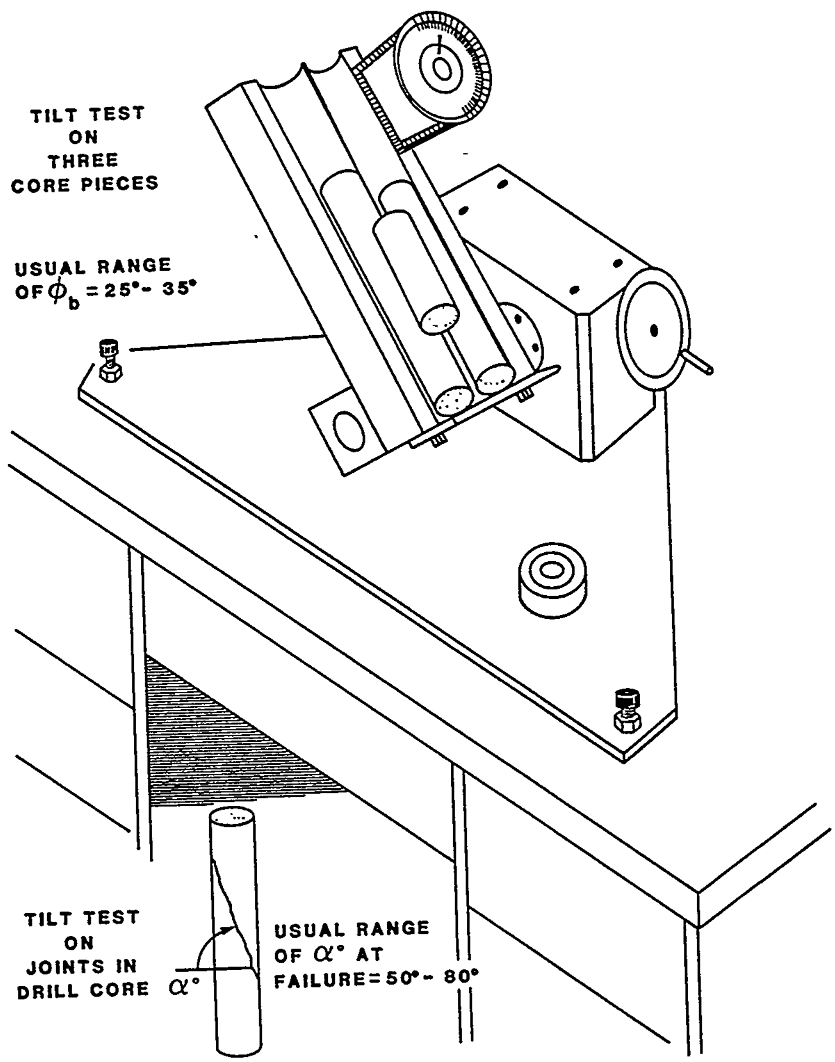
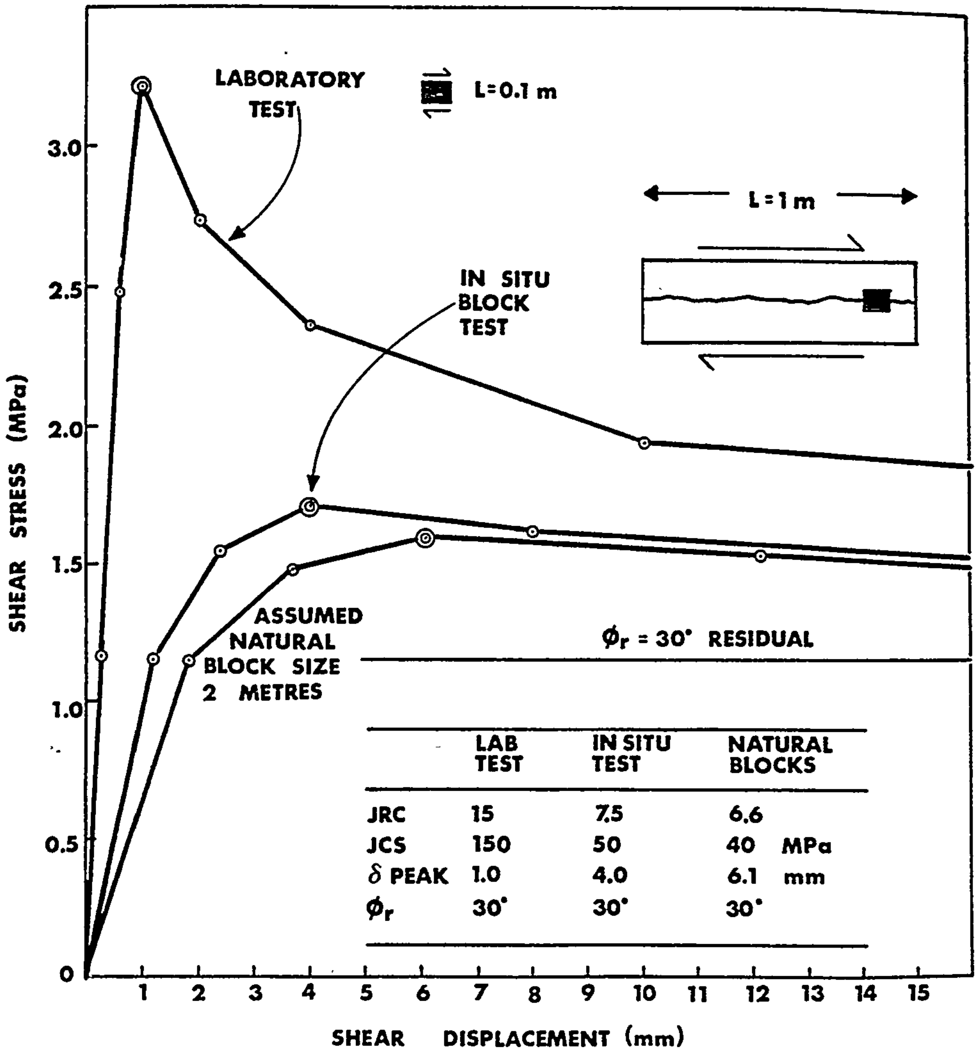


Figure 16. Tilt tests using whole and jointed core provide estimates of the basic friction angle (ϕ_b) and the joint roughness coefficient (JRC) respectively, after Barton (1981).



	LAB TEST	IN SITU TEST	NATURAL BLOCKS	
JRC	15	7.5	6.6	
JCS	150	50	40	MPa
δ PEAK	1.0	4.0	6.1	mm
ϕ_r	30°	30°	30°	

Figure 17. An example of shear stress-displacement modelling of the same rough rock joint, sampled at three different scales, after Barton (1981b).

beyond the scope of this topical report, the reader is referred to the following report:

Barton, 1981. Modelling Rock Joint Behavior From In Situ Block Tests: Implications for Nuclear Waste Repository Design. ONWI Contract E512-04700.

An example of one part of this modelling procedure is illustrated in Figure 17. Note the size dependence of JRC, JCS and the displacement (δpeak) needed to mobilize peak strength at different scales. The residual or basic friction angle is unaffected by scale, although the shear displacement needed to reach this minimum value is larger for the case of small samples, as suggested by Figure 17.

5.2 APPLICATION

The tests for quantifying the joint roughness coefficient (JRC), the joint wall compression strength (JCS) and the residual or basic friction angle (ϕ_r or ϕ_b) are applicable to the joints in granite, basalt, tuff and shale. However, the weaker varieties of shale may have unconfined compression strengths below 20 MPa. Values of JCS of 15 - 20 MPa represent the effective limit for characterization with the Schmidt (L) hammer.

If joints are saturated in situ, this is the condition they should be tested in to obtain appropriately conservative values of joint wall compression strength (JCS). Due to the softening of many varieties of shale with saturation, this again may cause problems for Schmidt hammer characterization.

The tests for JRC, JCS and ϕ_b have, so far as we are aware, never been applied to bedding partings or joints in bedded salt or salt domes respectively. In view of the likely influence of creep on joint behavior in these materials, further development work would be required before these methods could be recommended for these materials. At present, there would be no place for this type of data in the analyses performed in salt.

5.3 RESOLUTION AND RELIABILITY

The resolution and reliability of the characterization parameters JRC, JCS and ϕ_b (or ϕ_r) obviously determines the reliability of subsequent estimates of $\tau - \delta$, K_s, d_n and $K_j - d_n$ (see section 5.1.1 for definitions).

Miller (1965) indicated the following average dispersions of strength when measured with the Schmidt hammer:

Mean Compressive Strength (MPa)	Average Dispersion of Strength (MPa)
25	$\pm$ 20
100	$\pm$ 40
150	$\pm$ 60
200	$\pm$ 90

Part of the reason for this poor resolution was the small size of samples utilized. These had to be clamped to a rigid base. Barton and Choubey (1977) describe a simple technique for reducing the dispersion when using a Schmidt hammer on joints in situ.

Self-weight sliding tests (tilt or pull tests) conducted on small blocks give repeatable results of tilt angle (α) of $\pm 2°$ dispersion. Tests of ϕ_r and ϕ_b described by Barton and Choubey (1977) indicated dispersion of $\approx \pm 1°$. The logarithmic form of the shear strength equation (section 5.1.6) and the very large value of JCS/σ_{no}' operating during the self-weight sliding tests suggests that values of peak shear strength (ϕ') can be estimated to within approximately $\pm 2°$. Examples of shear stress-displacement, dilation and permeability coupling given by Barton (1981) indicate the potential for good agreement with the limited data available for validation.

5.4 COST AND TIME

A Schmidt hammer characterization of joints exposed in the test adit excavation (walls and roof, if accessible) will generally take no more than 1 - 2 days. Since calculation of results is a trivial task, a full characterization such as that illutrated in Figure 15 will cost approximately $1000, including purchase of the hammer ($250).

A portable tilting device (Figure 16) can be purchased/manufactured for under $500 (depends on size). Numerous measurements of ϕ_b on available drill core, obtained from the horizontal drilling program can be accomplished in one day, giving a total cost of approximately $1000.

In the initial stages of site characterization, self-weight sliding tests (tilt test) can be performed on joints recovered in the horizontal drilling program. Tilt-testing and back-calculation of the resulting values of the joint roughness coefficient (JRC), using previously obtained values of JCS and ϕ_b (or ϕ_r), can generally be performed at the rate of 10 joints per day. A quite complete characterization of jointed core could therefore be accomplished in two weeks at a total cost of approximately $10,000, including technical help.

The above costs are relevant to joint characterization of available, small diameter core samples. A limited number of small diameter axially jointed core samples may also be available from special purpose instrumentation and permeability holes, drilled in an HTM block test. (Examples are shown in Figure 12).

Self-weight sliding tests on larger jointed blocks is strongly advised, to avoid the uncertainties involved when extrapolating both JRC and JCS to assumed full-scale values. Large samples could be obtained by drilling holes co-planar with a joint, using large diamter coring crowns (i.e. 12 inches diameter), or by wire sawing to release rectangular jointed blocks, using equipment illustrated in Figure 13. Equipment modification, rental and labor would probably total approximately $2000 - $4000 per sample for the coring and sawing alternatives. Tilt testing and general characterization of these large samples would cost approximately $500. A useful program of large-scale joint characterization would probably cost $50,000 and take 3 - 4 weeks.

6. EXTRAPOLATION OF DEFORMATION MODULI

Recognition of the high cost of large-scale deformation modulus tests, and the particularly high cost of an HTM in situ block test, has encouraged the development of methods for extrapolating measured test data to other parts of a rockmass. Rockmass classification methods have also been utilized for estimating deformation-modulus. Recent applications include the Climax instrumented mine-by test (Heuze, 1981) and the Near Surface Test Facility (NSTF) at Hanford (Hocking et al. 1981 , Hardy and Hocking, 1980).

A comprehensive review of large-scale deformation modulus tests conducted at major dams and powerhouses has been published by Bieniawski (1978). Analysis of his results for four different categories of large scale tests:

- Plate bearing,
- Tunnel relaxation
- Flatjacks, and
- Pressure chamber,

incorporating more than 200 test values, indicates the following mean data:

Overall mean E = 24.0 GPa

Mean range $E_{max} - E_{min}$ = 28.8 GPa

(range/mean = 1.20)

A typical mean value of say 30 GPa will, therefore, generally imply a range of values of 36 GPa, extreme values being distributed approximately normally, i.e. $E_{min} \simeq 12$ GPa, $E_{max} \simeq 48$ GPa. Such variation appears to be typical for rock masses; it will only be reduced if test sites are unusually homogeneous and similar.

A good illustration of variability is shown in Figure 18, where measured values of deformation moduli obtained from large plate load tests, vary by up to a factor of three between roof and floor, left wall and right wall.

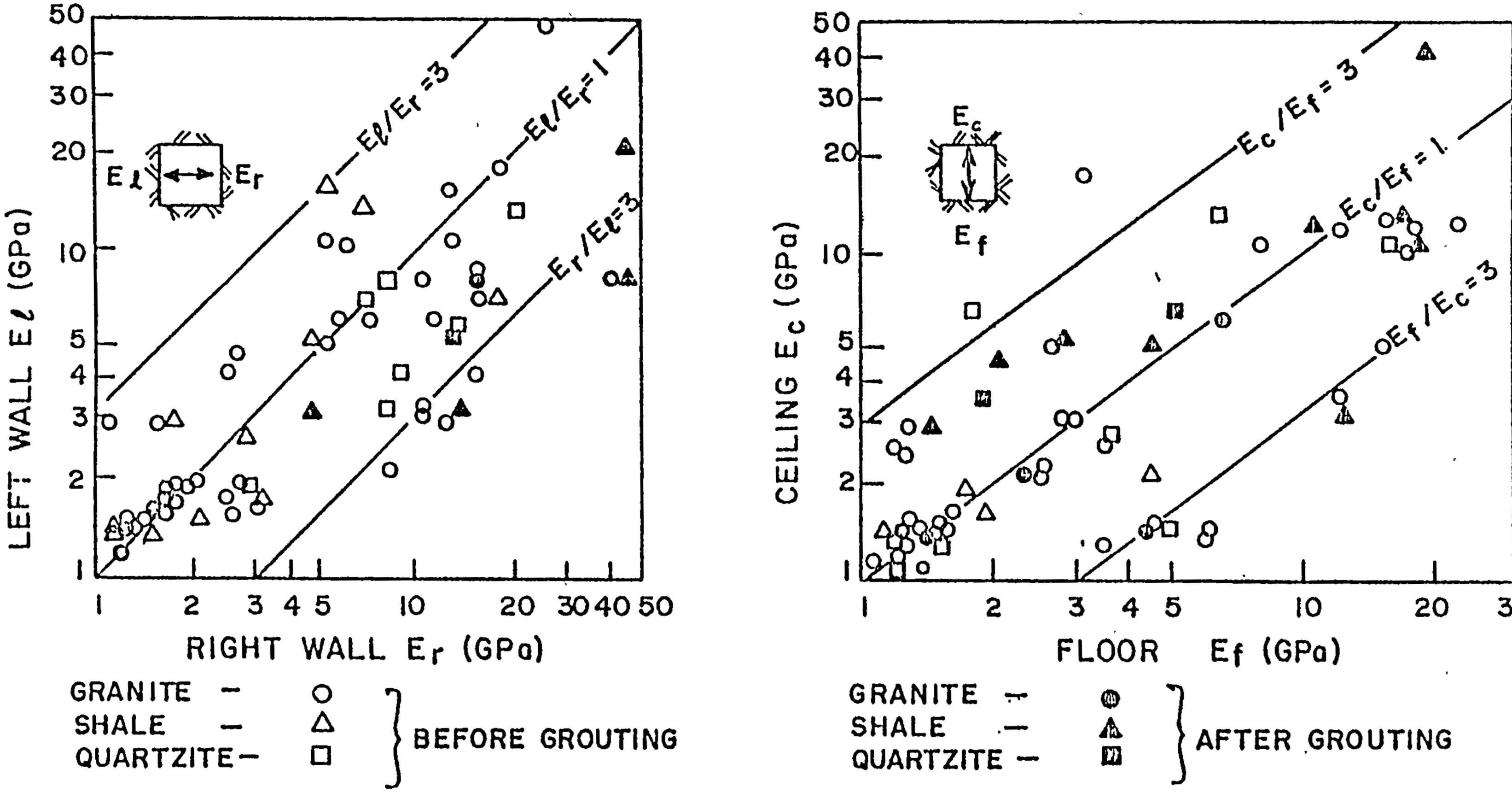


Figure 18 Variations of deformation moduli measured in large scale plate loading tests, after Rocha (1965), paper Q.28/R, 44 submitted to the 8th Congress of ICOLD held in Edinburgh in May 1964.

6.1 DESCRIPTION

Development of several rockmass classification methods in recent years provides a means of extrapolating large-scale test results to other locations. Bieniawski (1978) found that the CSIR rockmass rating correlated quite well with mean values of deformation moduli

$$E_r = 2\ RMR - 100\ (GPa)$$

RMR = rockmass rating (Bieniawski, 1976)

The RMR is dependent on the numerical ratings of uniaxial or point load strength, RQD, spacing of joints, condition of joints, presence of water and orientation of joints. Ratings are listed in Table 1.

A second widely used rockmass classification method is the NGl Q-system (Barton et al. 1980). The Q-value is calculated from the following relationship:

$$Q = RQD/J_n \times J_r/J_a \times J_w/SRF$$

Ratings for each of these factors are given in Table 2.

The normal distribution of deformation modulus measurements referred to earlier suggests that $E_{max} \approx 1.6\ E_{mean}$, $E_{min} \approx 0.4E_{mean}$. Corresponding estimates of E_{max}, E_{mean} and E_{min} based on the Q-value are compared with measured data in Figure 19.

6.2 APPLICATION

The above rockmass classification procedures should be applied at the site of HTM in situ block tests, so that measured values of deformation modulus (ambient, heated, loading and unloading) can be extrapolated subsequently to other parts of the repository. (It should be noted that the chief purpose of the above classification methods is for estimating rock support and reinforcement requirements. The test adit, and subsequent repository excavations will have been classified in a routine mapping operation.) The methods have been

TABLE 1. Rock mass ratings (RMR) for the CSIR geomechanics classification method, after Bieniawski (1976).

A. CLASSIFICATION PARAMETERS AND THEIR RATINGS

	PARAMETER		RANGES OF VALUES						
1	*Strength of intact rock material	Point-load strength index	> 8 MPa	4 - 8 MPa	2 - 4 MPa	1 - 2 MPa	For this low range — uniaxial compressive test is preferred		
		Uniaxial compressive strength	> 200 MPa	100 - 200 MPa	50 - 100 MPa	25 - 50 MPa	10-25 MPa	3-10 MPa	1-3 MPa
	Rating		15	12	7	4	2	1	0
2	Drill core quality RQD		90% - 100%	75% - 90%	50% - 75%	25% - 50%	< 25%		
	Rating		20	17	13	8	3		
3	Spacing of joints		> 3 m	1 - 3 m	0.3 - 1 m	50 - 300 mm	< 50 mm		
	Rating		30	25	20	10	5		
4	Condition of joints		Very rough surfaces. Not continuous No separation Hard joint wall rock.	Slightly rough surfaces. Separation < 1 mm Hard joint wall rock	Slightly rough surfaces. Separation < 1 mm Soft joint wall rock	Slickensided surfaces OR Gouge < 5 mm thick OR Joints open 1-5 mm. Continuous joints	Soft gouge > 5 mm thick OR Joints open > 5 mm. Continuous joints		
	Rating		25	20	12	6	0		
5	Ground water	Inflow per 10m tunnel length	None	None	< 25 litres/min	25 - 125 litres/min	> 125 litres/min		
		OR Ratio [illegible]	0	0	OR 0.0 - 0.2	OR 0.2 - 0.5	OR > 0.5		
		OR General conditions	Completely dry	Completely dry	OR Moist only (interstitial water)	OR Water under moderate pressure	OR Severe water problems		
	Rating		10	10	7	4	0		

B. RATING ADJUSTMENT FOR JOINT ORIENTATIONS

Strike and dip orientations of joints		Very favourable	Favourable	Fair	Unfavourable	Very unfavourable
Ratings	Tunnels	0	-2	-5	-10	-12
	Foundations	0	-2	-7	-15	-25
	Slopes	0	-5	-25	-50	-60

C. ROCK MASS CLASSES DETERMINED FROM TOTAL RATINGS

Rating	100 ← 81	80 ← 61	60 ← 41	40 ← 21	< 20
Class No		II	III	IV	V
Description	Very good rock	Good rock	Fair rock	Poor rock	Very poor rock

D. MEANING OF ROCK MASS CLASSES

Class No		II	III	IV	V
Average stand-up time	10 years for 5 m span	6 months for 4 m span	1 week for 3 m span	5 hours for 1.5 m span	10 minutes for 0.5 m span
Cohesion of the rock mass	> 300 kPa	200 - 300 kPa	150 - 200 kPa	100 - 150 kPa	< 100 kPa
Friction angle of the rock mass	> 45°	40° - 45°	35° - 40°	30° - 35°	< 30°

Table 2 Ratings for the N.G.I. Q-system of rock mass classification, after Barton et al. (1980). Reprinted with permission from Pergamon Press, Ltd.

1. ROCK QUALITY DESIGNATION (RQD)

		RQD
A.	Very poor	0 - 25
B.	Poor	25 - 50
C.	Fair	50 - 75
D.	Good	75 - 90
E.	Excellent	90 - 100

Note: (i) Where RQD is reported or measured as ≤ 10, (including 0) a nominal value of 10 is used to evaluate Q in equation (1).

(ii) RQD intervals of 5, i.e. 100,95,90, etc. are sufficiently accurate.

2. JOINT SET NUMBER

		(J_n)
A.	Massive, no or few joints	0.5 - 1.0
B.	One joint set	2
C.	One joint set plus random	3
D.	Two joint sets	4
E.	Two joint sets plus random	6
F.	Three joint sets	9
G.	Three joint sets plus random	12
H.	Four or more joint sets, random, heavily jointed, "sugar cube" etc.	15
J.	Crushed rock, earthlike	20

Note: (i) For intersections use (3.0 x J_n)

Note: (ii) For portals use (2.0 J_n)

3. JOINT ROUGHNESS NUMBER

(a) *Rock wall contact* and
(b) *Rock wall contact before 10 cms shear*

		(J_r)
A.	Discontinuous joints	4
B.	Rough or irregular, undulating	3
C.	Smooth, undulating	2
D.	Slickensided, undulating	1.5
E.	Rough or irregular, planar	1.5
F.	Smooth, planar	1.0
G.	Slickensided, planar	0.5

Note: (i) Descriptions refer to small scale features and intermediate scale features, in that order.

(c) *No rock wall contact when sheared*

		(J_r)
H.	Zone containing clay minerals thick enough to prevent rock wall contact	1.0
J.	Sandy, gravelly or crushed zone thick enough to prevent rock wall contact	1.0

Note: (ii) Add 1.0 if the mean spacing of the relevant joint set is greater than 3m.

(iii) J_r =0.5 can be used for planar slickensided joints having lineations, provided the lineations are orientated for minimum strength

4. JOINT ALTERATION NUMBER

		(J_a)	(ϕ_r) (approx.)
	(a) *Rock wall contact*		
A.	Tightly healed, hard, non-softening, impermiable filling i.e. quartz or epidote	0.75	(-)
B.	Unaltered joint walls, surface staining only	1.0	(25-35°)
C.	Slightly altered joint walls. Non-softening mineral coatings, sandy particles, clay-free disintegrated rock etc.	2.0	(25-30°)
D.	Silty-, or sandy-clay coatings, small clay fraction (non-soft.)	3.0	(20-25°)
E.	Softening or low friction clay mineral coatings, i.e. kaolinite or mica. Also chlorite, talc, gypsum, graphite etc., and small quantities of swelling clays.	4.0	(8-16°)
	(b) *Rock wall contact before 10 cms shear*		
F.	Sandy particles, clay-free disintegrated rock etc.	4.0	(25-30°)
G.	Strongly over-consolidated non-softening clay mineral fillings (continuous, but <5 mm thickness)	6.0	(16-24°)
H.	Medium or low over-consolidation, softening, clay mineral fillings. (continuous but <5mm thickness)	8.0	(12-16°)
J.	Swelling -clay fillings, i.e. montmorillonite (continuous, but <5mm thickness) Value of J_a depends on percent of swelling clay-size particles, and access to water etc.	8 - 12	(6-12°)
	(c) *No rock wall contact when sheared*		
K, L, M.	Zones or bands of disintegrated or crushed rock and clay (see G, H, J for description of clay condition)	6, 8, or 8-12	(6-24°)
N.	Zones or bands of silty- or sandy-clay, small clay fraction (non-softening)	5.0	(-)
O, P, R.	Thick, continuous zones or bands of clay (see G, H, J for description of clay condition)	10, 13, or 13-2[illegible]	(6-24°)

5. JOINT WATER REDUCTION FACTOR

		(J_w)	Approx. water pres. (kg/cm²)
A.	Dry excavations or minor inflow, i.e. < 5 l/min. locally.	1.0	<1
B.	Medium inflow or pressure, occasional outwash of joint fillings.	0.66	1 - 2.5
C.	Large inflow or high pressure in competent rock with unfilled joints	0.5	2.5-10
D.	Large inflow or high pressure, considerable outwash of joint fillings	0.33	2.5-10
E.	Exceptionally high inflow or water pressure at blasting, decaying with time	0.2-0.1	>10
F.	Exceptionally high inflow or water pressure continuing without noticeable decay	0.1-0.05	>10

Note: (i) Factors C to F are crude estimates. Increase J_w if drainage measures are installed.

(ii) Special problems caused by ice formation are not considered.

6. STRESS REDUCTION FACTOR

(a) *Weakness zones intersecting excavation, which may cause loosening of rock mass when tunnel is excavated.*

		(SRF)
A.	Multiple occurrences of weakness zones containing clay or chemically disintegrated rock, very loose surrounding rock (any depth)	10
B.	Single weakness zones containing clay or chemically disintegrated rock (depth of excavation ≤ 50m)	5
C.	Single weakness zones containing clay or chemically disintegrated rock (depth of excavation > 50m)	2.5
D.	Multiple shear zones in competent rock (clay-free), loose surrounding rock (any depth)	7.5
E.	Single shear-zones in competent rock (clay-free) (depth of excavation ≤ 50m)	5.0
F.	Single shear-zones in competent rock (clay-free) (depth of excavation > 50m)	2.5
G.	Loose open joints, heavily jointed or "sugar cube" etc. (any depth)	5.0

Note: (i) Reduce these values of SRF by 25 - 50% if the relevant shear zones only influence but do not intersect the excavation.

(b) *Competent rock, rock stress problems*

		σ_c/σ_1	σ_t/σ_1	(SRF)
H.	Low stress, near surface	>200	>13	2.5
J.	Medium stress	200-10	13-0.66	1.0
K.	High stress, very tight structure (usually favourable to stability, may be unfavourable for wall stability)	10-5	0.66-.33	0.5-2
L.	Mild rock burst (massive rock)	5-2.5	0.33-.16	5-10
M.	Heavy rock burst (massive rock)	<2.5	<0.16	10-20

Note: (ii) For strongly anisotropic virgin stress field (if measured): when $5 \leq \sigma_1/\sigma_3 \leq 10$, reduce σ_c and σ_t to $0.8\sigma_c$ and $0.8\sigma_t$. When $\sigma_1/\sigma_3 > 10$, reduce σ_c and σ_t to $0.6\sigma_c$ and $0.6\sigma_t$, where : σ_c = unconfined compression strength, and σ_t = tensile strength (point load), and σ_1 and σ_3 are the major and minor principal stresses.

(iii) Few case records available where depth of crown below surface is less than span width. Suggest SRF increase from 2.5 to 5 for such cases (see H).

(c) *Squeezing rock: plastic flow of incompetent rock under the influence of high rock pressure*

		(SRF)
N.	Mild squeezing rock pressure	5 - 10
O.	Heavy squeezing rock pressure	10 - 20

(d) *Swelling rock: chemical swelling activity depending on presence of water*

		(SRF)
P.	Mild swelling rock pressure	5 - 10
R.	Heavy swelling rock pressure	10 - 15

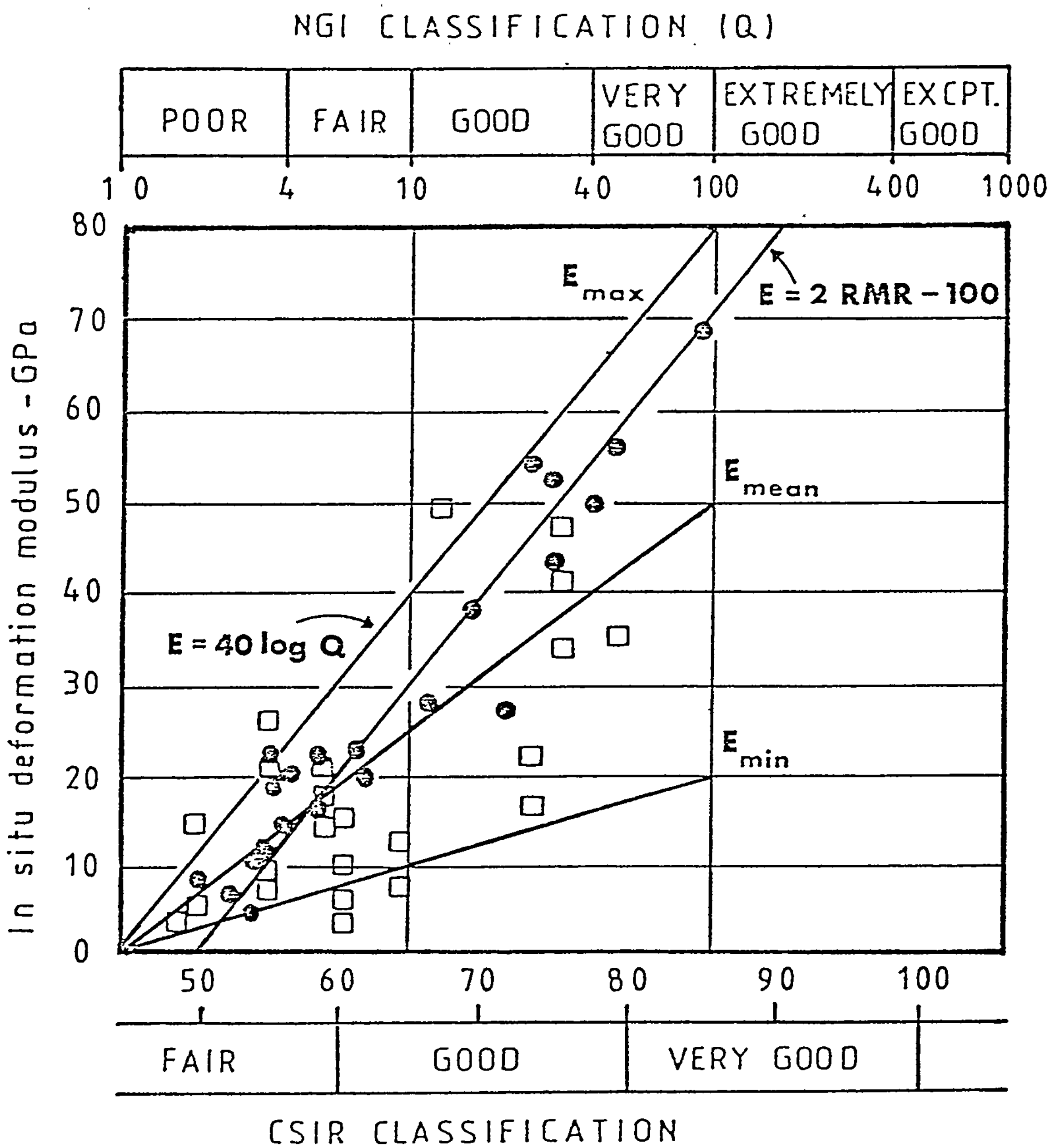


Figure 19 Estimation or extrapolation of in situ deformation modulus from two classification methods, modified from Barton et al. (1980). Reprinted with permission from Pergamon Press, Ltd.

correlated with jointed rockmasses, and will be applicable to granite, basalt, tuff and shale, but not to dome or bedded salt.

6.3 RESOLUTION AND RELIABILITY

In view of the inherent variability of rockmasses, the above classification methods should be viewed only as useful guides to the likely variation of deformation moduli. Estimates of E_{max}, E_{mean} and E_{min} obtained from classification are unlikely to be consistently accurate to better than $\pm$ 20%.

6.4 COST AND TIME

Classification of the test room walls and roof, and detailed classification of the HTM block facility represents no more than a one day task for an experienced engineering geologist i.e. $500. Subsequent classification of the repository excavations will be a part of routine mapping, and only the analysis of these mapping results would involve additional time and cost.

7. CREEP AND THERMAL TESTING IN SALT

Salt domes in Texas, Lousiana and Mississippi, and bedded salt formations in the Paradox Basin (Utah), and the Deleware Basin (SE New Mexico) have been considered or selected (as in the case of WIPP) for high level waste repositories. The petrology of salt specimens from any of these candidate formations is very similar; important properties are grain size, impurity content and rock fabric. In samples of bedded salt, grain size is usually larger, impurity content (especially clay lamellae) greater, and moisture content greater. Anhydrite is common on the grain boundaries of both forms, and both contain brine inclusions along grain boundaries and in the form of "negative crystals" (Hansen and Carter, 1980). In both forms, grain orientation is usually nonpreferential and microscopic inspection is typically required to discriminate trends in the fabric.

Structure differs significantly between bedded and domal salt. Candidate sites in bedded salt may offer horizontal, relatively undisturbed strata (WIPP, Gibson Dome, Elk Ridge) or folded strata (Lisbon Valley, Salt Valley). Diapirism is not confined to salt domes; it may be associated with folded salt beds such as the "pierced" anticline beneath Salt Valley. Diapiric salt formations generally offer more continuous, thicker units of pure salt probably due to selective transport of the salt (Frazier and McPherson, 1980). Large-scale commercial room and pillar mining of Gulf Coast salt domes has revealed the existence of brine pockets containing one acre-foot or more of fluid, and of brecciated, highly permeable zones where shearing has occurred recently.

Structural features of bedded salt (Salado Fm) pertinent to modeling of the WIPP facility in SE New Mexico have been classified (Harrington, 1980):

1. Clay breaks - interstitial clay on crystal surfaces which causes exploratory borehole core to break. No observed thickness.

2. Clay partings - joints with clay filling up to 0.125" (3.2mm), partially interlocking salt units via asperities associated with joint roughness.

3. Clay seams - joints more than .125" wide (usually 2.0") filled with clay. No interlocking.

Clay seams were determined the weakest of the three, owing principally to shear failure.

7.1 DESCRIPTION

7.1.1 Laboratory Testing of Creep

Mechanical behavior of salt is dominated by creep. Transient (primary) and steady state (secondary) creep have been observed and measured in the laboratory by many researchers, with the objective formulation of a constitutive creep law combining the effects of stress, temperature, time and strain rate for use in repository modeling. These factors influence primary creep rates to such an extent that it is important to model repository-scale loading rates and temperature rise, as closely as possible, to obtain the most relevant creep coefficients.

The method of creep testing commonly used is a triaxial creep test wherein a cylindrical core is loaded axially while being (triaxially) loaded hydrostatically. The axial strain is then plotted against time, for a given applied axial (deviatoric) stress, temperature, sample geometry, etc. (Senseny, 1980; Hansen and Carter, 1980; Herrmann et al. 1980; Wawersik and Hannum, 1980; Brown and Heuze, 1979). An empirical or semi-empirical (Fossum, 1977) power law form is determined from the data. Reasonable agreement between the power law constants calculated for the various domed and bedded salt species has been obtained (Hansen and Carter, 1980) but discrepancies can occur between the creep law formulations of different investigators.

Scale effects have been investigated (Senseny, 1980) with the result that laboratory scale experiments conservatively overestimate the creep rate encountered in field studies. Petrologic fabric, grain size and impurities seem to have a stronger effect on high temperature transient and steady state creep.

Overall, good agreement now exists between constitutive creep law predictions and lab test data. Primary and tertiary (when it is achieved) creep are still not well understood however (Pearson, et al. 1980). The institution of standarized creep test could help eliminate errors due to apparatus, loading rate and test duration.

7.1.2 Application of Constitutive Law to Field Test Data

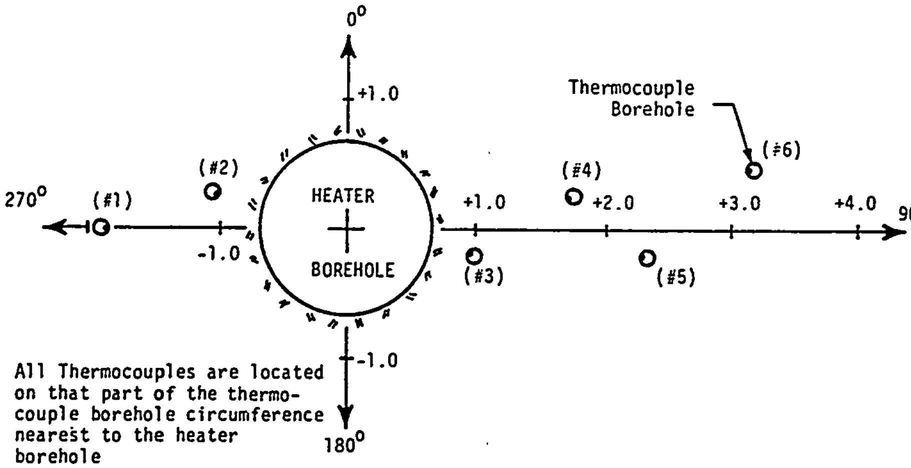
Agreement is also acceptable between creep law predictions and field test data, with an extensive room-scale experiment in bedded salt (Starfield and McClain, 1973), large-deformation monitoring of a high (90%) extraction room-and-pillar mining operation in a potash mine in New Mexico, and heater tests at Avery Island, Lousiana, thus far reported. All of the creep data presently available are one-dimensional and empirical, however, indicating the need for two- and three-dimensional data, and for a more fundamental creep model. Present numerical methods can be improved for better stability and accuracy; in addition, algorithms modeling time dependent behavior require additional work. (Pearson, et al. 1980)

7.1.3 Field Heater Tests in Salt

These tests involve the emplacement of canisters of live waste or simulated waste canisters containing electrical heaters. The zone of rock which is to be heated is instrumented with stress, temperature and displacement instrumentation. A temperature model based on thermoelasticity such as JUDITH (St. John, 1977), is typically used to provide a first order estimate of predicted rock response, for design of the instrument array.

Heater tests provide thermal and thermomechanical properties data, including such parameters as thermal conductivity, diffusivity, and expansion. A finite element or finite difference approach (e.g. programs SPECTROM, STEALTH and SALTY)(Wigley and Russel, 1980) is required to obtain these parameters from stress, temperature, and displacement data. Rock salt reacts drastically to the combination of overburden and thermal stresses. Large changes in roof-floor convergence, floor elevation, and pillar deformation occur which are up to 88% nonrecoverable, (Starfield and McClain, 1973) necessitating the use of a rheological model for parameter resolution.

Heater tests may be further classified according to whether they are designed with a simple geometry for investigation of rock properties and rock-canister interaction, or have extra heaters arrayed around the test canister to simulate a large canister array. The time frame on both types of tests is similar requiring from two to four years of heating followed by a cooldown period. The first type of experiment (Figure 20) was performed successfully at Avery Island. In addition to thermal and thermomechanical properties the experiment also investigated the behavior of crushed salt used to backfill the sleeve (Figure 21). Specifically, compaction of the backfill, corrosion of the sleeve and brine migration toward the heater were studied. Three heater tests were performed; one had no backfill and served as a control. The other two were very similar with power levels of 3 kw and 6 kw per central heater (Van Sambeek, 1980).



THERMOCOUPLE BOREHOLE NUMBER	RADIAL DISTANCE FROM HEATER CENTERLINE (FEET)	THERMOCOUPLE CHANNELS IN BOREHOLE
#1	1.94	179, 190-192
#2	1.09	194 - 199
#3	0.97	200 - 205
#4	1.71	206 - 210
#5	2.32	211 - 215
#6	3.18	216 - 220

Figure 20. Single header test configuration used at Avery Island, Louisiana. (from Van Sambeek, 1980)

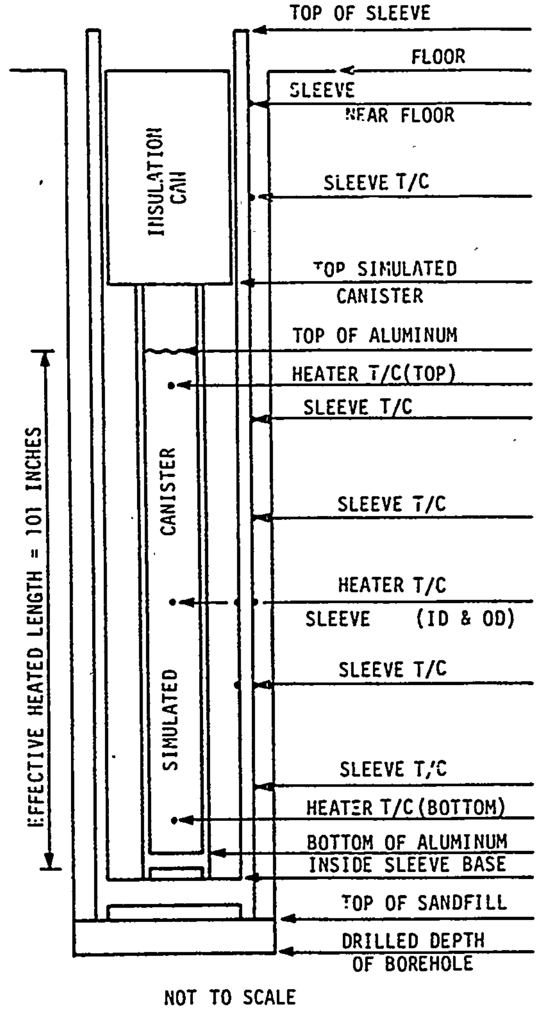


Figure 21. Schematic of heater borehole configuration for backfilled and non-backfilled heater tests at Avery Island, Louisiana. (from Van Sambeek, 1980).

Project Salt Vault (Starfield and McClain, 1973) incorporated the peripherally heated, "unit cell" test in two rooms (Figures 22 and 23). Room #1 contained an array of live waste canisters. No difference was noted between the two tests in any aspect which could be attributed to the use of rad waste in room #1.

An additional heated pillar type test was performed in Project Salt Vault. This involved pumping heat into the pillar between rooms 2 and 3 via a linear array of borehole heaters in each room. The heater arrays were oriented parallel to the pillar, close to the pillar base. The resulting data (Figure 24) was used to validate a room-scale model, STEALTH 2D. Pillar displacement was measured via horizontal extensometers and rigid inclusion stressmeters located in the pillar, vertical pipe-type roof-floor convergence gages oriented coplanar with the heater arrays, and tape extensometer readings between the pillar faces in rooms 2 and 3.

Heater tests provide an effective means of model validation on a realistic room-scale. A "unit cell" test in conjunction with a single canister heater test can provide the necessary input on thermal parameters, and an estimate of the response of the salt to repository conditions on a larger scale. A heated pillar, or other large-scale heater test in which >100 m^3 of salt is heated while under load may be required depending on the character of the rockmass, especially if low strength discontinuities are present (Harrington, 1980). Attempts to model the behavior of discontinuities in lab-scale studies have met with limited success, (Starfield and McClain, 1973) therefore field testing is likely the only method available for obtaining this important design information.

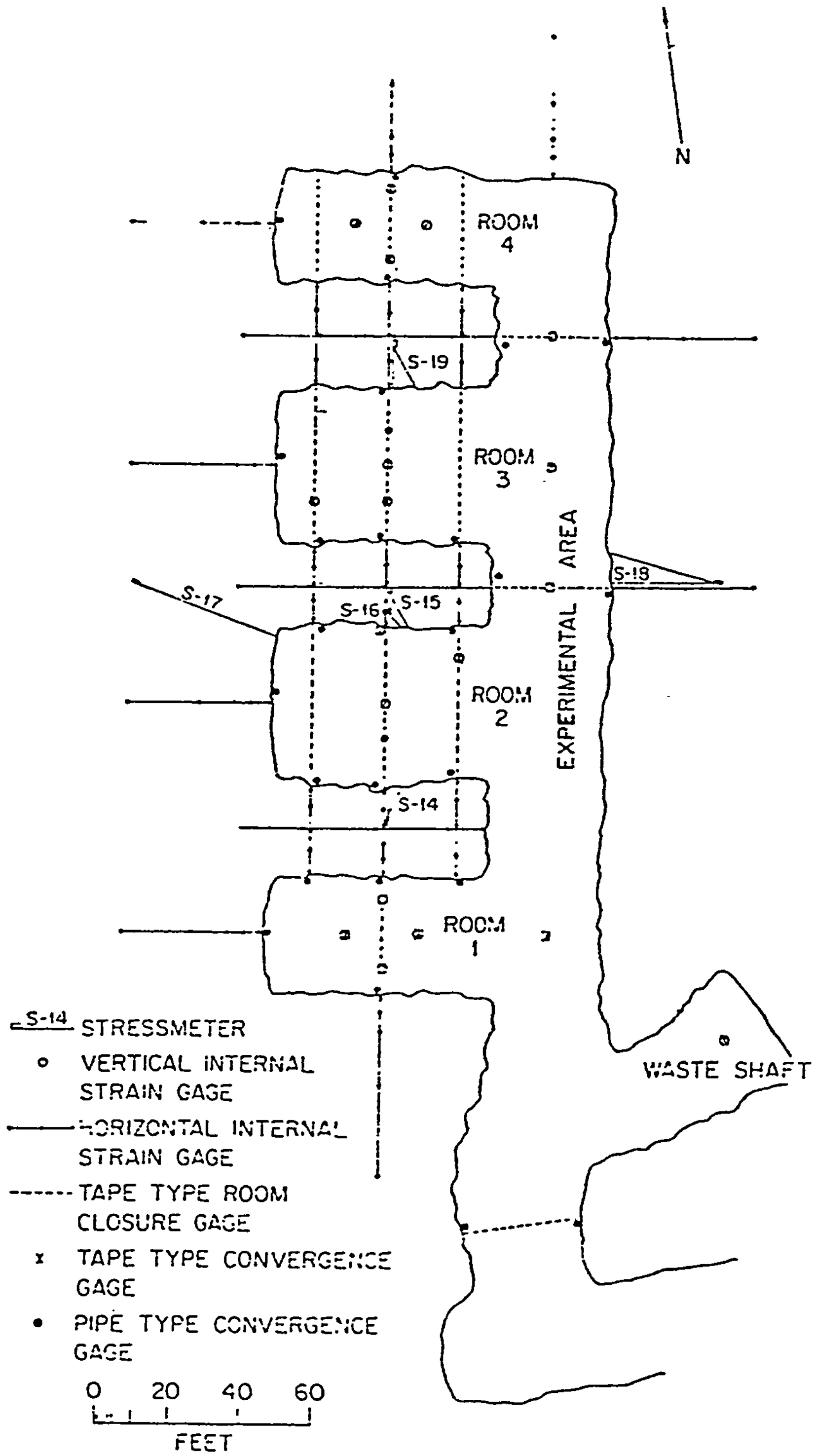


Figure 22 Stress and displacement instrument layout for Project Salt Vault, in bedded salt near Lyons, Kansas. Heaters, canisters and thermocouples are not shown. (from Starfield and McClain, 1973). Reprinted with permission from Pergamon Press, Ltd.

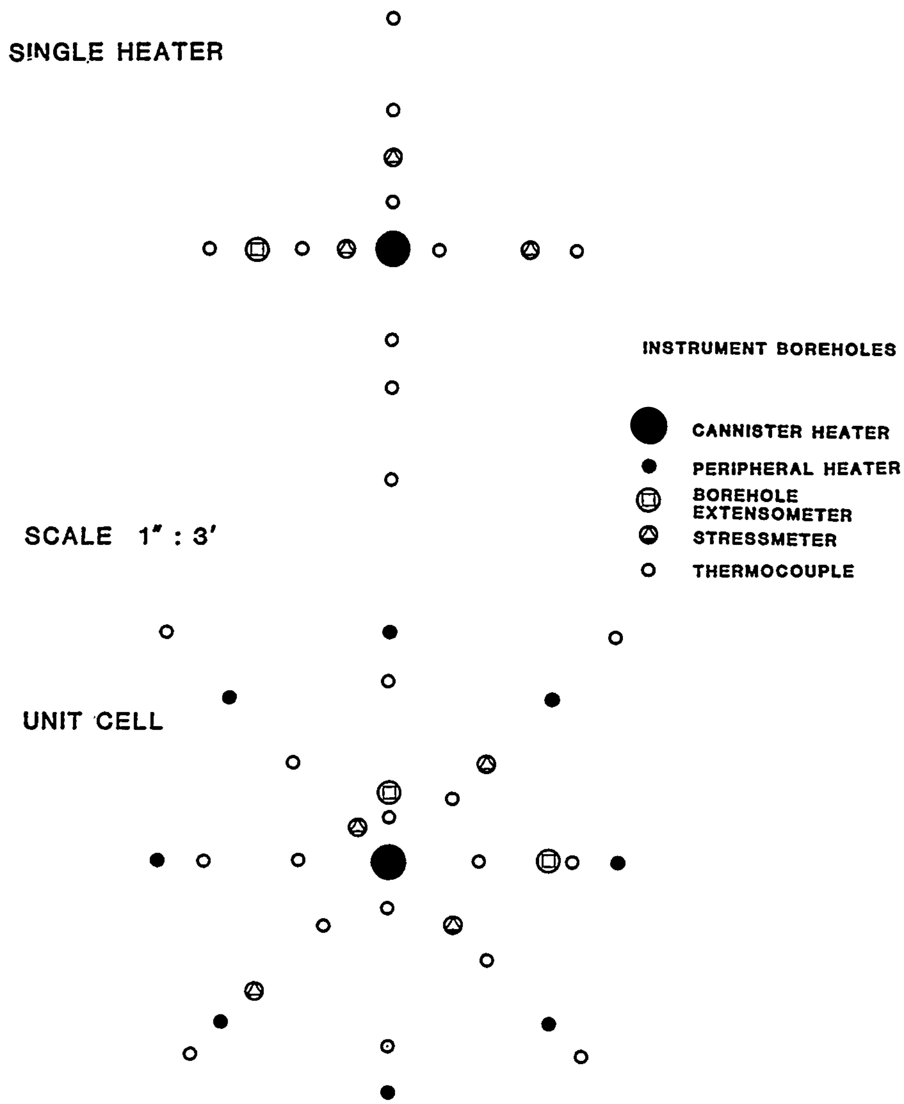
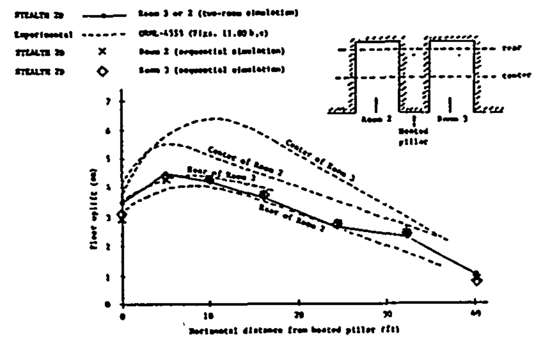
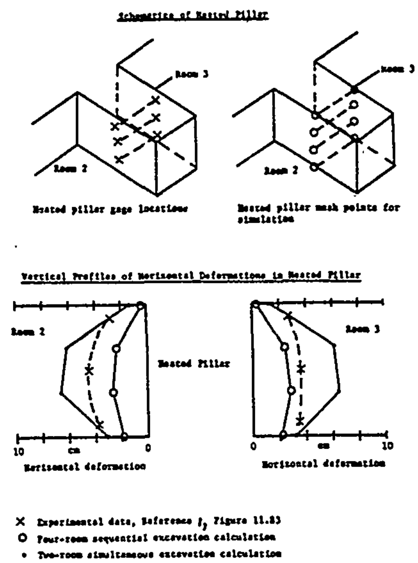


Figure 23. Schematic drawing of heater, stressmeter, extensometer and thermocouple layouts for a single heater test and a peripherally heated, "unit cell" test.



Floor uplift for four-room simulation — standard days 1020 to 1501.

(upper) Predicted and observed floor uplift from the heated pillar test, Project Salt Vault. Discrepancy of fit can be attributed to the unknown influence of pillar load, roof height, abutments, and in situ stresses. (from Wahi, et al., 1978)



Computed and experimental horizontal deformation of heated pillar walls from standard day 806 to 1500.

Figure 24. (lower) Predicted and observed pillar deformations from the heater pillar test, Project Salt Vault. Horizontal extensometer locations in the heated pillar are shown, as well as the measured deformation. (Wahi, et al., 1978)

All of the tests described above are being planned for the WIPP project in bedded salt (Dames and Moore, 1978). Large-scale experiments are particularly needed for bedded salt, because of the prevalence of discontinuities. A preliminary test layout for the WIPP facility is shown in Figure 25. A heated pillar test may be required in domed salt to accelerate rheological behavior into a manageable time period for observation. Such an experiment could be readily interpreted in view of the time dependence of existing rheological models.

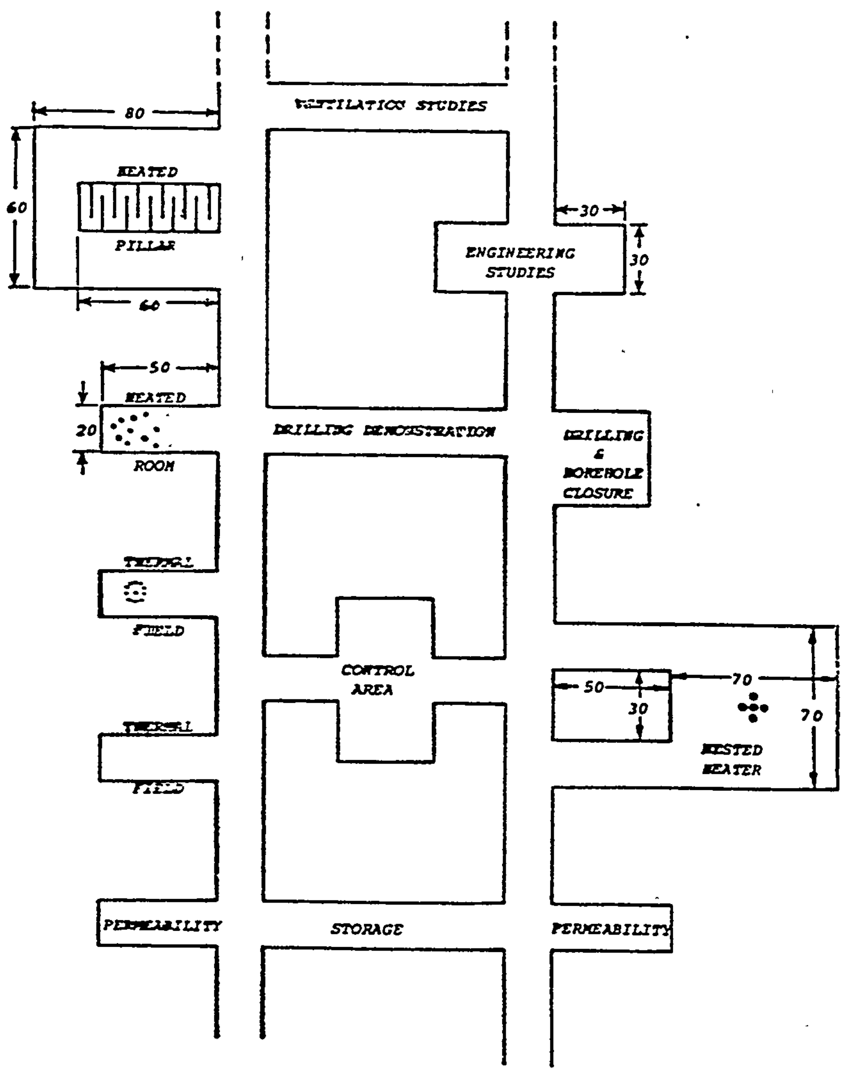
7.2 RESOLUTION AND RELIABILITY

The resolution and reliability of any in situ tests are probably better in domed or bedded salt than any competing geologic media, due to the outstanding homogeneity of candidate salt formations. The state of the art in temperature and displacement instrumentation is adequate for most field testing in salt. Stress instrumentation is a different matter, since most existing instruments have been designed around elastic media.

7.3 COST AND TIME

The cost of an in situ "unit cell" type test would be approximately \$250,000 - \$400,000 distributed over two or three years. This figure includes the necessary data acquisition system but presumes that a room has already been excavated. A single canister experiment providing additional data on borehole stability and brine migration could be added on at a cost of roughly \$200,000.

Large-scale heater tests such as the heated pillar experiment will require the excavation of a large facility and more drilling footage for heater and instrument holes. Once these costs are met, however, the test can be run over a period of two or three years at an additional cost of \$400,000 - \$600, 000. Considerable savings would be realized if several in situ tests were performed concurrently.



PROPOSED LAYOUT OF PRE-WIPP EXPERIMENTS TO BE PERFORMED IN A MINE DOUBLE-ENTRY SYSTEM

Figure 25. Proposed experimental layout for pre-Wipp investigations. Rooms at the left margin of the plan have been dedicated to (from top down): heated pillar test, room-scale heater test, "unit cell" test, single heater experiment, and permeability testing. (from Dames and Moore, 1978).

8. FLATJACK LOADING - FIELD SCALE TESTS

Creep of rock salt is controlled by environmental factors including deviatoric stress, confining stress and temperature, and by test-specific factors such as specimen size, loading rate and test duration. The optimum test for quantifying creep behavior would allow independent control over these parameters. The use of flatjacks in in situ testing provides the ability to control stress independently of temperature in such a test, while loading specimens of almost any size. In addition, two- or even three-dimensional creep studies may be conducted on large specimens. Such studies are needed to improve the accuracy of constitutive models of salt behavior (Dames and Moore, 1978).

8.1 DESCRIPTION

8.1.1 Cylindrical Loading

Flatjacks and the feasibility in testing which they allow are now finding increasing use in field testing in salt. The accelerated borehole closure tests at Avery Island are presently being conducted with circular flatjacks which load an in situ 1m diameter by 1m long core in uniform biaxial compression. A special core barrel was fabricated for this work, which has cutters set on its edge for widening the annular slot to 1.25" (31.8mm) (Figure 26). Borehole diameter is measured by diametral gages mounted across several diameters of the hole. In some tests, the hole is backfilled with crushed salt to study the consolidation of this material as the hole deforms. Elevated temperature capability is provided by incorporating heating elements into the semicircular, curved flatjacks. Data for these tests are not yet published, but preliminary indications are that secondary creep has been achieved, and that the test results agree reasonably well with predicted values, with some allowance for scale effects (Figure 27).

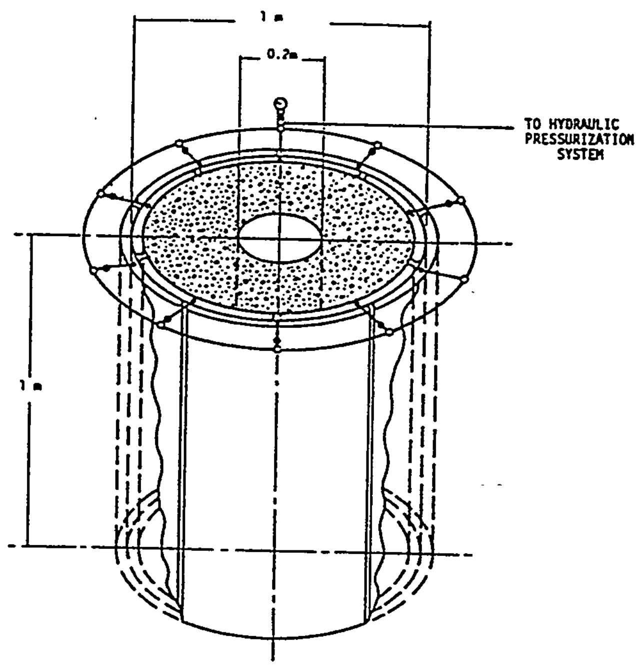


Figure 26. Circular flatjack test apparatus. A 1 m diameter by 1 m deep core is drilled into the floor, and left in place. Curved flatjacks (five are shown here) are grouted into the slot. Heaters are built into the flatjacks.
(from Van Sambeek, et al., 1980).

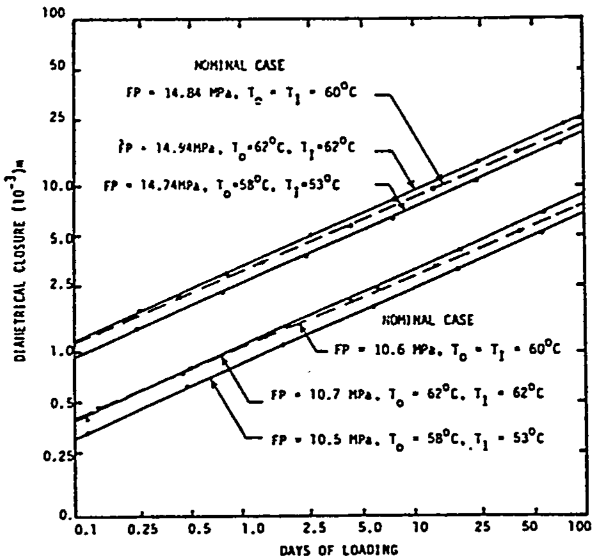


Figure 27. Predicted closure os a 0.20m diameter borehole as a function of time, for various flatjack pressures (FP), inner and outer temperatures (T_o and T_i). Predicted modeling done by RE/SPEC for the accelerated borehole closure experiments in progress at Avery Island, Louisiana. (from Van Sambeek, et al., 1980).

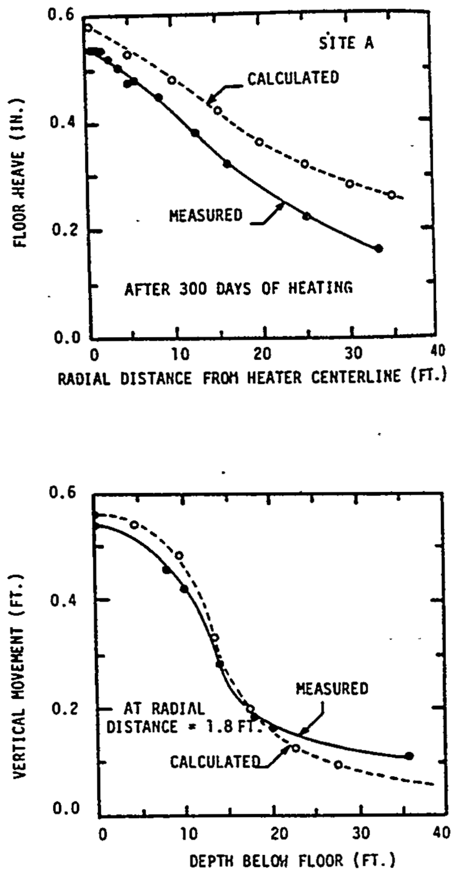


Figure 28. Predicted and observed displacements from a single heater experiment at Avery Island, Louisiana. Agreement of the prediction is considered "reasonably good". More accurate predictions could probably be made if the influence of adjacent pillars and abutments, and of the in situ stress, were well know. (Van Sambeek, 1980).

Additional studies of two-or three-dimensional creep could be made in situ using a similar test setup, or these tests could be performed in the laboratory on 1m cubes of salt, in an existing testing machine capable of loading specimens to 25 MPa triaxially at temperatures to 200°C.

In a heated pillar test, flatjacks could be used to monitor or regulate the vertical stress in the pillar. Such an approach would provide needed definition of the boundary conditions imposed on large-scale repository models.

8.1.2 Heated Block Tests

Eventually, the need for a triple-process coupled model for the interaction of thermo-mechanical-chemical-hydrologic processes in salt may arise. For this type of work, the best available field test for constitutive law development and validation is the in situ heated block test. (An example for jointed media is shown in Figures 1-3). The basic block test scenario provides for thermo-mechanical process control, and the flexibility to accommodate a range of geochemical and hydrological experiments. In the short term, validation of existing models for thermo-mechanical coupled conditions will ultimately be successful only with the control over applied stress that is attainable in the heated block test. Thermomechanical assessment of heater test data using existing algorithms (Van Sambeek, et al. 1980) is difficult because of the unknown influence of pillars, abutments, roof height and in situ stress.

8.2 APPLICATION

The method of flatjack loading is applicable to cylindrical or block specimens, in the field or in large laboratory "cube-test" facilities. Dome and bedded salt can be sawn or drilled with relative ease making sample preparation relatively inexpensive.

8.3 RESOLUTION AND RELIABILITY

At present, large-scale flatjack field testing has been initiated at Avery Island only. Agreement between theory and practice will determine the importance of these tests; if a significant scale dependence develops, the accelerated borehole closure test or some variant of it will become standard for characterization of domed and bedded salt. Field testing in salt formation other than Avery Island will determine the amount of variability which can be expected. Large-scale laboratory testing can also provide an estimate of variability in salt, once samples from different candidate sites become available.

A heated (HTM) block test should be performed in salt for evaluation of coupling mechanisms. The applicability of this test to various formations will be predicated on the variability in large-scale and in situ properties discussed above, and on the results of this first HTM block test.

The resolution and reliability of large-scale lab and in situ testing will be different for salt than for other media. Because of the rheological properties of salt, careful attention must be paid to loading history and loading rate during flatjack tests. Measurement of displacement and temperature in salt places some extra burden on existing geotechnical instrumentation, due to corrosion, etc. Stress measurements and any novel hydrological or geochemical experiments in salt will probably necessitate some instrumentation development.

8.4 COST AND TIME

The cost of a series of eight accelerated borehole closure tests of the type performed at Avery Island at various temperature and stress levels would be on the order of $300,000. Additional tests to study the effects of loading rate, test duration or other test parameters could be added at reduced cost per test. Each test would require at least one year to completion. A series of tests would take longer, since the tests are staggered. These estimates include data acquisition, but presume that an underground test facility is already available.

Large-scale ($1m^3$) lab tests on salt using electric heaters and flatjack loading to 25 MPa, with displacement or other instrumentation as required, could be performed for $30,000 or less for short duration tests. Long term (creep) tests could cost up to several times this figure, depending on the exact requirements. Tests of this type are very similar to in situ block tests, but with the triaxial capability. All of the thermomechanical loading conditions possible with the heated block test can be achieved, as can many of the hydrologic and chemical tests.

The cost of a hydrothermomechanical (heated)(HTM) block test in salt would be comparable to the cost in other media (section 4). Specialized hydrologic or chemical experiments or long term (creep) tests would increase costs slightly.

9. INSTRUMENTATION FOR LARGE-SCALE TESTING IN SALT

Several problems presently exist with available instruments for measuring stress and displacement for large-scale (in situ) experiments in rock salt:

- Stress monitoring instruments such as the IRAD rigid inclusion stressmeter and USBM borehole deformation gages (BDG) do not function well in inelastic media.
- Available rock mechanics instrumentation is designed for a useful life of 3 - 5 years at most, with environmental effects such as moisture, corrosion and high temperature the chief causes of failure.
- Creep in rock salt generally involves displacements about one order of magnitude larger than the displacements which available rock mechanics instruments are designed to measure, over a period of several years.

Experience with the IRAD stressmeter in site characterization experiments in various media has shown that the gage is not well suited to long term monitoring, high temperature application, or block tests wherein the stress is cycledoften (Cook and Ames, 1979; Van Sambeek, 1980). A real need does exist for a stress gage which performs under these conditions. Such instruments as the CSIRO cell or USBM (BDG) do not provide the desired stability and accuracy. A development effort is therefore required to produce a satisfactory alternative. The principle of operation of a flatjack pressure cell as used in concrete could probably be successfully applied to stress monitoring in salt. A means would have to be found of deploying such a flatjack type device at the bottom of a borehole or in a pillar, probably using a borehole-circular saw method.

Engineering a borehole instrument to survive for long periods can be a most vexing problem. Presently instrument longevity is tested during the course of field tests, when the instruments are in service. When failure occurs, a loss of data generally occurs with it, making this type of environmental testing unnecessarily expensive. A series of standard, extreme environmental tests should be developed which could be performed on instruments in the laboratory at lower cost.

Measuring the large displacements (e.g. up to 0.5 m) which occur in salt excavations will involve some changes to existing designs for strain gages and extensometers. It is automatically read instrumentation which is most subject to this problem. Where manual readings are possible, existing manual extensometers and closure meters are adequate for salt. A successful program of very large displacement (up to 3 m) monitoring has been conducted for the WIPP at a potash mine in SE New Mexico owned by the Mississippi Chemical Co. Experience gained from this program should be used to develop generally available working designs for instruments to monitor creep in salt.

Another instrumentation need in the NWTS field testing and repository monitoring programs is for an optical system to measure displacements in boreholes. A system for measuring lateral displacement at the bottom of boreholes (in the plane perpendicular to the hole) would find application in nearly every field test for thermomechanical properties. Other optical measurement systems employing different optical principles and state of the art electronics should be investigated.

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APPENDIX F-1

EXPLORATORY GEOCHEMICAL

TECHNIQUES

PRECHARACTERIZATION STUDIES

BY

DONALD LANGMUIR

HYDROCHEM SYSTEMS CORP.

GOLDEN, COLORADO

NOVEMBER 1, 1981

F-1

Phase I Report

EXPLORATORY GEOCHEMICAL TECHNIQUES TO BE USED DURING SITE SELECTION AND CHARACTERIZATION

by

Donald Langmuir
Hydrochem Systems Corp.
Golden, Colorado

Page No.

1.0 EXECUTIVE SUMMARY

Published geochemical data on groundwaters and rock systems which are being considered as repositories for high level radioactive wastes, are useful to obtain general geochemical and hydrologic characteristics near a potential site. However, such data are usually from wells and springs which sample shallow, phreatic-zone groundwater systems. These relatively shallow systems either receive meteoric recharge waters, or could discharge to the biosphere after unacceptably short residence times. General geochemical-hydrological characteristics of these relatively shallow zones can often be usefully evaluated using published geochemical data and graphical and statistical techniques.

Such available data and its interpretation should, in concert with published hydrogeological, geological and geophysical information, suggest more local water-rock (phreatic zone) or dry rock (at depths below the phreatic zone) settings worthy of in-depth appraisal as to their site-suitability. At this more localized scale of appraisal, new geochemical data should be collected, analysed and interpreted to assist in site selection. These new geochemical data collection efforts would involve sampling groundwaters from wells, and also rock materials and associated fluid inclusions from cores.

The data obtained from the ground water samples should include: field measured pH, oxidation potential (Eh), dissolved oxygen and temperature; and laboratory analysis for gases other than oxygen, and for major and minor species, on properly filtered and preserved water samples. Rock samples from cores should be analysed for their mineralogy and petrology (as well as their hydrologic properties). The above data can be introduced into geochemical water-rock reaction models. These models have the following capabilities. They can:

1) by the lack or degree of saturation of the water with respect to certain minerals, indicate the relative age of a groundwater, or its extent of mixing with other groundwaters;

2) reconstruct what minerals are dissolving or precipitating in the groundwater flow direction, and estimate the mineral and gas amounts involved;

3) predict the solubility of radionuclides that might be released from a breached repository, as a function of temperature in groundwaters at different salinities; and

4) consider the effects of ion exchange for some elements.

Analyses of the noble gas content of the groundwater can be used to compute the temperature of groundwater recharge from precipitation. Of course, cold groundwater recharge temperatures are indicative that the groundwater has a meteoric origin. Such an origin for the water is also indicated by a particular set of relative concentrations for the several noble gases.

Stable isotope data (especially for oxygen and hydrogen) can be collected from the groundwater, and from secondary minerals and fluid inclusions obtained by coring. Radioisotope data (especially data on radiocarbon and tritium) can also be obtained from the groundwater and secondary minerals. These combined data provide unique insights as to the suitability of a site which are not available by any other means. The stable and unstable isotope data yield information as to the earlier existence or present absence or existence and character of meteoric waters, and the approximate time that meteoric waters were present in the system. Obviously, if one can show that a rock or water/rock system has recently been or is now in contact with meteoric water, such a system is a poor candidate for a repository. The isotope techniques can be applied to groundwaters and secondary minerals in the phreatic zone, and to fluid inclusion waters and secondary minerals in deeper, dry-rock systems.

2.0 INTRODUCTION

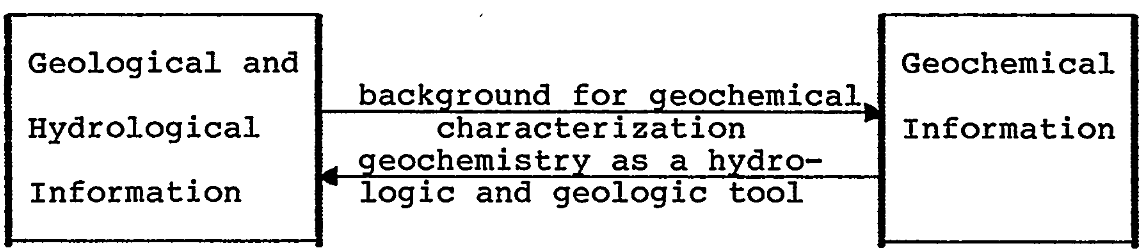
2.1 <u>The Need to Coordinate Characterization Efforts Involving Geochemical Techniques and Those of Related Disciplines</u>

The effective application of any geochemical exploratory technique whether descriptive, such as a groundwater quality map, or sophisticated, such as a geochemical reaction path computer model, depends on:

(1) the adequacy of geochemical data for the groundwater and enclosing geological formations; but also depends on

(2) the adequacy of geological and hydrological information available on that water-rock system.

The choice and pertinence of a given geochemical exploratory technique depends for example on the nature of groundwater flow in the formation - isotropic versus anisotropic - intergranular versus fracture flow for example, and the variability of hydrogeologic properties of the rock both areally and with depth. The geochemistry itself provides unique insights as to the hydrogeological properties of the formation.



2.2 <u>Two Major Groupings of Exploratory Geochemical Techniques; Those based on utilizing available data, and those generally requiring additional data collection</u>

The choice of techniques depends upon the availability, completeness, and quality of geochemical data on the groundwater and on associated geological formations. Two general groupings of techniques can be identified.

I. Techniques that may be utilized for characterization given inputs of available and estimated water quality and rock geochemical data only. Such techniques are necessarily relatively descriptive, and especially pertain to broad characterization of areally larger groundwater systems. A major role of groundwater geochemical techniques is as hydrologic tools.

II. Techniques useful for characterization if additional groundwater and rock sampling and geochemical analyses are possible. This would include: a) analyses of existing well waters and available cores and formation outcrops, and b) analyses of well waters and cores obtained from new wells. Techniques applicable under these circumstances are most appropriately directed towards characterization of smaller scale areas than considered in I above. Such techniques include modeling mineral saturation conditions, geochemical reaction paths, and isotopic dating of the groundwater. The applicability of available and newly collected goechemical data to the ultimate site selection process and to initial characterization is generalized diagrammatically in Figure 1.

3.0 GEOCHEMICAL TECHNIQUES UTILIZING AVAILABLE GEOCHEMICAL INFORMATION

3.1 Sources of Available Data

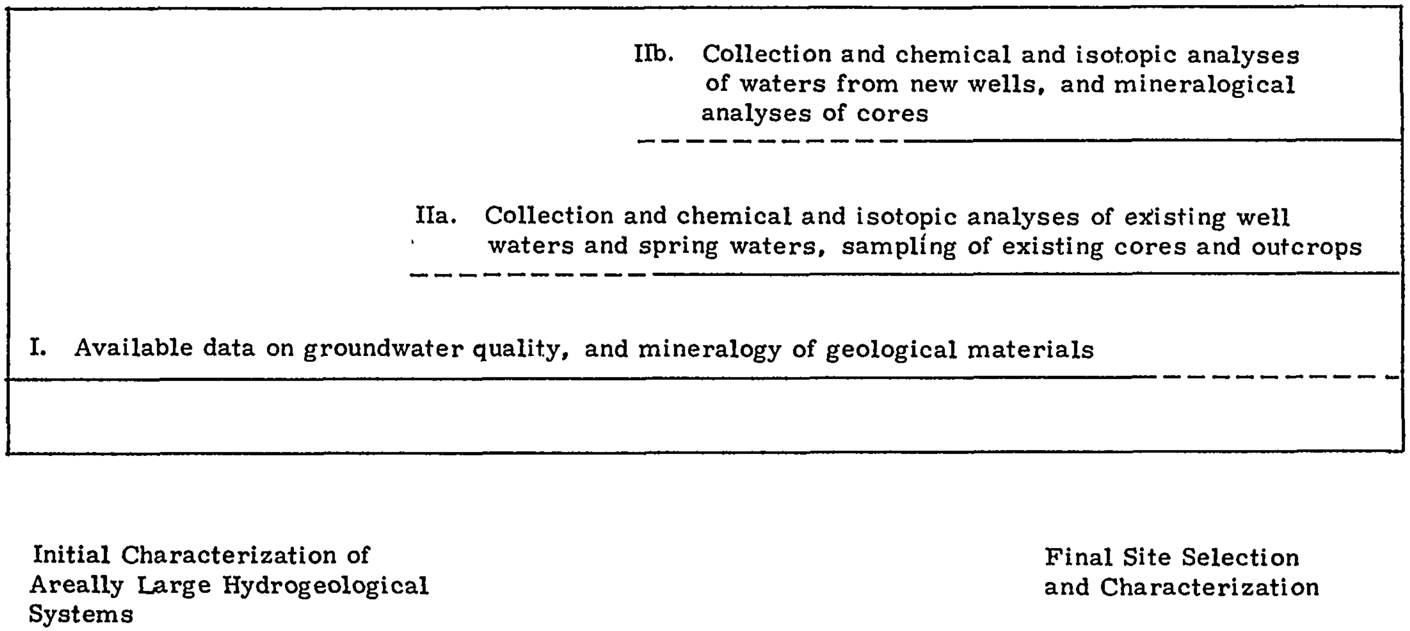
3.1.1 Sources of groundwater quality data:

a. USGS. Data computerized in WATSTORE (contains only USGS data)
b. EPA. Data computerized on STORET (contains much USGS data, plus additional data - see d. below)
c. DOE. Data from the NURE program. Computerized (includes only NURE data)
d. State and municipal agencies. Data collected for purposes of well permitting and public water supply monitoring. Some data computerized, some not. The data may or may not be in the STORET system.
e. Miscellaneous other sources.
    1. private water company files
    2. files of large industrial users
    3. consultant reports including environmental impact statements
    4. university theses and contract reports

3.1.2 Sources of rock geochemical data (including cores):

a. USGS and state geological survey reports and publications
b. Journal articles

Fig. 1. Sources of Geochemical Data for Site Characterization



c. University theses
d. Industrial files and reports

3.2 Problems with Utilizing the Available Groundwater Quality Data

1. Most of such data is from shallow wells ($<$500 ft deep) in areas of densest habitation.

2. Such data is usually for potable waters only.

3. The chemical quality of such well waters has often been modified by anthropogenic effects.

4. Such data is often from wells inexactly located, pumping from unknown depths and uncertain formations. Some such wells are dug. Many sampled wells are unavailable for future sampling.

5. Because wells are located near users, their areal distribution is usually too local for definitive characterization of the regional groundwater quality in a formation.

6. Available data rarely includes field measured values of pH, dissolved oxygen, Eh (redox potential), dissolved gases and temperature, or laboratory analyses of stable or radioactive isotopes or noble gases.

7. Water sampling has often not involved: a) pumping a well to constant composition prior to sampling; b) filtration in the field prior to acidification of samples for laboratory analyses; or c) proper preservation and storage of samples for determination of unstable constituents.

3.3 Nature of the Techniques

3.3.1 Graphical, Map Related Techniques: A host of map-related techniques have been employed to appraise available ground water quality data. These include isochemical maps, or maps that contour concentration variations of individual species or groups of species such as total dissolved solids in the groundwater. An isochemical map is given in Fig. 2. Quality versus map distance (see Fig. 3) or depth plots are also useful, as are maps of prevalent chemical character (PCC) (see Fig. 4). PCC is simply a listing in order of their decreasing concentrations, the equivalents per million of major cations and anions in the groundwater. Back (1961)

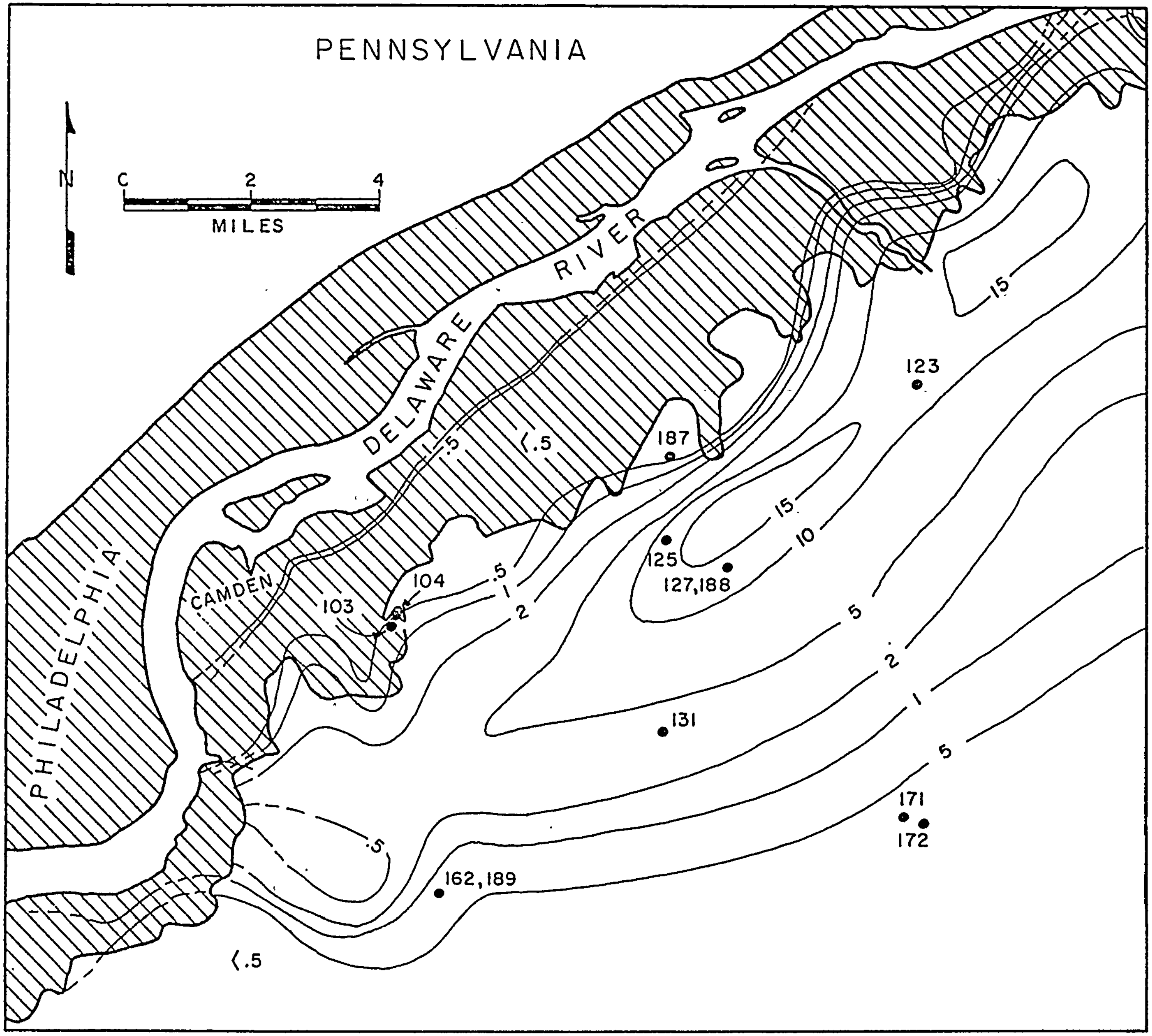


Figure 2 Generalized total iron concentrations in groundwaters of the Potomac-Raritan-Magothy Formations in New Jersey in parts per million in 1965. Numbered points are wells sampled. Crosshatching denotes the outcrop area of the formations. The formations dip towards the southeast from the outcrop area they become confined. (Langmuir and Whittemore, 1971). Reprinted with permission of American Chemical Society

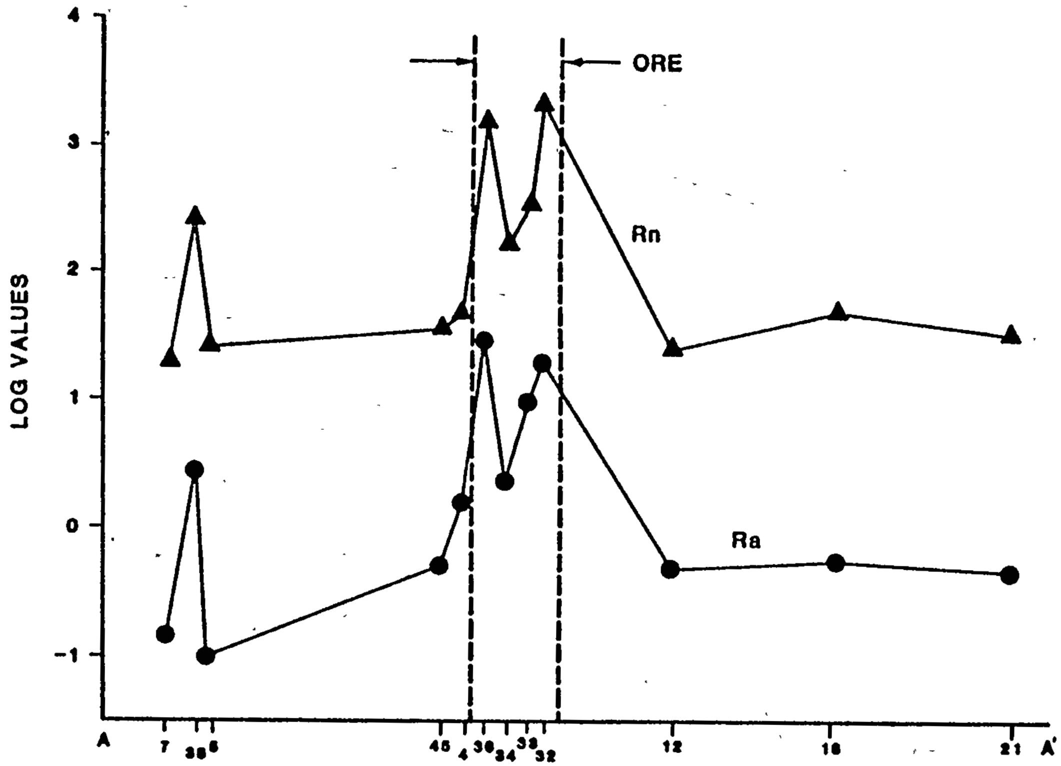


Fig. 3. Profile of log concentration values of radon in cph, and radium in pCi/l in lower Oakville Formation groundwaters in southeast texas along map profile AA' (9.2 km in length) in the direction of groundwater flow. Numbered values are for the wells sampled. The location of an uraniferous ore zone is denoted by "ORE". (Chatham, Wanty and Langmuir, 1981).

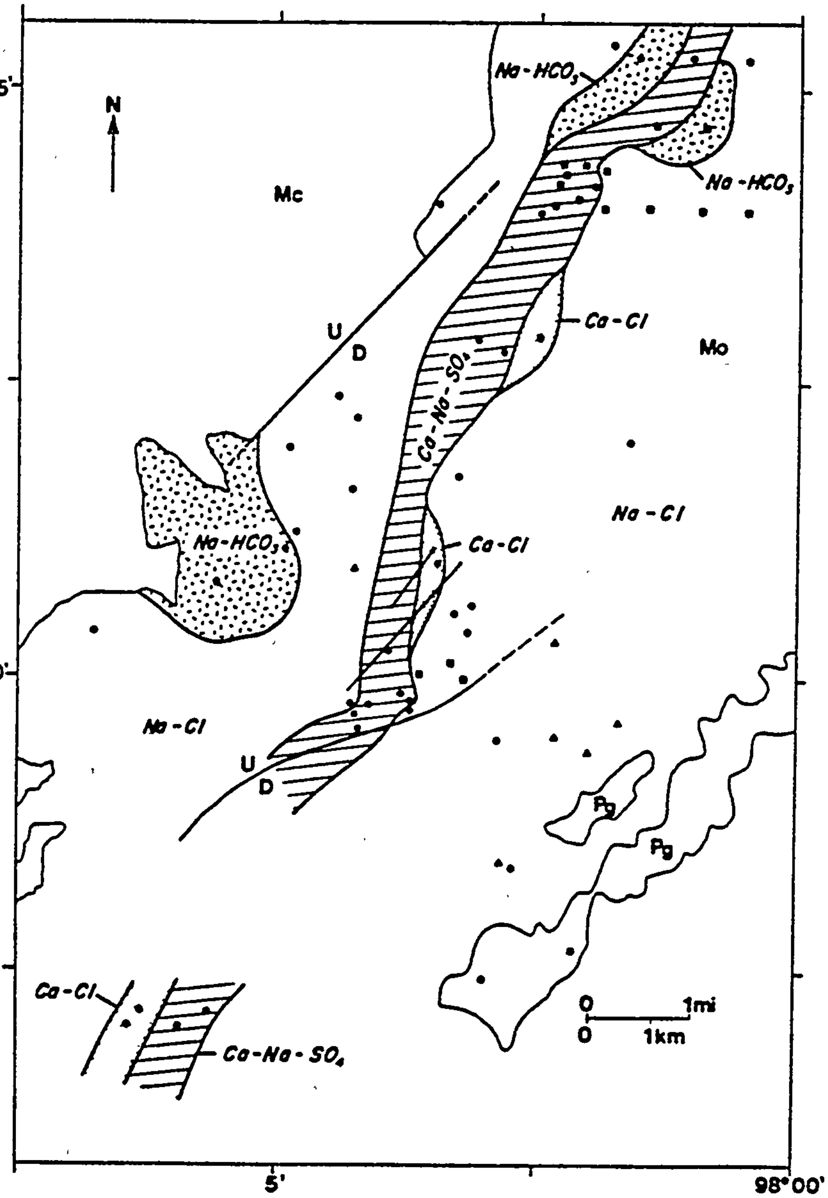


Fig. 4. Prevalent chemical character of lower Oakville Formation groundwaters in southeast Texas. Mc, Mo and Pg are the Catahoula, Oakville and Goliad Formations, respectively. (Chatham, Wanty and Langmuir, 1981).

introduced the similar concept of groundwater chemical facies. An example of this approach is given in map-cross-section form in Fig. 5. Langmuir (1969) proposed the concept of groundwater quality zones where each zone encompassed portions of a water-bearing formation of similar water quality and geohydrologic properties (see Table 1 and Fig. 6). Ion ratios in groundwater plotted in maps and profiles have also been found useful to describe groundwater quality trends.

3.3.2 Graphical, Diagrammatic Techniques: Hem (1970) has described a variety of diagrammatic graphical methods for depicting groundwater quality information and its variations. These include trilinear, circular, vector and Stiff diagrams and bar graphs. Examples of such plots are given in Figs. 7a-g and 8. Most such techniques allow rapid comparison of water quality data to identify differences or similarities in such data. Triagular percentage diagrams such as are shown in Figs. 7f and 7g allow one to decide if a water is a simple mixture of two other waters - such as sea water or a brine, and a fresh groundwater. Rectilinear ion ratio plots as given in Fig. 8 have been similarly employed.

3.3.3 Statistical Techniques: Statistical methods of evaluating groundwater quality data include coefficient of variation calculations for repeated groundwater chemical analyses from a single well or spring. It must be pointed out, however, that if significant time variations are evident in groundwater quality from a well (or spring) (see Fig. 9), the geological formation at the depth of the well intake is obviously a poor candidate for a repository. Such groundwater quality variations generally indicate a water-rock system open to mixing with meteoric or other waters.

Other statistical methods employed include analyses of variations in chemical composition versus map direction or depth, cluster analysis, multiple regression, principal components analysis, and Kriging (c.f. Davis, 1973; David, 1977; and Geostatistics, 1980). In general such methods provide less useful information than do water quality maps, or profiles plotted versus map distance.

Another application of statistical methods is in the estimation of concentrations of major dissolved ionic species in a groundwater which have not been chemically analyzed. Such an approach involves regression analysis and information on the equivalents per million cation-anion balance of the groundwater (see Chatham, Wanty and Langmuir, 1981).

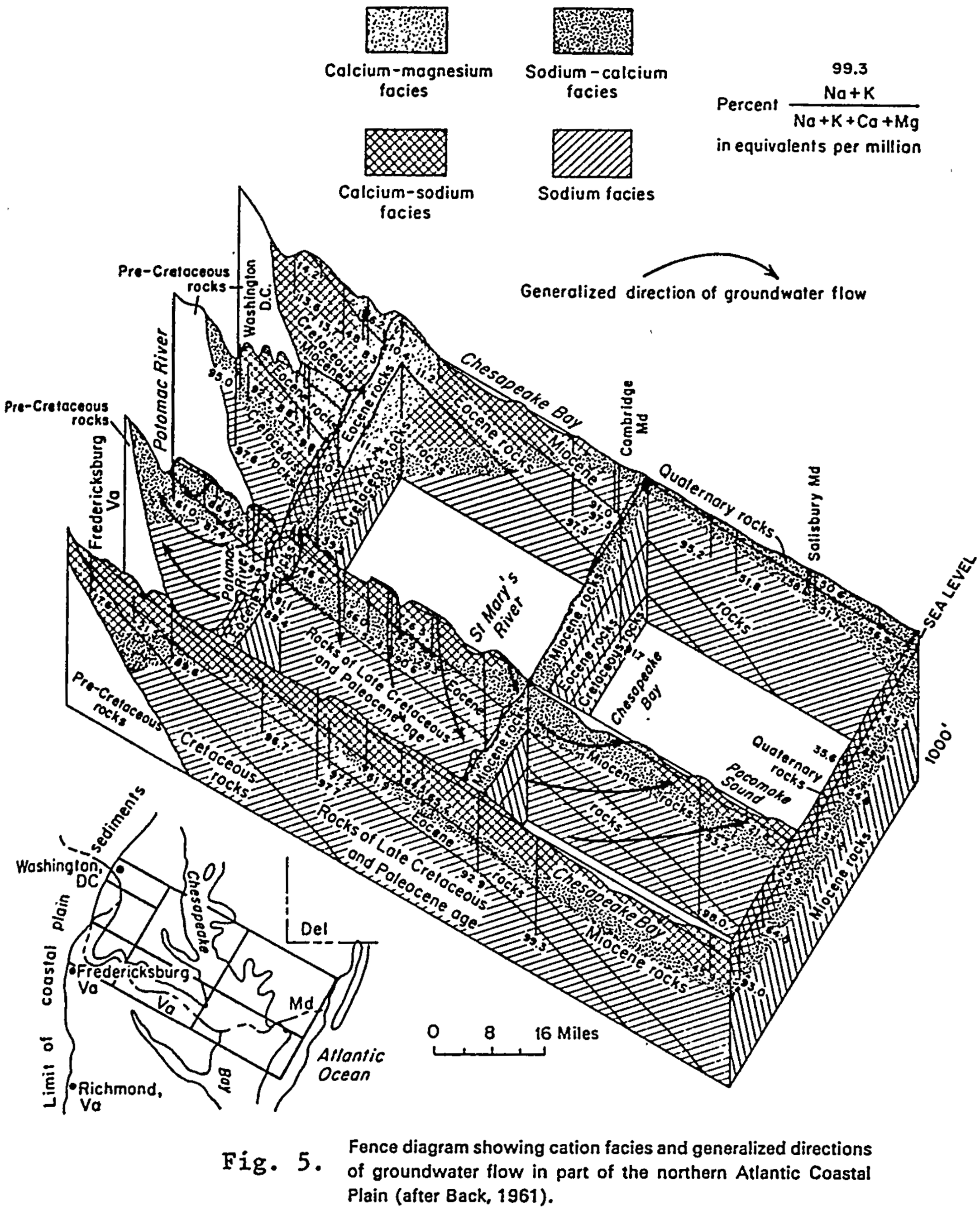


Fig. 5. Fence diagram showing cation facies and generalized directions of groundwater flow in part of the northern Atlantic Coastal Plain (after Back, 1961).

TABLE 1.–Prevalent chemical character and iron content in ground water from the Magothy and Raritan Formations in Camden and Burlington Counties, New Jersey. (From Langmuir, 1969).

Water Quality Zone Number	Location and Dissolved-solids content (location on figure 5)	Normal Range of pH Values	Principal Cations and Anions in Decreasing Order of Abundance	Iron Content	Remarks
1	Outcrop areas with dissolved solids <100 mg/1	5.0-6.0	Ca, Na, Mg; K; $HCO_3 \approx Cl, SO_4, NO_3$	Generally both total iron and Fe^{+2}<0.5 mg/1	Principal areas of high-quality recharge; from the Delaware R., precipitation, and streams.
2	Areas in and adjacent to outcrop with dissolved solids >100 mg/1	6.0-7.0	Ca, Na, Mg, K; HCO_3, SO_4, Cl, NO_3	Total iron and Fe^{+2} usually exceed 0.5 mg/1. Total iron up to 20 mg/1; Fe^{+2} up to 5 mg/1	Ground waters polluted or vulnerable to pollution in and adjacent to these areas. Dissolved solids may exceed 400 mg/1.
3	Downdip from outcrop areas, with dissolved solids <200 mg/1 or outcrop areas with dissolved solids 100-200 mg/1	6.0-8.0	Ca, Na, K, Mg; HCO_3, SO_4, Cl	Total iron<0.05 to 16 mg/1; Fe^{+2}<0.05 to 6.6 mg/1	Quality due to natural geohydrologic environment and reactions with geologic materials.
4	Downdip from outcrop areas with dissolved solids>200 mg/1	>8.0	Na>>Ca, K, Mg; HCO_3>>Cl SO_4	Both total iron and Fe^{+2} probably<0.3 mg/1 throughout	Quality deteriorates south of the 200 mg/1 contour due to mixing with residual saline waters. Chloride increases rapidly south of 500 mg/1 line.

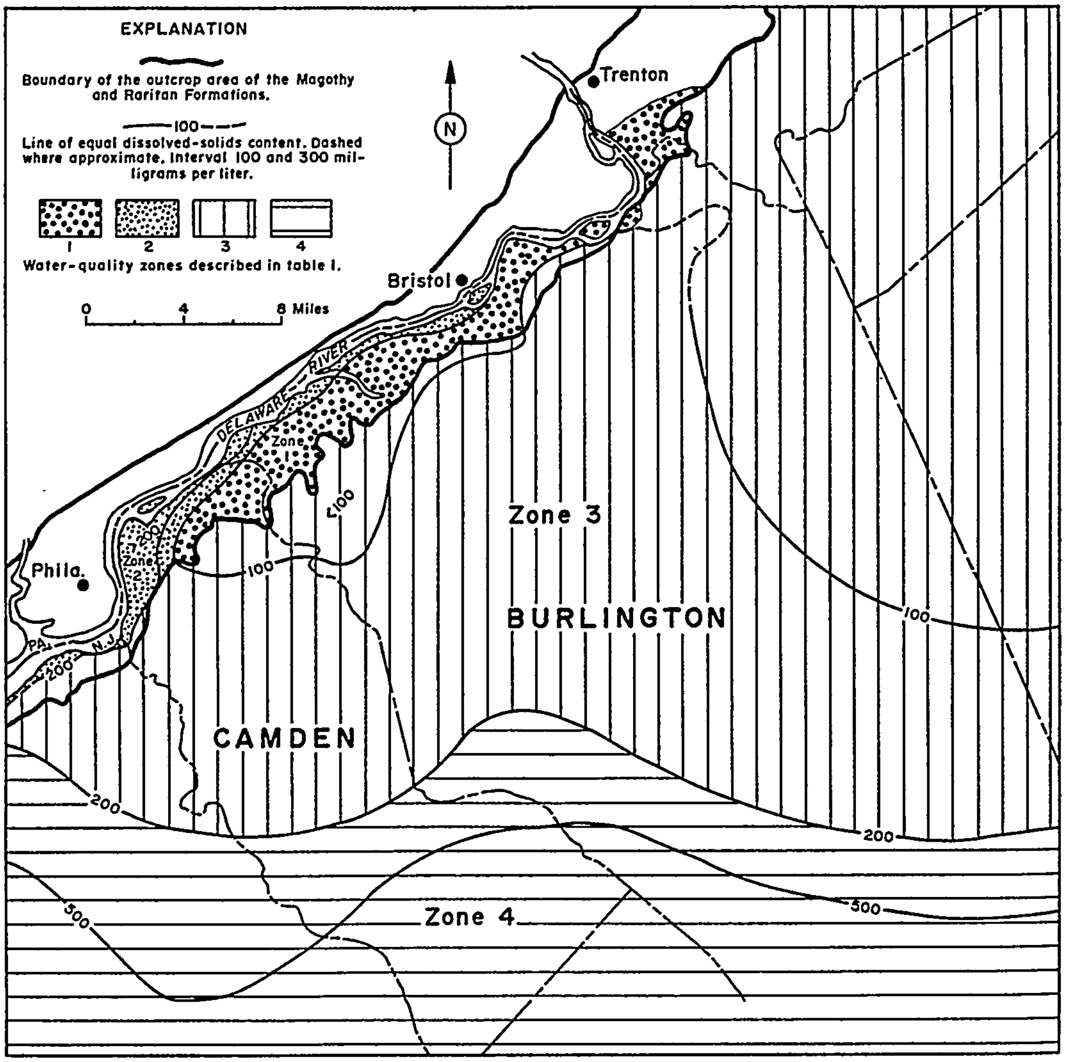
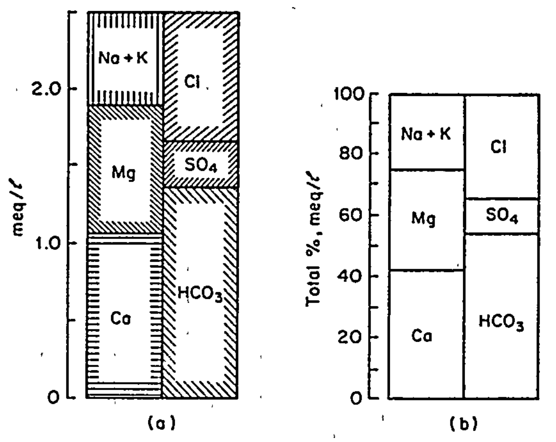
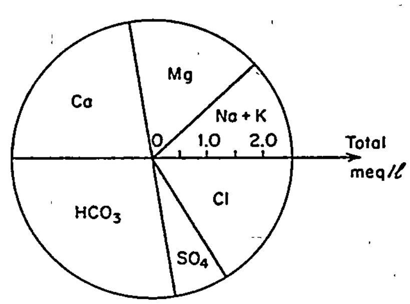


Fig. 6. Map showing generalized (total) dissolved solids content and location of water quality zones in groundwaters of the Magothy and Raritan Formations in Camden and Burlington Counties, New Jersey, 1966-67. (Langmuir, 1969).

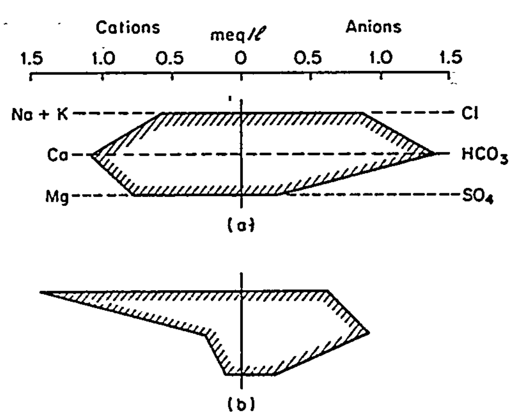
Figs. 7a-7c. Some graphical methods of describing groundwater quality data. See Davis and DeWiest (1966) and Hem (1970).



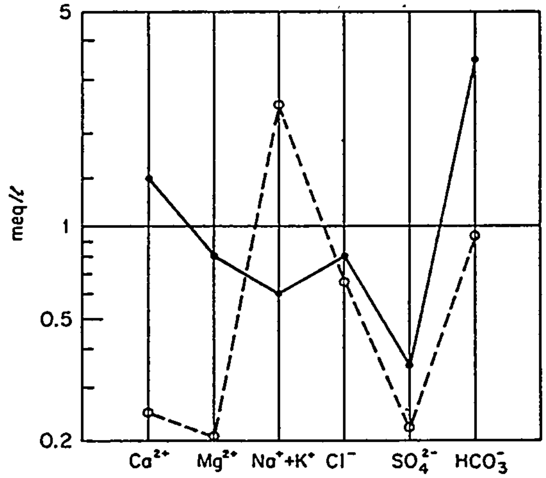
Chemical analyses of groundwater represented by bar graphs: (a) milliequivalents per liter; (b) percentage of total equivalents per liter (after Davis and De Wiest, 1966).



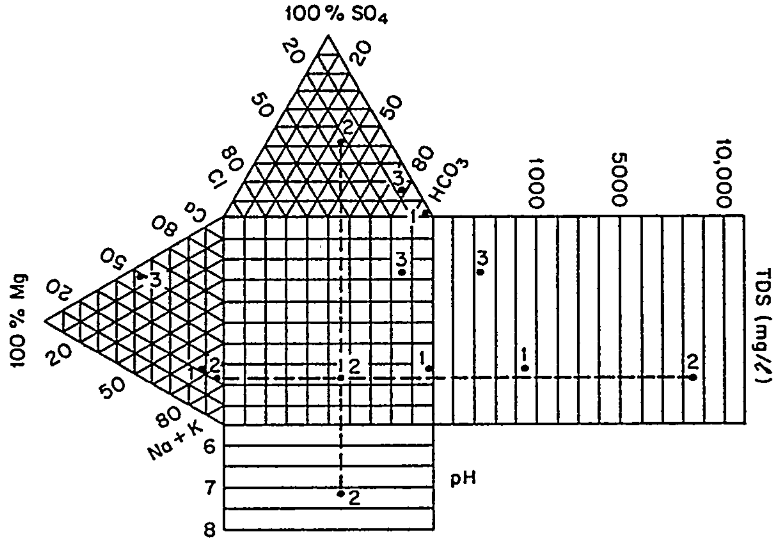
Chemical analysis of groundwater represented by a circular diagram. The radial axis is proportional to the total milliequivalents. (after Davis and De Wiest, 1966).



Two chemical analyses represented in the manner originated by Stiff. (a) The same analysis as in the previous figures; (b) second analysis, illustrating contrast in shape of the graphical representation (after Davis and De Wiest, 1966).

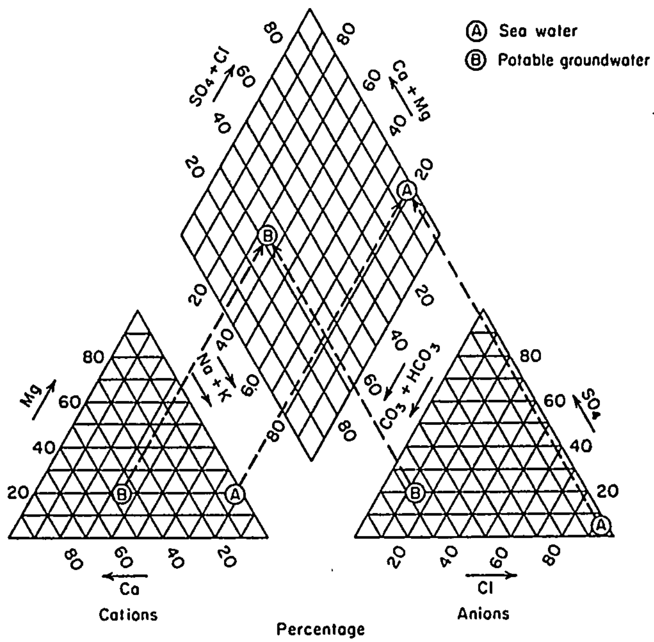


Chemical analyses of water represented on a Schoeller semi-logarithmic diagram

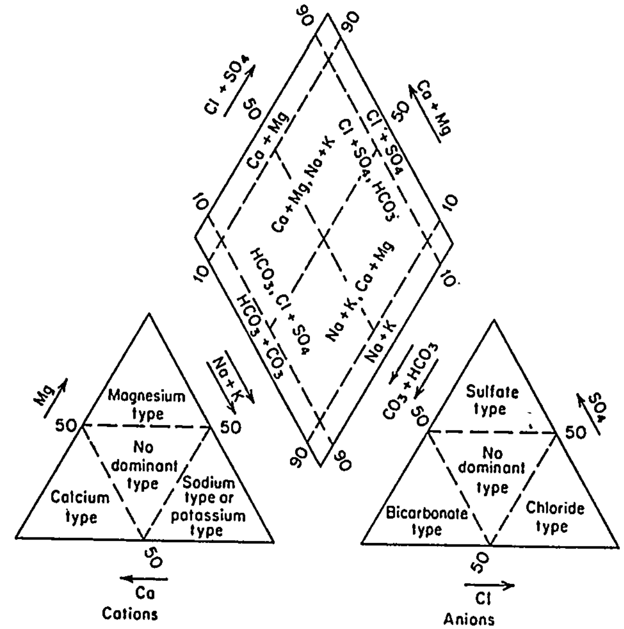


Chemical analyses represented as milliequivalents per liter on the diagram originated by Durov

Figs. 7d & 7e. Some graphical methods of describing groundwater quality data. See Davis and DeWiest (1966), and Hem (1970).



Chemical analyses of water represented as percentages of total equivalents per liter on the diagram developed by Hill (1940) and Piper (1944).



Classification diagram for anion and cation facies in terms of major-ion percentages. Water types are designated according to the domain in which they occur on the diagram segments (after Morgan and Winner, 1962; and Back, 1966).

Figs. 7f & 7g. Some graphical methods of describing groundwater quality data. See Davis and DeWiest (1966), and Hem (1970).

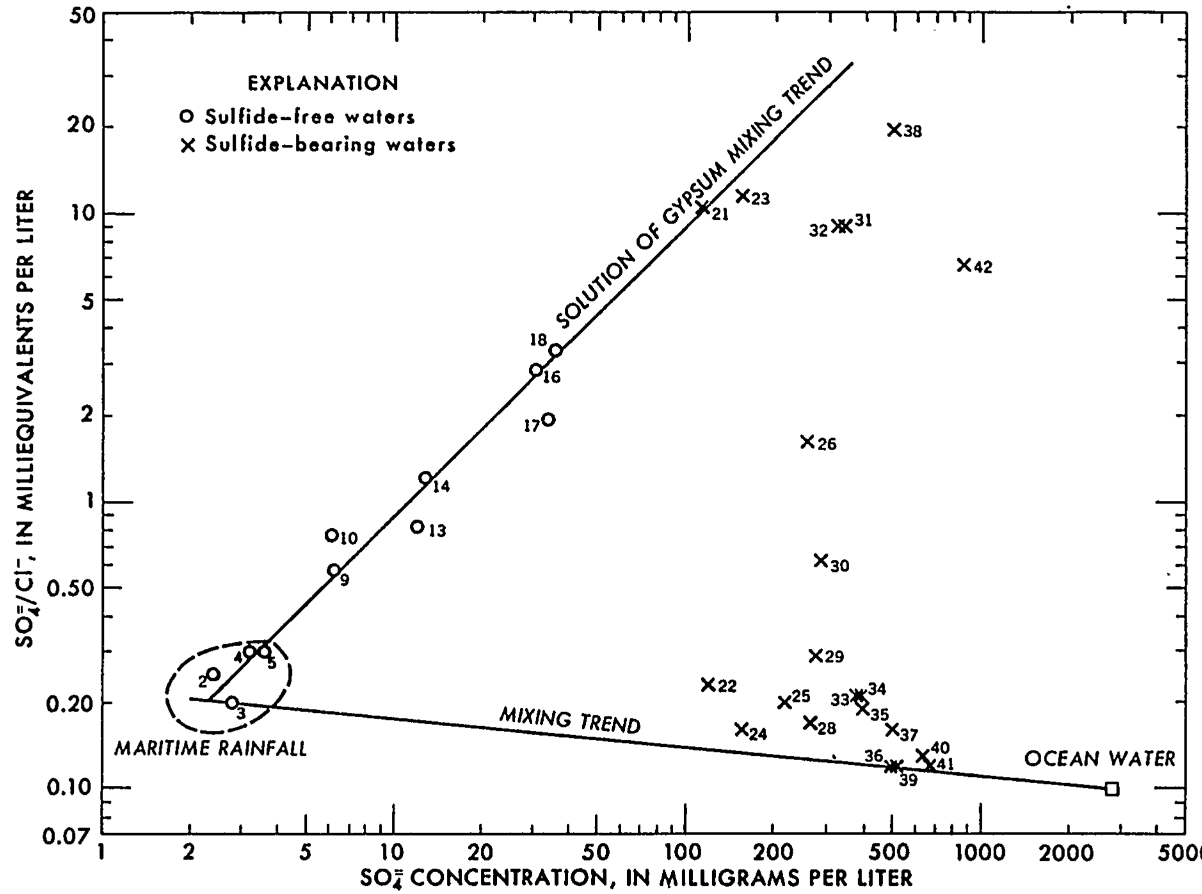


Fig. 8. Relationship between SO_4^{2-}/Cl^- and SO_4^{2-} concentrations in groundwaters from the Floridan aquifer (after Rightmire et al. 1974).

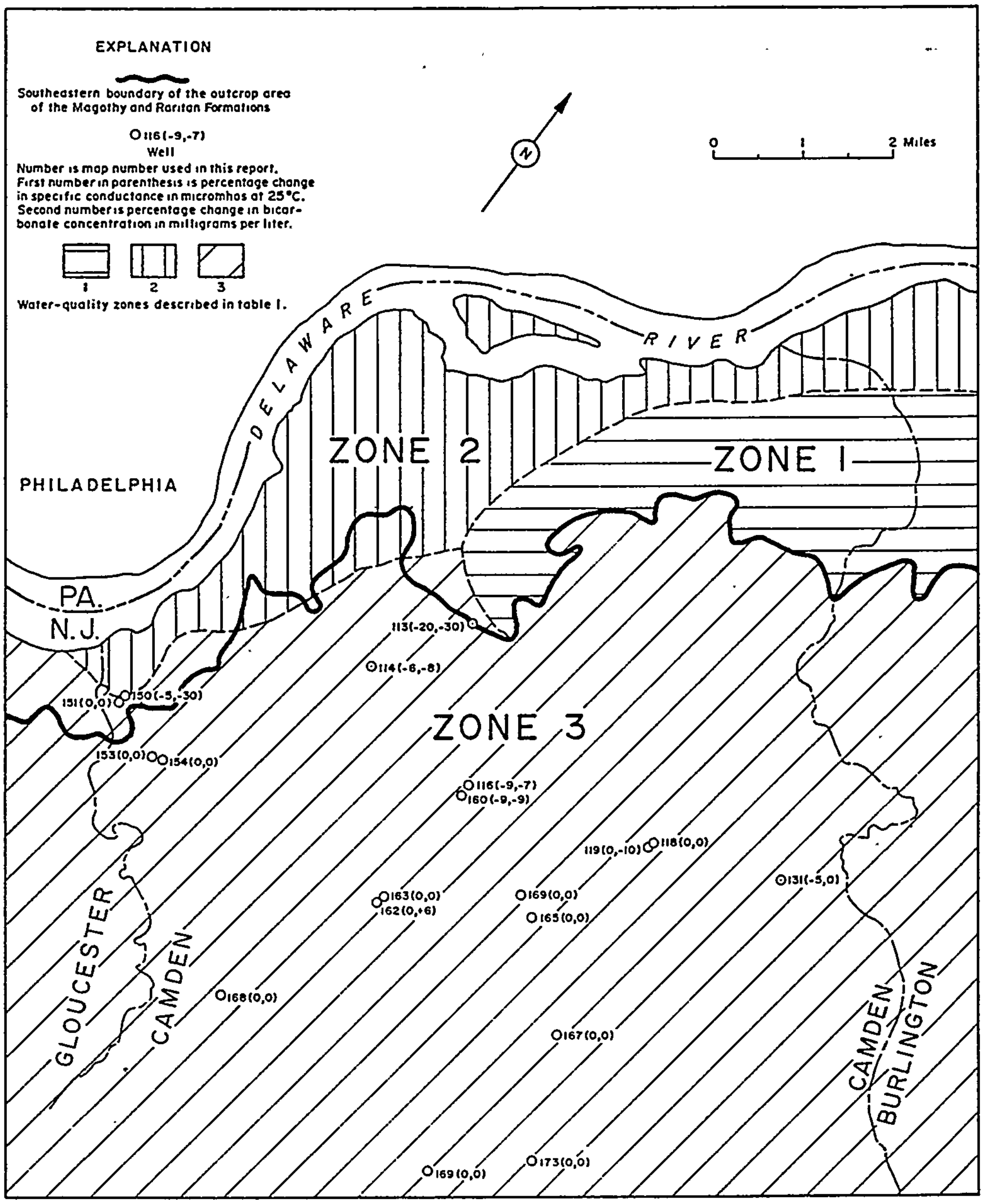


Fig. 9. Map showing percentage changes in specific conductance and bicarbonate ion concentrations in some wells tapping the Magothy-Raritan Formations in northern Camden County, between spring and late summer of 1966. (See Table 2 and Figs. 2, 6, & 10). (From Langmuir, 1969).

3.4 Applications and Merits of the Techniques

Groundwater quality can (1) remain relatively constant (rare), (2) vary continuously with map distance and/or depth, or (3) vary discontinuously. Map-related geochemical techniques are generally the most useful way to establish such variations. Some specialized graphical methods and statistical methods may also be useful. Constant composition may indicate: a) similar age and evolution of the groundwater; b) a non-reactive formation (rare); c) groundwater quality largely controlled by the quality of recharge (usually dilute groundwaters in a shallow formation); and d) relatively constant geological and hydrological rock properties. Continuously variant groundwater quality will usually be associated with systematic variations in geological and hydrological properties of the formation. Within unconfined formations such variations are unusual. Continuous variation in groundwater quality is expected in confined sedimentary rocks (see Fig. 6), with the most pronounced changes occurring in the direction of groundwater flow at the time of groundwater emplacement (see Fig. 10). Examples of such variations in the direction of emplacement groundwater flow within confined formations include:

a) disappearance of nitrate and sulfate with flow distance, increase in sulfide species with distance;
b) occurrence of Ca-HCO_3 type groundwaters under water table or shallow artesian conditions, becoming Na-HCO_3 and finally Na-Cl type waters with depth and distance (see Table 1 and Fig. 6); and
c) increase in total dissolved solids in the flow direction (Fig. 6).

These changes in groundwater chemistry variously reflect: reduction in oxidation potential or Eh with distance and depth of flow under confined conditions as shown in Fig. 11 (NO_3 and SO_4 reduced or eliminated); ion exchange (Ca out, Na in as indicated in Table 1), and increasing salinity due to mixing of shallow, dilute groundwaters with deeper saline waters; and dissolution of formation minerals with groundwater flow (Fig. 6).

Discontinuous variations in groundwater quality with map distance or depth indicate dissimilar histories and evolution of the groundwater, which results from discontinuous variations in the hydrogeological properties of the rock. Such geochemical variations can sometimes be used to infer the locations of faults, adjacent zones of relatively low

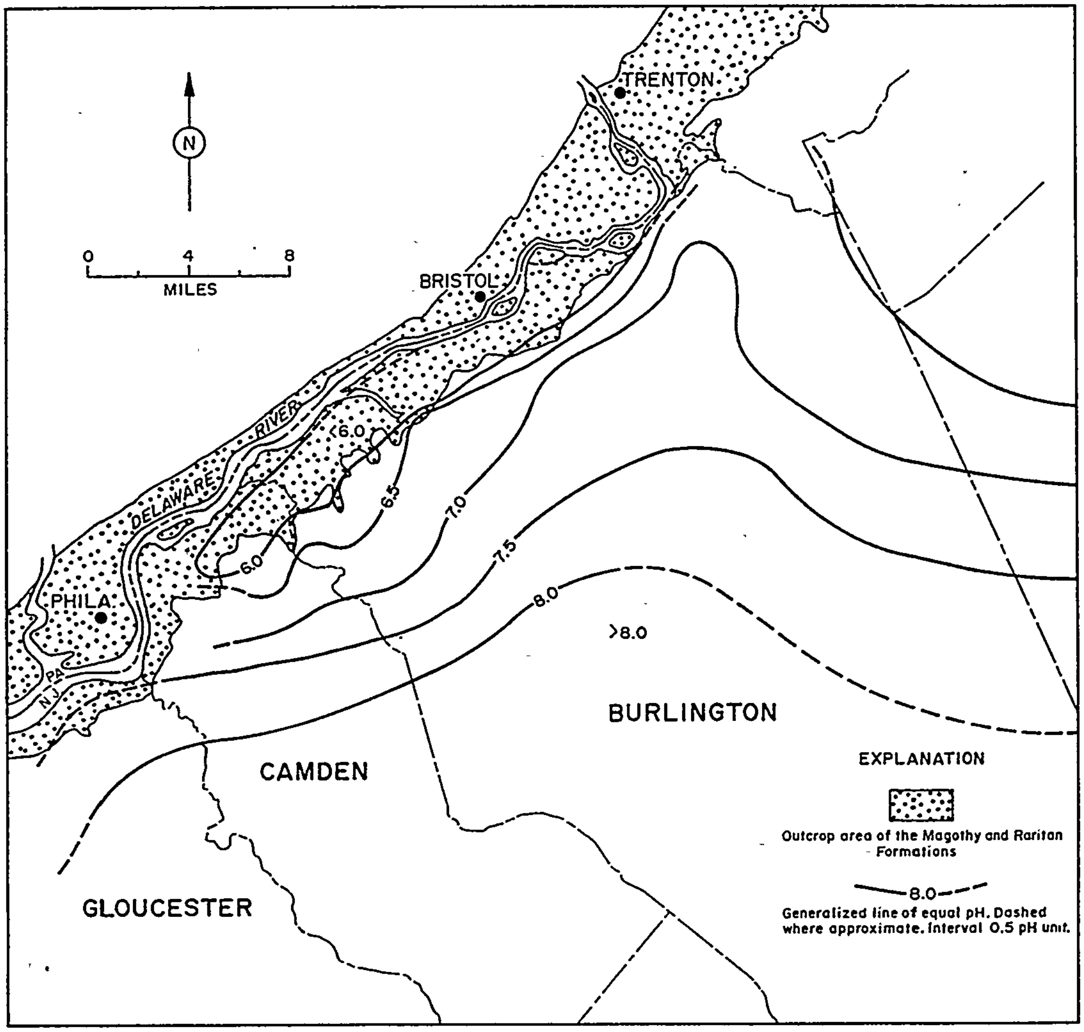


Fig. 10. Map of pH values in groundwaters of the Magothy-Raritan Formations in New Jersey. The aquifer is confined southeast of the outcrop area. The pH contours parallel the pieziometric contours at the time of groundwater emplacement, with pH values increasing in the direction of original groundwater flow (Langmuir,1979).

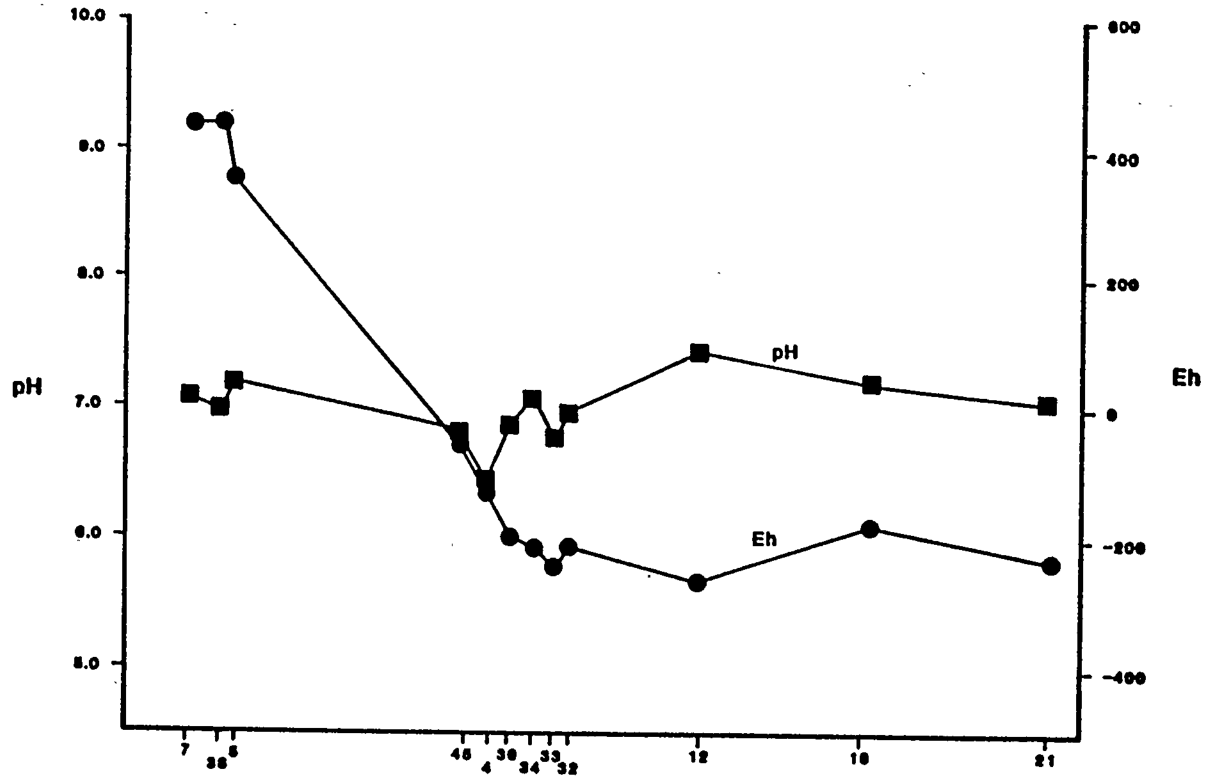


Fig. 11. Variations in Eh and pH in lower Oakville Formation groundwaters in southeast Texas along section AA' in the direction of emplacement groundwater flow. Highest Eh values are in the outcrop area of the formation. Lowest values are for confined groundwaters. (See Figs. 3 & 4). (Chatham, Wanty and Langmuir, 1981).

and high permeability, and the leakage of groundwater from overlying or underlying formations.

3.5 Limitations

Clearly, the ideal repository will be isolated from contact with recent meteoric waters. If groundwaters are present in the rocks chosen for the repository, they should preferably exist under relatively stagnant conditions. The groundwater is likely to be anaerobic (without dissolved oxygen; Eh (<0 volts), free of nitrate and often also of sulfate, and relatively high in total dissolved solids (TDS), with a prevalent chemical character of the sodium-chloride type. The water may also contain dissolved ferrous iron or hydrogen sulfide and methane. Unfortunately, available groundwater quality data is generally for shallow aquifers having waters low in TDS, iron and sulfide.

Published groundwater analyses coupled with basic information on the hydrogeology, geology and mineralogy of a water-bearing formation can unequivocally indicate that the formation contains young, meteoric water. (Chemically the water will have measurable dissolved oxygen (>0.1 mg/l), will hold measurable nitrate (usually), with dissolved ferrous iron absent, and usually be of the $Ca\text{-}HCO_3$ or $Ca\text{-}SO_4$ type, with a low TDS content). Significant cyclical changes in groundwater quality in a well water with time are additional evidence that the water contains an appreciable meteoric water content.

Published groundwater quality and related hydrologic and geologic information can thus often show that a groundwater and thus water-rock system is influenced by meteoric water inputs. However, many deeper (usually) groundwaters, which appear constant in composition over years of measurement, and are oxygen-free, and apparently isolated from meteoric groundwater inputs may in fact not be. Only stable isotopic data, and radioactive dating of these groundwaters can prove that they are in fact so isolated.

The ideal repository is likely to be situated at a depth below that of existing water wells. Thus the groundwater quality data from such wells is of limited applicability. If the repository is situated in a dry rock system below the phreatic zone, available groundwater quality data (or additional groundwater quality data) will not assist in the characterization of the repository. Only geochemical techniques that apply to dry rock systems (i.e. to secondary minerals and to fluid inclusions) will be useful. Such geochemical data will have to be collected, as it is rarely if ever available in the published literature.

3.6 Costs

Costs of the techniques involving the interpretation of available groundwater quality and rock geochemical data are largely the labor and computer costs involved in: 1) accumulating the water and rock data; 2) estimating missing groundwater quality data; and 3) constructing graphical representations of the water quality data and programming the data for statistical analysis.

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4.0 GEOCHEMICAL TECHNIQUES UTILIZING EXISTING DATA PLUS ADDITIONAL GROUNDWATER AND ROCK GEOCHEMICAL DATA

4.1 Data Requirements

As noted above, the collection of new water and rock geochemical data is most appropriate once the site selection process is to be focused on small areas identified through the earlier appraisal of available geochemical and other data. Under "Problems with utilizing available groundwater quality data", many of the deficiencies and limitations of existing data were noted. These include improper sampling and sample preservation of groundwater; lack of field measured values for Eh, pH, DO, and temperature; and lack of laboratory analyses of trace constituents (solutes at levels usually below 1 ppm), including stable and unstable isotopes and inert gases. Other common deficiencies of available data are: 1) the lack of petrological and mineralogical information on the formations involved; 2) the lack of chemical analyses and stable isotope data from fluid inclusions; and 3) the lack of stable and unstable isotope data from secondary minerals. The analysis and interpretation of isotopic data for fluid inclusions and secondary minerals represents the major geochemical approach possible (and an invaluable one) in dry rock systems. If information such as described above can be collected to supplement existing water and rock data, then the more sophisticated geochemical techniques for characterization can be employed.

4.2 Nature of the Techniques

4.2.1 Geochemical Water-Rock Reaction Computer Models

Examples of the static solution-mineral equilibria models are WATEQF, SOLMNEQ, WATEQ2 and MINEQL. The basic character and capabilities of these programs are examined by Nordstrom et al. (1979). A similar program which is designed to consider trace metals including radionuclides is MINSAT (Langmuir et al., 1981). Reaction progress or path, and mixing computer programs are also discussed by Nordstrom et al. Examples are EQ6 and MIX2, and a more versatile, recent program, PHREEQE (Parkhurst et al. 1980).

4.2.1.1 Applications and Merit

Among the geochemical water-rock reaction computer models, the static models can determine what minerals in a formation control the groundwater chemistry. The existence or lack of equilibrium and the degree of departure from equilibrium can indicate the relative age of groundwater or mixing with other groundwaters. The reaction path models can reconstruct what minerals are dissolving or precipitating in the groundwater flow direction, and estimate the mineral amounts and gas amounts involved. These models can also predict the solubility of radionuclide elements in the groundwater at different salinities and elevated temperatures. Some reaction path models can also consider simple ion exchange reactions involving major ions. Mixing models can determine if a given groundwater could have been produced by the mixing of varying proportions of two other waters.

The geochemical data requirements for optimum use of the above models are extensive. Field analyses are needed of Eh, DO, pH, and temperature. Samples must be filtered in the field prior to acidification for laboratory analysis of many major and most trace constituents. If not measured in the field, unstable constituents must be preserved upon sample collection for later laboratory analysis. In addition to the chemical analyses described above, the water analysis should include: 1) analyses of all constituents that form complexes or minerals with the elements or species of interest; 2) analyses of species that form important complexes with the same constituents; and 3) analyses of the major ions (those exceeding 1 ppm concentration) or of the specific conductance (etc.) to allow a calculation of the sample ionic strength. Also needed are mineralogic composition and ideally, mineral amounts in the geological formation.

The geochemical computer models and programs discussed above consider the degree of saturation of groundwaters with respect to individual mineral phases. The programs themselves cannot prove a given mineral is present in the rock, although they can suggest it is likely to be present, especially in the case of common rock-forming minerals. Proper use of the models demands that petrological and mineralogical analyses be made of rock cores from the horizon yielding groundwater to the well. Desirable information for the computer models involves:

a) preparation of thin sections for optical mineralogical analysis including determination of weight and volume percents of the minerals present.

b) the above information supplemented by X-ray diffraction analysis to confirm the mineral identifications from a), and to identify fine-grained minerals such as clays which are usually too small for optical identification.

c) a bulk chemical analysis of the major elements present in the rock, and minor or trace elements if they are of interest as potential reactants with the groundwater or with possible radionuclides released from a breached repository.

The optical mineralogy examination shows how potentially reactive minerals occur in the rock: i.e. as coatings on grains, within grains, as pore fillings, etc. The nature of such occurrences affects the accessability of the mineral to flowing groundwater, without which contact it cannot be an important reactant.

Applications of the water-rock reaction computer models include determining the degree of saturation of a groundwater with respect to a particular mineral of interest, which data may then be plotted in profiles such as Fig. 12, or maps as in Fig. 13. Of specific relevance to the radwaste program, PHREEQE for example, can compute how much spent fuel (UO_2) will dissolve in a given groundwater at a particular temperature (Henderson, Melchior and Langmuir, 1981).

Recommended methods of field and laboratory analysis of groundwater quality parameters needed to use these programs are described in a subsequent section of this report, along with their costs.

4.2.1.2 Limitations

As noted above, the use of the water-rock reaction computer models demands that careful field sampling and analysis, and extensive laboratory analyses be performed on the ground water. Also, ideally extensive geochemical information is needed on the rocks involved. Such information gathering requires some skill (especially the field chemical analyses) and experience. Also, a thermodynamically meaningful Eh cannot be measured in many groundwaters. Although Eh can sometimes be estimated with fair accuracy from the groundwater chemical analysis and mineralogy of the formation.

The water-rock reaction computer models are of little use when sampling younger groundwaters, the chemistry of which is controlled chiefly by the chemistry of input precipita-

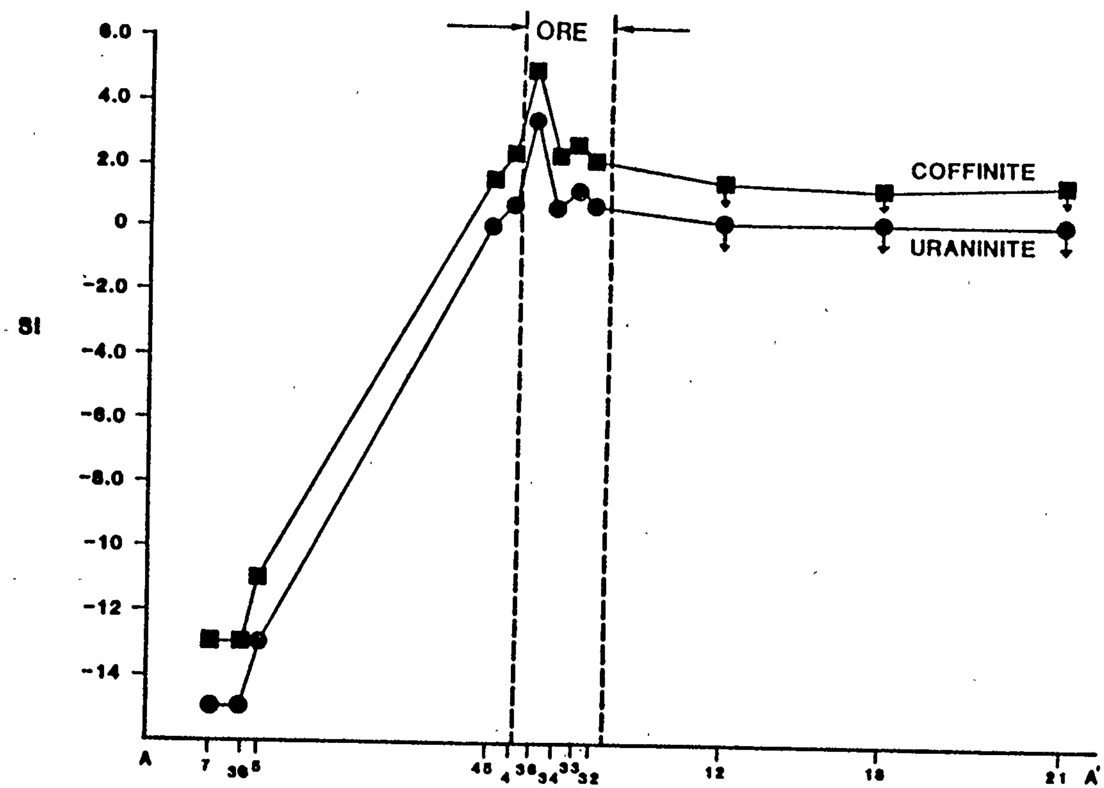

Fig. 12. Profile of saturation index (SI) values for coffinite ($USiO_4$) and uraninite (UO_2) in the lower Oakville Formation groundwaters. SI values greater than zero indicate supersaturation, less than zero undersaturation with respect to the mineral data plotted. Arrows indicate true SI values are less than as plotted. (See Figs. 3, 4, and 11). (After Langmuir and Chatham, 1980).

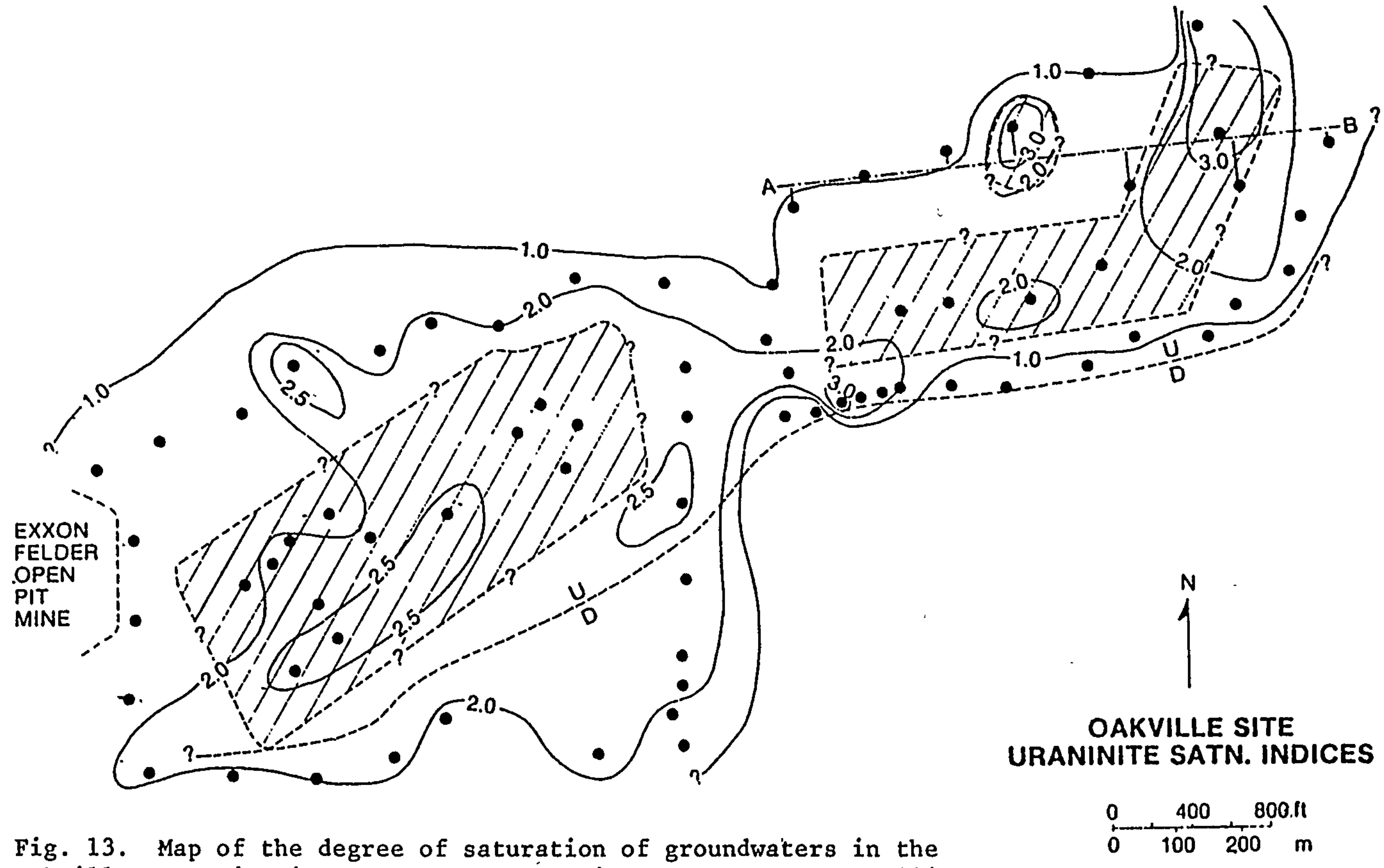

Fig. 13. Map of the degree of saturation of groundwaters in the Oakville Formation in southeast Texas, with respect to crystalline UO_2 (uraninite). The positive saturation index values indicate that the water is supersaturated with respect to uraninite, but at saturation with respect to pitchblende, the variety of UO_2 present. Wells sampled are shown as dots. Crosshatching indicates uraniferous ore-bearing zones. After Langmuir and Chatham (1980).

tion, and not by water-rock reactions. Unless multiple wells or springs can be sampled in the groundwater flow direction, the reaction path models cannot be used. The maximum utility of the water-rock reaction models is obtained when the water-bearing formation is relatively homogeneous and isotropic, and well-characterized hydrogeologically.

Further, these models deal solely with chemical (non-isotopic) species in the groundwater and their gas-solution-mineral equilibria. They are best suited to site characterization in rocks where groundwater flow directions are reasonably well understood, and groundwater flow distances and times are sufficient to yield significant changes in the water chemistry because of solution-mineral reactions. They would therefore be most useful in the characterization of younger shales and tuffs which have retained most of their primary porosity and permeability. They would have little application in rocks in which groundwater flow is chiefly limited to faults and other fractures, such as many basalts, granites, salt domes and bedded salt deposits.

4.2.1.3 References

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4.2.2 Noble Gas Tracers

The noble gases can be used to compute the temperature of groundwater recharge from precipitation. The solubilities of Ar, Kr, and Xe derived from the atmosphere are strongly temperature dependent, whereas those of Ne and He are not. (See Fig. 14). A comparison of the Kr or Xe concentration versus that of Ne is the best choice for reconstructing the temperature of recharge-precipitation.

Concentrations of the noble gases He and Ar cannot be used to reconstruct temperature information for the initial precipitation-recharge water in rocks that contain significant amounts of radioactivity. This is because both elements are produced by radioactive decay yielding concentrations in the groundwater in excess of their original inputs from the atmosphere.

Noble gases dissolved in water are sampled by siphoning or pumping the water to completely fill a 500 ml glass vessel. Excess water is flowed through the vessel to flush out all gases originally present in it prior to closing off the vessel (Gunter, 1973; Geochim. Cosmochim. Acta, 37, 495-513). Other sampling methods including those used for downhole collection are discussed by Mazor and Fournier (1973, ibid, 515-525). Samples of 1 ml of water are sufficient using mass spectrometry for analysis (Mazor and Fournier, ibid).

Analysis of the noble gases is performed by gas chromatography, thermal conductivity (accuracy not given; Gunter, 1973, ibid), or by mass spectrometry (accuracy ±8%) (Mazor and Fournier, ibid). Analyses of these gases are generally not commercially available. An estimate of cost by Hauser Laboratories of Boulder, CO, using mass spectrometry is $100-$200 per water sample for analysis of the complete suite of He, Ne, Ar, Kr, and Xe, with the lower price for multiple sample analyses.

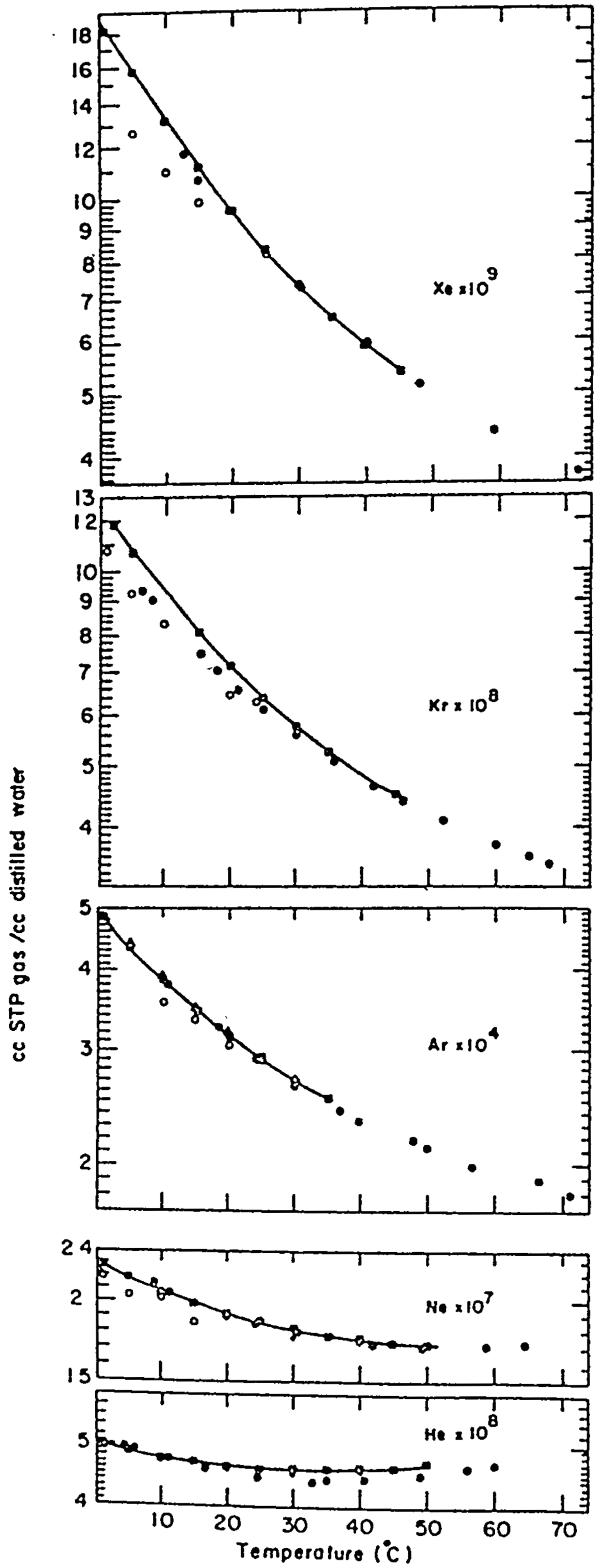

Figure 14 The solubility of the noble gases in water at various temperatures (from Mazor, 1976).
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4.2.3 Stable Isotope Data and Models

4.2.3.1 Introduction

Stable isotope data obtained from drill cores of whole rocks, by analysis of primary and secondary minerals, and from fluid inclusions and groundwater, can provide unique information regarding the history of a water-saturated or dry rock system. When combined with radioactive age dating of these same waters and/or rocks and minerals, the stable isotope data and their interpretation can yield information not available by hydrologic testing or other methods as to the earlier or present absence or existence of meteoric waters, for example, at depth in a rock being considered as a potential high-level radioactive waste repository. Obviously, if one can show that a rock or water/rock system has recently been or is now in contact with meteoric water, such a system is a poor candidate for a repository. The following discussion is background on stable isotope geochemistry intended to clarify ways in which these isotopes may be used as geochemical tools in the repository site-selection process.

4.2.3.2 Isotope Notation and Natural Abundances

Light isotope data are reported using so-called delta notation, calculated as the difference in parts per thousand (parts per mil) between a sample and some standard. Thus for oxygen:

$$\delta^{18}O = \left[(R_{sample} / R_{standard}) - 1 \right] \times 1000$$

where R = the $^{18}O/^{16}O$ ratio. Table 2 lists those elements whose stable isotope ratios are most commonly measured, their natural abundances, and the standards they are compared to. In every case the standard is assigned a value of zero, so that negative sample values indicate a depletion of the heavier isotope compared to the standard, and positive values indicate an enrichment of the heavier isotope. Analytical laboratories generally use working standards for each element, many of which are provided by the National Bureau of Standards. A list of working standards and a description of extraction techniques is given by Hoefs (1973).

Table 2. Data, symbolism, and standards for some important light stable isotopes.

Element	Stable Isotopes	Ratio Measured	Symbolic Delta Notation	Standard
Hydrogen	^{1}H = 99.9844%	D/H	$\delta^{2}H$ or	SMOW[a]
	^{2}H or D = 0.0156%		δD	
Carbon	^{12}C = 98.89%	$^{13}C/^{12}C$	$\delta^{13}C$	PDB[b]
	^{13}C = 1.11%			
Oxygen	^{16}O = 99.763%	$^{18}O/^{16}O$	$\delta^{18}O$	SMOW[a]
	^{17}O = 0.0375%			
	^{18}O = 0.1995%			
Sulfur	^{32}S = 95.02%	$^{34}S/^{32}S$	$\delta^{34}S$	CDT[c]
	^{33}S = 0.75%			
	^{34}S = 4.21%			
	^{36}S = 0.02%			

a = standard mean ocean water

b = belemnitella americana from the Cretaceous Pedee Formation, South Carolina

c = troilite from the Canyon Diablo meteorite

4.2.3.3 Isotope Fractionation

Because of the significant percentage differences in the atomic weights or masses of isotopes such as ^{18}O and ^{16}O or ^{2}H and ^{1}H, the individual oxygen and hydrogen isotopes tend to react differently in different water-rock reactions. Thus, when a clay mineral is precipitated from a groundwater, the $^{18}O/^{16}O$ ratio in the clay will be greater than its value in the water. This effect is called isotope fractionation.

There are three processes (chemical and physical) that result in isotopic fractionation. These are: 1) isotopic exchange reactions, where isotopes of an element common to both reacting species are redistributed between the reacting species; 2) kinetically controlled one-way reactions where the reaction rate depends upon the isotopic composition of the reactants and the products; and 3) chemical and other effects including evaporation-condensation, crystallization-melting, adsorption-desorption, and diffusion-thermodiffusion. The isotope fractionation resulting from these processes may be described by a so-called fractionation factor, α, where $\alpha = R_A/R_B$. R_A and R_B are the ratios of heavy to light isotopes in phases A and B, respectively. Alpha is a function of temperature, and can either be determined experimentally (for solids or liquids) or calculated from statistical mechanics (for gases or liquids). The most complete compilation of alpha values is given by Friedman and O'Neil (1977).

4.2.3.4 Stable Isotopes of Carbon and Sulfur

Stable carbon isotopic data gives information on the sources of carbon in carbonate species - whether they were organic or inorganic, and whether the groundwater has evolved in the presence or absence of a gas phase. (See Dienes, Langmuir, and Harmon, 1974). The $\delta^{13}C$ content of the water must also be measured in order to correct ages of groundwaters when using the ^{14}C method. (See Wigley and Muller, 1981).

The $\delta^{34}S$ content of sulfate in groundwater can ideally be used to establish the source of the sulfate; whether it has been derived from the oxidation and dissolution of sulfide minerals, from organic matter, or from the dissolution of sulfate minerals and in particular gypsum. Unfortunately bacterial sulfate reduction to sulfide produces large isotopic effects. Sulfate reduction is a common process in organic-bearing sediments such as shales and sandstones, where it complicates the interpretation of $\delta^{34}S$ data from dissolved sulfate. In part for this reason $\delta^{34}S$ data should be performed with a concurrent analysis of the $\delta^{18}O$ content of the dissolved sulfate, which reduces the ambiguity of interpretation of the $\delta^{34}S$ data. (See Fritz and Fontes, 1980).

4.2.3.5 Stable Isotopes of Oxygen and Hydrogen

The stable isotope ratios most useful for determining whether a rock or rock/water system has or has not been affected by meteoric water are $^{18}O/^{16}O$ and D/H. For this reason, following discussion of stable isotopes is restricted to those of oxygen and hydrogen. As part of the water molecule, these isotopes are practically ubiquitous in the subsurface; in groundwater, fluid inclusions and hydrated or hydroxylated minerals such as clays. Extensive data exists to show that different water sources in the crust have different and characteristic oxygen and hydrogen isotopic compositions, as do the minerals that precipitate from these waters. Thus one can often use the isotopic composition of a water sample or rock to distinguish among waters or rocks which may have been or are derived from meteoric, oceanic, connate, metamorphic, or primary magmatic sources (c.f. Taylor, 1974; 1979).

The Natural Distribution of Oxygen and Hydrogen Isotopes in Water:

A systematic relationship between D/H and $\delta^{18}O$ in precipitation was first noted by Friedman (1953). Based on the mean D/H - $\delta^{18}O$ values of all precipitation from the International Atomic Energy Agency network, the line

$$\delta D = [(8.17 \pm 0.08) \quad \delta^{18}O + (10.56 \pm 0.64)] \text{ per mil}$$

was fit with a correlation coefficient of r = 0.997. It has since been demonstrated that lines of similar slope but of slightly different intercept provide a slightly better fit for precipitation in some areas. The line

$$\delta D = [8 \quad \delta^{18}O + 10] \text{ per mil}$$

(Craig, 1961) has been accepted as the fit on a world-wide basis, and is called the meteoric water line. There are many models to describe this linear relationship between δD and $\delta^{18}O$, none of which fully explain it. A review of these models is given by Gat (1980).

The worldwide isotopic composition of sea water is fairly constant ($\delta D = 0$ and $\delta^{18}O = 0$). Work by Urey and others (1951) and Lowenstam (1961) indicate it has been that way throughout the Mesozoic and Cenozoic Eras.

Craig and others (1956) and Craig (1963) demonstrated that essentially all the water in geothermal systems is of surface derivation. Further, nearly all the waters show a characteristic $\delta^{18}O$ shift; the result of isotopic exchange with silicate and carbonate country rocks. Implied is a larger rock than water to rock oxygen reservoir. The lack of this shift requires either no interaction (no isotopic exchange) between the water and rocks, or a very large water to rock oxygen ratio. Taylor (1979) shows how to reconstruct the probable water to rock ratio responsible for alteration of a rock such as a granite from the D/H and $\delta^{18}O$ content of fluid inclusions and unaltered and altered rock.

D/H and $\delta^{18}O$ data show that meteoric waters are the major constituent of what has previously been thought to be original connate or formational waters associated with oil-fields in the mid-continent region of the United States (Clayton and others, 1966; and Hitchon and Friedman, 1969). Figure 15 (from Taylor, 1979) illustrates this. The plot shows; (1) a strait line trend in the isotopic composition of the brines from any given area, and their unique character; and (2) the intersection of the brine line with the meteoric water line at appropriate values for present day meteoric water. The increasing salinity in these brines is either because of solution of evaporites and/or because of shale membrane filtration.

The isotopic composition of both magmatic and metamorphic waters are tightly confined as displayed in Figure 16. Alteration or mineral formation by fluids of magmatic origin is generally restricted to hydrothermal ore deposits (c.f. Rye, 1966) or at least localized to areas immediately adjacent to or within intrusive bodies (Taylor and Epstein, 1963, 1968; and Taylor and Forester, 1973).

Figure 17 generalizes the possible pathways isotopic values of a meteoric water can take in natural surface and subsurface environments.

The Distribution of Oxygen and Hydrogen Isotopes in Rocks:

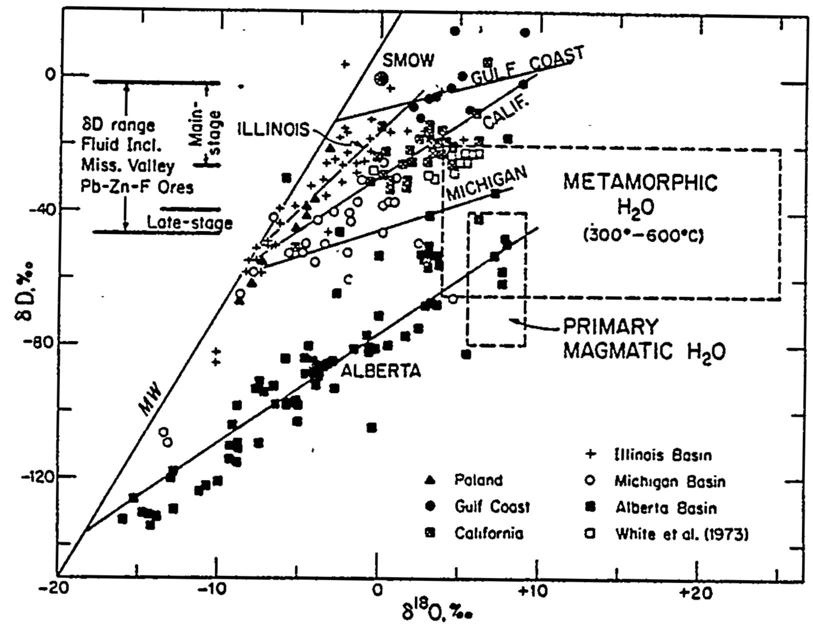

Fig. 15. Plot of δD versus $\delta^{18}O$ for oil-field brines from North America and Poland. Also shown is the Meteoric Water Line, and SMOW (standard mean ocean water), and the calculated fields of primary magmatic and metamorphic waters. The figure is from Taylor (1979).

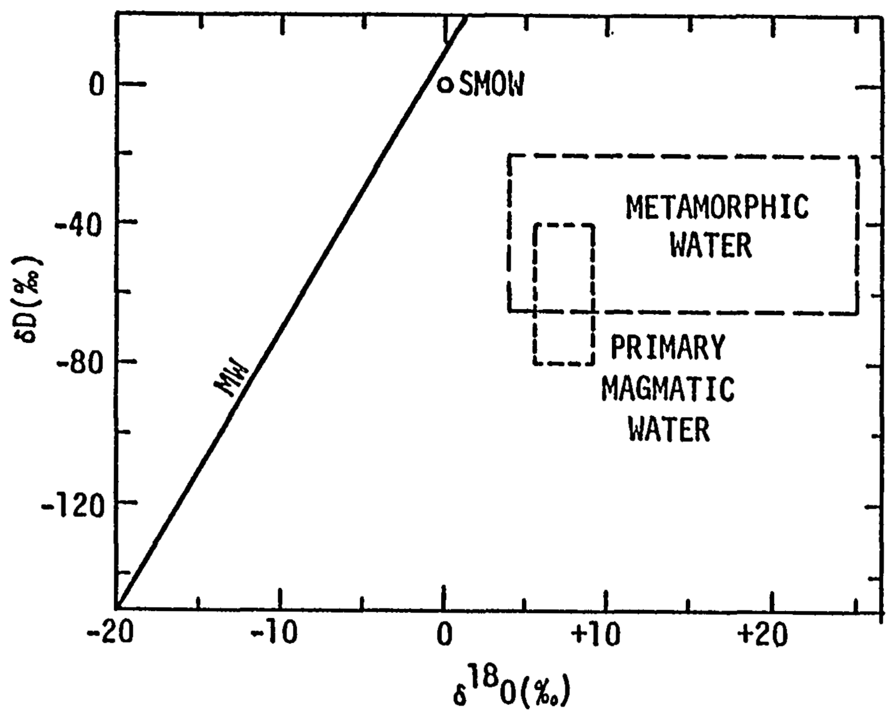

Fig. 16. MW denotes the meteoric water line, SMOW is the isotopic composition of standard mean ocean water. The fields of metamorphic water and primary magmatic water are after Taylor,(1974).

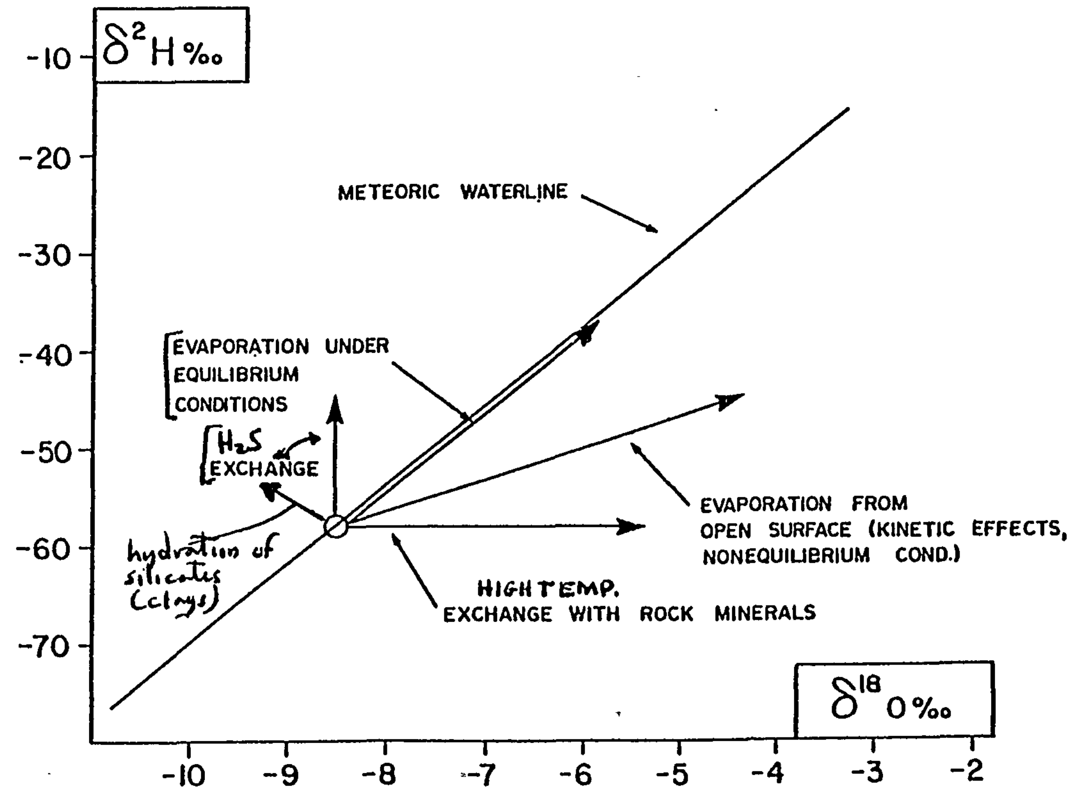

Fig. 17, A generalized δ^2H versus $\delta^{18}O$ plot showing the Meteoric Water Line and processes commonly responsible for deviations from this line. Modified from Fritz and others, (1979).

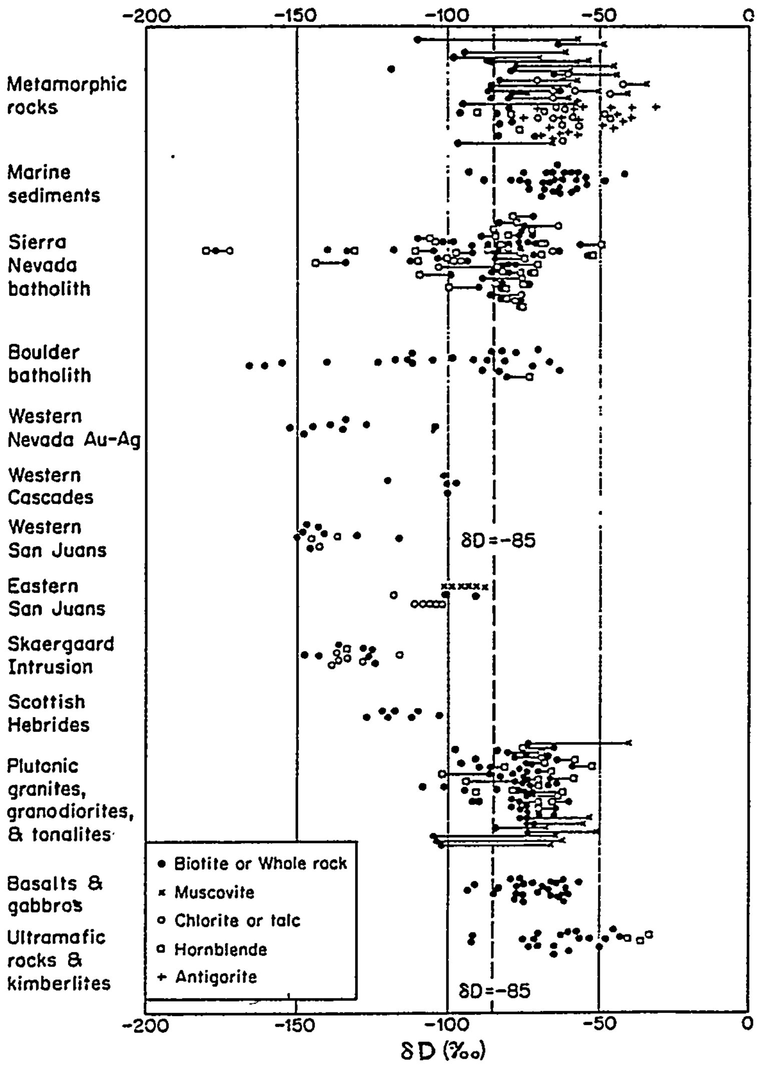

Fig. 18. A compilation of available δD analyses of minerals from igneous, metamorphic, and hydrothermally altered rocks from a variety of localities. The plot is from Taylor (1974).

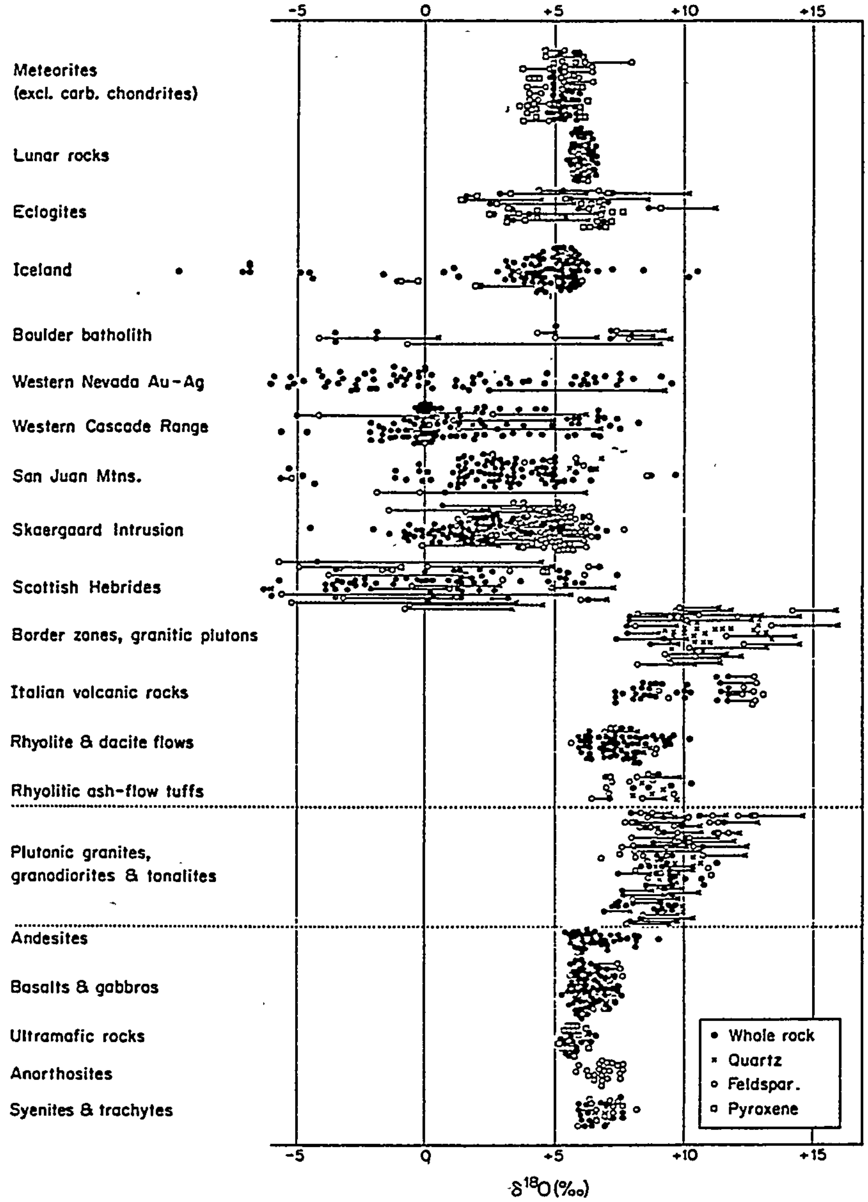

Fig. 19. A compilation of $\delta^{18}O$ values of igneous rocks and mineral separates from a variety of localties. The plot is from Taylor (1974).

Figures 18 and 19 illustrate the $\delta D - \delta^{18}O$ value ranges for many rock types including granites, basalts and tuffs. Igneous rocks, particularly the more mafic suite, are highly constrained. Single mineral or whole rock values outside these normal ranges for unaltered rock indicate isotopic exchange has occurred.

$\delta^{18}O$ and D/H Behavior of Clays:

Clay minerals formed as alteration products in basalts, tuffs and granites initially have an isotopic composition in equilibrium with local subsurface waters. Such clays may be supergene or hypogene in origin; that is they may have formed by alteration involving relatively fresh, meteoric waters, or waters or more deep-seated origin, respectively. δD and $\delta^{18}O$ data measured on the clays can usually distinguish these water sources. (See Figure 20). The isotope data indicate that most hypogene waters are themselves originally of meteoric origin.

Clays such as kaolinite can preserve their original isotopic composition for tens of millions of years at temperatures below 100°C. However clays in which the hydroxyl bonds are in direct contact with easily removable interlayer water (e.g. halloysite) will rapidly change in D/H ratio with time. Montmorillonites also tend to preserve their original D/H composition through time at low temperatures, although they are more readily altered than is kaolinite.

Experimentally detemined fractionation factors for D/H and $\delta^{18}O$ between clay minerals and water are presented in Figures 21 and 22. Where clay minerals are formed at near-ambient temperatures their isotopic composition defines a line parallel to the meteoric water line. The isotopic composition of soil clays falls on the appropriate clay line and relates directly to the D/H - $\delta^{18}O$ values of local meteoric water. This is illustrated in Figure 23. The kaolinite line shown is that of Savin and Epstein (1970). The data are from Lawrence and Taylor (1971). It is possible to draw similar lines for other clay minerals where the clay line distance from the meteoric water line is determined by the appropriate fractionation factors. Once formed, most clay minerals tend to preserve their $\delta^{18}O$ value so long as there is no mineralogical or chemical alteration (Lawrence and Taylor, 1971, 1972). Deuterium may exchange with time and its values are a less reliable indication of conditions of clay formation. Additional discussion of the isotopic exchange behavior of clay minerals may be found in the paper by Savin (1980).

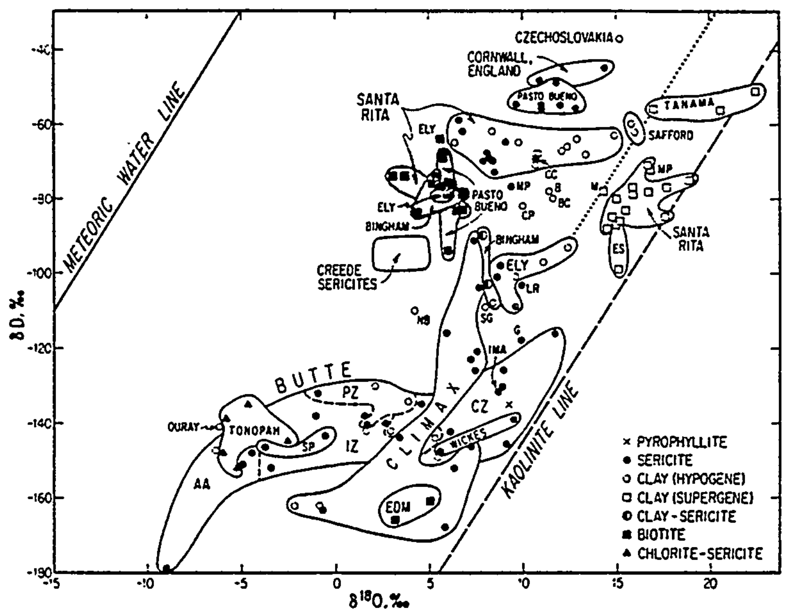

Fig.20. Plot of δD versus $\delta^{18}O$ for most of the available analyses of OH-bearing minerals from ore deposits. The kaolinite line of Savin and Epstein (1970) is shown for reference. The dotted line is drawn to emphasize the separation of supergene (to the right of the line) and hypogene clays. Plot is from Taylor (1979).

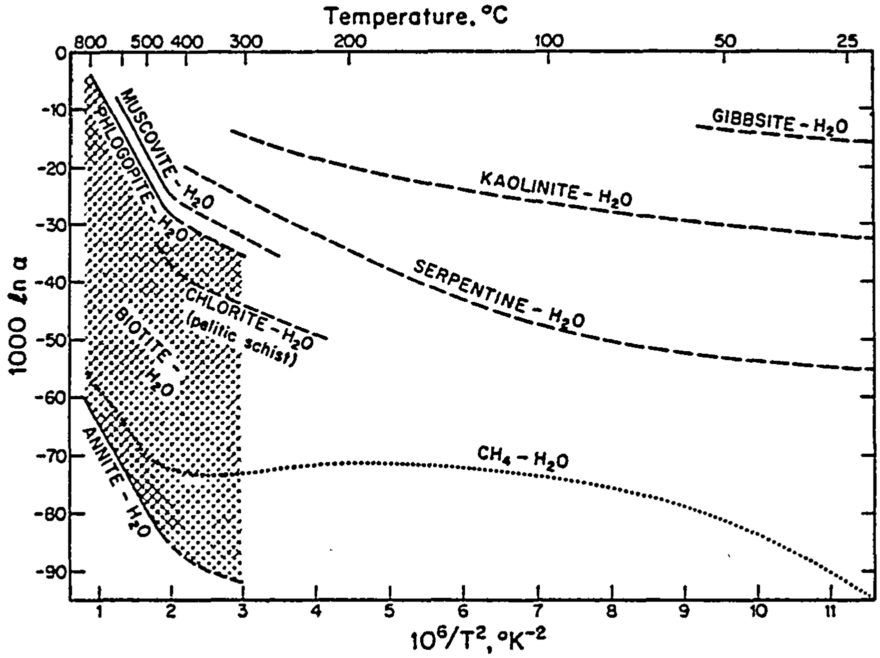

Fig. 21. Equilibrium hydrogen isotope fractionation curves for various mineral-H_2O systems. The solid lines represent data by Suzuoki and Epstein (1976). The dashed lines are empirical extrapolations based on natural assemblages (Savin and Epstein, 1970a; Lawrence and Taylor, 1971; Wenner and Taylor, 1973). The dotted line is the calculated CH_4-H_2O curve of Bottinga (1969). Note that below the critical point of H_2O, the curves are all based on values for *liquid* water. The figure is from Taylor (1979).

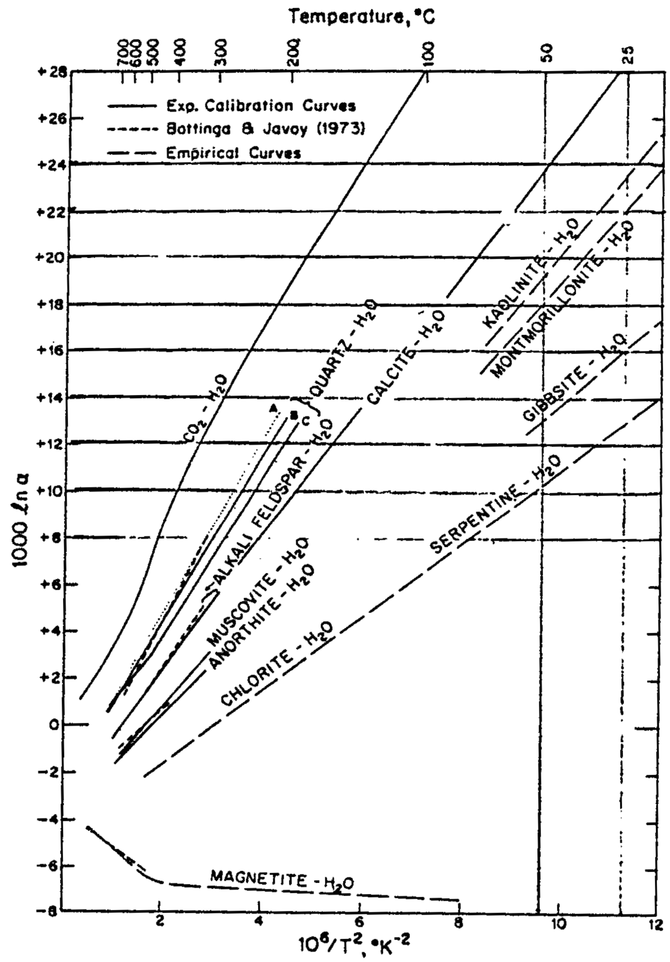

Fig. 22. Experimentally determined equilibrium oxygen isotope fractionation curves for various mineral-H_2O systems, all based on using $\alpha = 1.0412$ for calcite-H_2O instead of 1.0407: calcite-H_2O (O'Neil et al., 1969); quartz-H_2O (the dotted curve A is based on the quartz-feldspar curve of Blattner, 1975, recalculated to be compatible with the alkali feldspar-H_2O curves of O'Neil and Taylor, 1967; B = "partial" exchange and C = "complete" exchange experiments of Clayton et al., 1972); muscovite-H_2O (O'Neil and Taylor, 1969); and anorthite-H_2O (O'Neil and Taylor, 1967). Also shown is a calculated CO_2-H_2O curve (Bottinga, 1968), and some empirical curves based on natural assemblages; magnetite-H_2O (high-T portion = Anderson et al., 1971; low-T portion = Wenner and Taylor, 1971); serpentine-H_2O (Wenner and Taylor, 1971); kaolinite-H_2O (Savin and Epstein, 1970a); and gibbsite-H_2O (Lawrence and Taylor, 1971). The positions of some estimated curves for quartz, alkali feldspar, muscovite, and magnetite by Bottinga and Javoy (1973) are also indicated.

The figure is from Taylor (1979).

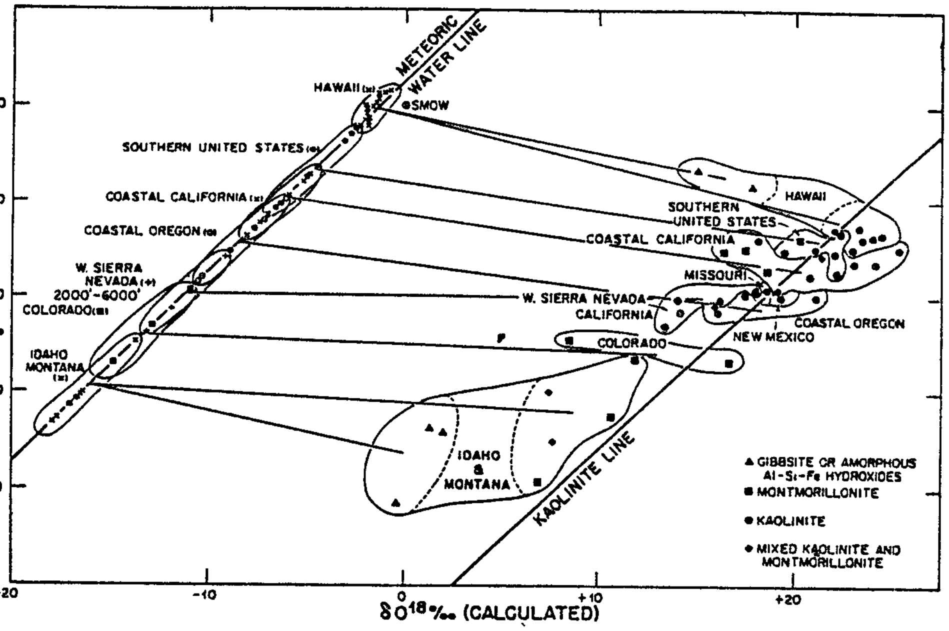

Fig. 23.. Plot of δD versus $\delta^{18}O$ for clay minerals and hydroxides from modern soils formed on igneous parent rocks in the United States, from Taylor (1974).

4.2.3.6 Fluid Inclusions

Fluid inclusions are fluid-filled defects in crystals which occur in most minerals. The trapped fluid (predominantly H_2O) is a small sample of the fluid present at the time crystal growth closed the defect. Although the original trapped fluid was generally homogeneous, most inclusions have undergone changes on cooling to surface temperatures. These changes result in the formation of new phases such as a gas bubble, immiscible liquids or daughter minerals. Fluid inclusions are divided into three categories: (1) primary, where fluids are trapped at the time of growth of the mineral; (2) pseudosecondary, where fluids are trapped in healing fractures at the time of crystal growth, and (3) secondary, where fluids are trapped in healing fractures subsequent to crystal growth. To date, most fluid inclusion studies have been on hydrothermal ore deposits and minerals.

Evaporites and low temperature fracture fill minerals also contain fluid inclusions. Roedder (1972) provides a very complete description of how to establish the original temperature of emplacement of fluid inclusions, as well as to measure inclusion salinity and fluid chemistry. It is possible to crush fluid-inclusion containing minerals and to measure both D/H and $^{18}O/^{16}O$ ratios on the contained waters (c.f. Landis and Rye, 1974).

4.2.3.7 References

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4.2.4 Unstable Isotope Data and Models

4.2.4.1 Age Dating

Age-dating of groundwater or secondary minerals from the concentrations or concentration (activity) ratios of stable and unstable isotopes is a complex undertaking. Even when dating from measurements of the most commonly used radioactive isotopes, ^{3}H, and ^{14}C, a detailed knowledge of the groundwater geochemistry and hydrogeology is a necessary prerequisite. For example, accurate ^{14}C dating demands a complete understanding of the inorganic and organic carbon budget of the water, which includes measurement of the water's ^{12}C and ^{13}C content. This preliminary information plus the analysis of ^{14}C is then introduced into computer programs such as CARISO or WATEQF-ISOTOP to adjust the ^{14}C results to give a correct age.

The radioactive isotopes most often used for groundwater dating are ^{3}H (halflife 12.35 yrs) and ^{14}C (halflife 5570 yrs). Other radioactive isotopes being considered as dating tools include ^{39}Ar (269 yrs), ^{40}Ar (from decay of ^{40}K; 1.3 billion yrs) ^{81}Kr (2.2 x 10^{5} yrs), ^{85}Kr (10.3 yrs), and ^{36}Cl (3.01 x 10^{5} yrs). Dating attempts have also been made using ^{4}H, $^{234}U/^{238}U$, ^{222}Rn (3.825 days), and amino acids.

Apart from ^{3}H and ^{14}C, dating based on the other isotopes listed above is in the experimental-developmental stage. Data interpretation and correction including model development for computer correction is in its infancy for these elements. (See Davis and Bentley, 1981).

Groundwater Dating Using ^{14}C and Tritium

In a manner similar to ^{14}C production, ^{3}H is produced naturally in the earth's atmosphere by interaction of cosmic-ray-produced neutrons with nitrogen. Atmospheric testing of nuclear weapons has raised the levels in the same way as with ^{14}C. Few measurements of natural tritium in precipitation were made prior to the nuclear testing, but estimates are that it was in the range of 5 to 20 TU (tritium units; TU = 1 ^{3}H atom in 10^{18} atoms of hydrogen). Since the half-life of tritium is 12.3 years, groundwater recharged prior to 1953 is expected to have tritium concentrations of less than 2 to 4 TU. The usefulness of tritium in groundwater studies is enhanced by its not being significantly affected by reactions other than radioactive decay.

It is essential that whenever the ^{14}C content is analyzed in a groundwater sample, a tritium analysis is also performed. If the sample has $^{3}H > 1$ TU, the water is of subrecent age (<50 years old), or consists of a mixture of older and recent water. ^{14}C and tritium data can also provide age limits. For example, $a^{14} = 130$ pmc and $^{3}H = 100$ TU obviously indicates recent water; $a^{14} < 50$ pmc and $^{3}H < 0.1$ TU almost certainly indicates waters hundreds or thousands of years old. Other uses of tritium data are to distinguish different age zones within the modern-water part of groundwater flow systems, and to distinguish zones of groundwater mixing.

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4.2.4.2 Isotope Disequilibrium

When radioactive elements spontaneously decay in a closed water-rock or dry rock system, their daughter products will accumulate in place. Given sufficient time (which depends on the half-life of the parent isotope), its immediate daughter isotope will attain isotopic equilibrium with it. In other words, both isotopes will approach the same activity. However, in a hydrologocally open geologic system, differences in the relative mobilities of the isotopes in the decay chain will lead to migration and loss of the more mobile isotopes by leaching. The existence of resultant disequilibrium among the isotopes in a decay chain can be evidence that the rock has been open to leaching (usually by meteoric water) since formation of the minerals involved.

The isotopes most often considered for studies of disequilibrium are those in the ^{238}U and ^{235}U decay chains. (See Shirvington, 1979). Another useful chain for this purpose is that of ^{232}Th (H. P. Schwarz, 1981, verbal communication). The radioactive uranium and thorium isotope data can also be used to date the minerals containing them, such as the minerals forming secondary fracture fillings. Ideally, it is possible to date the time that the rock was an open hydrologic system by examining the activity ratios of several isotope pairs of which the parent isotopes have ranges of half-lives. According to Schwarcz (ibid), leaching events of about 30,000 to 10^6 years age can in principle be so dated. Problems with such techniques include for example the greater mobility of the daughter ^{234}U than parent ^{238}U, not because of a solubility difference, but because of ^{234}U losses caused by alpha recoil during the decay process.

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4.2.5 Suggested Methods and Procedures for Field Sampling and Chemical Analysis, and Laboratory Analysis of Groundwater

The general scheme for sampling and field analysis of groundwater as well as sample preservation for laboratory analysis is given in Figure 24. Field analytical methods and equipment are briefly described in Table 3, and at greater length in the following text. Sample collection methods for certain laboratory analyses are described in Table 4. Techniques for field chemical analysis of these and other chemical parameters are described in detail in references listed at the end of this section.

4.2.5.1 Methods and Procedures for Field Chemical Analysis

Chemical analyses of unstable parameters must be made on site in the field, except when unstable species (such as sulfide) can be preserved immediately upon collection. If field measurement is not possible, samples to be analyzed for dissolved oxygen and other gases can often be either preserved or the gas extracted in the field for later laboratory analysis.

Measurements which must be made in the field include temperature, Eh, and pH. If analyses of unstable constituents are not performed immediately, the results obtained may not be indicative of the true values of the formation water. Bicarbonate should be measured at the well-head, or within 24 hours on unfiltered samples, refrigerated from the time of collection. Processes such as degassing, mixing with air, heating or cooling, and exposure to light may affect the results of unstable parameter analyses.

As noted in Figure 24, a well to be sampled should be pumped until the temperature and specific conductivity (SpC) have attained steady values before any other measurements are performed. This insures that fresh formation water is being sampled, rather than water which has been lying stagnant in the well casing. A period of 10-15 minutes is usually required for these parameters to stabilize, depending on the depth, casing diameter, and discharge rate of the well. Before making any field measurements, the electrodes and any buffers used should be allowed to temperature-equilibrate with the well water. The use of a rubber washtub aids in this process. While making measurements, all equipment should be kept out of direct sunlight. Between stops, all buffers should be kept on ice in a portable ice-chest. Meters and electrodes are most safely stored and transported

FIGURE 24

Groundwater Sampling

Order of business at field sites.

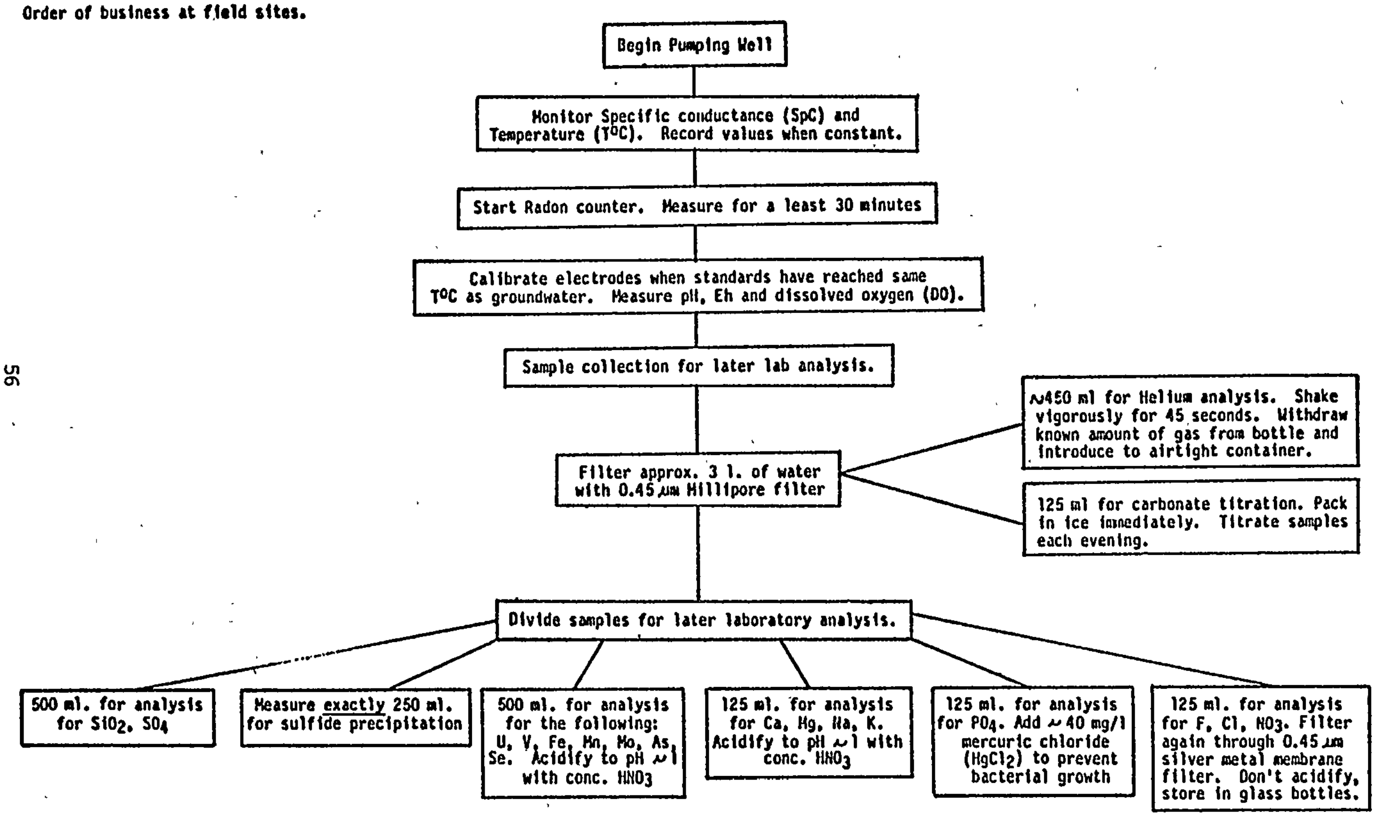


Table 3. A summary of suggested field analytical methods. All measurements should be made in non-flowing water at the discharge point of a well or spring unless otherwise noted.

Parameter	Analytical Method
pH	Corning Model 610A pH-Millivolt Meter, Corning standard combination pH electrode. Apparatus calibrated with three NBS primary standard buffers (pH 4.01, 6.86 and 9.18) and corrected for temperature effects.
Eh (mv)	Corning Model 610A pH-Millivolt meter, Corning asbestos fiber junction saturated calomel electrode, homemade platinum electrode. Calibrated with ZoBell's solution and corrected for temperature (Nordstrom, 1977). Readings monitored as sample flows past electrodes. When stabilized, flow is stopped and a final reading recorded.
temperature ($T^{o}C$)	Standard mercury thermometer, calibrated from $-20^{o}C$ to $+120^{o}C$ in $0.5^{o}C$ increments.
specific conductivity (μmhos/cm)	Yellow Springs Instruments Model 33 Salinity-Conductivity-Temperature Meter. Reading recorded when steady.
dissolved oxygen (DO) (mg/l)	Yellow Springs Instruments Model 57 Oxygen Meter. Probe placed in flowing sample at well discharge point and allowed to equilibrate with sample before final reading is recorded.
hydrogen * sulfide (mg/l)	Corning Model 610A pH-Millivolt Meter, Corning asbestos fiber junction saturated calomel reference electrode, Orion solid state silver-sulfide specific ion electrode. Meter calibrated to zero millivolts with shorting strap. Reading recorded when steady.

TAble 3. Continued

Parameter	Analytical Method
bicarbonate, carbonate (mg/l)	Fresh sample 0.45 μm Millipore filtered, immediately packed in ice for analysis each evening. All samples titrated to pH 4.5 with 0.01658 N sulfuric acid (Brown, Skougstad, and Fishman, 1970).
Radon (pCi/l)	Western Systems Merac IV (miniature electronic radon alpha counter). 500 ml glass bottle filled about 85% full with fresh sample and shaken vigorously for about 45 seconds. The MERAC IV is fit tightly over the mouth of the bottle and counted for 30 minutes. The number of counts per hour is roughly equal to pCi/l Rn.

* Hydrogen sulfide may also be determined in the laboratory upon samples treated in the field with zinc acetate and sodium hydroxide. The laboratory analysis should be within 24 hours of sample collection (Presser and Barnes, 1974, Water-Resources Inv. 22-74, U. S. Geol. Survey)

Table 4. A summary of sample collection methods.

Parameter(s)	Sampling Method
Ca, Mg, Na, K	0.45 μm Millipore® filtered, acidified to pH 1 with concentrated nitric acid. 125 ml collected.
Ra	0.45 μm Millipore® filtered, acidified to pH 1 with concentrated nitric acid. 1 liter collected.
U, V, Fe, Mn, Mo, As, Se	0.45 μm Millipore® filtered, acidified to pH 1 with concentrated nitric acid. 500 ml collected.
SiO_2, SO_4	0.45 μm Millipore® filtered, not acidified. 500 ml collected.
PO_4	0.45 μm Millipore® filtered, treated with 40 mg/l mercuric chloride ($HgCl_2$). 125 ml collected.
U-234, U-235, U-238	0.45 μm Millipore® filtered, acidified to pH 1 with concentrated nitric acid. 4 liters collected.
F, Cl, NO_3	0.45 μm Selas® silver metal membrane filtered. Unacidified, stored in glass bottles. 125 ml collected.
He	500 ml bottle with Swagelock® cap fitted with rubber septum. Bottle filled about 85% full, shaken vigorously for 30 seconds. 20 cm^3 of air is withdrawn from the bottle with a graduated syringe and introduced into an evacuated stainless steel canister. A lead-lined cap is then screwed onto the canister.

in a suitcase with foam-rubber cutouts to hold and protect them. The following sections describe in detail some of the more important field measurements and procedures.

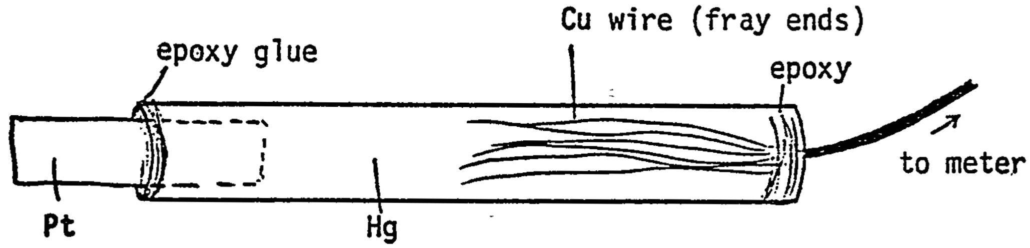
Determination of Eh

A. Equipment Required:

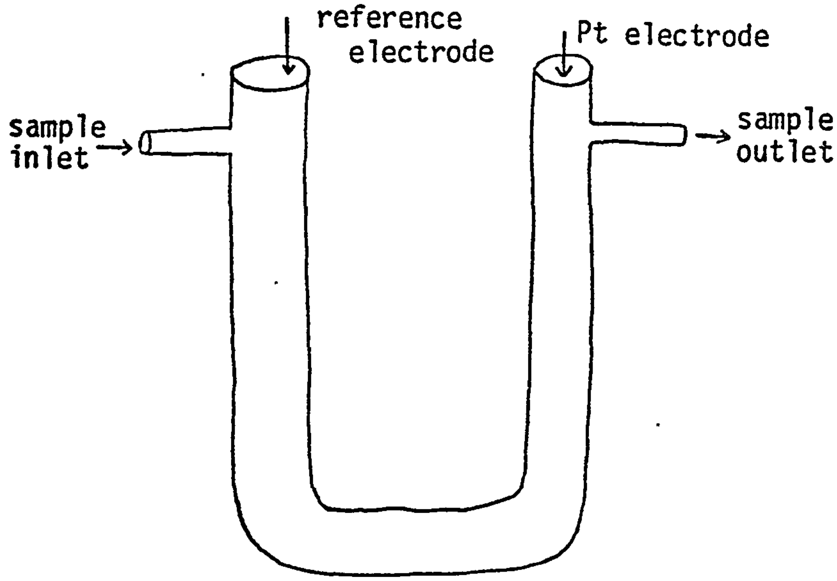
1. pH-millivolt meter - We recommend the Orion model 399A over the Corning model 610 because of its greater stability and ease of calibration. The Orion meter also comes in a compartmentalized attache' case for easy transport to the field.

2. Reference electrode - Most highly recommended is the Orion double-junction reference electrode for its relative freedom from poisoning. Ag-AgCl and especially calomel types poison quickly in the presence of dissolved sulfide. Asbestos fiber junction design is preferred over fritted glass junctions because of the lower liquid junction potentials encountered.

3. Platinum electrode - Although commercial platinum electrodes are available, it is easy to make a superior electrode in the lab. Cut a piece of 1 cm. (inside diameter) rigid acrylic tubing about 10-15 cm. long. A strip of bright platinum scrap measuring approximately 1 cm. wide x 2-3 cm. long x 0.25 mm. will suffice for the electrode. Insert the platinum into the tubing so that about 1 1/2 - 2 cm. projects out of the end. Seal the platinum in the end of the tube with an epoxy or similar glue, being careful not to get glue on either end of the platinum. When the epoxy is dried, fill the tube with mercury to within about 1 cm. of the top. Use a stripped piece of copper wire for the lead. Dip the copper wire in the mercury and seal the top with epoxy. The sketch below may be helpful:



4. Commercial soft-glass or pyrex U-tube with two sidearms as shown below:



The two electrodes should be fitted with rubber stoppers to form a tight seal and prevent air leakage. Hose clamps should be fitted on the inlet and outlet hoses to stop the flow when necessary. Several U-tubes should be available in case one breaks in the field.

B. Procedure:

1. Electrodes must be calibrated before each measurement with ZoBell's solution. See Nordstrom (1977; Geochim. Cosmochim. Acta 41: 1835-1841) or Langmuir (1971) for a recipe for ZoBell's solution and the temperature dependence of its potential.

2. Once the meter is calibrated, insert the electrodes in the U-tube aparatus, being careful to let any air bubbles escape through the top before pressing the electrodes into the tube. Allow the water to flow through the tube.

3. Monitor millivolts versus time, taking readings every 30 s. or one minute. Typically, the Eh should drop (less often increase) smoothly as a function of time, and level off at a single value, which may

fluctuate ±5-10mV over the course of a few minutes. When a stable reading is achieved, cut off the flow entirely, and watch the reading closely. It should either remain the same or drop 5-30mV, but it should then be steady. If the reading rises when flow is stopped, there is air in the line. This air should be removed and the measurement procedure repeated.

4. Repeat the measurement a few times. The value recorded without flow should be reproducible to within ±20 mV, and under ideal conditions will be accurate (representative of the true solution Eh) to within ±50 mV. If there is a noticeable smell of sulfide in the water, the electrode should be polished with fine crocus cloth or a paste of scouring powder between each measurement and the electrode and meter system should be checked for drift after each measurement with ZoBell's solution. Assume drift is linear with time to make a drift correction. Drift is to be expected in waters low in concentrations of redox-sensitive species, and especially in sulfide-rich waters where the Pt and reference electrodes may be poisoned.

5. The final Eh adapted should be the arithmetic average of the replicates taken. Individual results may obviously be discarded if problems are encountered during a given run (e.g. - air in lines, excessive electrode poisoning, etc.) In the presence of sulfide, the bright Pt surface will turn a pale straw-yellow. If this occurs, polish the electrode as before and repeat the measurement.

Notes on Eh measurements:

- The response of the Pt electrode is a function of its surface area, among other things. The greater the surface area of the electrode, the more rapid and stable the reading. A large surface area will also decrease the amount of time required for the reading to stabilize.

- Normally, the millivolt reading in the flowing cell will stabilize within 5-10 minutes, although as much as 30 minutes may be required in some cases. Longer response times are characteristic of more dilute, poorly poised waters (waters of low redox capacity).

Poising is analogous to buffer capacity for pH measurements (see Langmuir, 1971, Stumm and Morgan, 1981).

- The U-tube apparatus described above has many advantages over other methods: it is inexpensive; it is made of readily-available materials; it is easily controlled (i.e. easy to cut off flow, remove air bubbles); and it is an efficient flow system for wells which produce very little water.

- In all measurements, the meter and electrodes should be out of the wind (behind a shield, etc.) and in shadow. Direct sunlight adversely affects the stability of the meter and electrodes, causing excessive drift.

pH Determination

A. Basic Information:

Langmuir (1971) has described many of the details of field pH measurement techniques. Some specific points will be addressed here, and a brief procedure will be given. For more information on specific pH buffers, consult the above reference.

The Orion model 399A pH-millivolt meter described above is an excellent field instrument and is therefore recommended over other commercially-available models.

B. Equipment:

1. A plastic or hard rubber flat-bottomed washtub (approximately 10 liter capacity) can serve as a bath in which to equilibrate the buffers and electrodes to the ambient groundwater temperature.

2. A small ringstand with electrode clamps makes equipment handling much easier in the field. Electrode breakage is less likely if the leads are well organized and out of the way.

3. Stock buffer solutions should be carried into the field in 1 liter plastic bottles and kept cool in an ice chest. Working buffers should be stored in smaller (125 ml) narrow mouth plastic bottles. They

should be kept on ice between sample sites, and placed in the water bath when pumping begins so that they will reach the groundwater temperature. Buffers of pH 4.01, 6.86 and 9.18 are suggested.

4. A field model combination-pH-reference electrode is strongly recommended. Field-designed electrodes have a special plastic protective sheath, and are available from Orion, Corning and Markson Scientific, among others. Before going out into the field, be certain that the pH electrode is small enough to fit inside the small buffer bottles. Two or more such electrodes should be taken on any field trip in case of breakage.

C. Procedure:

1. After the electrode and buffers have reached the groundwater temperature ($\pm 1^{\circ}C$), calibrate the apparatus as follows:

   a. First calibrate in the buffer which is expected to be closest to the groundwater pH. Set the water and buffer temperature on the meter's temperature compensation dial. Use the "calibration" knob on the meter to adjust the reading.

   b. Immerse the electrode in a second buffer, preferably the one next closest to the sample in pH and bracketing the sample pH. If the pH reading in the buffer is not within 0.05 pH units of the expected value, use the "slope" knob to adjust the reading, and repeat step (a) above.

   c. Measure the third buffer. (This is not necessary if calibration in the first two buffers is satisfactory [$\pm$0.05 pH units], and they bracket the sample's pH.) If the third buffer is not within 0.05 pH units of the expected value, repeat the entire calibration procedure (a) and (b) above with fresh buffer solutions. If that fails, try a different electrode or replace the filling solution in the reference electrode. Inspect the reference junction in the faulty electrode and remove any stray dirt particles with a stream of sample or distilled water, and dab gently with a lint-free tissue, such as Kimwipes or lightweight, ashless filter paper.

2. Once the electrode is calibrated, take the reading of the water sample in a large plastic beaker partially submerged in the washtub of water. The reading should stabilize within one minute.

3. Flush the beaker with fresh sample and repeat the measurement, checking for reproducibility. If the second (and third) measurements are not within 0.05 pH units of the first, repeat the entire procedure (including calibration) after checking the electrode contacts, the meter power supply, the electrode and the buffer solutions. (This will rarely be necessary.)

Filtration Apparatus

A. Filters and Filter Plates:

There are two major filter apparatus designs: one is a flat, small capacity filter plate through which sample water is pumped with the use of a peristaltic or similar pump; the other is a large volume (2-4 liter) housing with a filter at one end - compressed N_2 gas is used to force the water through the filter. We have had better experience with the latter, although the equipment required for the former method is adequate if carefully used and is far less cumbersome and space-consuming. The Millipore Company makes a variety of filter types. Their equipment is well-made and highly reliable for field use. All samples should be filtered with 0.45 μm pore-diameter filters, such as those made by Millipore or Schleicher and Schuell. The filtrate should be absolutely clear, or else the procedure should be repeated. Suspended solids in the samples will often dissolve upon acidification, causing erroneous chemical analyses.

Laboratory instrumentation and measurement techniques for water quality analysis of major and some trace element species are given in Table 5. More detailed descriptions of these and other laboratory chemical analytical methods are given by Brown and others (1970), and in Methods for Chemical Analysis of Water and Wastes (1974).

Table 5. Tabulation of analytical methods and their respective detection limits and accuracies.

Species	Detection Limit	Accuracy	Analytical Method
SiO_2	0.1 mg/l	2 significant figures	Spectrophotometric with Molybdate blue
Ca	0.1 mg/l	±10%	Atomic Absorption Spectrophotometry (AAS)
Mg	0.1 mg/l	±10%	AAS
Na	0.1 mg/l	±10%	AAS
K	0.1 mg/l	±10%	AAS
HCO_3	10 mg/l	±0.5%	Potentiometric Titration
Cl	2 mg/l	±5%	Mohr Titration
SO_4	5 mg/l	--	Gravimetric - $BaSO_4$ Method
F	0.1 mg/l	--	Specific Ion Electrode
PO_4	0.01 mg/l	--	Spectrophotometric-phosphomolybdate
NO_3	0.3 mg/l	--	Specific Ion Electrode
H_2S	1.0 mg/l	--	Specific Ion Electrode
Eh	--	±10mv	Platinum Electrode
DO	0.1 mg/l	--	DO Probe
Rn	1 pCi/l	--	Portable Alpha Counter
pH	--	±.05 units	Field pH Meter, Combination Electrode
SpC	--	±10 μmhos	Conductivity Probe and Meter
T^oC	--	$\pm 0.2^oC$	Thermometer
U	0.1 μg/l	--	Fluorimetric
V	1 μg/l	--	Spectrophotometric-Gallic Acid Method
Fe	0.01 mg/l	--	AAS
Mn	0.01 mg/l	--	Graphite Furnace AAS
Ra-226	0.1 pCi/l	±10%	Radon Emanation, Alpha Scintillation
As	2 μg/l	--	Hydride Generation, AAS
Mo	2 μg/l	--	Spectrophotometric, Thiocyanide Method
Se	2 μg/l	--	Sames as for As
He	--	±0.01 mg/l	Mass Spectrometry

References

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Wood, W. W., 1976, Guidelines for collection and field analysis of ground-water samples for selected unstable constituents: Tech. Water-Resources Inv., Bk 1, Chap. D2, 24 pp.

4.2.6 Costs of some Methods of Chemical and Isotopic Analysis of Waters and Rocks

Insofar as existing wells and springs are available for sampling, the chief costs involved in applying geochemical techniques employing groundwater quality data, are in the labor and costs of sampling and chemical and isotopic analysis, computer programming the data, and data mapping, plotting (etc.), and finally data interpretation. The costs of running the computer programs that perform geochemical water-rock reaction modeling are usually a few dollars per run.

A general rock ananlysis for 17 components including the major elements and 5 trace elements, all reported as oxides, costs about $90. Determination of the weight and volume percent of minerals present in a rock costs $150 without clays, and $170 with clays. X-ray diffraction analysis of all minerals present costs $90 if done qualitatively, and more if done quantitatively. (The above prices are from the Crystal Research Laboratory of Golden, CO, as of April, 1981.)

Some typical 1980-1981 costs of laboratory analyses of major and minor chemical species in waters and rocks are given in Tables 6 and 7.

Table 8 gives approximate 1981 costs, as well as sample sizes and methods of analysis of the more important stable and radioactive isotopes. Discussion below further expands on the methods of sampling and analysis of some of these isotopes.

Waters for D/H ratio measurement, are passed over hot uranium metal. The reaction is $U + 2H_2O = UO_2 + 2H_2(g)$. While it it possible to use this approach on any sized sample, it has always been difficult to obtain reproducible results on samples of less than about 8 ml of H_2O.

$^{18}O/^{16}O$ ratios in water can be done by two methods. The choice of the method is dictated by sample size. The more precise method involves equilibration of a measured amount of $CO_2(g)$ (of established isotopic composition) with a fixed amount of the water (usually 10 ml). The less precise technique involves reaction of the water with BrF_5 and requires less than 20 ml of water.

Table 6

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TABLE 7

GEOCHEMICAL WATER ANALYSES

Minimum of 10 Samples*

APRIL 1981

Analysis	Detection Limit mg/l (ppm)	Each	Analysis	Detection Limit mg/l (ppm)	Each
Aluminum	0.1	$4.00	Molybdenum	0.002	$2.50
Arsenic	0.002	5.00	Nickel	0.002	3.00
Barium	0.1	3.50	Phosphate	0.02	4.00
Beryllium	0.002	4.50	Potassium	0.05	3.00
Boron	0.1	5.00	Selenium	0.002	6.00
Cadmium	0.001	3.00	Silica	0.5	5.00
Calcium	0.1	3.50	Silver	0.001	3.00
Carbonate &			Sodium	0.05	2.50
bicarbonate	1.	3.20	Strontium	0.05	3.50
Chloride	2.	3.20	Sulfate	5.	4.50
Chromium	0.001	4.00	Uranium	0.002	4.00
Cobalt	0.002	3.00	Uranium	0.0001	6.00
Copper	0.001	3.00	Vanadium	0.002	5.00
Fluoride	0.1	3.50	Zinc	0.002	2.50
Iron	0.05	2.50			
Lead	0.005	3.00	Alkalinity		3.20
Lithium	0.01	3.00	Hardness		4.50
Magnesium	0.01	3.50	pH		1.50
Manganese	0.01	2.50	Specific Conductance		1.50
Mercury	0.0002	5.00			

Dissolved solids (conductivity method)	1.50
Total solids (residue on evaporation)	5.00
Radium - 226 (0.5 pCi/ℓ)	40.00
Radium - 226 (0.05 pCi/ℓ)	50.00

*For lots of less than 10 samples add 30% to above prices.
Additional analyses and lower detection limits — prices on request.
Some analyses available at lower cost for higher detection limits.

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TABLE 7 (contd.)

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APRIL 1981

SAMPLE PREPARATION CHARGES	
ROCK SAMPLES	
Pulverize and Blend:	
Less than 2 pounds	$ 2.60
2 to 5 pounds	3.50
5 to 10 pounds	4.00
Over 10 pounds ... add	.40/lb over 10 lbs.
Core Splitting	16.00/hr.
Drying	.50
Compositing by weight	.60 per sample included in composite
SOIL and STREAM SEDIMENT SAMPLES	
Sieving (less than 2 pounds)	1.00
Drying — porous sample bags	.50
— non-porous containers	1.00
VEGETATION SAMPLES	
Dry, pulverize, blend	3.50
SAMPLE DECOMPOSITION CHARGES	
Nitric-perchloric acid digestion	1.30
Silicate decomposition — acid	3.50
Silicate decomposition — fusion	5.00
Plant Ashing:	
Dry ashing, nitric-perchloric digestion, % ash determination	4.00
Wet ashing	4.00
THIN SECTIONS	
Base Price	6.00
Additional charges will be made for slabbing, impregnations, grinding in oil, etc., when necessary.	
DIAMOND SAW CUTTING	16.00/hr.

Note: Additional charges may be made for non-routine samples.

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TABLE 7 (contd.)

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ANALYSES FOR MINERAL EXPLORATION
ROCK, SOIL, STREAM SEDIMENT AND VEGETATION SAMPLES

APRIL 1981

Prices do not include sample preparation and decomposition except as noted below.
Detection limits for major elements per customer's specification.

Element	Detection Limit, ppm□	Price	Element	Detection Limit, ppm□	Price
Aluminum	–	$5.00	Phosphorus	50	$4.00
Antimony	1	6.00*	Potassium	–	3.00
Arsenic	1	4.50	Radium	$5x10^{-7}$	12.00
Barium	10	4.00	Rubidium	10	4.00
Beryllium	1	3.50	Selenium	1	5.50
Bismuth	1	4.50	Silicon	–	9.00*
Cadmium	0.2	2.50	Silver	0.5	3.00*
Calcium	–	3.00	Sodium	–	2.50
Carbonate	–	6.00	Strontium	10	4.00
Chromium	10	3.00	Sulfur (total)	100	8.00
Cobalt	5	2.50	Thorium	2	15.00*§
Copper	2	2.00	Tin	10	6.00
Fluorine	10	6.50*	Titanium	–	7.00*
Gold	.02	4.50*	Tungsten	1	5.00*
Iron (total)	–	2.50	Uranium	2	4.50
Iron (ferrous)	–	7.00*	Uranium	0.1	6.50
Lead	5	2.00	Vanadium	10	5.00
Lithium	10	3.00	Water (H_2O+, H_2O-)		9.00
Loss on ignition		4.00	Water (total)		6.00
Magnesium	–	3.00	Zinc	1	2.00
Manganese	10	2.50	Zirconium	50	9.00*
Mercury	.01	5.50*			
Molybdenum	2	2.50			
Nickel	5	2.50			

□Detection limits for vegetation are approximately 1/10 listed values
*Sample decomposition included in price
§Also see gamma spectrometry price list

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TABLE 7 (contd.)

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URANIUM, THORIUM, RADIUM, AND POTASSIUM IN ROCK SAMPLES BY GAMMA SPECTROMETRY

Uranium and thorium in equilibrium with their decay products can be reliably determined at levels as low as one part per million by measurement of gamma ray spectra of rock samples. In the same radiometric measurement, radium may be determined to 0.5 parts per trillion (picocuries per gram) and potassium to 0.2%, absolute.

The method utilizes a multichannel analyzer which accumulates the gamma energy spectra of coarse or finely divided rock samples which have been sealed in metal cans to prevent escape of gaseous radon and thoron. The spectrum, obtained in digital form, is mathematically analyzed for the radioactivity of specific nuclides present in the sample. Results are reliable to approximately ±10% for 10 ppm or more of uranium or thorium on samples which are in secular (radiogenic) equilibrium.

Rocks and soils which are not in radiogenic equilibrium will exhibit high or low apparent concentrations of uranium (and sometimes thorium) depending on the recent geologic history of the sample. A comparison of chemical (fluorometric) uranium analyses with the gamma spectrometric analyses can provide useful information for studies of the age, genesis, and weathering of uranium-bearing rocks. Whether the sample is in equilibrium or not, our gamma spectrometric analysis provides a reliable measure of radium.

Results of analyses are reported as eU, ppm (radium-equivalent uranium, parts per million), eTh, ppm, and % K. Radium-226 concentration (in parts per trillion) can be calculated by multiplying eU, ppm by 0.342.

Prices:	eU, eTh, K	$16.00
	eU, eTh	$11.00

GROSS GAMMA EQUIVALENT URANIUM

This analysis measures the total gamma radioactivity of a rock or soil sample without energy discrimination. Results are reported as the concentration of uranium in equilibrium with its decay products which would have the same total radioactivity as the sample. The method is less selective than the gamma spectrometric method since it does not distinguish between uranium series, thorium series, and potassium radioactivity in the sample.

Price each: $4.00

Price each with gamma spec analysis: $2.00 additional

Where D/H and $\delta^{18}O$ ratios are to be measured on fluid inclusion waters, inclusion populations and volumes are first estimated from polished sections. Appropriate rock fragments are then cleaned, loaded into stainless steel tubes, pumped to a vacuum and crushed. The gases and liquids are then removed in a vacuum line. Where the populations of both primary and secondary inclusions are significant, it is often possible to extract their fluids using thermal decrepitation to open the inclusions. In most minerals both primary and secondary inclusions will decrepitate at the same temperature. Trial runs can be made on polished sections to establish which inclusions break at a given temperature. Because neither crushing or thermal decrepitation release all of the fluids in inclusions, rock sample sizes must be large enough to assure recovery of the 20 to 30 ml of water needed for both isotopic measurements. After the inclusion waters are removed, the remaining rock can be leached for a few hours with several milliliters of distilled water. This water is then analyzed for major ions. By calculating the appropriate dilution factor, the major element chemistry of the inclusion waters can then be obtained. In general, only isotope ratios for δD and $\delta^{18}O$ are measured on inclusion fluids.

For the other stable isotope ratios listed in Table 8, a general rule of thumb is that the sample should be large enough to produce more than 150 micromoles of the gas to be analyzed. This can require as little as 10 mg of some silicates for $\delta^{18}O$ mineral values, or as much as 70 mg for δD values for some hydrous minerals. The problem of reproducibility in small samples as described above applies to some of these systems as well.

In the case of $T(^{3}H)$ and $T/^{3}He$, it may be possible to make these measurements on smaller sample sizes than given in Table 8, using techniques that are not as yet commercially available.

Table 8 Sample sizes required, methods of analysis and 1981 costs of analysis of important radioactive and stable isotopes. Data mostly from A. Muller, Sandia National Laboratories, Albuquerque, New Mexico.

Isotope or Isotope Ratio	Appropriate sample size for analysis: Water[a]	Appropriate sample size for analysis: Rock	Analytical Method[b]	Cost	Remarks
δD with $\delta^{18}O$	3–10 ml	< 20 mg	MS	\$35–40	
$\delta^{18}O$	3–10 ml	< 20 mg	MS	\$25	
$\delta^{13}C$	10 ml of water with C_T = 3 meq/l	~ 10 mg	MS	\$25	Water volume required is inversely proportional to total carbonate content.
$\delta^{34}S$	1 L	2 g of sulfide material	MS	\$40	
T (^3H)	1 L (500 ml for single analysis)	———	LSC or GPC	\$250	
T/^{3}He	1 L	———	LSC for T GCMS for He	\$300–350	Technique not readily commercially available.
^{4}He	50 L	———	GCMS	\$400–500	Technique not readily commercially available.

Table 8.(contd.)

^{14}C	60 L with C_T = 3 meq/l	~10 g of pure carbonate material	LSC or GPC	$250–300	$\delta^{13}C$ should be run on all samples collected for ^{14}C. T should be run on all samples collected for ^{14}C. Same cost for acid-soluble carbonate mineral as for water. Add $50 if carbon in organic carbon. Price of ^{14}C likely to reach $400/sample in the near future.
	100 ml	~ .02 g (?)	TAMS	$400	TAMS method has higher sensitivity LSC or GPC (to date), permitting dating to 100,000 years via ^{14}C.
^{36}Cl	4 L	______	TAMS	$1200–1800	Limited commercial availibility of analysis.
^{39}Ar	2 x 10^4 L	______	GPC	$400 (?)	Method not commercial.
$^{238}U/^{234}U$	1 L	______	AS	$60–75	

[a] C_T denotes total carbonate (H_2CO_3 + HCO_3^- + CO_3^{2-}).

[b] Abbreviations used for analytical methods denote as follows: MS = mass spectrometer; LSC = liquid scintillation counter; GPC = gas proportional counter; GCMS = gas chromotograph-mass spectrometer; TAMS = Tandem accelerator-mass spectrometer; AS = alpha spectrometry.

APPENDIX F-2

GEOCHEMICAL TECHNIQUES

FOR SITE CHARACTERIZATION

BY

DONALD LANGMUIR

HYDROCHEM SYSTEMS CORP.

GOLDEN, COLORADO

NOVEMBER 1, 1981

F-2

Phase II Report

EXPLORATORY GEOCHEMICAL TECHNIQUES TO BE USED DURING SITE SELECTION AND CHARACTERIZATION: APPLICATION TO THE SIX GEOLOGIC MEDIA

by

Donald Langmuir
Hydrochem Systems Corp.
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Page No.

1.0 SCOPE

This report will first address the recommended use and limitations of the geochemical techniques described in the Phase I report to the selection and characterization of sites for repositories in the individual geological media. Discussion will focus in particular on the use of the techniques to establish the degree of isolation of a potential repository from the biosphere. The second part of the Phase II report will focus on what is known regarding the geochemical mobility and hazard of environmental contamination by radionuclides and fission products that might escape from a breached repository in each of the six geologic media.

2.0 APPLICATION OF GEOCHEMICAL TECHNIQUES TO SITE SELECTION AND CHARACTERIZATION IN THE SIX GEOLOGIC MEDIA

2.1 Executive Summary

Geochemical characterization of groundwaters, secondary minerals and fluid inclusions, and rock geochemistry in the six geologic media has two fundamental purposes: first, to establish the suitability of the water-rock or dry rock media as a repository; and second, to allow prediction of the hazard of radionuclides and fission products being released from a breached repository to groundwater and subsequently to the biosphere.

Geochemical techniques provide unique information as to site suitability and to the potential mobility of radioisotopes. A chief characteristic of the ideal site in any of the media is that it is and has been hydrologically isolated from the biosphere. Such isolation of present groundwaters in any of the media is suggested by descriptive groundwater chemical evidence that the water is of constant composition and is oxygen free.

The static geochemical water-rock reaction computer models may be used given a groundwater chemical analysis and rock geochemical data, to establish the degree of saturation of groundwaters with respect to minerals in non-saline groundwaters in shale, granite, tuff and basalt. Marked undersaturation or supersaturation with respect to major rock-forming minerals suggests relatively young groundwaters, or groundwaters subject to mixing. The path or progress models may be used to predict the solubilities and mobilities of radioisotopes that might be released from a breached repository into non-saline groundwaters in the same rock media (not in salt formations). At present such applications have been attempted only for uranium.

Concentrations of noble gas tracers (especially Xe, Kr and Ne) in groundwaters in any of the media can be used to reconstruct the temperature of groundwater (meteoric) recharge.

Stable isotopes of oxygen, and deuterium in groundwaters or in secondary minerals or fluid inclusions in secondary minerals in dry rock, can indicate both the source of the water analyzed, or of the water no longer present which has been involved in secondary mineral formation (meteoric, connate, metamorphic, etc.) in any of the media.

The techniques described above may suggest or demonstrate that a given groundwater or secondary mineral has been derived from a meteoric source. However, only dating of the water or of secondary minerals can indicate the age of such events. The radioisotopes most often used for dating are tritium and C-14. Tritium and C-14 methods may be applied to the groundwater, and C-14 to secondary carbonate minerals in dry rock in any of the media. Ages up to about 20 yrs and 50,000 yrs respectively, may be determined by tritium and C-14 dating methods.

Isotope disequilibrium methods which usually involve isotopes in the U-238 or U-235 decay chains, demonstrate whether a rock system has been closed or open to leaching by groundwater since rock formation. Application of this method is probably limited to granites and uraniferous shales. The existence of isotope equilibrium is excellent evidence that a rock is isolated from groundwater flow, and thus appropriate for siting of a repository.

Based on results of this report a statement may be made as to the geochemical characteristics most appropriate for such a rock in the ideal repository. One can list in decreasing order of preference those characteristics most desirable in the media to be selected. These are:
1) Impermeable, dry, and without fractures, faults or secondary minerals. In the case of granites or uraniferous shales, the rock should be in isotopic equilibrium, not disequilibrium.
2) If secondary minerals are present, stable isotopes should indicate that they are not of meteoric origin. Age dating of secondary carbonate minerals with C-14 should show

the isotope absent (carbonates older than about 50,000 yrs).
3) If groundwater is present, it should be oxygen free, saturated with respect to major minerals, not of meteoric origin, and without C-14.
4) If the groundwater present is of meteoric origin based on stable isotope or other data, it should be oxygen free, saturated with respect to major minerals, and without C-14.

2.2 Introduction

The applicability of geochemical techniques that involve the use of published data and new data collection and interpretation, is summarized in Table 1. The table indicates which techniques are most or least useful for characterization of the six rock types, whether in phreatic zones or dry rock systems. Because of similarities in the applicability of these techniques to, for example, both bedded and domed salt, and to granites and basalts, the following discussion is organized by technique rather than by rock type. The data needs for application of each of these techniques are discussed in the Phase I report. The existence of such geochemical data for groundwaters, rocks, minerals and fluid inclusions is assumed here. Technique selection priorities in Table 1 in any case take into account the costs associated with acquiring (including measuring) these data.

The ideal repository will be sited either in dry rock below the phreatic zone, or in a groundwater-rock system isolated such that the groundwater cannot discharge to the land surface. For a groundwater flow system to have a significant discharge rate, it must have a significant recharge rate. Although some groundwater recharge can be as leakage from other formations via aquitards or cross-formational faults, for example, the ultimate groundwater recharge source will generally be meteoric water. Thus, the absence of waters of meteoric origin, strongly supports the conclusion of isolation of the rock-water system. For this reason a chief purpose of applying the geochemical techniques described in Table 1 to the several geological media is to prove the presence or absence of meteoric water. Geophysical, geological and hydrological evidence may indicate isolation of the dry rock or water-rock system, but only geochemical techniques can unequivocally prove such isolation or the lack of it.

Table 1. Applicability of geochemical techniques for site selection and characterization to the six geological media. Techniques are ranked according to recommended relative priority, in decreasing order of priority.

Media	Phreatic Zone				Phreatic Zone or Dry Rock Systems					
	Descriptive Techniques	Geochemical Water-Rock Reaction Computer Models		Noble Gas Tracers	Stable Isotopes		Unstable Isotopes			
							Age Dating		Isotope Disequilibrium	
		Static Models	Path or Progress Models		Phreatic Zone	a) Dry Rock	Phreatic Zone	b) Dry Rock	Phreatic Zone	Dry Rock
Bedded Salt	1	2	2	1	1	1	1	1	2	2
Domed Salt	1	2	2	1	1	1	1	1	2	2
Shale	1	1	1	1	1	1	1	1	1	1
Granite	1	1	1	1	1	1	1	1	1	1
Tuff	1	1	1	1	1	1	1	1	2	2
Basalt	1	1	1	1	1	1	1	1	2	2

Footnotes:

a) The stable isotopy of dry rock is that of fluid inclusions and secondary minerals.

b) The age dating of dry rock is chiefly of secondary carbonate minerals.

2.3 Descriptive Appraisal of the Groundwater Chemistry

Descriptive appraisal of the groundwater chemistry as defined here denotes such an appraisal excluding the isotopic and noble gas composition of the water which are later discussed in detail. The data available for such an appraisal will be in part previously published, and in part obtained by new chemical analyses. Methods of appraisal may be simple comparisons between groundwaters, or graphical or statistical comparisons as defined in the Phase I report. Regardless of the descriptive approach, there are three types of variations in groundwater quality that provide evidence of meteoric inputs to the groundwater. These are trends (or the lack of them) in groundwater quality, spatially among several wells, and temporarily in single wells, and changes in the state of oxidation or reduction of the groundwater.

Systematic spatial trends, laterally or with depth, in the groundwater concentrations of major and minor dissolved species within a formation usually indicate interconnection of such groundwaters. If such trends include water table groundwaters, a meteoric origin for all the waters in the trend is likely. The lack of such trends, however, cannot disprove a meteoric origin for the waters being considered. Spatial trends are most often observed in rock media with relatively homogeneous, isotropic hydrologic properties, which include some tuffs. Where significant groundwater flow is chiefly in fracture zones (in some basalts and tuffs and especially in granites and shales) and/or in solution zones (in bedded or domed salts), the groundwater chemistry will generally be highly variable over short distances (100's of meters) both vertically and horizontally. Such chemical variability proves the anisotropy of groundwater flow in such rock, and the waters' isolation from each other (c.f. Fritz and others, 1979), but cannot prove the degree of hydrologic isolation of the groundwater from the biosphere.

Groundwaters whose chemical composition changes with storm events, seasonally or on a yearly (or longer) basis, are clearly affected by meteoric waters. Temporal changes are expected in unconfined water-rock systems in any of the media, but will rarely be seen deeper, confined systems, which nevertheless may have been affected by meteoric waters within the past tens or hundreds of years.

The ideal phreatic zone repository is likely to be in contact with groundwaters void of dissolved oxygen because of their long-term isolation from the atmosphere. Thus, information on the oxidation state of the groundwater is useful evidence for the isolation or non-isolation of the groundwater. The presence of dissolved oxygen ($>$0.1 mg/l) in the groundwater is certain evidence of recent meteoric water input. Other evidence for such input is the presence of significant nitrate in the water. More isolated groundwaters will be oxygen free, and have an oxidation potential (Eh) near or below zero volts, no nitrate, and possibly be low in or sulfate-free with a significant H_2S and/or methane content. Dissolved iron and manganese, and reduced forms of other minor metals are further evidence for relative isolation of the groundwater. The argument for long-term isolation based on low Eh is less defensible in rocks which contain organic matter or ferrous iron minerals, which may deplete the oxygen content of a groundwater a short distance from the recharge zone. These include black shales (organic matter, pyrite and siderite), and some tuffs and basalts (ferrous silicate minerals).

The above techniques can indicate when a groundwater is almost certainly of meteoric origin, because of its temporal or spatial variability and oxidation state. However, groundwaters which are oxygen-free and of constant composition, are usually older but also of meteoric origin. The descriptive techniques suggest which water-rock systems should be precluded from further investigation. However, other geochemical techniques are needed to decide when constant composition, oxygen-free waters are truly isolated from the biosphere.

2.4 Geochemical Water-Rock Reaction Computer Models

The static and path or progress water-rock reaction computer models cannot as yet be applied to the study of reactions in saline groundwaters (waters with salinities exceeding that of sea water; 35,000 ppm in total dissolved solids). This is because the models do not incorporate reliable activity coefficient corrections for such high salinities. This precludes model application to the saline groundwaters or brines present in bedded and dome salt, or to similar waters in any of the other media. Saline groundwaters are often present at depth in marine shales, but are less common in granites, tuffs and basalts.

These models have two important applications in the repository siting program, especially in shales, granites, tuffs and basalts. First, the static models can determine the degree of saturation of groundwaters with respect to minerals present in the geologic media. If such programs indicate saturated conditions exist with respect to the major rock forming minerals (particularly silicates and metal oxyhydroxides) this provides evidence that the groundwater has been isolated from mixing with fresh meteoric waters, probably for tens of years or more.

The path or progress models may be used along with information on mineral saturations from the static models to: 1) reconstruct the evolution history of the groundwater in the direction of groundwater flow; and 2) to predict the solubility of radionuclides and fission products that might escape from the repository into the groundwater. The computer program PHREEQE (Parkhurst and others, 1980) has recently been modified for this purpose to evaluate the solubility of uranium from spent fuel rods in different groundwaters as a function of temperature (Henderson and others, 1981). Thermodynamic data for other important radionuclide minerals and solution complexes is needed and must be incorporated in such programs before the solubilities of other potentially toxic nuclides in the different media groundwaters can be accurately predicted. Such solubility data will suggest the maximum mobilities of the elements involved. Radionuclide geochemistry is considered in detail in the second part of the Phase II report.

2.5 Noble Gas Tracers

Determination of noble gas content should be a routine analysis when groundwaters are sampled from a potential repository. As noted in the Phase II report, the relative concentrations of these gases (particularly of Xe, Kr and Ne) indicate the temperature of groundwater recharge (proof of meteoric origin). Such data may for example, show that groundwater recharge occurred under colder or hotter climatic conditions than exist today, giving information on the possible age of groundwaters of meteoric origin.

2.6 Stable Isotopes

The stable isotope chemistry of groundwaters, secondary minerals, and fluid inclusions in secondary minerals provides unique insights as to the origins of the waters and minerals involved. Secondary minerals by their presence in the fractures and faults in shales, granites, tuffs and basalts, are evidence of the incursion of waters younger than the bulk rock. The stable isotope chemistry (especially 0-18 and deuterium content) of fluid inclusions can indicate for example if the water is meteoric, connate or magmatic in origin, and the temperature of inclusion formation. In dry rock media, stable isotope data from fluid inclusions and secondary minerals, and age dating of those minerals (see the next section) will be the chief evidence available as to the extent of and length of time of isolation of the media from meteoric waters. The following discussion details some applications of the stable isotope geochemistry of subsurface waters and secondary minerals to the siting problem in the six geological media.

2.6.1 Bedded and Domed Salt Deposits

While the mineralogy of evaporite deposits varies somewhat, nearly all contain carbonates, sulfates, halides and authigenic clay minerals. Where crystalline, the carbonates, sulfates and halite commonly contain fluid inclusions. It was shown in Figure 17 (Phase I report) that fluids undergoing evaporation follow one of a family of isotopic trends. Fluids in primary fluid inclusions, unaffected by post-depositional mixing should follow an evolutionary path similar to one of the lines in Figure 17 (ibid). Further, these waters should be in isotopic equilibrium with existing authigenic clay minerals. Where meteoric water has entered the system and mixed with the formational waters, an approximate amount of mixing can be determined as follows: 1) based on alphas and the $\delta D - \delta^{18}O$ values of authigenic clays, the $\delta D - \delta^{18}O$ content of formational waters can be calculated; and 2) two equations

$$\delta^{18}O \text{ measured} = \delta^{18}O \text{ original} \times \% \text{ original water} + \delta^{18}O \text{ meteoric} \times \% \text{ meteoric water}$$

$$\delta D \text{ measured} = \delta D \text{ original} \times \% \text{ original water} + \delta D \text{ meteoric} \times \% \text{ meteoric water}$$

with two unknowns allows a direct solution. In addition, fluid migration as inclusion waters results in inclusions with healing tracks showing direction of migration.

Where secondary inclusions contain isotopically dissimilar fluids, one or more episodes of fracturing, fluid penetration and fracture "healing" is/are indicated. Such events, ideally, could be tied to local geologic events for timing.

As will be the case for each rock type, stable isotope geochemistry places no constraints on the timing of mixing events. It may be possible to date some clay minerals using Rb/Sr methods (^{87}Rb half-life of $5x10^{10}$ yrs) (Della Valle, 1981). It may also be possible to similarly date the contents of some fluid inclusions (G.P. Landis, personal communication, 1981). Clay minerals are often zoned around evaporite basins (B.F. Jones, personal communication, 1981). With or without zoning, one's ability to use clay minerals as an indicator of the isotopic composition of formational fluids is wholly dependent on being able to identify and separate the individual clays.

2.6.2 Basalts and Granites

It is possible to characterize the initial $\delta^{18}O$ values of unaltered basalts and andesites quite accurately: 6.5 ± 1 ‰ (per mil) (Taylor, 1974). The isotopic composition of granites, while not as tightly constrained as basalts, is confined to a fairly narrow range of values. When these rocks are altered by meteoric waters under hydrothermal conditions isotopic temperatures and water/rock ratios can be calculated (Taylor, 1974).

At ambient temperatures fluids generally do not penetrate these rocks completely but rather are restricted to fractures. The presence of amorphous silica, iron or manganese oxides, carbonates, zeolites or clay minerals along fractures indicates fluid movement and implies an open system. Both amorphous silica and carbonates are likely to contain fluid inclusions. In low temperature environments these inclusions are usually small and as a single phase. Where the inclusions are in amorphous silica, they allow both direct measurement of the isotope ratios of the fluid and provide a good isotope geothermometer. Carbonates can exchange oxygen with the included fluids negating their use as a geothermometer.

As noted previously, the δD - $\delta^{18}O$ content of the clays formed in fractures allows direct calculation of the δD - $\delta^{18}O$ ratios of the clay-forming fluid. Zeolites, common in tuffs and basalt, might work equally well except that to date not enough is known about the necessary fractionation factors.

Where the rock system is now dry, stable-isotope evidence for the presence of meteoric water based on analysis of fluid inclusions cannot in itself reveal the timing of, or the amount of fluids that have moved through the system. In those rocks where water is still present in fractures more can be learned. Fritz and others (1979) performed such a study on the Stripa Granite in Sweden. Similar arguments could be made if the host rock were basalt. $\delta D - \delta^{18}O$ values from their study are plotted in Figure 1. Fritz and others (1979) divide the fluids into three groups whose populations are generally separated isotopically. They argue, based on this separation and chemical differences, that there is no mixing of the waters, and that the waters may represent two different meteoric waters involved in recharge (shallow versus intermediate and deep). They further suggest that waters in the intermediate and deep zones show no evidence of water-rock interactions. Some data (particularly in the deep group) plot to the left and above the meteoric water line, appropriate for waters altering primary minerals to hydrated silicates in a system where the water/rock ratio is small. These conditions are reasonable for this environment. Most of the waters show no oxygen isotope exchange with the wall rocks, yet alteration products exist. These alteration reactions are quite slow but obviously there has been enough flow-through of groundwater of meteoric origin to allow the alteration reactions to go to completion. This requires that the system has been open to the movement of meteoric waters for an extended period of time, contrary to conclusions of the authors.

2.6.3 Ash Flow Tuffs

The unaltered isotope ratios of ash flow tuffs are more variable than those of other igneous rock types, even where compositional differences are small. The glassy, poorly welded nature of some tuffs makes them particularly susceptable to alteration both before and after cooling. The isotopic compositon of the glass should indicate the original unaltered value. The $\delta^{18}O$ content of one or more alteration phases may allow the source of altering fluids to be determined. Where δD values can be obtained for clays, further characterization of the altering fluids is possible. Because fluid flow in these rocks is not restricted to fractures, it may be possible to map whole rock isotope values, contouring the extent of alteration and its pathways. Such contouring has been done successfully in the past for hydrothermally altered systems (Forester and Taylor, 1972; Casadevall and Ohmoto, 1977). Extensive alteration of these

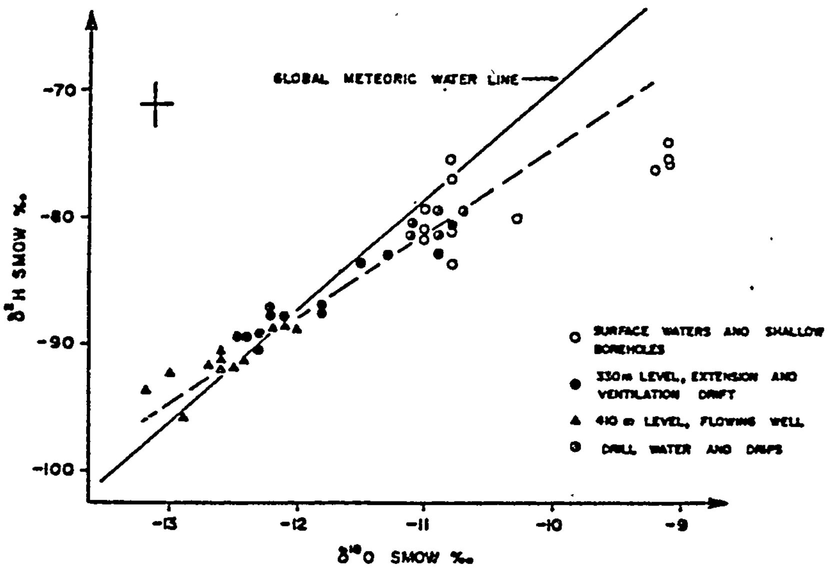

Fig. 1 A plot of $\delta^{18}O$ versus $\delta^{2}H$ of waters from the Stripa area. The dashed line is a best fit through all groundwater points. From Fritz and others (1979).

rocks can cause what was once an aquifer to become an aquitard. Where aquitards can be related directly to the amount of alteration, whole rock $\delta^{18}O$ mapping could assist in defining these areas. The proof of existence of such an aquitard would require confirmation from for example hydrologic testing, independent of the stable isotope data. The discussion of isotopic equilibrium between alteration phases in granites and modern waters presented in the section on granites applies here as well.

2.6.4 Shales

Deposition and shallow burial of shales does not require isotopic equilibrium to be attained between the solid phases and the associated waters (Lawrence and Taylor, 1972). Likewise compaction dewatering or even deep burial are not likely to cause isotopic redistribution so long as the mineralogy is not changed. The result is a rock whose minerals are detrital and almost totally unreactive to groundwater. There are however, a few reactions that can leave isotopically finger-printed phases indicating reaction with more recent groundwaters: 1) oxidation of sulfides to sulfates, where the $\delta^{34}S$ values mark the source of the sulfur and the $\delta^{18}O$ values the source of the oxygen; 2) oxidation of iron phases; and 3) the deposition of carbonates along fluid pathways. As before, the occurrence of alteration products indicates an open system has existed, and the source of the fluids can be determined. In this case little else can be learned unless detrital clay minerals can be shown to have been involved in the alteration reactions, allowing some investigation into the amount of fluids required to attain isotopic equilibrium between the solid phases and the altering fluid. Such reactions are unlikely in shales.

2.7 Unstable Isotopes

2.7.1 Age Dating

As noted in the Phase I report, the most useful radioisotopes for dating recent groundwaters (up to about 50,000 yrs) are tritium and C-14. Other groundwater dating techniques such as Cl-36 can ideally be used to date groundwaters up to 10^6 yrs old (Davis and Bentley, 1981). Because practically all groundwaters are mixtures of variable amounts of waters of different origins and residence times, groundwater ages computed from radioisotope data are at best mean or relative ages.

Background tritium levels in groundwater can range from ≤0.5 TU (tritium units), to 1.5 TU in uraniferous rocks. Values less than 3 TU indicate groundwater ages greater than 20 yrs; 3-20 TU water recharged between 1953 and 1961; and greater than 20 TU water originating after 1961. Tritium-radiocarbon dating can be applied to groundwaters in any of the six geological media. C-14 dating can be used to date secondary carbonate minerals in fractures and veins found in shales, granites, tuffs and basalts. Whereas other geochemical techniques such as stable isotope methods can indicate that a groundwater or secondary mineral has been affected by meteoric water, only age dating can indicate the timing of such inputs to the water-rock or dry rock system.

2.7.2 Isotope Disequilibrium

In principle, the existence of isotopic equilbrium among parent and daughter radionuclides in a rock indicates that the rock has been isolated from groundwater flow since its formation. Because of differences in the relative groundwater mobilities of parent and daughter products, moving groundwater will preferentially remove the more mobile elements or isotopes in a given decay chain. As noted in the Phase I report, the isotope decay chains most often used in disequilibrium studies are those of U-238 and U-235. Dates of past groundwater leaching events can theoretically be obtained by considering the relative activities of several isotope pairs having ranges of half-lives in a decay chain. The existence of isotopic equilibrium (rare) in a rock is excellent proof of the suitability of such a rock as a repository. Such techniques have so far been applied only to uranium-rich rocks, such as granites and uraniferous shales.

3.0 THE POTENTIAL MOBILITY HAZARD OF RADIONUCLIDES AND FISSION PRODUCTS FROM A BREACHED REPOSITORY: GEOCHEMICAL CONSIDERATIONS

3.1 Executive Summary

The risk of biosphere contamination by radionuclides from an hypothetically breached repository depends on the nature of the rock media and its associated groundwaters, and upon the time since burial of the waste. There is some dispute as to which of the radionuclides are most toxic in terms of time after burial. The consensus is that Cs-137 and Sr-90 are the most toxic up to 600-1000 yrs. For times beyond 1000 yrs, published lists of important nuclides variously include isotopes of Am, Np, Pu, Ra, Th and U. Isotopes of Tc, I, Pd, Pb, Sn and Se have also been suggested as potentially toxic in case of a breach.

Empirical studies of radionuclide mobilities in geologic media have to-date been relatively qualitative. We currently lack a basic understanding of the adsorption behavior of the radionuclides in complex natural systems. We also lack thermodynamic data on potentially important solids and solution complexes of the actinides in particular. Laboratory distribution coefficient studies, which have generally lumped the adsorption and precipitation behavior of the nuclides, when combined with a general understanding of the oxidation-reduction and complexation behavior of these elements allows very general statements to be made regarding the potential mobilities of the actinides and their fission products.

The most mobile of these elements are those of anionic character, which include Tc, I and Se. These are followed in mobility by Cs, Sr, Ra and Pb, and in some oxidizing environments by Np, Pu and U, and independent of Eh by Am and Th. Pd and Sn are highly immobile in general. Np, Pu and U are highly immobile in reduced waters. Distribution coefficient studies indicate that the radionuclides will generally move 10% or less as far or as fast as bulk groundwater. Highest mobilities will be in oxidized, saline groundwaters low in sulfate, in geologic media low in sorbent minerals or organic matter. Thus, mobilities will be least in shales, slightly greater in tuffs, generally greater in granites and basalts, and greatest in NaCl brines associated with salt domes and bedded salt.

Solubility calculations for U, Pu, Np and Am for expected groundwater pHs and Eh conditions (Wood and Rai, 1981) indicate that actinide solubilities are generally least in reduced groundwaters and slightly greater for U, Pu, and Np in oxidized groundwaters. Such solubility calculations, which generally give <u>maximum</u> possible concentrations, indicate that except for Pu, concentrations of these actinides will not exceed NRC standards in reducing groundwaters, and will only exceed the standards by ten-fold for Np and Pu in oxidized groundwaters.

Although mobilities of the radionuclides appear to be generally low enough to avoid environmental contamination, the inadequacies in our understanding of their basic geochemistry suggest that in-situ studies of radionuclide mobilities be made at each potential repository, using injection wells. Such studies are particularly necessary in rocks in which groundwater flow is fracture controlled (granites, basalts, and many tuffs and shales).

3.2 Introduction

Spent nuclear fuel from light water reactors contains numerous radionuclides and fission products of potentially toxic nature. The purpose of this part of the Phase II report is to examine what is known about the mobilities of these isotopes in groundwaters that might be expected in the six geological media, so as to predict the risk of biosphere contamination in the event of a breached repository. Repositories are likely to be situated at such depths that atmospheric oxygen or measureable dissolved oxygen will be absent, and oxidation potentials will be of intermediate (Eh about zero volts) or more negative values. Groundwater pHs are likely to be in the range of 6.5 to 10 (Wood and Rai, 1981).

Hollister and others (1981) have described the waste cannisters expected within such repositories as being cylindrical and about 3 m in length, with a radius of about 0.3 cm. Several studies have addressed the temperature gradient and isotherm distribution around cannisters in different rock media (e.g. Cook and Witherspoon, 1978; Hollister and others, 1981; and Witherspoon and others, 1981). Hollister and others considered thermal gradients surrounding cannisters buried in pelagic seafloor sediments. Witherspoon and others (1981) studied temperature effects in a dry quartz monzonite. These studies concluded that elevated temperatures did not develop beyond a few meters in the water-saturated sediment, however in the dry quartz monzonite the 100°C isotherm extended outward about 50 m after 100 yrs, assuming a reasonable (5 kw) output per cannister. Thus, models of elemental mobility should be designed to deal with a range of temperature conditions, and should also consider the effects of variable groundwater and rock geochemistry, and radioisotope activities and decay rates.

3.3 The Important Radionuclides

Studies by several workers have determined the chemical composition of spent high-level nuclear fuel from a light-water reactor (c.f. Ames and Rai, 1978), and have evaluated the consequent potential toxicity risk or hazard to the biosphere of the more important radionuclides (c.f. Gera and

Jacobs, 1972; Ames and Rai, 1978; and Barney and Wood, 1980). Based in part on their conclusions, and on reports by Bredehoeft and others (1978), Ames and Rai (1978), and Wood and Rai (1981), in Table 2 are listed fourteen elements whose radioisotopes are likely to be important in geological media following a repository breach, both because of toxicity and because of relative geochemical mobility. When more than one radionuclide is listed, the first listed is the one of greatest initial concern, the second becoming more important with time. Some of the isotopes listed are highly radioactive and toxic in the initial waste products. The others which are decay or daughter products of the initial isotopes, increase in relative importance with time. Because the breaching of a repository could occur at any time after burial, it is of interest to establish the relative importance of the radioisotopes in the spent fuel with time.

The isotopes Sr-90 and Cs-137 are responsible for nearly all of the initial radioactivity in the spent fuel. They are considered the most toxic nuclides present for the first 600 yrs after burial (Bredehoeft and others, 1978). Given half-lives of 29 and 30 years, respectively, for Sr-90 and Cs-137, and the rule of thumb that an approximately 10^3-fold reduction of radioactivity occurs for every 10 half-lives, 600 yrs of storage reduces the radioactivity of these isotopes by 10^7 times.

The remaining twelve isotopes in Table 2 increase in relative importance after 1000 yrs. Figure 2 from Bredehoeft and others (1978) depicts the radioactivity (biological hazard) with time of the nuclides Np-237, Pu-239, U-233, Th-229 and Ra-226. Pu-239 is the most hazardous, and Np-237 the second most hazardous nuclide from 1000 to 10,000 yrs after burial. From 10,000 to 10^6 years, Ra-226 is the most hazardous nuclide. Ra-226 and Th-229 become most hazardous from 1 to 10 million years. Wood and Rai (1981) suggest a slightly different list of important radionuclides. They propose that after 1000 yrs of burial the important radionuclides are U, Np, Pu and Am.

3.4 Geochemical Mobility of the Important Radionuclides

The key environmental issue once a time-sequence of importance of radioisotopes has been established, is the potential geochemical mobility of these isotopes in groundwaters within the six geological media. Geochemical mobility depends upon the adsorption and solubility behavior of each element. These properties in turn are functions of the salinity, pH, oxidation potential (Eh), temperature, and the

Table 2. Important radionuclides in unprocessed nuclear fuel from a light water reactor. The list is ordered in terms of decreasing hazard. (See text).

1)	Sr-90	8)	Th-230, Th-229
2)	Cs-137	9)	Pb-210
3)	Tc-99	10)	Sn-126
4)	I-129	11)	Se-79
5)	Np-239, Np-237	12)	Pu-242, Pu-239
6)	Ra-226, Ra-225	13)	U-233
7)	Pd-107	14)	Am-241, Am-243

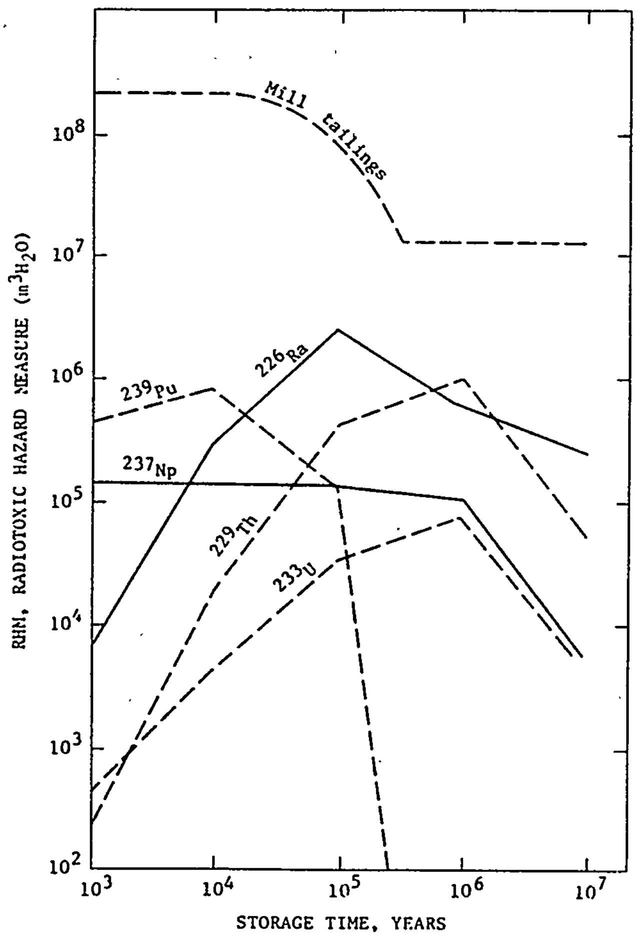

Fig. 2. - Injestion hazard of selected radionuclides in high-level waste during 10 million years. The figure is from Bredehoeft and others (1978).

types and concentrations of complexing ligands or cations present in the groundwater, and in the case of adsorption the nature of the sorbent phase and the concentrations of species that are competitively adsorbed by the sorbent.

Table 3 summarizes some pertinent properties of the elements of interest, including their predominant aqueous species expected in reducing waters and waters of intermediate oxidation state, and ranges of measured or computed distribution coefficients (K_d values).

For elements that form highly mobile (soluble) aqueous species, or insoluble oxides and hydroxides, depending on the pH and oxidation state of the water, Eh-pH diagrams provide a useful means of visualizing the importance of such conditions in each case. Shown in Figures 3-9 are such diagrams for several of the elements listed in Table 3.

Most of the published empirical data on mobilities of these elements in solutions in contact with geologic materials is cast in terms of K_d values, where K_d is defined as:

$$K_d \text{ (ml/g)} = \frac{\text{mass of solute on solid phase per unit mass of solid}}{\text{concentration of solute in solution}}$$

For radionuclides K_d may also be defined as $K_d = c_r/c_s$ where c_r is the isotope's activity in pCi/g measured in or on the rock, and c_s its activity in pCi/ml in the solution.

Studies of radionuclide attenuation or mobility have generally not distinguished the effects of adsorption and precipitation (c.f. Friedman, 1976). Most published K_d data has lumped all geochemical controls on mobility in the single K_d value. This fact makes it difficult or impossible to accurately predict radionuclide movement in complex natural rock-water systems, and helps to explain the wide range of K_d values for most elements listed in Table 3.

The smaller K_d values listed reflect behavior of the more mobile elements, the larger K_d values that of the least soluble and/or most strongly adsorbed elements. As indicated by the table, for intermediate or reduced Eh's and pH's expected in a repository groundwater (6.5-10; Wood and Rai, 1981) mobilities of the elements Sr, Cs, Tc, Ra, Th, Pb, Sn, Pu, and Am are largely independent of the groundwater Eh. K_d values for the cationic elements in this list will generally increase with pH. (Only Tc is anionic).

Table 3. K_d values and redox behavior of elements with important radionuclides, for expected pH conditions (pH 6.5-10) in a repository. K_d values are from Ames and Rai (1978) and Langmuir (1981, unpublished notes) unless otherwise indicated. Roman numerals indicate the valence number of positively charged dissolved species. See Text.

Element	Values of K_d (ml/g)	Species in Groundwater of Intermediate Oxidation State	Species in Reduced Groundwater	Remarks
Sr	≤ 10	Sr(II) species	Sr(II) species	Complexes with sulfate. Adsorbed by clays.
Cs	≤ 10	Cs(I) species	Cs(I) species	Highly mobile as Cs^+, adsorbed by clays.
Tc	0.007-2.8	TcO_4^-	TcO_4^-	Highly mobile. K_d correlates with organics.
I	>1	I^-, IO_4^-	I^-	Highly mobile.
Np	<1 - <150	NpO_2(I) species	Np(IV) species, NpO_2(c)	K_d low for minerals.
Ra	25-500	Ra(II) species	Ra(II) species	Precipitates in high sulfate waters.
Pd	$>10^2$	$Pd(OH)_2$(c)	Pd(c)	Highly immobile in general.
Th	$5 - 5 \times 10^5$	Th(IV) species, ThO_2(c)	Th(IV) species, ThO_2(c)	Highly immobile. Strongly adsorbed.

Table 3. (Continued)

Element	Values of K_d (ml/g)	Species in Groundwater of Intermediate Oxidation State	Species in Reduced Groundwater	Remarks
Pb	5-20	Pb(II) species	Pb(II) species	Carbonate and sulfate complexes important. Insoluble in high carbonate or sulfate waters.
Sn	$\gg 1$	SnO_2 (c)	SnO_2 (c)	Highly immobile.
Se	>1	SeO_4^{2-}	SeO_4^{2-}	Strongly adsorbed by Fe(III) oxyhydroxides.
Pu	$>1 - 7.3 \times 10^3$	PuO_2(c)	PuO_2(c)	Highly immobile.
U	$> 1 - 10^7$	UO_2(II) species	U(IV) species, UO_2(c)	Mobile as UO_2(II) species, Highly immobile as U(IV) species.
Am	$< 1 - 5 \times 10^4$	Am(III) species	Am(III) species	Relatively immobile.

Tc and I; Wildung and others, (1975). Np; Sheppard and others, (1975), and Routson and others, (1975, 1976). Th; Rancon, (1973), and Riese and Langmuir, (1981). Pb; Rickard and Nriagu, (1978). Pu; Evans, (1956), and Nishita and others, (1976). U; Langmuir, (1978), and Hsi and Langmuir, (1981). Am; Van Dalen and others, (1975), Sheppard and others, (1976).

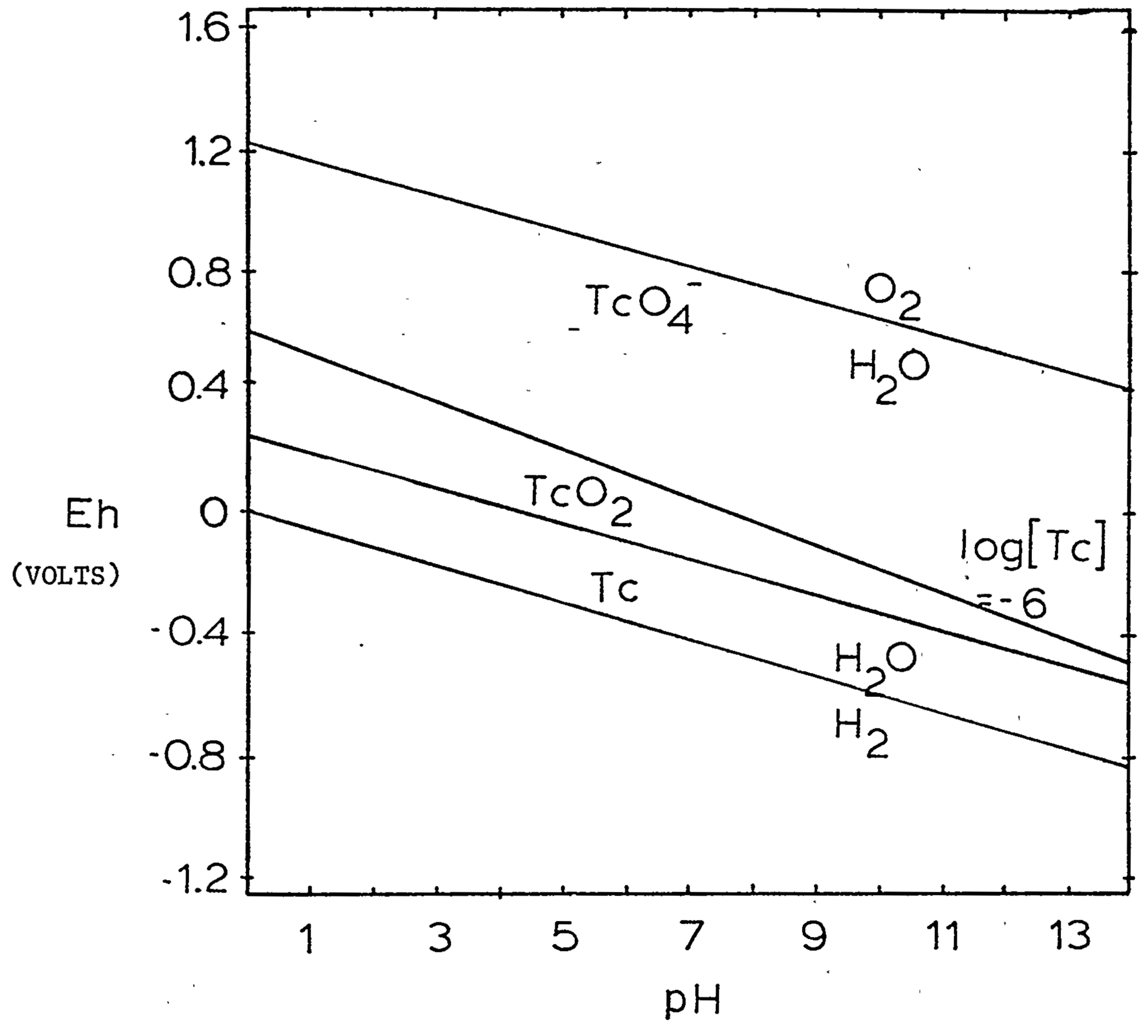

Figure 3 Eh-pH diagram for Tc in pure water at 25°C and 1 atm total pressure. Modified after Pourbaix (1966). Reprinted with permission from Pergamon Press, Ltd.

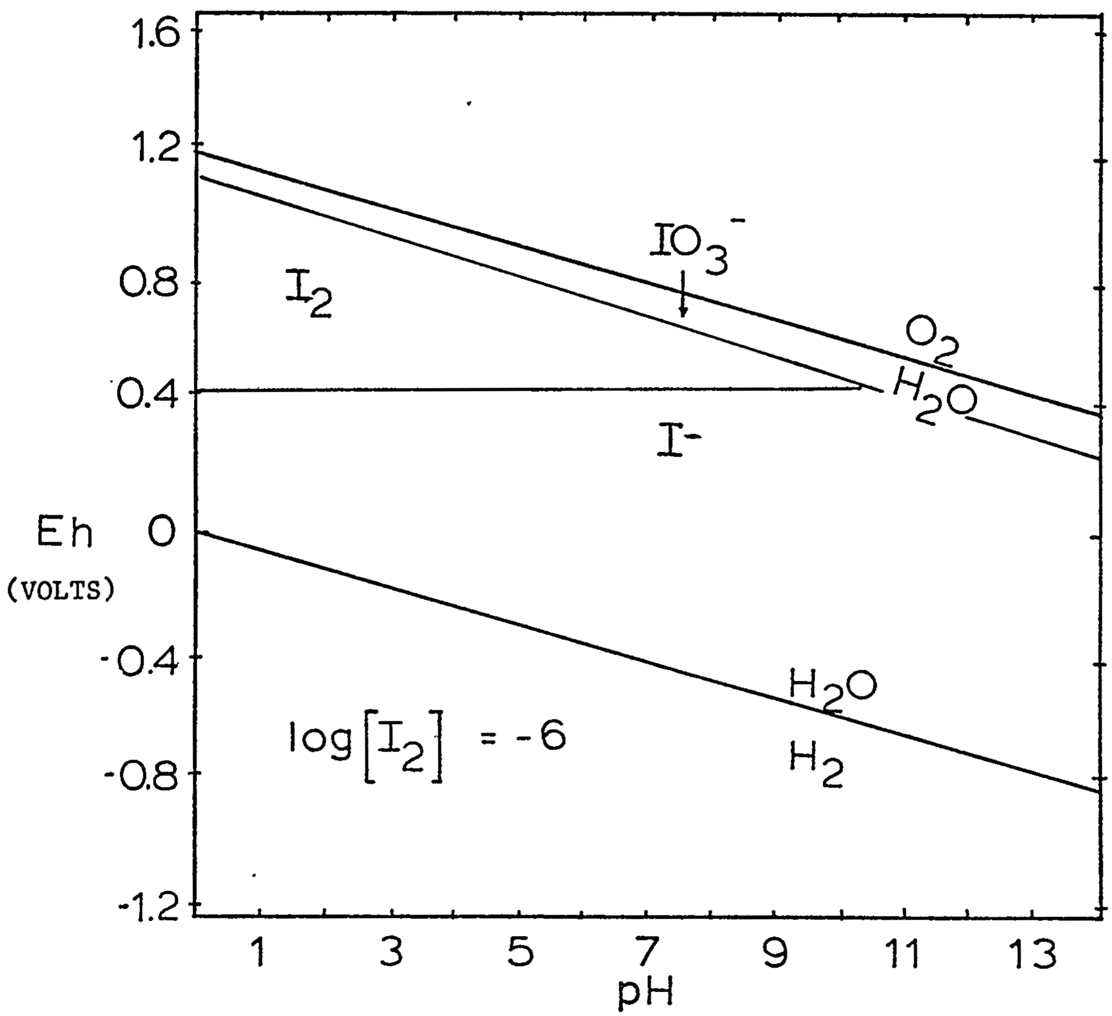

Figure 4 Eh-pH diagram for I in pure water at 25°C and 1 atm total pressure. Modified after Pourbaix (1966). Reprinted with permission from Pergamon Press, Ltd.

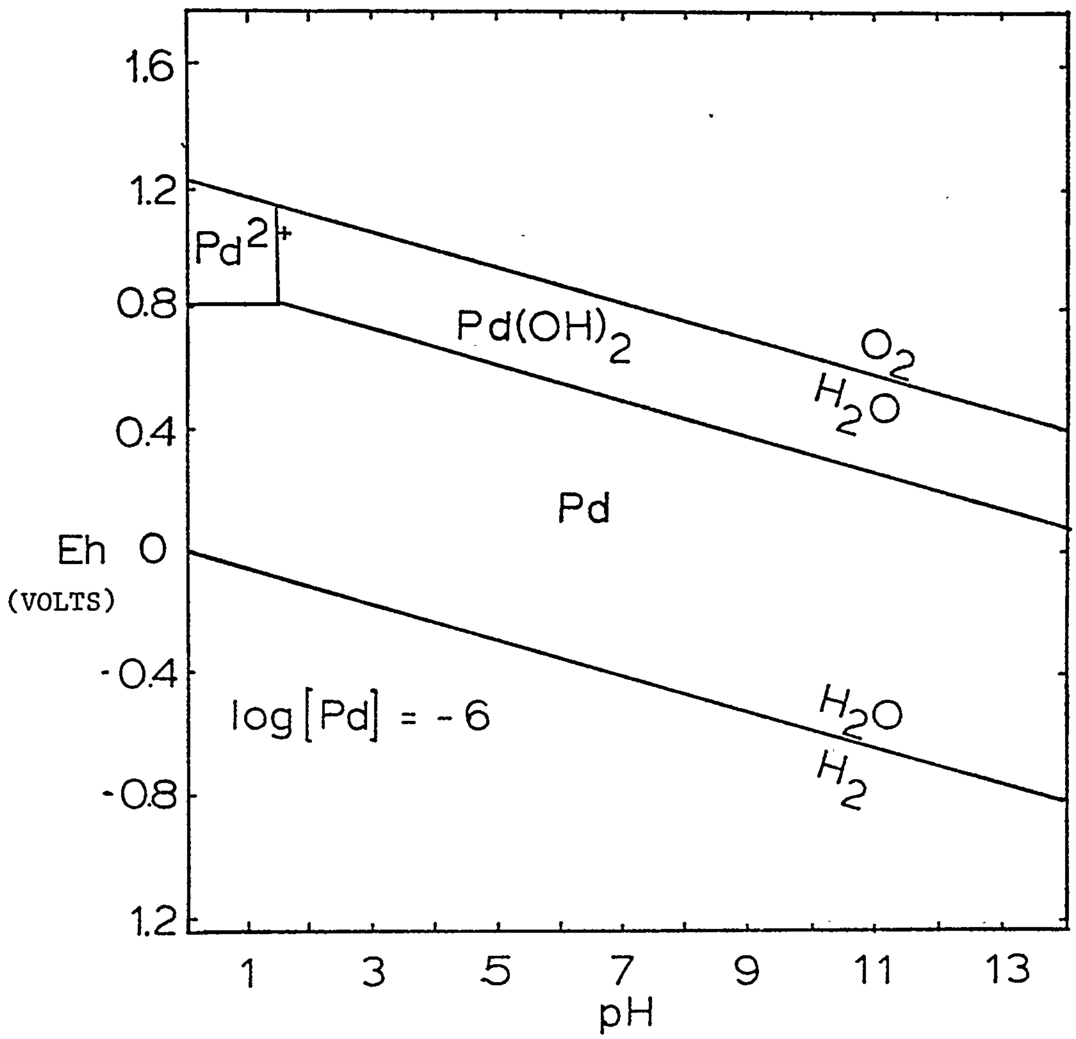

Figure 5 Eh-pH diagram for Pd in pure water at 25°C and 1 atm total pressure. Modified after Pourbaix (1966). Reprinted with permission from Pergamon Press, Ltd.

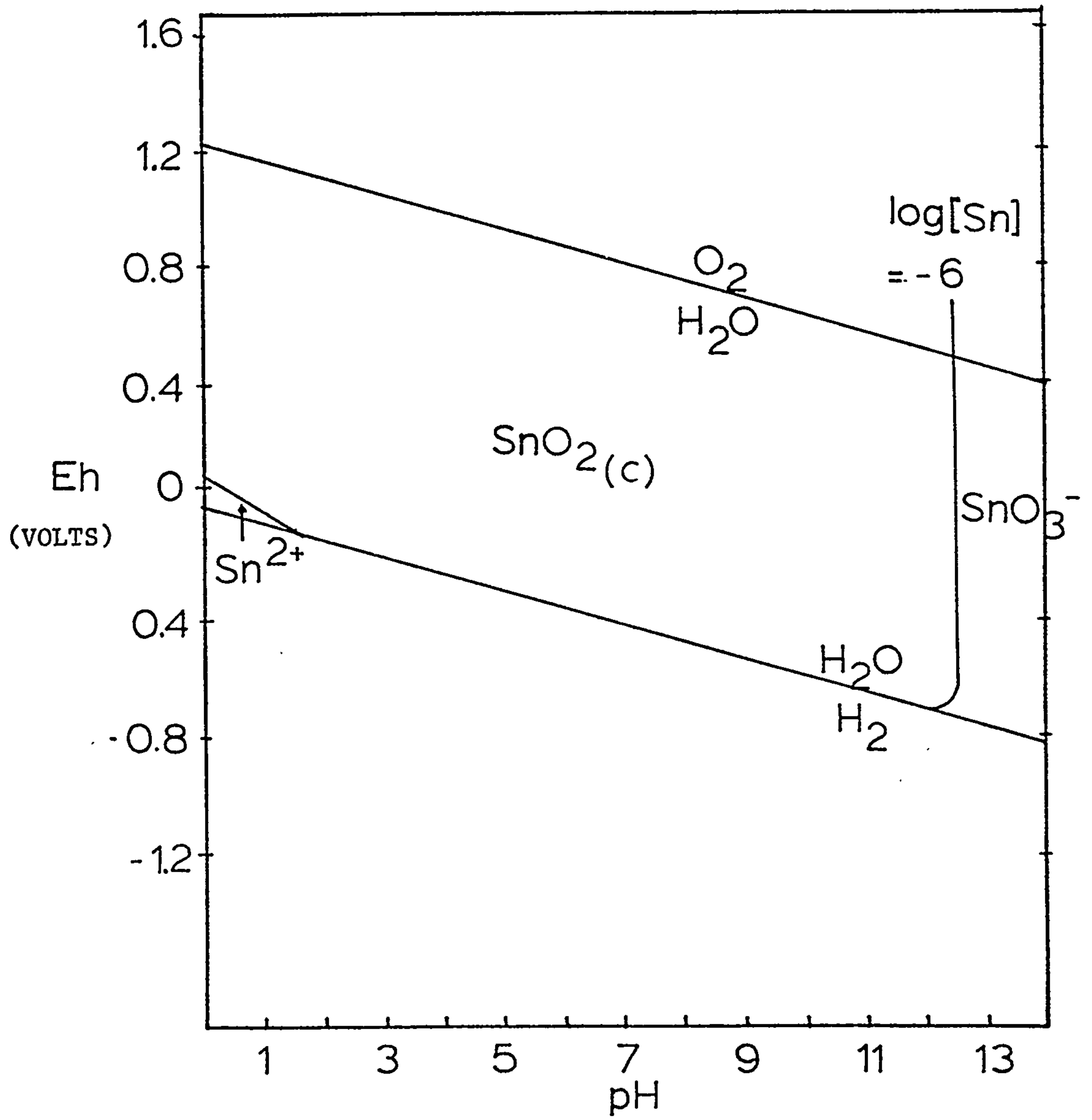

Figure 6 Eh-pH diagram for Sn in pure water at 25°C and 1 atm total pressure. Modified after Pourbaix (1966). Reprinted with permission from Pergamon Press, Ltd.

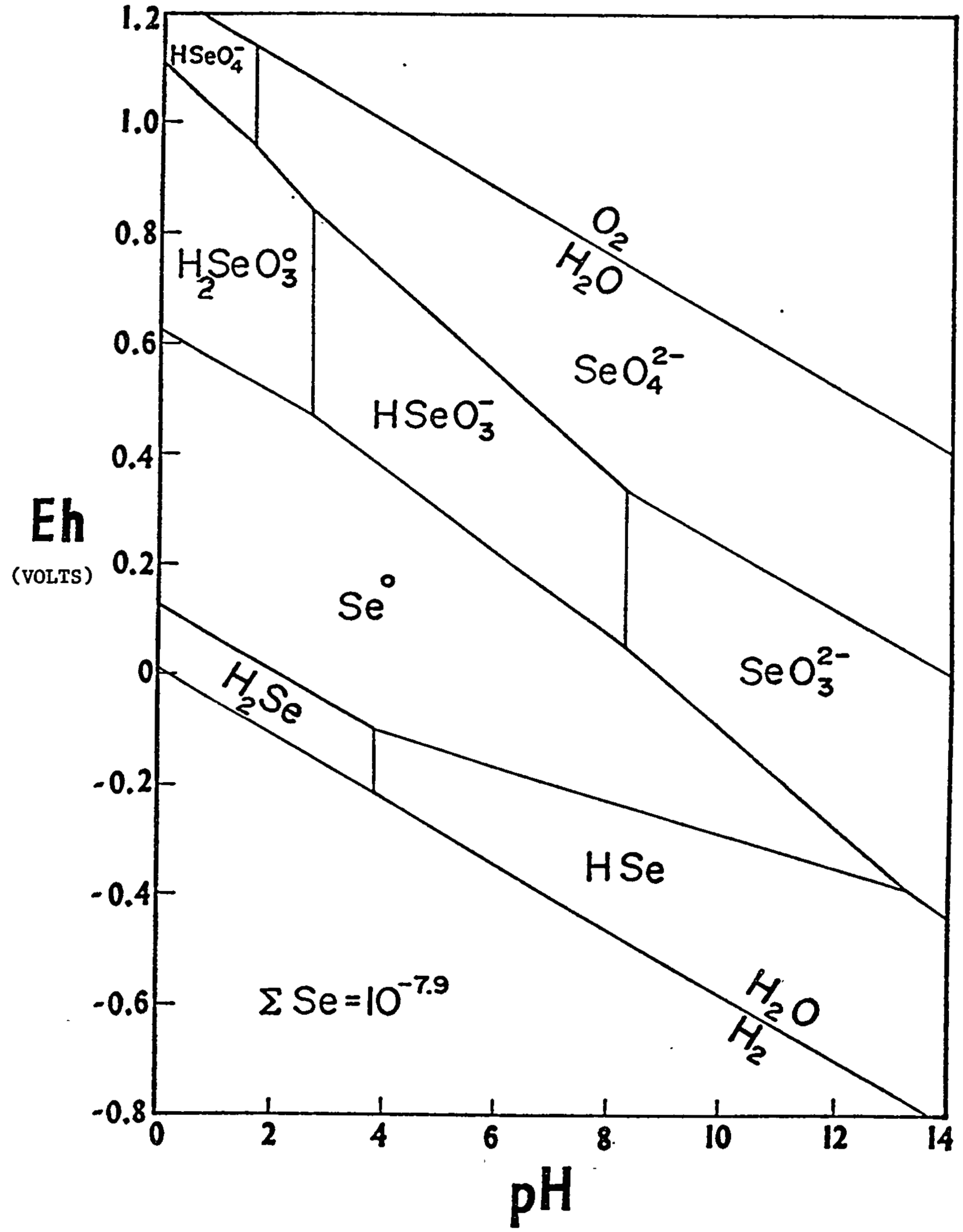

Fig. 7, Eh–pH diagram for Se at 25°C and 1 atm total pressure. Based on unpublished data of Langmuir (1981).

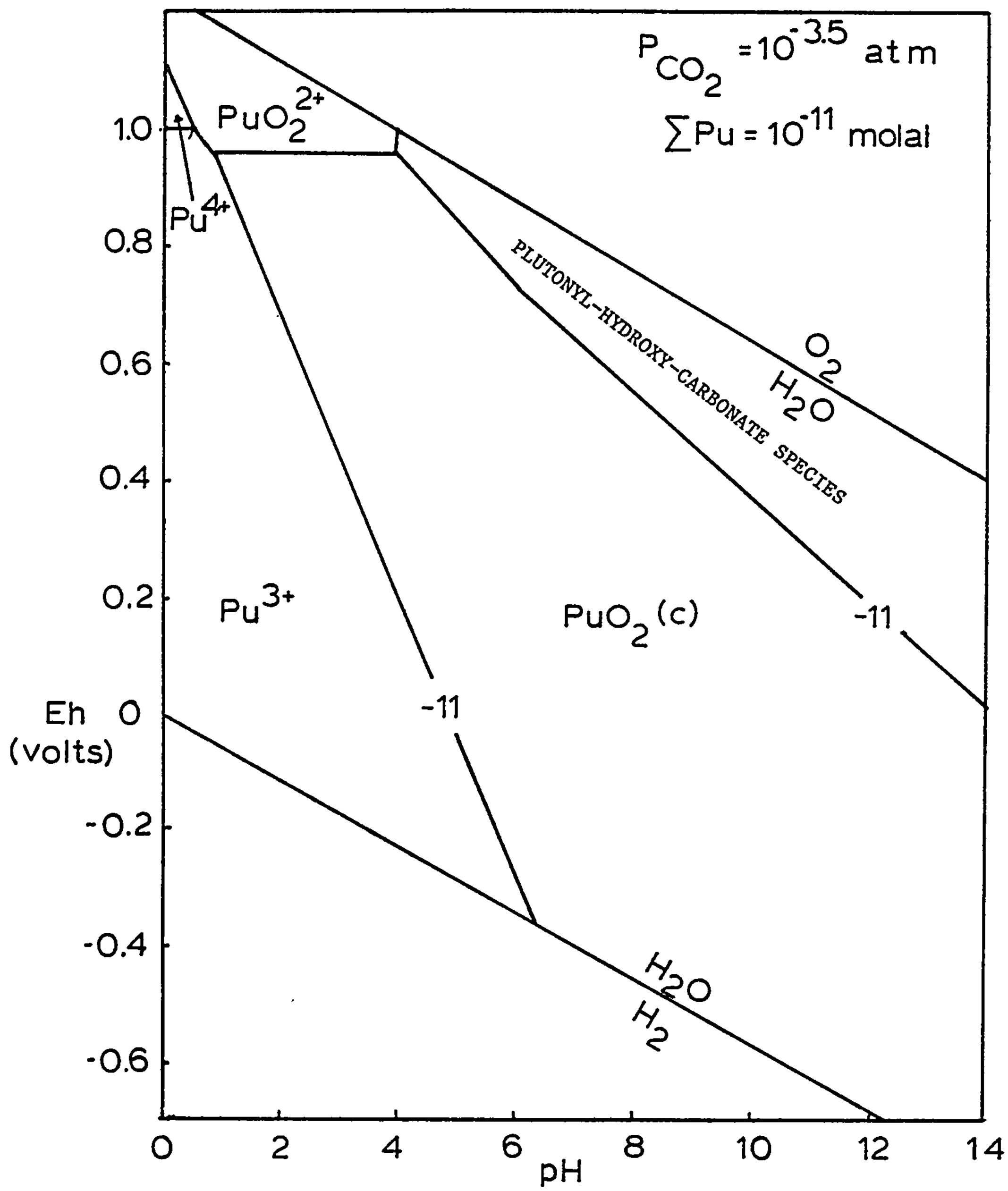

Fig. 8. Eh-pH diagram for Pu at 25°C and 1 atm total pressure, based on unpublished data of Riese and Langmuir, (1981).

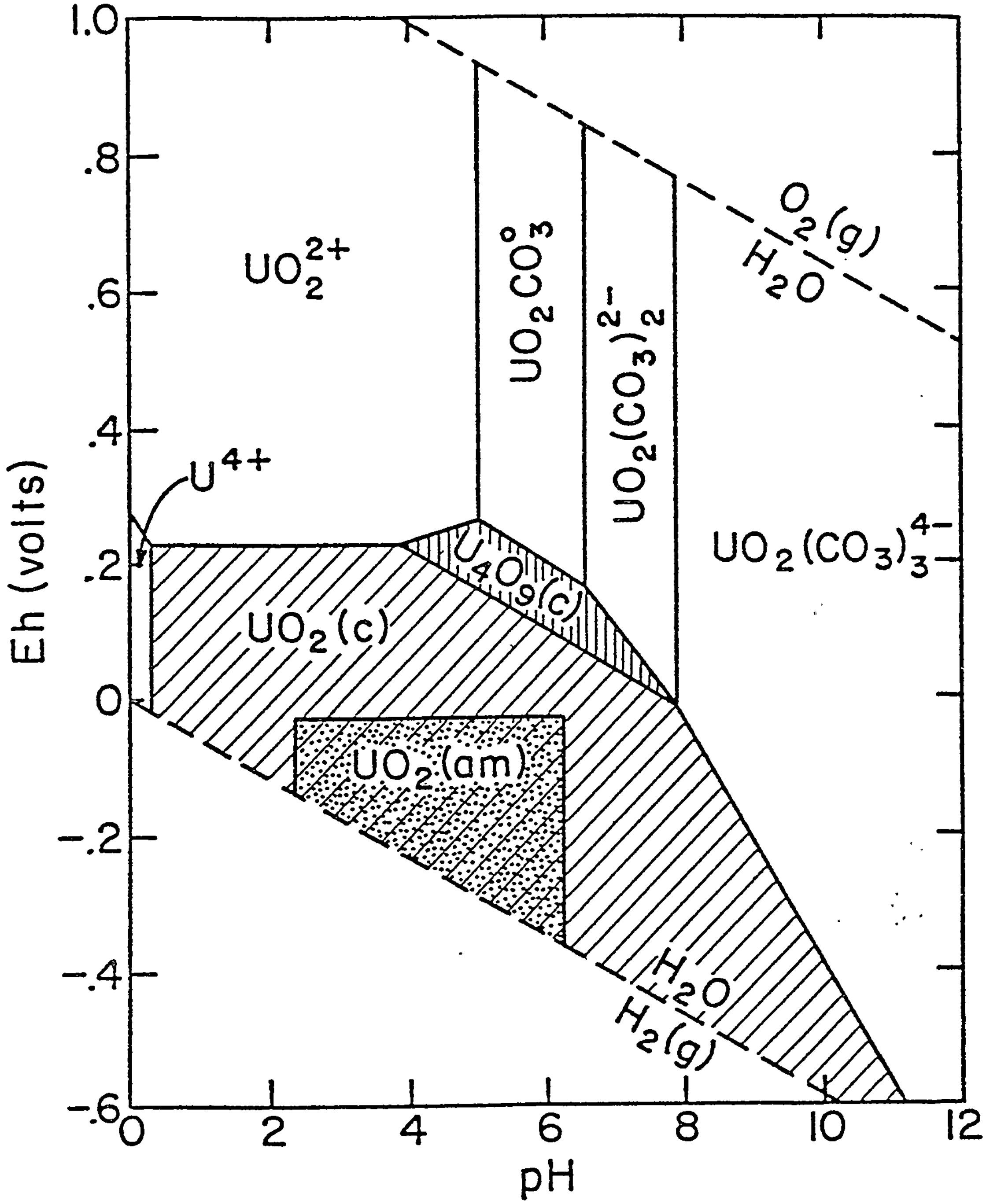

Figure 9 Eh-pH diagram in the $U-O_2-CO_2-H_2O$ system at 25°C for $P_{CO_2} = 10^{-2}$ atm, showing the stability fields of amorphous $UO_2[UO_2(am)]$, ideal uraninite $UO_2(c)$, and $U_4O_9(c)$. Solid-solution boundaries are drawn at 10^{-6}M (0.24 ppm) dissolved uranium species. From Langmuir (1978). Reprinted with permission from Pergamon Press, Ltd.

If one can assume a constant value for K_d for a particular element in a natural water-rock system (a highly dubious assumption for most of the elements in Table 3), then the mobility of the element relative to that of bulk water can be determined from the equations (see Figure 10):

$$x_a = \bar{v}.t/(1 + \frac{\rho_b}{n} K_d)$$

and

$$x_b = \bar{v}.t$$

where x_a and x_b are the respective distances of movement of the radionuclide, and of bulk water or a non-retarded constituent such as chloride or tritium, $\bar{v}$ the average linear velocity of the groundwater, t is time, and ρ_b and n the bulk mass density and porosity of the media respectively. As shown in Figure 10, x_a and x_b are measured at the 0.5 point of the relative concentration profile.

$K_d = 0$ for a species indicates it moves as fast as the bulk water. $K_d = 1$ indicates retardation of the species relative to bulk water flow by perhaps 5 - 11 times (Freeze and Cherry, 1979). When K_d values exceed 10^2, the species can be considered practically immobile in groundwater.

The application of K_d values measured in laboratory column and batch studies to predict mobilities in groundwaters is an appropriate science at best. Those elements which have a single oxidation state, which form weak complexes or are not complexed in general, and are adsorbed, but not generally precipitated in minerals, are the most reliably modelled using K_d values. These include; Tc, I, Se, Cs, Sr, and Ra (listed in approximate decreasing order of mobility). As is evident from their low K_d values in Table 3, these elements are also among the most mobile in groundwater systems. Among the least mobile elements are those that occur in the groundwater in 4+ valent form. These include Th, Pu and Sn, and in reducing environments Np and U. These elements will be strongly adsorbed as hydroxyl complexes, and highly insoluble as oxides and hydroxides at most groundwater pHs expected in a repository. Of intermediate mobilities are Am (III), and Pb (II) and UO_2(II) which form strong carbonate complexes in alkaline groundwaters which are weakly adsorbed.

The K_d concept is defined for application to groundwater flow through relatively isotropic, homogeneous rocks. Some tuffs will have such properties.

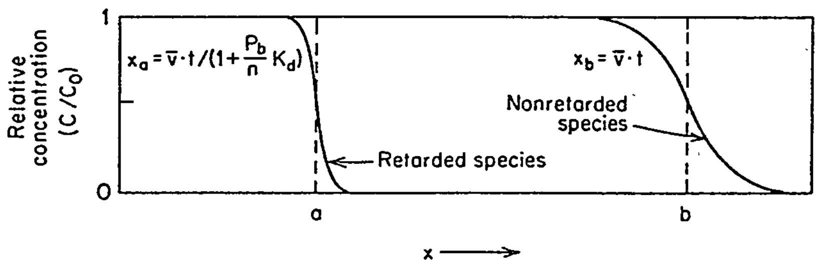

Figure 10 Advance of adsorbed and nonadsorbed solutes through a column of porous materials. Partitioning of adsorbed species is described by K_d. Relative velocity = $1/[1+(\rho_b/n)K_d]$. Solute inputs are at concentration C_0 at $t>0$. After Freeze & Cherry (1979), reprinted by permission of Prentice Hall

However, groundwater flow in shales, granites and basalts will generally be along faults and fractures. To the extent that elemental mobilities are controlled by adsorption in such cases, the volume of the open fracture and surface area of its walls will govern the extent of adsorption expected during groundwater flow. In such cases K_d values cannot be used to predict radionuclide movement. Instead, Freeze and Cherry (1979) suggest the distribution coefficient K_a, which is defined as

$$K_a(ml/cm^2) = (\bar{v}/v_c - 1)/\ A$$

where $\bar{v}$ is the average groundwater velocity as before, v_c the velocity of the radionuclide measured at its 0.5 relative concentration point, and A the surface area to void space (volume) ratio of the fracture. Unfortunately, measured values of K_a are unavailable, so that predicting radionuclide transport in fractured rock is not feasible at present.

Another approach to the problem of radionuclide mobilities is to assume the worst. That is that maximum concentrations of the radionuclides are limited only by the solubilities of their oxides or hydroxides, and not at all by adsorption. Wood and Rai (1981) have used this approach for U, Np, Pu and Am, the elements they consider most potentially hazardous beyond 1000 yrs after burial of the waste. Taking into account the effect of known complexes of these elements on their solubilities, they have estimated conservative solubility values for the actinides for pH 6.5-10, under highly oxidizing (assuming a repository breach in the presence of fresh meteoric water), and under reducing conditions. They compare these solubilities to MPC (maximum permissible concentrations) set by the U. S. Nuclear Regulatory Commission in 1980. The conclusion is that for reducing conditions the maximum U and Np concentrations would be well below the MPC values. (See Figure 11). Only solubilities of Pu-239 and 240, and Am-241 would exceed or approach these values in reducing groundwaters. Even in highly oxidizing groundwaters only Np-237, Pu-239 and 240 and Am-241 approach or exceed MPC values.

The greatest uncertainty in the model predictions of Wood and Rai is in the availability of reliable thermodynamic data for the relevant solids and solution complexes of the actinides. If important naturally occurring complexes of these elements have either been ignored or have thermodynamic stabilities much greater than assumed, the solubilities of the radionuclides could be much greater than

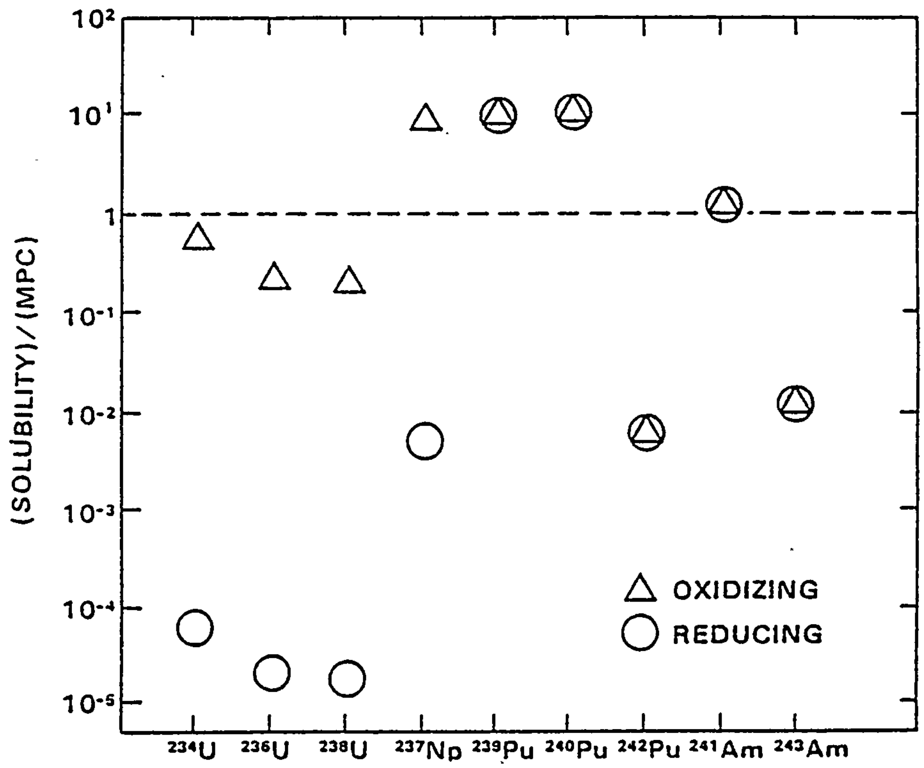

FIGURE 11. Comparison of solubilities of actinide compounds [UO_2(c), $UO_2(OH)2$, NpO_2(c), PuO_2(c), Am (soil)] with the maximum permissible concentrations (MPC as set by U.S. Nuclear Regulatory Commission 1980) under assumed repository conditions: 25°C, 1 atm., pH = 7, Eh = 0.29V (oxidizing) or -0.27V (reducing). From Wood and Rai (1981).

estimated. Also, because activity coefficient data for the multivalent actinides is poorly known and has been ignored by Wood and Rai, predicted actinide solubilities, particularly in saline groundwaters are likely to be in considerable error. Nevertheless, adsorption in natural geological media that contain clays, zeolites and/or iron and manganese and/or titanium oxyhydroxides will generally reduce these maximum concentrations well below the values limited by solubilities alone.

Adsorption removal of Cs-137 and Sr-90 will be most effective in geological media that contain an abundance of mineral and/or organic sorbents. These include shales (especially clays) and tuffs (especially zeolites) and to a less extent granites and basalts which contain clays and secondary oxyhydroxides in their fractures and faults. Adsorption is unlikely to greatly retard mobilities of radiosiotopes in bedded salt or salt domes, although saline groundwaters high in sulfate will tend to precipitate Pb-210 and Ra-225 and 226.

In view of the naive state of our scientific understanding of radionuclide mobilities in geological media, it is critical that we perform field tests of the adsorption capacity of potential site rocks in-situ using injected tracers. Specifically, a conservative tracer such as bromide could be introduced with a spike of one or more actinides such as Pu or Am by injection into a single well. Pumping the injected solution back up the well after varying time periods will indicate the rock's in-situ capacity to adsorb or precipitate the actinides. A single well test has the advantage that the injected and recovered water will move largely through the same avenues of flow in both directions. The results of such tests can be compared with laboratory tests of adsorption, which to date have had little critical application or proof of applicability under actual field conditions.

4.0 SOME SUGGESTED GEOCHEMICAL ACTIVITIES DURING DRILLING AND TESTING OF POTENTIAL SITES

1) In the drilling process one should if possible use local lake water in the drilling fluid. Because of evaporation it will have a unique D/H and $\delta^{18}O$ composition relative to that of the groundwater. Development of the well by pumping can be continued until the D/H and $\delta^{18}O$ analysis returns to that of the natural groundwater. Tritium analyses of the lake water and groundwater will also indicate when the well has

been thoroughly flushed of drilling fluid. Such a flushing is mandatory before meaningful geochemical information can be obtained from the natural rock-water system.

2) In the hydrological testing process, chemical and isotopic data should be collected during pump tests. The variability or constancy of groundwater chemistry will support or refute conclusions as to rock hydrologic characteristics based solely on the hydrologic data: e.g. is there really a recharge boundary - if so the groundwater chemistry will differ. Substantial changes in groundwater chemistry can be expected during pumping of highly anisotropic rocks. The isotopes will indicate whether the groundwater is largely of shallow or deep meteoric origin, etc., and approximately how old it is. The chemical and isotopic data may indicate the relative size as well as degree of isolation of the groundwater body being pumped by the well.

3) Packers should be used during pump tests to isolate the various water-bearing zones for separate chemical and isotopic analysis. The differences in chemistry will support or refute hydrologic evidence for the degree of isolation or interconnectedness of the water-bearing zones.

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APPENDIX G-1

HYDROLOGIC TECHNIQUES
FOR
PRECHARACTERIZATION STUDIES

BY

ERTEC WESTERN INC.

LONG BEACH, CALIFORNIA

NOVEMBER 1, 1981

G-1

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HYDROLOGIC TECHNIQUES FOR PRECHARACTERIZATION STUDIES

1.0 BACKGROUND AND PURPOSE

Based on extensive research conducted over the past 15 to 20 years, it is generally agreed that one of the most practical methods of isolating nuclear wastes from the biosphere is by deep burial in stable geologic media. Such burial achieves a high degree of physical isolation; however, questions remain concerning the rate at which certain of these waste materials may return to the biosphere via transport by ground water or other mechanisms.

To help minimize this uncertainty, a highly structured procedure has been developed to screen and evaluate potential high level radioactive waste disposal sites. The process can be divided into two basic components, a precharacterization phase (wide areal coverage-broad view-limited detail) and a site characterization phase (restricted areal coverage-focused view-considerable detail). The purpose here is to briefly describe and evaluate hydrologic data gathering/evaluation techniques which are applicable during the precharac-terization phase of site evaluation.

2.0 SCOPE

A detailed understanding of site hydrology is one of the most critical requirements for evaluation of the long-term behavior of a geologic repository for nuclear wastes. The most significant hydrologic factors include the following:

- Nature and flooding potential of surface drainage network.
- Location, extent, and hydraulic characteristics of subsurface water-bearing strata, i.e. aquifers and aquitards.
- Recharge to and discharge from the ground-water flow system(s).
- Age of ground-water and the rate of water movement within the flow system(s).

- Surface water and ground-water chemistry.

- Effects of potential future climatic fluctuations on the surface water and ground-water systems.

Methods of hydrologic investigation appropriate to address each of the above categories are discussed in this or in related chapters of this report. Many commonly used methods of hydrologic studies are more closely allied with other investigative categories. These methods are described and evaluated in other appropriate chapters and are not duplicated herein. Examples are ground-water chemistry, borehole drilling, geophysical and lithologic logging, and geologic (hydrostratigraphic) mapping.

This chapter on hydrologic methods will be divided into three major sections based on the stages of exploration or site evaluation during a precharacterization study. These are:

1. No drilling at a site; surface based studies only,

2. Information available from existing drill holes in addition to that from surface based studies, and

3. Information available from drill holes installed during the precharacterization study in addition to that from existing drill holes and surface based studies.

Given the structure of these stages of investigation, it is apparent that methods appropriate in stage 1 are also viable in stage 2 and additionally, all methods are appropriate in stage 3. With this understanding, and to minimize discussion, hydrologic methods are herein described only for that stage in which they are first directly applicable.

3.0 HYDROLOGIC METHODS

3.1 Surface Based Methods

3.1.1 Flood Frequency

To provide effective isolation of radionuclides from the environment, nuclear repository sites should be located so that the surficial hydrologic system, during both anticipated climatic cycles and extreme natural phenomena, will not cause unacceptable adverse impacts on the long-term repository performance. The most obvious adverse condition is surface flooding and its potential areal extent. Several methods have evolved for evaluating flood magnitude and frequency. These have been summarized by Benson (1962).

3.1.1.1 Singular Flood Frequency Analysis

Numerous formulas for determining flood flows and flood frequencies have been developed, but are too general to be of much use (Benson, 1962). A more recent and reliable general method applies the use of statistical analysis to data of annual peak discharges. Statistical analysis provides a means of reducing large volumes of discrete data to more meaningful terms, such as mean, standard deviation and skew coefficient. The distribution of the flood data can be expressed by a curve that defines the frequency of occurrence and probability of exceedance for various flood events. This frequency curve is then used to determine magnitude of floods of specific recurrence intervals such as the 100-year recurrence interval flood.

Several methods exist for constructing frequency curves. Recently, the U.S. Water Resources Council (WRC) has attempted to promote a consistent approach to flood flow frequency analysis in Bulletin No. 15, "A Uniform Technique for Determining Flood Flow Frequencies" (1967). Improvements and updates to Bulletin No. 15 were published in Bulletin No. 17 (1976). The most current publication by the WRC, Bulletin No. 17A (1977), "Guidelines for Determining Flood Flow Frequency", expands and revises methodologies presented in Bulletin 17. Federal, state, local, and private organizations are encouraged to use these guidelines to assure uniformity, compatability, and comparability in flood frequency determinations.

A log-Pearson Type III distribution is recommended in Bulletin 17A for defining the annual flood series. Computer programs to ease the computational load involved in a statistical analysis of this type are available. The U.S. Army Corps of Engineers and the U.S. Geological Survey (USGS) have produced flood flow frequency programs, based on Bulletin 17A recommendations, that can be purchased for private use.

Systematic discharge data are the most reliable for determining flood frequency distribution (WRC, 1977). Occasionally, there exists information about major floods which occurred either before or after the systematic record. This information can be used to estimate peak discharges and thereby extend the period of record. The USGS may have historical flood data included in its reports, or in computer files. Other agency records, newspapers, and nearby residents may also provide historical flood information.

The skew coefficient calculated from a flood record is sensitive to extreme events, consequently unreliable results may be obtained from short records. For systematic records of less than 25 years, the use of a generalized skew coefficient is recommended (WRC, 1977). Generalized skews are listed for the entire United States in Bulletin 17A. For systematic records of ove 100 years, use of the calculated skew is appropriate. For records between 25 and 100 years, it is recommended that a weighted skew be calculated. Computational methods are listed in Bulletin 17A. Also, Bulletin 17A shows computations involved in computing a generalized skew from surrounding stations for those who elect not to use the WRC-derived skews.

Resolution of flood analyses are affected by both the reliability and length of the discharge record. Long term records of 50-100 years are the most desirable. Costs involved in applying a flood frequency computer program are machine-dependent, but are normally minor in comparison with labor costs. The primary cost and time factor is locating adequate flood data for the analysis.

3.1.1.2 Regional Flood Frequency Analysis

If flood data are available from numerous stations covering a homogeneous area of concern, a regional flood frequency analysis is useful for predicting the flood hazard at any site within that region. Regionalization of flood data averages the frequency curves from an area, yet maintains the variations due to differences in basin characteristics (Riggs, 1973). Multiple regression techniques are used for this type of analysis because a given mean flood can be related to basin characteristics while at the same time averaging the residuals that are due to chance. The main application of regional flood frequency analysis is to provide estimates of the characteristics of the flood hazard at ungaged sites and to improve estimates of flow characteristics at gaged sites.

The initial step of a regional flood frequency study is calculation of the individual exceedance probabilities. The derived mean and standard deviation of each station record are separately related to basin characteristics to define a regionalized frequency curve that illustrates the defined range as well as the range where its use is questionable. Commonly used basin characteristics include drainage area, main channel slope, percent of basin covered by lakes or swamps, 2 year-6 hour maximum rainfall, mean annual precipitation, mean annual runoff, mean basin elevation, channel length, basin shape and other geographical factors (Riggs, 1973). More recently, channel geometry measurements have been incorporated (Fields, 1975). The preceeding is not a definitive list, these factors plus any others deemed significant in producing runoff variations should be investigated.

Regressions are commonly computed by a calculator or by computer program. A preferable approach (Riggs, 1973) is to select a small number of basin characteristics that have a clear relationship to flood peaks, compute the regression equation, and check the regression coefficients for significance. Many computer programs are available which select the most highly significant variable, then select the next most related variable, compute the regression on the two and test for significance, and then proceed similarly to test all variables for significance.

An individual station frequency curve developed from a regional study can only be considered approximate. According to Riggs (p. 11, 1973), the standard error of estimate is between the standard error, S, and $S/\sqrt{N}$, where N is the number of flood records available for analysis. Computer costs and time required to complete a regional study are more extensive than a singular flood frequency analysis because more data are involved and numerous computer runs are required.

3.1.1.3 Rainfall-Runoff Models

Rainfall-runoff models are frequently used to extend short-term (5-15 years) flood records (Carrigan, et al, 1977). Data required for the USGS version of this model type include concurrent short-term records (nominally 5 years) of rainfall, evaporation, and discharge. The model is calibrated using these data, then together with long-term records of rainfall and evaporation (which are more readily available) is used to synthesize a long-term discharge record (Carrigan, 1973). Model calibration adjusts 10 parameters to determine the minimum mean square error in estimating the magnitude of flood discharge. The model uses the solutions of mathematical expressions to estimate infiltration, soil moisture storage, and surface runoff routing. The standard error in calculating synthetic flood peaks from rainfall data has been reported to be on the order of 30 percent (Carrigan, 1973). The accuracy of the calibration is dependent on the accuracy of the data used and the number of flood peaks analyzed.

The decision as to whether or not flood events should be estimated by a rainfall-runoff model ultimately depends upon the effort required to calibrate a watershed model, the availability of data, and the accuracy of alternative methods. Estimated floods can be used to improve the definition of flood potential by including the results into a flood flow frequency analysis (WRC, 1977).

Other rainfall-runoff models currently used include those developed by the U.S. Army Corps of Engineers (HEC-1) and the U.S. Soil Conservation Service (TR-20). The HEC-1 program uses rainfall-snowfall-snowpack-snowmelt measurements to define a runoff hydrograph. The program is flexible in its capability, being able to derive a unit hydrograph and loss rate parameters or to "reconstitute" an observed runoff event given the average rainfall, the drainage area, and runoff hydrograph parameter values for starting flow and base flow recession computations (U.S. Army Corps of Engineers, 1973).

The TR-20 program is more comprehensive in the detail required to define input parameters. It also computes surface runoff from rainfall data; however, it uses a runoff curve number which reflects soil type, nature and extent of vegetative cover, antecedent moisture conditions, and other general hydrologic factors of the area (U.S. Soil Conservation Service, 1972).

Input rainfall data from local measurements or regional extrapolations can be input to HEC-1 and TR-20. The National Oceanic and Atmospheric Administration (NOAA) has published a series of documents giving percipitation-frequency data for the entire U.S., ranging from the 2-year, 6-hour event to the 100-year, 24-hour event. Also available are hydrometeorological reports published cooperatively by NOAA and the Corps of Engineers, which present criteria for estimating the probable maximum precipitation (PMP). The PMP as defined by the American Meteorological Society is "...the theoretically greatest depth of precipitation for a given duration that is physically possible over a particular drainage basin at a particular time of year" (NOAA and Corps of Engineers, 1977). General storm PMP estimates cover general rains over large areas. To derive a general storm PMP, the convergence PMP (precipitation due to atmospheric conditions) is estimated and combined with the estimate for orographic PMP (due to changes in elevation). Local storm PMP estimates are needed for areas in the southwestern United States due to the very intense and localized thunderstorms common to this area (NOAA and Corps of Engineers, 1977).

A typical procedure for using the HEC-1 or TR-20 programs would be to estimate the PMP or the 100-year, 24-hour event and then use this data as input to the program to derive a 100-year recurrence-interval (or greater) flood event. Many variables enter into rainfall-runoff computations, such as the antecedent soil moisture conditions and the intensity, distribution and duration of short-term rainfall. Thus, a 100-year rainfall event may or may not cause a 100-year runoff event. For the purposes of repository studies, use of PMP estimates and conservative values for other sensitive variables is suggested.

Accuracy of the HEC-1 and TR-20 programs can be improved by "reconstituting" a runoff hydrograph from a known rainfall event, much like the procedure for calibrating the USGS rainfall-runoff model. Manipulation of several variables (loss rate, basin lag, and peaking coefficient) is usually necessary to calibrate the program.

3.1.1.4 Determining the 100-Year Flood Plain

Several computer programs exist for determining the water surface profile resulting from a 100-year or other recurrence interval flood. The complexities and iterations involved in calculating the profiles are best handled by modern computer capabilities. The U.S. Soil Conservation Service program described above (TR-20) includes options for calculating the water surface elevation at any desired cross section. Other programs available for calculating water surface profiles include WSP-3 (U.S. Soil Conservation Service) and HEC-2 (U.S. Army Corps of Engineers). All these programs require discharge, Manning's roughness coefficient, channel slope, and a surveyed channel cross section to produce a water surface profile at each section of interest.

The derived water surface elevations reflect the expected profile resulting from the given discharge under free-flow conditions. Many times during flood conditions debris of various types create backwater conditions, especially at narrow cross sections where debris is prone to accumulate. Under backwater conditions the extent of flooding may be significantly increased due to the altered relationship between discharge and water level. Therefore, mapping flood profiles is often a judgment decision and is best performed by those with experience in flood studies.

3.1.1.5 Flooding Caused by Structural Failure of Dams

Flooding may occasionally occur due to natural phenomena such as earthquakes and landslides or possibly by failure of manmade structures. Assessment of flooding due to geologic hazards is speculative. However, the flood hazard posed by failure of dams and reservoirs can be quantified. For use in the National Program for Inspection of Non-Federal Dams, a dam safety version of the HEC-1 program has been developed (U.S. Army Corps of Engineers, 1978). This program can be used to estimate the overtopping potential of a dam and also estimates the downstream flooding hazard resulting from an assumed structural failure of the dam. Input to this program is similar to the HEC-1 program. Inflow hydrographs for various recurrence interval storms are routed through the reservoir to determine which events would overtop the dam. For the evaluation of an assumed structural failure (breach) of the dam, a failure hydrograph is developed based on user-specified breach criteria and is routed downstream to desired locations.

3.1.2 Potential Climatic Change

Future climatic changes could adversely affect the long-term isolation of a repository site through alteration of the potential for surface flooding and the nature of groundwater flow systems. Presently, the most effective means to evaluate the potential for and affects of future climatic change is through investigation of a region's climatic and hydrologic history. Short-term changes in climates (up to a few thousand years) can be estimated from examination of historic rainfall and flood information, dendrochronology (tree-ring dating studies) and archeological data. Climatic changes occurring over the past 10,000-15,000 years can be implied through the study of glaciology, stratigraphy, palynology, pedology, isotope geology and hydrology, geomorphology, and geochemistry (USGS, 1978A). Due to the limited scope of this study, only the more widely used methodologies will be discussed.

Application of dendrochronology is dependent on the species of trees available and access to the site. A minimum of 10 trees with two cores per tree is usually needed to accurately assess the conditions of an area, however, this is extremely site dependent (personal communication, Elaine Kennedy, Laboratory for Tree-Ring Research). Typical costs would be $2,000 for collection, dating, and chronology development and an additional $2,000 for a climatic analysis. Costs are in 1981 dollars.

Palynology, the study of fossilized pollen, spores, and seeds, has been applied to provide insight into past climates (Leopold, 1967). Comparisons are made of present-day pollen in rainfall to the pollen types entrapped in dated sediments. Using these comparisons, a vegetative pattern is derived which is in turn related to climatic changes (Leopold, 1967). Application of this method can be initiated if sufficient fossilized materials exist. Pollen traps can be made from standard rain gages equipped with 10-micron mesh filters placed in the funnel (Leopold, 1967).

Two governmental agencies actively engaged in climatic research (past as well as future impacts) are the U.S. Geological Survey and the National Science Foundation. Both agencies support work or cooperate with universities and research institutions on climate-related studies. The U.S. Geological Survey is presently involved in short-term climatic variability projections (USGS, 1978B). This includes the task of estimating the probability of occurrence of rare climatic events and their effects on hydrologic conditions.

3.1.3 Recharge - Discharge Delineation

Recharge and discharge area mapping is useful for estimating the amounts of ground-water flow and the gradient in a flow system. It is primarily useful in evaluating flow in localized water table or confined aquifers. It is not as useful for large scale regional systems because the areas of recharge and discharge are likely to be larger in areal extent and more difficult to characterize. Generalized water-balance studies are more appropriate for these conditions.

Mapping can be done by field observation or by air photo interpretation. Field mapping may include observation and measurements of springs, seeps, changes in stream flow, phreatophyte and other evapotranspiration areas. Measurements of evapotranspiration can be made by using a lysimeter to measure the amount of water a plant takes from the soil, or by enclosing the plant and measuring the amount of water added to the surrounding air. Numerous methods are available to estimate evapotranspiration.

Air photo interpretation can be done on black and white, color, or color infrared photography. Color infrared generally provides the best data for hydrologic investigations. Heavily vegetated areas and open water generally are discernible on color infrared imagery. These can be discerned with more difficulty on color and black and white photography.

The reliability of these methods is very high. Human error in vegetation identification and human and instrument error in field measurements are possible sources of error. Air photo interpretation should be field checked before the data is accepted as valid. Cost and time involved in air photo interpretation is described in the chapter on remote sensing.

The cost of a ground survey may be approximated as the cost of a two-man crew, a vehicle, and surveying instruments. The base cost (in 1981 dollars) would be on the order of $500 per day for a crew, $50 per day for a field vehicle, and as little as $100 purchase price for a hand transit (Brunton) and measuring tape. The rental for more expensive optical or laser surveying instruments may range up to a few hundred dollars per day. Discharge measurements can be made by one person using a plywood V-notch wier or small portable flume in about an hour. The time and cost will be increased by using higher quality wiers, flumes or permanent measuring structures and recorders.

3.1.4 Surface Water Chemistry

Because surface water provides a potential link between ground water and people, it is necessary to examine the possibility of connection between surface water and the ground water from a potential repository site. The primary reason for investigating surface water quality is to search for constituents that indicate the discharge of ground water from the site. There are two possible approaches to this search.

In one approach there is some knowledge or reasonable hypothesis about the water quality constituents that can be expected in the ground water. This knowledge may be obtained from available data, or by samples from springs and existing wells. Once the constituents of the ground water are identified, the surface water is examined for the same constituents. If there are no actual data on the ground-water quality, the general geology of the site and of the region might support a hypothesis about the kind of constituents that should be anticipated in the ground water. The surface water is then examined for the anticipated constituents.

In the other approach, only the surface water quality is examined. For certain constituents the data can be plotted in the form of profiles showing concentration as a function of distance along the stream or of location in a lake. Sudden changes in the concentration without tributary surface water inflow would be indicative of the discharge of ground water into the surface water system.

The most important location for sampling the surface water is downstream of the potential repository site, or more specifically, in the vicinity where it is suspected that water leaving the site may be entering the surface water.

There is no predetermined frequency for sampling the surface water. In principle, the sampling should be scheduled to cover those times when the ratio of ground-water flow to surface water flow would be expected to change.

The selection of tests to be performed on surface water should be based on the constituents that are expected in the ground water and on surface water constituents that may react with those in the ground water (such as a reaction might cause a decrease in a constituent of the surface water). Most of the constituents of interest will be inorganic and many of the standard parameters of surface water quality will not be useful.

Table 1 indicates some of the tests that might be used. It is by no means exhaustive. All of the tests listed are described in Standard Methods (APHA, 1976) and the precisions shown in the table were taken from the same source. The cost per test in the table are prices advertised or quoted by 3 laboratories, 2 in Illinois and 1 in California (in 1981 dollars).

3.2 Existing Drill Hole Methods

TABLE 1. TESTS FOR SURFACE WATER QUALITY

Test[1]	Precision[2]	Cost Per Test[3] Source A	Source B	Source C
Temperature	0.1°C	-	-	-
pH	0.1 pH Unit	3.00	3.00	3.00
Specific Conductivity	1%	3.00	3.00	3.00
Total Dissolved Solids	13 mg/l	6.00	8.00	
Dissolved Oxygen	0.05 mg/l	7.00		8.00
Calcium	2%	10.00	10.00	10.00
Sodium	4%	10.00	10.00	10.00
Magnesium	5%	10.00	10.00	10.00
Potassium	3%	10.00	10.00	10.00
Iron	0.6%	10.00	10.00	
Manganese	6%	10.00	10.00	
Strontium	2 mg/l		10.00	
Aluminum	0.7%	10.00	10.00	
Lead	19%	10.00	10.00	
Barium	8.6%	10.00	10.00	
Copper	3.4%	10.00	10.00	
Selenium	<1%	18.00	17.00	
Mercury	2.4%	20.00	17.00	
Cadmium	13.3%	10.00	10.00	
Chromium	2.3%	10.00	10.00	
Silver	10.6%	10.00	10.00	
Arsenic	1%	20.00	17.00	
Dissolved Silica	4%	10.00	10.00	
Alkalinity	1 mg/l	5.00	6.00	6.00
Nitrate	7%	10.00	10.00	10.00
Sulfate	2%	12.00	10.00	10.00
Chloride	1.7%	6.00	6.00	6.00

(1) See _Standard Methods_ for Description
(2) From _Standard Methods_
(3) Price _Sources_:
A - Gulf Coast Laboratories, Inc., Park Forest, Illinois
B - Aqualab, Inc., Streamwood, Illinois
C - Montegomery Laboratories, Pasadena, California

3.2.1 Head Measurements

Measurement of hydraulic head within ground-water systems is necessary for evaluating direction of flow and can provide insight to volume of flow. Hydraulic head measurements are best made in drill holes specifically emplaced for such purpose where subsurface condition and well (or piezometer) design factors are known. However, useful head information can be obtained from existing drill holes if careful field procedures are followed. Consequently, methods are discussed here rather than in the subsequent section of this report on site study drill hole methods.

Measurements of hydraulic head in a formation can be divided into two types. Either the depth to water below the surface is measured, or the pressure (and therefore height of a column of water) is measured at a known elevation. Depth measurements are accomplished by lowering a probe into the borehole and directly measuring the depth to water. Pressure methods involve placing a sensor at a known depth connected to a reading device at the surface. The pressure methods have the advantage that the sensor can be sealed into a restricted zone and several piezometers can occupy a single borehole.

Water levels in a suitable repository site could be very deep. None of the methods for measuring head which are discussed are limited by depth, but special attention will be given to the problems caused by great depth to water. This information is from Garber and Koopman (1968) and personal experience.

A steel surveyors tape, marked in hundredths of a foot is the most basic method for measuring water levels in a borehole. For deep boreholes, corrections should be made for mechanical and thermal strain. Coefficients of strain can be determined experimentally, obtained from the manufacturer, or computed from known material properties. A tape should be periodically recalibrated to assure that no plastic (permanent) deformation has taken place. Tapes can usually be read to within 0.01 foot. Reliability is very high. Possible sources of error are poor calibration, errors in predicting thermal and mechanical strain, and human error in reading the tape and making strain corrections.

Electric probes using resistance measuring devices or float activated switches are commonly used to measure water levels. With a resistance device the probe consists of two conductors with a gap between them. Each conductor is attached to one wire of a two-wire cable which leads to the surface where it is attached to a resistance or voltage measuring circuit. With a float switch, the sensitivity can be adjusted to measure any interface in the fluid column in a borehole. For example, the interface between drilling foam and water, or between diesel fuel or oil and water can be found by varying the density of the float in the switch. The depth is found by measuring the length of wire lowered into the hole. Some commercially available probes are marked at various intervals. Soiltest markets a probe with bands on the wire at 5 foot intervals. These bands have a tendency to slip on the wire, rendering data inaccurate. Another maker uses a white TV antennae lead wire, with lengths printed on the wire graduated by centimeters. A third method of measuring length of wire is by causing the wire to run over a wheel before entering the borehole and counting the number of turns of the wheel. If this can be done without the wheel slipping, the depth to water will be the circumference of the wheel multiplied by the number of revolutions.

All of these methods are subject to thermal and mechanical strain of the wire, wear of the wheel causing the circumference to change, or slip of length markers on wire. Due to insensitivity of switches and electrodes, the electric methods only have a resolution of about 0.1 foot.

An air line is a method for measuring the pressure at a known point and therefore the height of the column of water above that point. It consists of a gas supply and pressure gage on the surface, and a tube running from the gas supply to a point below the water level in the borehole. Gas is forced through the line at a rate low enough to minimize head loss in the line. The pressure required to maintain flow of the gas is considered to be the same as the pressure at the outlet. The elevation of the water level in the borehole is then the pressure in pounds per square inch (psi) times 2.31 feet per psi plus the elevation of the outlet of the gas line. This conversion is based on the density of pure water at $68^{\circ}F$ ($20^{\circ}C$). Differences in fluid density should be accounted for by changing the conversion factor. For very long or thin tubes, losses due to friction should also be accounted for. Possible sources of error are high head losses in the tube, fluid density changes, error in determining elevation of gas outlet, and instrument error in determining pressure. The best pressure gages can be read only to about 0.1 psi and therefore have a resolution of about 0.23 feet.

The costs of all of the methods mentioned so far, including steel tape, electric methods, and a gas line, will range from $50 to a few hundred dollars (1981 dollars). A motorized reel for a wire or tape can be purchased commercially or can be constructed for a few hundred dollars. The installation of a gas line would take a few hours for a technician and a laborer to install. Time needed to make a measurement would be a few minutes for shallow sites to an hour or more for boreholes with very deep water levels.

Electric transducers have recently been gaining in popularity. These use either a strain gage or potentiometer to change a pressure input into an electric signal. The electric signal can then be reconditioned and recorded either by an analog or digital recorder. This method has the advantage that several of the transducers can be placed in single borehole and sealed in different zones with cables leading to the surface. Strain gage transducers have an accuracy of up to 0.15% of full scale and have a resolution that is limited only by the resolution of the electric signal reading equipment, which is nearly infinitesimal. Potentiometer transducers have an accuracy of about 1% of full scale and a resolution limited by the type. Wire coil potentiometers have stepwise response as the slides move from one wind to the next. Composition carbon potentiometers have an infinitesimal resolution.

Possible sources of error are in determining the elevation of the transducer, variations in fluid density, temperature effects on the electronic circuits, and errors in calibration of the transducer.

A wide variety of read-out instruments and recorders are available for these transducers, ranging in cost from a few tens of dollars for a voltmeter to over $8,500 for a multichannel digital recorder. The cost of transducers may be as low as a few dollars. Quality transducers such as those sold by Sinco cost several hundred dollars each. Cable costs an additional $0.75 per foot. All costs are in 1981 dollars. Time to install the system may range from several hours to a few days for large and deep systems. Reading time is instantaneous to a few minutes.

3.3 Study Site Drill Hole Methods

3.3.1 Numerical Modeling

Numerical models are methods of solving differential equations by replacing a continuous media with a discretized domain in which parameters such as transmissivity and storage coefficient are modeled as constant across the discrete element. The numerical solutions in common use are the finite element method and finite difference method. Both methods have been applied to a variety of ground-water flow problems and the methods and several computer codes for solving them are well accepted tools for solving ground-water flow problems (Lawrence Berkeley Laboratory, 1979).

Modeling has two applications to information needs: by solving the so-called inverse problem, system parameters can be determined if boundary and initial conditions and the current state of the system are known, and when calibrated, the model can be used to predict response to changed conditions.

The inverse problem solution generally consists of a trial and error substitution of transmissivity values and storage coefficient values (for transient problems) until the model recapitulates known head distribution. The values of transmissivity and storage coefficient are then assumed to be close to actual field conditions. The problem associated with this approach is that there are many sets of input parameters that can combine to produce outputs similar to field conditions. Further, boundary conditions and history of the system are generally not well known. The less exactly these are known, the more flexibility there will be in the transmissivities and storage coefficients which can yield outputs which match field conditions.

When used as a forecasting tool, a model of a ground-water system is created either using data obtained from field tests or by solving the inverse problem during calibration. Forecasting can be used to estimate transit time for water flowing through the repository to the biosphere, and the modification to ground-water flow which could be caused by climatic change, excavation of the repository, or by catastrophic events such as flooding, tectonic uplift or subsidence, and deep erosion. The application to information needs is in predicting flow paths and velocities based on varying assumptions about boundary conditions and flow system properties.

Numerical solutions currently exist for both continuous and fractured media. The theory and procedures for numerical simulation of flow in fractured media are not as well defined as for porous media, however, significant research in this subject area has been conducted. Representative discussions are those by Barenblatt, et al (1960), Duguid and Lee (1977), Gale (1977), and Streltsova-Adams (1978). If in fractured media the fracture spacing is small compared to the cell or element size in the model, a continuous model can be applied. If there are a limited number of large joints or faults within the model boundaries, then a hybrid model, combining both continuous and fracture media flow, should be used.

The resolution of numerical methods depends on the size of the cells or elements used in the model. As this size approaches zero, the numerical solution approaches the analytic solution. The cost of computation increases with the number of equations to be solved, so a compromise is called for.

Reliability is based on the amount and precision of information available on head distribution, media characteristics such as transmissivity and storage coefficient, and boundary conditions such as recharge and discharge. Therefore, without drilling and testing, the reliability may be quite low. Reliability of fracture flow models is generally less than that for continuous porous media models.

All costs for numerical modeling are in 1981 dollars. The cost of applying a simple model where no calibration is required may be as low as a few hundred dollars. The cost will increase with the number of cells or elements, and therefore the number of equations which must be solved. If calibration is required to obtain input parameters, the cost will increase dramatically. The cost for a simple model could be a few thousand dollars and would increase with the complexity of the model. The costs involved in obtaining field data are discussed in other sections.

The time required is about one day if calibration is not required and about two weeks if it is. Computer turn-around time will be a major factor as will the method of editing files and reading data. For example, interactive CRT terminals with good editing features will be much faster than card readers. Turn-around time may be several hours on heavily used systems, depending on user priority.

3.3.2 Aquifer or Borehole Tests

Subsurface hydrologic tests are designed to measure hydrogeologic properties of the geologic media such as transmissivity, storage coefficient, anisotropy, inhomogeneity (i.e. the presence of barriers or other changes in transmissivity), and the presence of sources or sinks. The vast majority of theoretical study is based on the assumption that the medium is porous. Description of standard testing procedures can be found in Walton (1970), Kruseman and Ridder (1979), Lohman (1972), Stallman (1971), and many other sources. Theoretical development of test procedures in fractured media is less well defined. This is largely a result of economics as more water and oil and gas development has taken place in porous than in fractured media, and thus the need for research has been greater. Descriptions of test methods for fractured media can be found in Snow (1968), Miani, et al (1972), and Gringarten and Witherspoon (1972).

The methods used in the two types of media are more alike than different. The difference is that porous media are likely to be isotropic in either two or three dimensions, whereas fractured media are generally not isotropic. Care must be taken in placing piezometers in fractured media so that the pressure measured is the one desired. It is possible for flow paths to be similar or unconnected and for pressure to vary from one fracture to the next.

All tests have in common a stress to the system at a point and the measurement of the propagation of the stress through the system with time or distance or the dissipation of the stress at the point of application. In the most common test, the constant discharge test, a well is pumped at a constant rate and drawdown and recovery of the water level is observed in the test well and possibly in other observation wells. Transmissivity can be determined from the rate of drawdown or recovery; storage coefficient can be determined from the delay in drawdown. Inhomogeneity can be determined from irregularities in the drawdown rate and anisotropy can be determined from differences in drawdown rates at different observation wells in different directions from the pumping well.

A constant head test is similar with the exception that a constant head is maintained in the pumping well and changes in discharge are measured in the pumping well while changes in drawdown are measured in the observation wells. Both of these tests can be performed with discharging or injection wells. Both can be performed with single or straddle packers to isolate zones of interest. Isolation will be especially important in fractured media where the testing of individual fractures or fracture zones may be desired.

Falling head tests require no pump. Either gravity or the pressure of the subject subsurface zone is relied on to do the work. A slug test or slug injection test is a special case in which a known volume of water is "instantaneously" (quickly) added to the well or a solid of known volume is used to displace water in the well. The reverse of this test, in which a known volume of water is "instantaneously" removed from the well, is called a borehole test or rising head test. A falling head test performed after water is injected into a well long enough to reach equilibrium (constant injection rate to keep borehole at constant level) is analyzed in the same way as a constant discharge test. If the system is not in equilibrium, the analysis will be similar to the recovery portion of a constant discharge test. Numerical solutions have been devised for tests in which neither head nor discharge are held constant. Pumping or discharge tests are most appropriate in permeable media from which significant volumes of water can be produced. Injection tests are most appropriate in fractured and unfractured low permeability media. Where properties of individual fractures may be of interest, such as in granite and basalt, straddle-packer injection testing procedures should be employed.

3.3.2.1 <u>Well Size and Spacing</u>

Wells should be large enough to accommodate screens, pumps, and instrumentation necessary for the tests being performed. Generally, materials being tested will have low conductivity and only a small amount of water will be produced or injected. For materials of low conductivity, injection is generally the preferred method of testing. In the case of injection, pumps, motors and instruments are located on the surface. Fluid flux is generally very low and can be handled adequately with 1/4" tubing. The only equipment in the hole would be packers, tubes to inflate the packers, and the tube carrying the injection fluid. For this type of test, NX holes are adequate. For discharge type tests, larger hole sizes are required. For very conductive materials with discharges on the order of 1,000 gpm or more, and where screen must be installed, holes of ten-inch diameter or more may be required.

Two considerations are important when determining the number of wells. First, the degree of anisotropy will govern the number and placement of piezometers and, second, the degree of inhomogeneity will govern the number and spacing of test wells to be used. The spacing of piezometers is based on the expected response of pore pressure in time and space to changes of pressure in the test well. Transient hydraulic theory based on realistic assumptions should be used to predict where a measurable pressure change will occur within an acceptable time period. Distances may be from a few feet to a few hundred feet.

The spacing of test wells is based on the degree of inhomogeneity of the media being tested. In fractured media the hydraulic characteristics may vary significantly from one fracture to the next. A program to characterize a repository site should be designed to determine the distribution of transmissivity in the fractured media. The program design should therefore allow for testing a large enough sample of fractures to be statistically valid. Spacing will be dependent on degree of fracturing and the extent of interconnection.

In essentially unfractured media such as shale or salt, the spacing of test wells can be greater because of the homogeneity of the deposits. In addition, it is desirable to penetrate such low permeability media in as few locations as feasible to obtain necessary information.

3.3.2.2 Other Considerations for Specific Media

Salt, both dome and bedded, is highly soluble. Any injection test operations in salt should use natural formation water (or a comparable solution) at the temperature of the formation or at the temperature expected in a repository in order to achieve reliable results.

Shales and certain clays, such as montmorillonite, tend to swell and change the geometry of their structure with the addition of water molecules. These types of materials should also be tested using only natural formation water or its chemical equivalent as water chemistry may influence the response to wetting.

3.3.2.3 Resolution and Costs

Resolution is affected by a number of factors including well construction, knowledge of geology, control of pumps and valves, and measurement of head. Well and screen design and construction influence the effective radius and entry loss of the well due to such factors as caving during drilling, mud invasion of the media, gravel filter placement, and degree of well development.

Knowledge of geology is necessary to evaluate the presence of leaky confining units, partially penetrating conditions, boundaries, and presence of fracture or porous conditions. It can be difficult to discriminate between a leaky confining layer and a recharging source, for example, based soley on test data. A knowledge of stratigraphy and structure can aid in resolving these types of problems. Inaccurate control of discharge in constant discharge tests or head in constant head tests can have serious effects on the accuracy of parameter determinations.

The effects of fluctuations in the nominally constant parameters are more dramatic if they occur early in a test. Typical resolution is one or two significant figures for constant discharge tests. The others are less accurate because the theoretical assumptions (instantaneous change in head, fully cylindrical radial or spherically radial flow) can never be achieved. These tests provide order-of-magnitude resolution at best. All of the tests are reproducable. That is, the same test at the same borehole at a different time is likely to yield very similar results.

Cost of a constant discharge test may be as low as $200 per day for a test with a pre-existing well, a pump in place, and one technician to monitor the test. A constant discharge test should be conducted for a long enough period of time for suspected boundaries to be detected and for delayed gravity drainage in phreatic aquifers. If a pump is needed for a pre-existing well the cost would be increased. A small submersible pump costs a few hundred dollars to purchase. Larger pumps cost many thousands of dollars. A power source, either a drop from a utility line, or a generator should be provided. A generator may cost on the order of $100 per day rental but varies depending on size. Monitoring and data recording equipment would be required. Equipment ranges from a simple steel tape with chalk for about $50 to automatic digital recorders and electric transducer piezometers for over $10,000. All costs presented herein are in 1981 dollars.

Time required varies with the amount and quality of information desired. A slug injection test can be completed in one hour, while a constant discharge test may be conducted for 30 days or more to detect distant boundaries.

In very tight media, pumps for injection tests can be quite small, and often are not used at all. High pressure bottled gas, such as nitrogen, can be used as the driving mechanism. The reason for the use of small pumps is that it is not desirable to use pressures much in excess of natural equilibrium formation pressures. If high injection pressures are used there is the possibility of expanding or creating fractures, and altering the parameters being measured. Cost is therefore from less than $100 to several thousand dollars depending on whether gas or a pump and what type of pump is used.

Cost of packers is based on the size and design of the packers. Simple inflatable packers for small holes, such as NX size, which are not subjected to any adverse conditions can be manufactured or purchased for as little as one to two hundred dollars. Larger, more rugged, or more versatile packers cost more, ranging upwards to many thousands of dollars.

Costs of extra length testing periods is based on labor, rental, and subsistence. Most pumping or injection tests can be performed by one geologist or engineer and one technician. If heavy items, such as pumps, packers, and instrumentation are to be moved in a borehole, a hoist and operator may be required.

Costs are the sum of labor and subsistence, the rental of equipment, and the amortization cost of owned equipment.

3.3.3 Tracer Tests

A ground-water tracer is any matter or energy which can be introduced to and carried by water in a flow system. They are used in determining flow path and velocity, hydraulic conductivity, porosity, and dispersivity. A tracer can be natural, such as the thermal plume downgradient from a geothermal heat source. It can be introduced accidentally such as from a chemical spill or from the atmospheric testing of nuclear weapons. Or, they can be deliberately injected for the purpose of studying a flow system. Conservative tracers are those which pass through the medium unchanged by chemical reaction, decay, or adsorption.

An ideal tracer is one which is non-toxic, inexpensive, miscible with and moves with ground water, easy to detect in trace amounts, has a low natural background, does not affect the natural flow of water, and is chemically stable for long periods of time. For most purposes it is desirable that the tracer not be filtered nor sorbed by the medium being studied. However, studies of filtration and sorbtion can be conducted with tracers with know behavior relative to the phenomenon being studied.

Water temperature can be used as a tracer because water has a high specific heat capacity relative to many other materials. Temperature anomalies have been traced up to five miles from the source at the Hanford Reservation in Washington (Davis, et al, 1980). Large changes in temperature can cause a density gradient which can alter the direction of flow. For this reason, small temperature differences and accurate measurements of temperature should be used.

Solid particles can be used where pore or fracture openings are large enough to allow passage. Tracer tests using numbered pieces of paper, bacteria, yeast, virus, and dyed clubmoss have been successfully conducted. Clubmoss spores are about 30 um in diameter and will therefore pass through most permeable materials. They require special dyes for coloration, plankton nets for collection, and a microscope for identification. Neither bacteria nor virus can travel large distances in ground water. Bacteria are large enough to be filtered and virus, although smaller, have unbalanced electric charges and are attracted by surface charges on solid particles. Yeast is similar in migration characteristics to bacteria and has the advantage of easy detection and negligible health hazard. Particles such as these are not affected by molecular diffusion and are used where information on this mechanism is not desired.

Ionized inorganic substances such as bromide, iodide, and chloride have been used with some success. They can be detected by observing electrical conductivity changes or through chemical analysis. Chloride is present at relatively high concentrations in natural water. The appearance of a small additional amount from a tracer test is difficult to verify. Iodide has poorly defined sorption characterisitics and is therefore not generally used. Bromide and thiocyanate (SCN) are commonly used. Both are inexpensive, easily detectable in concentrations of 50 ppb, and have slight to moderate sorption.

Organic ions are useful because many of them have no natural background and are detectable in concentrations as low as 100 ppt using high performance liquid chromatography (HPLC). They are generally not sorbed on silicate minerals and are chemically stable. A major drawback is their expense.

Fluorocarbons, uncharged fluorinated organic molecules, are also used. They are highly detectable (to 1.0 ppt using HPLC) nontoxic and nondegradable. Some of them do show moderate sorbtion.

Fluorescent dyes such as fluoroscein, rhodamine WT, rhodamine B, sulphorhodamine B, lissamine, and photine have been used for decades. Fluoroscein has seen use for nearly a century. All can be detected with a spectrofluorometer or less expensively and less sensitively with a filter fluorometer such as the Turner III or the Bowman fluoro/colorimeter. Detection at a concentration of 100 ppt is possible. Visual detection at concentrations in the low parts per million range is possible.

Most of these dyes have strong sorption properties and are generally not used in porous media other than gravel. Their best application is to surface flow and fractured media with relatively large openings or to porous media with short travel distances between injection and detection. Radioactive tracers are no longer used in field tests except in tracing non-potable water which is isolated from potable sources. They are also used in laboratory tests and for short term tests in tracing the movement of water within a well. Present concern about health hazards and the difficulty of detection limit the usefulness of these tracers.

The resolution of tracer tests is generally $\pm 5\%$ regarding concentration and therefore less than $\pm 5\%$ in determining aquifer parameters. Reliability is high in determination of flow path and velocity but lower in determining hydraulic conductivity, storage coefficient, and dispersivity.

Costs (in 1981 dollars) for tracers and their detection range from a few dollars for dyes where visual detection is appropriate to several hundred dollars for chemicals with more complex detection procedures. Injection of the tracer and obtaining a sample at a point downgradient is often the most costly part of a tracer program, especially if this involves pumping.

Time required is effectively determined by the travel time of the ground-water tracer from the injection point to the sampling point.

3.3.4 Core Tests

Permeability tests of drill hole core samples can be done in a laboratory, with a falling head or constant head permeameter, or indirectly using the relationship between grain size, fracture or pore size, and permeability, or the relation between consolidation and permeability.

A permeameter is an apparatus that can measure the head loss and volume of water flowing through a sample. As the name implies, a constant head permeameter is designed to maintain a constant head loss across the length of the sample. The conductivity can then be found directly from Darcy's Law. A falling head, or variable head permeameter usually consists of a standpipe above the sample. The standpipe drains as water flows through the sample, changing the head and therefore the gradient. Hydraulic conductivity can be computed from the equation:

$$K = aL/A(t_1 - t_0) \ln h_0/h_1$$

where

a = cross-sectional area of standpipe

L = length of sample parallel to flow

A = area of sample orthogonal to flow

t_0, t_1 = times at which heads are h_0 and h_1

h_0, h_1 = starting and final heads

The permeant (fluid being used to measure conductivity) should be actual formation water if possible. Other fluids may have different chemical and physical characteristics which could render the test results meaningless.

Conductivity may be determined indirectly using the relationship between pore size, grain size, and fracture aperture to conductivity. Capillary tube and parallel plate models have been used to explain flow phenomena (Cory, 1969). Cory has shown theoretically that for flow between flat, parallel plates, the flow is governed by the relationship:

$$u = i\rho g\ b^2/12\mu$$

where

ρ = fluid density

b = plate aperture

i = potential gradient

μ = fluid viscosity

u = fluid velocity

g = acceleration due to gravity

An equivalent conductivity for a single fracture is therefore (from Darcy's Law):

$$K = b^2 \rho g/12\mu$$

For a rock mass, the conductivity would then be the above relationship multiplied by the proportion of a section of rock covered by the fracture opening, summed for all fractures. Cory also developed a relationship for capillary tubes. This is:

$$u = r^2 \rho g\ i/8\mu$$

where r is the radius of the tube.

The conductivity of a single tube is therefore (from Darcy's Law):

$$K = r^2 \rho g/8\mu$$

The conductivity for a rock mass is then the above value multiplied by the proportion of a section of rock consisting of capillary tubes, summed for all tubes. For a porous medium the sum of this proportion would be the effective porosity and the radius would be the pore size for uniform media.

Conductivity is computed as part of standard triaxial soil testing. There are several other terms besides permeability which enter into the rate of consolidation. These other terms cannot be determined with precision. The use of consolidation tests to determine permeability is therefore of very low reliability.

The resolution of permeameter tests depends on the quality of head flow measuring devices. Due to low flow rates in most rocks suitable for a repository, a flow meter would not be used. Likely method for flow measurement would be using a stopwatch to time a measured volume of fluid collected at the downstream end of the apparatus. Volume measurements to a resolution of ± one milliliter are easily obtainable using a one liter volumetric flask. Time measurements can easily be made to the nearest 0.1 second using an ordinary stopwatch. The head loss can be measured to within a millimeter using a water manometer. Resolutions much higher than are justified in extrapolating to field conditions are therefore possible.

Resolution in measuring fracture aperture and pore sizes is also very high. Microscopy can be used to measure the size of fractures or pores, and sieve and hydrometer analysis can be used to measure the grain size of granular materials. In effect, the resolution is greater than is justified by field data because the samples collected may not be representative. A core sample consists of a minute proportion of the repository volume.

Reliability of lab tests is commonly low because samples cannot be delivered to a lab in an undisturbed state. Fracture apertures are likely to be larger than _in situ_, and void ratio is likely to increase. Parallel plate and capillary tube models do not account for irregularities in geometry, further reducing reliability.

The major cost will be incurred for obtaining the samples to be tested. This will generally require core drilling which may cost in excess of $100 per foot (in 1981 dollars) depending on rock type, depth, and hole diameter. Drilling time for obtaining samples would be much greater than the time required to do the testing. Drilling could be at a rate of a few feet per hour or less. The tests themselves can be conducted in a few hours to a few days.

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APPENDIX G-2

HYDROLOGIC TECHNIQUES

FOR SITE CHARACTERIZTION

BY

Ertec Western, Inc.

Long Beach, California

G-2

November 1, 1981

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HYDROLOGIC TECHNIQUES FOR SITE CHARACTERIZATION

1.0 BACKGROUND AND SCOPE

The siting of nuclear waste repositories in geologic media will be a tiered process involving broad scale or precharacterization studies and site specific or characterization studies. Based upon the results of the regional precharacterization studies, specific areas with appropriate geologic and hydrologic conditions will be identified as potential nuclear waste repositories. These areas are then investigated in detail in the site characterization phase to fully evaluate their suitability for safe long-term storage of nuclear waste.

The types of geologic media presently being considered for waste repository siting include domed and bedded salt, granite, tuff, shale, and basalt. These materials present a great diversity in geologic and hydrologic characteristics and behavior. This diversity precludes the design and application of a single set of geologic and hydrologic field testing, data gathering, and evaluation techniques. While many field techniques may be applicable to all media or conditions, others may be highly site or media dependent.

During both precharacterization and site characterization studies, one of the most important elements in evaluating the potential of a site as a nuclear waste repository is a thorough understanding of hydrologic conditions. The key hydrologic features are both regional and local in nature and are:

1. The potential flood hazard in and adjacent to the repository site, especially at the projected location of access shafts.

2. The interrelationship between surface-water and ground-water systems.

3. The existing or natural surface-water and ground-water chemistry.

4. The vertical and areal extent and hydraulic characteristics of shallow local aquifers near or within the site and of regional ground-water flow systems which encompass the siting area.

5. The areal distribution and amounts of ground-water recharge and discharge to local and regional ground-water systems.

6. The potential impacts of future changes in the hydrologic regime such as long-term climatic fluctuations or increased ground-water development in local or regional ground-water systems.

7. The mode of occurrence, amount, and rate of ground-water movement in the storage media at the projected repository depth.

8. The age and residence time of ground water within the storage media at the projected repository depth.

The purpose of this report is to describe hydrologic data collection and evaluation techniques applicable to a site characterization study in any of the potential geologic media. It is anticipated that information adequate to define items 1-6 above will be compiled during precharacterization studies. Therefore, techniques discussed herein will apply primarily to items 7 & 8. Some of the techniques described are the same as these employed in precharacterization studies. They are, however, employed in a more limited area and for a more specific purpose. Additional techniques appropriate for evaluating the hydrologic characteristics of the anticipated repository site and zone (the specific geologic media at depth) are described which were not considered in precharacterization studies because of the difference in level of detail. It should also be noted that a significant portion of item 8 relates to age dating of ground water. This subject is addressed in the appendix for geochemical methods.

The most appropriate methods of data collection and evaluation to address the key hydrologic issues of a site characterization study are described below. The discussion is divided into two sections: 1) Surface Water; and 2) Ground Water. As indicated previously, the major emphasis is evaluation of the ground-water system and/or behavior in the projected repository zone at depth.

2.0 SURFACE WATER

Basic data collection and computer simulations to evaluate the frequency and magnitude of flood events and the areal extent of inundation along streams and drainage channels within a selected site would be conducted during precharacterization studies. During site characterization, this previous work should be reevaluated to determine if it is of sufficient detail to adequately define the flooding hazard at the proposed location of the access shaft(s) and surface facilities which would need to be constructed for an operational repository. If the existing runoff and flood flow analyses are deemed inadequate, further work should be conducted for the specific stream channels which may impact the site. This additional work would likely involve channel surveys, detailed topographic mapping and runoff and flood flow simulation with the expanded data base. A description of the field techniques and simulation models required and their respective costs and reliability was provided in the report on techniques for precharacterization studies (Appendix G-1).

3.0 GROUND WATER

It is assumed that precharacterization ground-water studies will have adequately defined all local and regional aquifers and/or flow systems, the hydrogeologic properties of shallow aquifers, and the extent and type of interconnection between the various components of the ground-water system within and in the vicinity of the repository site. Because of scale, the precharacterization studies will not have defined, in any detail, the hydrogeologic properties of the actual repository zone. Consequently, the main objective of the program at this phase is characterization of the hydrogeology at potential repository depths and in specific geologic media.

Hydrogeologic techniques described in this section are appropriate for evaluating the occurrence and mode and rates of movement of ground water within a repository zone. This information can then be used to evaluate the potential for ground-water transport of radioactive contaminants away from the repository and their eventual fate within the hydrologic system.

A major constraint on hydrogeologic testing during the characterization phase will be the number of boreholes available. Because it would be disadvantageous to artificially reduce the integrity of the repository zone, only a limited number of boreholes will be drilled. Consequently, hydrogeologic testing will be conducted in boreholes drilled for geologic, geomechanical, or geochemical testing as well as in those which may be drilled specifically for hydrogeologic purposes.

3.1 Coring and Core Testing

Most if not all boreholes drilled into the repository zone will be cored and core samples will be available for hydrogeologic evaluation. Laboratory examination and testing of core samples will provide information on lithology, porosity and permeability or hydraulic conductivity of the bulk rock material, and, in the case of fractured or bedded media, an indication of the type, orientation, and density of fractures or bedding planes if the core samples retain integrity. The major disadvantage of coring is that it provides discrete samples which may not be indicative of the rock mass as a whole.

Specific methods for coring and core testing and their reliability and cost are described in detail in a separate appendix. The results which can be obtained from such testing have been described here as they provide a good initial estimate of subsurface conditions and can be useful in planning subsequent testing.

3.2 Geophysical Logging

As with coring and core testing methods, descriptions, applicability, and results of various geophysical logging techniques are described in a separate appendix. Specific geophysical logging techniques with hydrogeologic aplications and the types of results which can be obtained are briefly outlined in the following paragraph.

A full suite of geophysical logs should be run in each borehole pentrating the respository zone. The logs with greatest application to ground-water characterization studies are: 1) electric (spontaneous potential and resistivity); 2) natural gamma; 3) induced induction (conductivity); 4) neutron; 5) bulk density; 6) caliper; and 7) acoustic velocity. The types of hydrogeologic information which can be obtained from the suite of logs listed includes lithology, porosity and permeability, and the location of fractures, major bedding planes, and water bearing zones.

While not a geophysical logging technique, downhole T.V. cameras have application as a means of evaluating gross fracture conditions in appropriate media.

Geophysical logging is conducted within the actual repository zone and as such results may be more representative of actual subsurface conditions than those obtained from testing of core samples. However, the precision of numerical results obtained from geophysical logging is less than those obtained from core testing.

3.3 Discharge and Injection Testing

Because one of the major criteria for repository siting is that the repository zone be in low permeability material, it is not envisioned that open well discharge or pump tests will be applicable to any significant extent. The exception would be if shallow aquifers overly the repository zone and require further testing during the charactrization study. These type of tests have been described in the precharaterization hydrologic techniques report.

Open borehole injection testing or injection testing with packers is most appropriate for characterization studies. Injection testing, both constant head and slug, involve input of fluid or gas to the borehole and monitoring of the rate of uptake or decline of induced head. Packers may be installed to restrict the zone of testing. Other equipment involved includes a pump or source of fluid or gas for continuous or slug injection and electronic or pressure transducer equipment to monitor head response.

Injection tests will provide reliable information on transmissivity, hydraulic conductivity, and fracture continuity of the media tested. In fractured or brittle media, only low pressure injection should be used; otherwise additional fracturing of the media may occur. In media subject to dissolution, only gases or formation fluid (or its man-made equivalent) should be used to prevent alteration of the repository zone.

The duration of injection tests in low permeability media could range from 5 to 15 or more days. The cost of injection tests may range from a few to several tens of thousands of dollars. The major cost items are pumping equipment, labor, and equipment to measure head at significant depths. Cost of pumps may range from a few hundred dollars total for a low capacity unit to upwards of $100/hour for a high capacity pumping unit (use of such a unit would be the exception in the type of testing being envisioned for characterization studies). Water level or head measurement devices are single cost items and would not be charged to an individual test. Electronic water level indicators cost several hundred dollars to purchase. More sophisticated pressure transducer units which could be used for either liquid or gas injection in a deep well environment would cost from $10,000 to $15,000 to purchase.

3.4 Straddle-Packer Testing

Straddle-packer tests are a specific type of discharge (pump) or injection borehole test in which two packers are used to isolate a particular zone in the borehole and evaluate hydraulic conductivity and head. In fractured media, individual fractures can be isolated and tested by this procedure as well as interconnection between fractures. In unfractured media the hydraulic conductivity of selected zones can be determined.

Dual straddle-packer test equipment (two packers at the top and bottom of the interval) has recently been developed. This test mode should provide improved results over standard straddle-packer units because of reduced fluid or pressure leakage from the test interval.

To conduct straddle-packer tests, pressure transducers should be used to monitor heads below, within, and above the straddled interval. Response of these heads to pumping and subsequent recovery or to low to moderate pressure injection of liquid or gas is used to determine the hydraulic conductivity. The same media-specific constraints as in open well injection testing apply as regards injection pressure and materials. Because of the general low permeability of the media being tested it is assumed that most straddle-packer tests will be long term - low capacity rather than short term - high capacity.

The cost of straddle-packer tests at the depths being considered will generally range from $10,000 to $25,000 per interval tested. This is a reflection of the complexity and duration of the tests. Hydraulic conductivity values derived from such tests are generally reliable but do apply to only the restricted zone tested. The cost to conduct a dual straddle-packer test of approximately 5-day duration would be about $50,000 per interval tested. For each borehole where such tests were conducted, mobilization, set-up and tear-down costs would be an additional $20,000 to $40,000.

3.5 Tracer Testing

Ground-water tracer tests have been widely used in recent years for evaluating aquifer characteristics *in situ*. For ground-water characterization studies, tracer injection tests can be used to define directions and rates of flow of ground water and thereby potential leakage from a repository zone. In saturated media, the numerous available tracers discussed in the precharacterization studies report are applicable. For unsaturated media, the use of gas injection, usually nitrogen, provides reliable results. Tracer injection tests can be conducted in open boreholes but more commonly packers would be used to isolate zones or fractures of interest. As with other types of injection testing, pressures should be maintained at a low level to avoid additional fracturing of the media. Gas tracers would be most applicable to media subject to dissolution. Nearby observation wells are desirable for tracer tests and if possible may be pumped to reduce the time of testing. The distance to observation wells will impact the length of time required to conduct the test and thus is a cost consideration. Single borehole tracer tests can be employed to evaluate vertical movement in the repository zone but are much more complex and produce less reliable results than twin borehole tests.

Tracer tests can be expensive, time consuming, and will usually only be conducted within the repository media. Reliable results can be obtained and the analysis of data from these tests can provide perhaps the best assessment of contaminant transport through a repository media. Deep well injection tracer tests can cost upwards of $25,000 per interval tested. Duration of tests is variable. In addition to these costs, observation wells may be required for use as tracer detection points.

Special techniques have been developed for the analysis of tracer tests which provide for the evaluation of flow rates and path, dispersivity, and the homogenity of the repository media. These parameters are used in the modeling of both ground-water flow and contaminant transport.

3.6 Flow System and Contaminant Transport Modeling

The numerical modeling of ground-water flow provides both an interpretive and predictive tool for the characterization study. Data from both precharacterization and site characterization tests and studies will supply necessary input parameters for the modeling of the ground-water flow system. A variety of models and modeling approaches exist. The model selected for a particular application should be suited to conditions present and the model should be well documented. If possible, for most repository sites a three dimensional model should be applied which can take into account recharge and discharge and both horizontal and vertical movement of ground water. The general low hydraulic conductivity and ground-water flow rates anticipated in reposiitory zones will not preclude reliable modeling results but will increase costs due to the necessity for long term model runs. The types of media will impact modeling and the reliability of results. In unfractured media such as domed and bedded salt, tuff, and perhaps shale, tests conducted will provide a good indication of bulk hydrogeologic properties of the rock mass. If there is not a high level of variability of hydrogeologic properties, there will be a relatively high level of confidence in modeling results. In fractured, media, such as granite and perhaps basalt, it is unrealistic to assume that sufficient data could be collected to define the hydraulic characteristics of all fractures involved. When such media are modeled, two approaches are possible: 1) treat the system as discrete fractures; or 2) assume homogeneity and average out test results over the rock mass involved. For the first approach there is insufficent data and the latter involves a simplifying assumption and retreat from reality. Consequently, the results of modeling in fractured media will be viewed with a lower level of confidence.

The overall reliability and resolution of ground-water flow models is dependent upon the reliability and resolution of the input data. In most cases, sensitivity tests should be performed to determine the significance of each input parameter. The most significant parameters can then be used to model a range of conditions and to develop a range of results. Further sensitivity and statistical analyses can then be performed, if warranted, to derive the most probable result. For repository modeling, however, the reliability and spatial distribution of data collected will usually be such that a very small range of conditions exists and further sensitivity analyses are not required.

The costs of ground-water modeling are quite variable and depend upon the machine used, the size of the area to be modeled, and the number of discrete zones which must be considered. At two-dimensional ground-water flow model in unfractured media will generally cost about $20,000 ($7,000 for data processing and $13,000 for labor). A three-dimensional model will usually cost about $30,000 ($15,000 for data processing and $15,000 for labor). Modeling costs in fractured media may be two to three times the above values because of the additional time required to evaluate the larger and more complex data base derived from hydrologic tests and the greater degree of complexity in the modeling approach.

By coupling a contaminant transport model with the ground-water flow system model it is possible to generate a detailed repository model which can be used to simulate leakage from the repository. When calibrated, the coupled repository model can be used to predict the impact of changes in repository conditions such as long term climatic changes, or increased ground-water development near the repository. The repository model can provide an excellent tool for evaluating repository performance.

A number of transport models are available. The model selected must be compatible with the ground-water flow model. The transport model, as a minimum, should be able to take into account contaminant dispersivity, ion attenuation and absorption, isotope decay rates (and daughter decay rates), and thermal effects.

Description of existing transport models, necessary input data, their reliability and cost factors are provided in the appendix on geochemical methods.

APPENDIX H

SEISMOLOGICAL TECHNIQUES

BY

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November 1, 1981

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SEISMOLOGICAL TECHNIQUES

1.0 INTRODUCTION

The seismological techniques applied to precharacterization and site characterization studies of potential sites for storage of nuclear waste materials are directed towards two major concerns. The first concern is that of identifying potential sources of earthquakes that could affect the chosen site, including estimates of the maximum earthquakes and return periods for all significant shocks. The second concern is to predict the levels of strong ground motion that might occur at the site. To address these concerns requires integration of several disciplines: geological and geophysical data describe the geologic structure, geological and seismological data describe the tectonic environment as well as the currently active seismic sources, and seismological data describe the current fault processes and the propagation of seismic ground motions. Clearly, the appropriate seismological techniques can be broad ranging and will interact strongly with some of the geological and geophysical techniques.

The applications of seismological techniques for precharacterization and site characterization studies are essentially the same. Some differences in detail, such as desired resolution, can occur as precharacterization studies proceed through site screening and eventual selection of a specific site. The similarity arises because seismic hazards for sites can originate throughout the surrounding region rather than just in proximity to the site. Thus, regional considerations of seismic hazard for the selection process are equally important for the final site characterization. Furthermore, the assessment of seismic hazards is not expected to be greatly influenced by the large amount of subsurface data obtained from drilling and logging during site characterization. One exception to this predominantly regional aspect of the seismological studies is the determination of site-specific levels of strong ground motion. These determinations must depend on the measured elastic properties of the site bedrock and overlying soil column.

The type of geologic medium under consideration as the host rock for a repository does not greatly affect the choice and application of seismological techniques. Again, this condition arises because of the need to consider regional sources of seismic hazard rather than just those local to the site. The regional tectonic environment in which the host rock resides is the more important factor.

For example, large bodies of granite occur in northern Minnesota (very low seismicity, but some large shocks), the Sierra Nevada (moderate seismicity), and central Idaho (moderate seismicity). Similarly, salt domes occur in a band along the Gulf Coast where numerous growth faults are active, and in another band farther inland where current tectonic conditions are more stable. Consideration of salt dome media raises the possibility that seismological studies of higher resolution will be desired because the salt media is of limited extent, there are contrasts in material properties at the boundaries of the salt, and stability of the salt must be demonstrated. Preliminary indications in the radwaste storage program suggest that only those areas having long-term tectonic stability are likely to be nominated as potential storage sites (Nevada Test Site is a notable exception). For these stable areas, the regional tectonic stability will be the concern of seismological studies.

Seismological studies can provide some site-specific data for characterization if local microearthquakes are occurring. These data include: approximate orientation of stress axes, stress drops in local shocks, gross elastic properties of the medium, and identification of local faults releasing stresses seismically. The seismological techniques all relate to observing seismic waves radiated by earthquakes (or shots) and analyzing the data for properties of the seismic source and the transmission path. The various techniques are broadly applicable to each of the possible host media.

For each characterization area, studies will proceed from regional concerns, such as the sources for maximum earthquakes, to local concerns, such as ground motion attenuation and ground motion response of the site. This progression emphasizes the identification of any serous concerns early in a program and developing engineering data subsequently.

Three categories of techniques are used to organize the descriptions given herein: (1) Compilation of seismicity data to include both instrumentally based catalogs and historical reports that pre-date the instrumental data, (2) seismographic measurements using fixed monitoring networks, portable networks, or special experiments, and (3) seismological analysis that might use any of a broad range of analytical procedures.

2.0 COMPILATION OF SEISMICITY DATA

Seismicity data in various forms exist for every region having potential sites for the disposal of radioactive waste. This data results from the eyewitness accounts of persons experiencing local shocks, from observatory seismograph stations that may be in or near the region, and possibly from local networks of seismograph stations. Taken together, these data provide the longest possible period of observations.

2.1 Historical Data

Because earthquakes, particularly large and damaging earthquakes, may occur only infrequently, historical reports are often needed to supplement instrumental data that seldom represent more than about 40 or 50 years. In some cases, the most damaging earthquake (apparently) in a region has taken place before the use of modern seismographic instruments, and great importance then rests on the compilation of historical data.

2.1.1 Description

The objective of compiling and reviewing historical data about the occurrence of earthquakes is to extend the total duration of observations to the greatest time period feasible. Observed earthquakes provide a lower bound on estimates of the maximum earthquake as well as indicating the response behavior of local areas to strong ground motions.

The sources of historical data on earthquakes can be varied. For most regions, some form of compilation or catalog already exists. These catalogs may be complete with respect to the actual occurrence of earthquakes. In other cases, additional data may yet be available through historical research for early time periods or for descriptions of particularly significant events. Sources for additional data may be early newspapers, church and civil records, or personal diaries for example. Different regions will typically have different resources, and a seismologist may be helped considerably by a historian familiar with the local region. For some potential radwaste sites, the surrounding region may contain sites that have been investigated for other critical facilities such as nuclear power plants. Review of the safety analysis reports may be helpful and save time in compiling the historical data. Review of the literature for similar or complementary studies is also a necessary task.

When the historical data have been compiled, they must be critically assessed to evaluate their completeness and reliability. Records will almost certainly be incomplete because not all shocks are large enough to have been reported, or significant enough that a written record was made. In sparsely settled regions, significant shocks may have passed unnoted in the various historical sources. An understanding of the location of population centers and how the demography changed with time contributes to assessing the historical data.

Consideration must be given also to the accuracy of earthquake reports. Most reports originate from untrained observers and persons accustomed to earthquake phenomena. Furthermore, reports have been known to be exaggerated to make the story sound better. However, careful study generally allows reasonable intensity values to be assigned.

2.1.2 Application

Review and evaluation of historic seismicity data must be a part of any program to assess seismic hazard. Even in areas of high seismicity and lengthy periods of instrumental observations, the historical data are still necessary to enlarge the data base. The historical data add completeness for the larger events over a time period often significantly longer than the instrumental record. The historic record may identify active tectonic structures for which the earthquake return period is too long for shocks from those structures to have been observed instrumentally.

In many siting studies or site characterizations, a large, old earthquake may be a major safety concern because descriptive data are few and uncertainties large. Thus, historical investigations on particular earthquakes can be a significant part of the seismic hazard investigation.

Usually, studies of the historical data on seismicity are needed only at the precharacterization stage. There are no elements of characterization needs that would change the compilation or analysis of historical data. If a particular, large shock is related to a safety concern, investigations concerning to that shock may continue beyond the precharacterization studies.

2.1.3 Resolution

Resolution for this seismological technique is described in terms of the ability to identify the time, location and magnitude of an earthquake's occurrence. Because the true values of these parameters are unknown, we must use estimates of the uncertainties.

The exact time of occurrence of earthquakes is not a necessary parameter for seismic hazard analysis. Even with instrumental data, precise timekeeping is needed primarily to determine earthquake locations. Time is useful to distinguish reports of separate events from reports of a single, widely felt event. Consideration of time standards should be on a case-by-case basis for older earthquakes because standards vary greatly with location and date. Time for many shocks in the last hundred years may be uncertain by only a matter of minutes. Some earlier shocks may be uncertain by hours or even days.

Historical reports depend strongly on where people were situated relative to the epicenter of an earthquake. If accounts of surface ruptures from faulting are available, the earthquake's location is known. In the absence of surface faulting, epicenters may be assigned to the location of the most strongly felt effects and this lcoation depends upon the population distribution. For shocks large enough and observed well enough that detailed isoseismal maps can be drawn for the surrounding area, epicenters (or more properly, mesoseismal areas) can be estimated with perhaps 5 to 10 km of uncertainty. The actual uncertainties must be evaluated on a case-by-case basis.

Magnitudes of historically reported earthquakes are assigned using maximum epicentral intensities or the area over which a particular level of shaking was felt. Scatter in the data upon which these emperical relations are based (Toppazada, 1975; Richter, 1958; and others) suggests uncertainties of a quarter or half magnitude unit are normal. When the felt reports of an earthquake are sparse and do not represent the epicentral area, the uncertainty may be larger and controversial.

2.1.4 Reliability

One aspect of the reliability of historical seismicity data is the uncertainty of the earthquake parameters, and the uncertainty is discussed in the resolution section above. The other reliability consideration is the degree to which historical catalog of earthquakes is a complete record of seismicity and is free of purely spurrious entries.

The historical record obviously contains only those shocks that were felt and were considered worthy of written descriptions. Analysis of the record can lead to a description of the completeness in the form of statements that all shocks of a particular magnitude or larger are likely to have been reported from a particular date onward. The analysis can consider population distribution and likely earthquake effects, or a statistical analysis of the recurrence of earthquake intensities (Stepp, 1973) can be used to measure completeness of a data set.

Sometimes erroneous earthquake reports appear in the historical records. Dates may be incorrectly recalled by witnesses, or dates may be transcribed wrongly in original compilations. Independent earthquakes at about the same date have later been falsely considered as separate reports of the same event (Townley and Allen, 1939, p. 22). Locations may be greatly in error because of impressive phenomena away from the epicentral zone (Balderman et al., 1978). Some reports may appear merely because a community wanted to be included in the excitement of the time (Hadsell, 1968). Often, original eyewitness reports must be read critically to perceive what the observer probably experienced rather than what he described. For example, accompanying "volcanos" in nearly mountains are usually dust clouds from landslides, and an "earthquake" lasting for days describes an aftershock sequence.

2.1.5 Base Cost

Compilation and review of historical data on seismicity can be done at two distinctly different levels of effort. The first involves review of previously compiled historical catalogs relavent to the given site area and review of the literature for any studies of the historical data. This level of effort can probably be accomplished for most areas within one or two man-weeks of effort. The second level involves historical research into original newspapers, official records, and whatever other documents may prove useful. Field investigations of suspected fault traces may be useful. Base costs for this type of program are not appropriate because of a wide range of possible program objectives and tasks.

2.1.6 Base Time

If a review program is planned, the first level of effort described in base cost, a few weeks of calendar time should usually be adequate. If further, investigative efforts are needed, then, a base time is inappropriate here as was a base cost in the section above.

2.2 Instrumental Data

Seismographic instruments began to be used effectively in the late 1800's, but only a few stations were available. The number and quality of stations improved steadily until the 1960's when there was rapid development of seismographic networks which continues today. Results from these networks provide our most quantitative seismicity data, and these results are usually refered to simply as the instrumental data. Like the historical data however, the instrumental data must be used with care and consideration given to the inherent limitations. The term instrumental date is used here to include all observations prior to any seismic monitoring conducted as part of the precharacterization and site characterization studies.

2.2.1 Description

Compilation and review of the instrumental data on seismicity is done to incorporate the results of prior observations into the assessment of seismic hazard. Results of these studies are then used to support seismological studies, geologic and tectonic studies, estimates of strong ground motion, and design of local seismograph networks if needed.

Several sources may be available for catalogs of instrumentally determined earthquake locations. The examples given herein are for seismicity data relavent to potential repository sites in the contiguous United States. A worldwide catalog of seismicity is maintained by the National Oceanic and Atmospheric Administration (NOAA) reporting earthquake locations determined by the U.S. Geological Survey and many of the university seismological groups. A similar catalog is prepared by the International Seismological Centre (BISC), Edenberg, Scotland, containing independent epicenter determinations. The NOAA catalog tends to be about a year behind the current date, and the BISC is several years behind. Many of the university seismological groups also prepare catalogs of earthquakes occurring within or near their local seismograph networks. Other limited catalogs have been prepared in special studies for government agencies, utilities, and industrial concerns. Literature review is necessary to determine if any special studies may have been done locally in the site region.

The instrumental data catalogs can be used separately, if several are available, recognizing that each catalog has its individual qualities of accuracy, reliability, spatial coverage and time coverage. Alternatively, the catalogs for a given area may be concatenated into a single catalog using some criteria for selecting the most reliable location when different locations are given for the same event in the various catalogs.

The seismicity data should have the form of catalog listings for reference, possibly computer tapes or files for further analysis, and maps or cross sections for visual display. A wide range of visual displays may be made according to project needs by chossing parameters such as areas, scales, magnitude range, hypocenter depths data sources, and time periods.

When the instrumental data have been compiled, they must be critically reviewed to evaluate their completeness and accuracy. Seismographic networks have earthquake detection and location capabilities that depend upon their geometrical configuration, instrumentation, and operating procedures. These capabilities change in time as the networks are improved or modified. Completeness of the seismicity data is a function of earthquake magnitude and indicates the likelihood that all shocks of a given magnitude have been detected and located. The calculated earthquake hypocenters are subject to errors introduced by observational errors in identification of phase arrivals and errors in modeling the seismic wave transmission paths. Responsible use of the seismicity data entails consideration of the magnitudes and potential effects of thee data uncertainties.

2.2.2 Application

The instrumental seismicity data are one of the fundamental tools for studies of tectonics, but preliminary understanding of the regional geology and tectonics aids evaluation of the seismicity data. The instrumentally determined seismicity data alone can be misleading for estimating seismic hazard, and the data must be combined with historic data as well as geologic and tectonic data. The instrumental data are useful to effectively design local seismic networks if local monitoring is needed.

Review and evaluation of the instrumental data must be a part of any program to assess seismic hazard. The seismicity may identify particular faults as active, indicate fault zones not readily recognized from the surficial geologic data, contribute to tectonic analysis, and provide a statistical basis for characterizing the seismicity. The raw data collected is also the basis for seismological studies of earthquake processes as well as the structure and properties of the geologic media transmitting the seismic energy.

Review and evaluation of the instrumental data are needed only at the precharacterization stage. There are no aspects of the site characterization needs that would change the review and evaluation. However, if significant issues concerning the instrumental seismicity should arise, the assessment of the data could continue during the site characterization stage. Also, if an earthquake monitoring network is necessary (considered as a separate technique here), evaluation of those results would continue as the network was operated.

2.2.3 Resolution

Resolution for this seismological technique is described in terms of the ability to identify the time, location and magnitude of an earthquake's occurrence. The true values of these parameters will be unknown, but uncertainties can be estimated.

The precision with which an earthquake can be located (time, geographic coordinates, and depth) depends upon the number of seismograph stations recording the shock, the geometrical relationships of those stations to the true epicenter, the number of nearby stations, the accuracy in identifying and timing the arrivals of the seismic waves, and the degree of correspondence between the assumed travel paths and the true travel paths for the seismic waves. The interactions of these various factors must be considered on a case-by-case basis for each data set.

Some broad generalizations can be made for the contiguous United States areas. Origin times are usually not of much interest; for early data, they may be uncertain by a few seconds; for regional networks, perhaps one second; and for local networks, a few tenths of a second. Epicenters for early data or in areas of poor seismographic coverage may be uncertain by a few tens of km; regional networks may have average uncertainties of five to ten km; and local networks may have uncertainties as low as a few tenths of a km. Depth is the most uncertain of the location parameters. Good depth estimates require nearby seismographic stations or specialized analysis. Hypocentral depths are often assumed at some reasonable value unless local stations are available. Depth uncertainties of five to ten km are common; use of good local networks may give depth uncertainties of about 1 km.

The magnitude parameter is an attempt to characterize the "size" of a complex phenomena using a single parameter. In effect, magnitude measures size only in a particular band of energy implied by a magnitude definition. In practice, many magnitude scales are used, and they do not necessarily give the same values. Even for a single magnitude scale, an average value is assigned from many estimates and may be uncertain by one or two tenths of a unit.

2.2.4 Reliability

One aspect of the reliability of the instrumental data is the uncertainty of the earthquake parameters as discussed in the resolution section above. The degree to which the instrumental data reflect all of the seismicity that actually did occur is a second concern which is termed completeness. For instrumental data, completeness applies only to the time period and geographic area of coverage for the seismographic stations.

Clearly, very small earthquakes will not all be detected and recorded by a network of widely spaced seismographs. For each network, there is some threshold magnitude for which we can give a high probability that all shocks of that magnitude or greater have been reported. The seismicity record is likely to be incomplete for earthquakes below the threshold. Each network's threshold depends upon the station-to-station spacing, the useful operating sensitivity of the stations and the characteristics of background noise. Regional networks vary considerably, but in the western U.S.

they may have thresholds on the order of magnitude 2.5 to 3, those in the eastern U.S. may be closer to 2.0. Local networks often have thresholds as low as magnitude 1.0 according to their design. Statistical analysis of the rates of occurence of earthquakes as a function or magnitude can provide estimates of the threshold magnitudes.

2.2.5 Base Cost

Compilation and review of the instrumental data can be done at two distinctly different levels. The first involves compilation of the appropriate catalogs for a given area, review of the literature relative to the regional seismicity, preparation of graphic displays, and generalized estimates of the accuracy and completeness. This level of effort can usually be accomplished in two or three man-weeks of effort. The second level of effort involves a detailed analysis of the accuracy and completeness. Analytical mdoels may be run using the network geometry and various degrees of arrival time errors to predict the resulting uncertainties in each of the location parameters. Special studies may be done for each earthquake of particular significance to determine the location uncertainties for that event. Special studies may be done to determine the magnitudes. Statistical analysis may be used to precisely define the data completeness, perhaps as a function of time. Base costs for this type of program are not appropriate because of a wide range of possible program objectives and tasks.

2.2.6 Base Time

If a review program is planned, the first level of effort described in Section 2.2.5, about a month or perhaps two of calendar time should usually be adequate. If further, investiative efforts are needed, a base time is not appropriate because of the wide range of possible needs.

3.0 SEISMOGRAPHIC MEASUREMENTS

Compilation and evaluation of seismicity data, both historical and instrumental, may not fully answer all of the seismic hazard concerns for a potential radioactive waste disposal site. Some of these concerns can be further addressed by seismographic measurement programs designed specifically for the region and site being considered. Local networks of seismographic sstations can be established to monitor earthquakes on an extended basis, and temporary networks of portable instruments can be used for special objectives over short periods of time. Special field experiments may be used for objectives such as determining crustal velocities and bulk elastic parameters or measuring seismic wave attenuation.

3.1 Fixed Monitoring Networks

Networks of more or less permanent seismograph stations are often judged necessary to improve the data base available for characterizing the tectonic environment and seismic hazard of a potential site. Such judgement depends upon the compilation of prior seismicity data and careful assessment of that data.

3.1.1 Description

When the seismographic monitoring networks are used in precharacterization and site characterization studies, the overall objectives are threefold: first, to detect and locate local earthquakes with greater sensitivity and accuracy than available otherwise; second, to provide data for other seismological techniques; and third, to monitor any changes that might occur in the tectonic environment. Most often these objectives can be translated into performance criteria, such as earthquake detection sensitivity or location accuracy. Different combinations of instrumentation/operation can lead to comparable performances. Use of monitoring networks as a technique for precharacterization and site characterization studies comprises four aspects: (1) a distributed array of seismographs, (2) a means of recording the seismic signals, (3) a means of collecting the seismic data, and (4) routine procedures for determining earthquake locations and compiling the seismicity data. The order of items 2 and 3 can be interchanged; data can be recorded at the stations and collected for analysis, or data may be telemetered to a central facility for recording and analysis. Program planning for a seismic network must consider the tectonic environment, seismological objectives, logistical needs, and cost constraints.

Although most fixed networks for earthquake monitoring today use data telemetry and centralized recording, some on-site recording is still appropriate. A typical need could arise when an array element is required at a particular site for which telemetry may not be practical or available on a timely basis. Such a station would consist of a seismometer, amplifier and filter, timing system, recorder and power supply. To best utilize the recording medium, generally magnetic tape, local signal processing is done to detect and record only the occurrence of significant seismic events. Instrumentation manufacturers can provide self-contained systems to perform these functions. Early seismograph stations were all independent with local clocks and local recording on film or paper.

The usual telemetered seismic station comprises a seismometer, amplifier/filter, voltage controlled oscillator (for FM transmission), and power supply. These components serve to detect seismic signals, amplify and condition them for transmission. For networks monitoring local earthquakes which may be of quite small magnitudes (down to $M_L = -1$ or -2 in the extreme), the seismic stations must have high sensitivity to signals in the approximate range of 1 to 50 hz; exact response and magnification depend upon the network objectives and location. If commercial power is not available at a site, the hardware components should be of low-power design to minimize demands on the power supply. Power supply can be from commercial lines, batteries, or solar panels. All of the hardware must be protected from the environment by some type of enclosure(s).

For telemetry, telephone lines may be used if they pass near desired network sites, or if sites can be chosen in locations to use the phone lines. Procurement of full-time channels on telephone lines can be a problem in some areas. If radio telemetry is used, each seismic station must also have a transmitter and antenna. Radio frequency allocations from the Federal Communications Commission are required for the transmitters. At the central recording facility, radio antennas and receivers are needed for each telemetry channel. For both telephone and radio telemetry, the signal from each seismic station is recovered by discriminators which demodulate the FM signals.

At the central recoding facility, the seismic signals are recorded in either analog of digital format. Analog recordings on paper or film are generally suitable for objectives of event detection, hypocenter determination, focal mechanism and statistical studies. Seismic signals may be recorded on analog or FM magnetic tape for later conversion to digital magnetic tape format. Digital format may also be recorded on-line, and is most useful in waveform studies to determine source spectra, source time functions, and stress drops. If magnetic tape recording is used, some means of event detection and a recorder triggering system is also needed to conserve the use of magnetic tape. Some systems have a sophisticated on-line computer system to monitor network activity, trigger recording, pick seismic phase arrivals, determine preliminary estimates of earthquake locations, provide operators with an interactive system to refine locations, and manage the storage of the seismicity data base.

A final aspect of an earthquake monitoring network is the routine procedures for data reduction, determination of epicenters, reporting of results, quality control and maintenance. These procedures will depend strongly on the network instrumentation and the objectives desired.

3.1.2 Application

The technique of monitoring for the occurrence of earthquakes will likely find universal application in pre-characterization and site characterization studies. Any site in a region having Quaternary or recent tectonic activity will require a complete description of the current tectonic environment. Many studies have indicated the utility of microearthquake observations in delineating active tectonic structures, indicating stress orientations and measuring the bulk elastic properties of crustal rocks. Even a site considered to be tectonically quiet will need to demonstrate the lack, or low level, of microearthquakes. Most potential sites for a waste storage facility will require installation of a seismic monitoring network. Notable exceptions are Nevada Test Site and Hanford, Washington where networks already are operating.

For any network, the prime application is considered to be the measurement of current seismicity. This application includes the detection and location of earthquakes, compilation of seismicity statistics such as recurrence curves, and compilation of seismicity catalogs and maps. Further seismological studies such as focal mechanisms and spectral analysis are considered below under Seismological Analysis Techniques (Section 4.0).

3.1.3 Resolution

Resolution for an earthquake monitoring network is described in terms of the capability to determine the time, location and magnitude of earthquakes that are observed. The true values of these parameters are unknown, but their uncertainties can be estimated. Network capability is strongly dependent upon the network geometry, the usable sensitivity of the instruments, and the true locations of the earthquakes. Location capabilities diminish rapidly for shocks at the periphery of the network and beyond. The area of interest should be contained within the network bounds.

Average spacing between network stations may vary from a few km for very local monitoring up to 50 km and more for regional monitoring. Epicenter uncertainties seem to be on the order of 1/5, or less, of the average station spacing for shocks within the network and well-recorded. Considerable variation can occur depending upon the size of the shock and the onset character of the seismic waves. Hypocentral depths have greater uncertainties, and generally require data from a station whose epicentral distance is comparable to the hypocentral depth if the depth estimate is to be reasonably constrained. Even with nearby station control, uncertainties in depth estimates may be two or three times greater than those for epicenters. Lateral variations in the seismic velocity structure in some areas can contribute significantly to systematic location uncertainties.

Origin times of local earthquakes are determined to much greater precision than needed for purposes other than the location process itself, and some special seismological studies. Origin times for local shocks usually have uncertainties no greater than a few tenths of a second.

Earthquake magnitude is not a very precise number because a single parameter is inadequate to express the "size" of such a complex phenomenon as an earthquake. Magnitudes may be uncertain by about one tenth of a unit. Microearthquakes frequently are assigned magnitudes according to the duration of shaking greater than some threshold. These duration magnitudes provide a useable comparative scale, but their uncertainties may be larger.

3.1.4 Reliability

Reliability of fixed network monitoring includes the uncertainties described above as well as whether the network has faithfully detected all occurrences of earthquakes within its area of coverage. Each network will have some threshold magnitude above which all earthquakes will be recorded and located. Some shocks of smaller magnitudes may be recorded and located under favorable circumstances. Other small shocks may be recorded on some stations but not well enough to permit locations to be determined. And some even smaller shocks may not be recorded on any stations. The network threshold magnitude will depend on station spacing and useful magnifications of the stations. Regional networks generally have thresholds on the order of magnitude 2.5 or 3, and local network are often useful to thresholds of about 1.0. Again, these values are highly dependent on each individual network.

Operational reliability of the instrumentation is also a factor. Hardware is susceptible to electrical and mechanical failures, and stations in the field may be subject to vandalism. Networks of many stations can tolerate an inoperative station better than networks with fewer stations. Preventative maintenance on a regular basis and repair on a reaction basis can usually limit the downtime.

3.1.5 Base Cost

Costs for a monitoring network can show considerable variation according to the number of stations needed, the type of telemetry used, the local environmental factors, the type of on-line monitoring systems, and the number of earthquakes requiring routine data analysis. Seismological analysis beyond the routine determination of earthquake locations and magnitudes and the compilation of seismicity data is considered in another section. For a typical network using both telephone and radio telemetry, central recording on triggered magnetic tape and some analog recording, a very rough rule of thumb suggests that hardware and installation of the network would cost about $8,000 to $10,000 per station (in 1981 dollars). Operational costs after installation are on the order of a man-year for a network of 10 to 15 stations. Actual costs would depend greatly on the network configuration used. Current cost estimates can be given for some typical network elements as follows using products of three major instrument manufacturers. The prices are approximate and subject to change. Furthermore, products of the different manufacturers may vary in their specifications, capabilities and compatibilities with other equipment.

	Seismic Stations Major Items
Seismometer	$395 - 1175
Amplifier/Filter	300 - 380
Voltage Controlled Oscillator	220 - 275
Calibrator	195 - 225
Instrument Case	225 - 290
Radio Transmitter	640 - 1100
Radio Antenna	110 - 120

Other site capital costs include site preparation, enclosure, power supply, spares and permitting.

	Central Recording System Major Items
Radio Antenna	$110 - 120
Radio Receiver (1 ch)	940 - 1,075
Discriminator (1 ch)	250 - 280
Paper Recorder/Amplifier (1 ch)	1,750 - 2,700
Film Recorder (20 ch)	24,000
Event Trigger (6 ch)	1,740
Digital Recorder (24 ch)	28,250
Timing Systems	2,000 - 2,100
Time Code Antenna	125 - 310
Time Code Receiver	600 - 1,200
Satelite Time Code System	2,200

Other Central Recording Station capital costs include office space, instrument racks, power supply, system integration, maintenance/test equipment, and spares. All cost presented herein are in 1981 dollars.

3.1.6 Base Time

Time required for an earthquake monitoring network can be divided into the time for installation and the time for routine operation. The actual work of network installation is inversely proportional to the personnel available for installation and would typically run from 1 to 4 months for a network of 10 to 12 stations. An additional factor is the lead time for obtaining any necessary permits and for manufacturing instrumentation. Currently, delivery times for equipment may range from 3 to 6 months.

The time required for routine network operation to characterize the seismicity, provide data for seismological analysis, or monitor any changing seismicity depends upon the rate of seismic activity and the degree of confidence desired. For potential radwaste sites, networks should be installed early in the program so that the maximum monitoring time can be obtained. Geologic processes and cycles influencing seismicity can occur on time scales much longer than that available for precharacterization and site characterization studies. Analysis and interpretation must necessarily be done at certain points in the program with the data available. However, some degree of monitoring should continue and probably become part of the operating procedure for the eventual repository facility.

3.2 Portable Monitoring Networks

Even with good coverage provided by a permanent seismographic network, needs can arise for enhanced measurement capabilities. Portable networks may be desired for purposes such as better locating the aftershocks of larger shocks, study of earthquake swarms, or better capability near particular faults whose activity is uncertain. When the objectives can be accomplished in a few weeks or months, networks of portable seismic stations are very useful.

3.2.1 Description

Conceptually, portable seismographic networks are identical to the fixed networks. However, emphasis is more often placed upon on-site recording rather than telemetry, and the monitoring objectives can be attained in a shorter period of time. The portable networks may be used to augment a permanent network, or perhaps in place of a permanent network for a short time. Most often, the objectives are greater detection sensitivity and better epicenter accuracy through closer station spacing.

The network may consist of completely independent portable stations each with its own seismometer, amplifier, filter, recorder, and timing system. Alternatively, radio telemetry may be used to a temporary central recording facility. For their radio equipment, service contractors often have frequency allocations that are valid over large regions so networks can be operated any place in that region. There can be degrees of "permanence" as a network is designed for a few months or many months of operation.

When the completely self-contained seismograph stations are used, each station must be visited periodically to change the data records, replace batteries and check the station operation. Data recording can be done on paper records, either ink or smoked paper, or on magnetic tape. Magnetic tape equipment includes analog or triggered digital formats. Each station includes a local precision clock that is calibrated against radio time signals during the periodic station visits. Some systems can record radio time signals directly.

For the telemetry systems, the seismic signals are FM modulated with voltage controlled oscillators and broadcast by radio to a central recording facility. Line-of-sight radio links are needed, so radio telemetry for portable networks is generally limited to networks with small apertures or with favorable topographic conditions.

Data collected from the temporary self-contained stations, or recorded centrally, are reduced and used for determining earthquake locations or for seismological analysis in a manner identical to that for permanent networks.

3.2.2 Application

Portable earthquake monitoring networks may be called into use when detailed seismic monitoring is needed for a limited time. The application may be an intense, short-term study of seismicity near some particular tectonic feature or perhaps near the epicenter of a significant earthquake within the region of interest to site characterization studies. Many of the detailed study applications can be planned in advance to optimize the temporary array design and instrumentation capability. However, if a significant earthquake should occur, quick reaction is desirable to place stations in the field and maximize the data to be gained from monitoring aftershocks in great detail. For such application, the portable stations must be on hand and ready for deployment. Prudent operation of a fixed network should probably include the availability of at least a few portable stations to respond to special seismographic opportunities.

3.2.3 Resolution

Resolution for a portable earthquake monitoring network, as for a fixed network, is described in terms of the capability to determine the time, location and magnitude of the earthquakes that are observed. The discussion in Section 3.1.3 applies also to temporary networks. In general, temporary networks will use smaller average spacing of stations, perhaps on the order of 2 to 10 km. Epicenter uncertainties may be 1 km or less. Hypocenter depth estimates may be comparable, but can be subject to systematic errors if the seismic velocity function is not well determined for the network local area.

3.2.4 Reliability

Reliability of portable network monitoring includes the uncertainties described above as well as the ability of the network to faithfully detect all shocks that occur. The discussion of Section 3.1.4 for fixed networks is applicable to portable networks.

With portable seismographic stations, operational reliability is an important consideration because the equipment is necessarily subject to more abuse in mobilization and demobilization. Field systems are designed for moderately rugged use, but still failures can occur. The field systems usually depend upon battery power, which in turn is one of the main causes of station failure. Loss of data from some stations between station visits sometimes occurs, but in general the portable networks are capable or providing high quality data unobtainable otherwise.

3.2.5 Base Cost

Costs for using a portable network can range widely according to the number of stations used, the type of instrumentation, the duration of monitoring, and the number of shocks requiring routine data analysis. Seismological analysis beyond the routine determination of earthquake locations and magnitudes and the compilation of seismicity data is considered in another section.

Instrumentation for portable seismograph stations can be either analog or digital according to the objectives of the network. Analog records are adequate for determining locations and focal mechanisms. Digital data are better suited to spectral analysis studies if such studies are contemplated. In areas of low seismicity, digital equipment may be used for its event-recording capability so that stations need be attended less frequently. Service contractors providing temporary seismographic networks can be expected to charge their equipment at both 10 percent of purchase price per month of use. Current cost estimates for some typical equipment can be given using products of three major instrumentation manufacturers. The prices (in 1981 dollars) are approximate and subject to change. Furthermore, the products of different manufacturers may vary in their specifications, features, and compatibility.

Major Items

Seismometer:	$395 - 1175
Analog System (1 ch): (amplifiers/filter/timing/recording)	$3200 - 4700
Digital System (1 ch): (Amplifiers/filter/timing/event detectors/ recording)	$6500 - 9000
Digital System: (timing/event detectors/recording)	$4000
Digital Playback System:	$2500 - 5000

Telemetered systems, if used, would have instrument costs comparable to those listed for fixed networks.

Installation costs for a portable network could range from about 1/5 to 2 man-days per station depending upon the instrumentation used, the calibration required, and access to the station site. In many cases, actual setup requires only about an hour at a site, but much more time may be used finding a suitable site. The telemetered systems require somewhat longer time to check out the radio links.

Field operations of a portable network require on the order of one man full time for about 4 to 6 stations. Here also, one of the major time factors is travel between the various stations. The analog stations require a service visit each 24 hours unless a different record length has been selected. However, 24-hour records are a good compromise between recording capacity and the time precision needed for local earthquakes. Digital stations need a service visit only when their recording capacity is exhausted which is a function of seismic activity and battery drain.

Routine data reduction, determination of earthquake hypocenters, and compilation of seismicity data will depend upon the recording format (analog or digital) and the number of earthquakes detected by the temporary array. Aftershock sequences can produce great volumes of data in a few days, or only an occasional shock may be detected when monitoring near a fault of particular interest. Average effort for each shock to be located might range from one-fourth to several man-hours, and some special cases would be worthy of further effort.

3.2.6 Base Time

Portable networks are usually installed over a period of a few days. If the network is to monitor aftershocks of a significant earthquake, time is critical and efforts are made to install the network as quickly as possible. With enough personnel, these networks have been operating within the first day following an earthquake.

The duration of operation depends upon the seismological objectives desired. Aftershock monitoring of moderate shocks, magnitude 5.5 and less, generally extends over only 1 or 2 weeks. Shocks of magnitude 6 and larger have significant aftershocks for months, and a monitoring network may be converted to permanent status. Monitoring may be done over a few days or weeks to determine typical levels of microearthquake activity.

3.3 Crustal Refraction Profiles

For seismological needs, refraction profiles to measure seismic velocities and crustal layering are conceptually similar to refraction profiles at moderate depths for petroleum exporation and at shallow depths for engineering data. The crustal measurements generally use much more widely spaced survey points, sample columns of rock materials, and have less resolution. The resulting seismic velocity structure is used in the earthquake hypocenter determination process and for many seismological and geophysical studies.

3.3.1 Description

In refraction profiling, travel times are measured for seismic waves that have refracted in layered media so that part of their travel path is essentially horizontal. Deeper layers are sampled as the surface distance between the seismic source and the receiver is increased. The slope of a linear portion of a travel-time-versus-distance curve indicates the velocity of the deepest layer penetrated by the waves measured, and the zero-distance intercepts of the linear portions can be used to estimate the depths to the velocity layers. Refraction techniques for shallow and moderate depths are described in the Geophysics Section (Appendix B-3).

For seismological needs, crustal structure and seismic velocities are desired to depths at least as great as those reached by earthquake energy received at the seismographic recording stations. These desired depths in the contiguous U.S. can range from about 10 to 15 km for local networks recording shallow shocks, to a few tens of km for most regional networks. In the Pacific Northwest, some shocks are on the order of 150 km deep. A crustal model with flat or gently dipping velocity layers is convenient computationally, but has varying degrees of faithfulness to the actual structures encountered by seismic waves. These models are adequate for a majority of situations, but are sometimes modified to incorporate lateral variations.

In practice, the source-receiver distances must be several times greater than the depths of the velocity layers to be measured. Thus, for crustal structure profiles, the sources and receivers must be separated by tens and even hundreds of km depending upon the particular objectives. For these distances, large shots are often needed to put enough seismic energy into the ground. Large blasts used by mining or quarrying operations are often used as seismic sources. Recording stations are usually self-contained, possibly with radio links for control. Seismograph stations such as those described for temporary monitoring in Section 3.2 are often laid out in a linear array for crustal refraction profiles. Interpretation of the travel time data is similar to that for the geophysical applications (Appendix B-3) except that special care must sometimes be given to the identification of weak signal onsets in the presence of background noise.

3.3.2 Application

The primary application for crustal refraction profiles is to provide appropriate velocity-structure models for use in locating earthquake hypocenters. Most earthquake location schemes compare calculated arrival times of seismic waves with the instrumentally observed arrival times. The calculated travel times in turn depend upon knowledge of seismic wave propagation velocities, i.e., the crustal velocity structure. The crustal velocity structure plays a significant role in many of the seismological analysis techniques that may ultimately be applied to the seismic data.

Data from crustal refraction profiles may be used to constrain the interpretation of other regional geophysical data such as gravity and magnetics. Data from many techniques may be used simultaneously to derive a structure model that best satisfies all of the data. The seismic and gravity data can be used to infer the bulk elastic constants of the crustal media.

3.3.3 Resolution

Resolution for this technique is measured by the uncertainties in estimates of seismic velocities, depths to refracting layers, the identification of individual layers as having significantly different velocities, the dips of the layers, and identification of lateral changes in any of these parameters. Each of these parameters is affected not only by the measurement conditions, such as source-receiver offset, receiver spacing and signal-to-noise ratio, but by the degree to which the true crustal structure can be modeled by a layered structure. The technique cannot recognize layers for which the velocity is less than the overlaying layer.

Depth estimates may be uncertain by about 5 to 10 percent of the depth. Most workers report measured velocities to the closest tenth of a km/sec, occasionally to a hundredth. These values represent average velocities, so the resolution is likely to be no better than 0.1 or 0.05 km/sec. Shooting profiles in both directions are necessary if the velocity layers are dipping. The identification and separation of various layers is often an interpretive choice, and typical resolution is not an appropriate quantity.

3.3.4 Reliability

When velocity layers are present and not too complicated structurally by steep dips and faulting, the refraction method can provide good estimates of the structure. With increasing structural complication, the results more and more represent some average of the properties of the media. Low velocity layers are not detectable, but influence the apparent velocity of the next deeper layer of increased true velocity. However, this averaging represents to some extent the effects experienced by earthquake energy, so the results are still useful in many seismological applications.

3.3.5 Base Cost

Field equipment for crustal refraction profiles is usually drawn from available portable seismograph stations as described in Section 3.2.5. Research projects involving the development of specialized instrumentation are not appropriate to include in a base cost. For many refraction profiles the field effort consists of deploying a linear array, recording an explosion or brief series of explosions and then demobilizing the array. Typical field costs can range from a full-time person for each station down to perhaps 1/4 of a full-time person for each station for the duration of the field effort, plus transportation and subsistence. Analysis costs may be on the order of a few man-weeks to reduce and interpret the data with variations depending upon the number of stations, number of shots, data quality, and structural complexity.

3.3.6 Base Time

Field efforts are typically on the order of a week. Longer times may be needed if the array is moved between shots. Extended times may be used if many shots from a mining or quarrying operation are used, and the shots are scheduled according to the quarry's needs. Analysis times can be on the order of a few weeks, or longer, depending on the particular project.

3.4 Other Experiments of Special Design

Other field measurements may be undertaken to address particular concerns that arise during the precharacterization or site characterization studies. Each case represents a special experiment designed as appropriate to the needs. Some representative techniques can be envisioned, but details would depend upon the objectives. Some possible measurements might be as follows:

- Calibration of time delays for individual seismographic stations using shots within or near the array.
- Installation of special stations to help resolve the deep structure (shape) of plutons or salt bodies.
- Installation of seismometers in deep boreholes to measure attenuation of surface-wave energy as a function of depth.
- Installation of seismometers in adjacent boreholes to measure in-situ wave velocities.
- Using controlled shots and perhaps additional stations to measure lateral attenuation of seismic energy.
- Using three-dimensional arrays in and around mining operations to monitor rock bursts or changes in the natural level of microearthquakes.

These examples are not meant to be exhaustive. Seismic waves observed are influenced by the properties of the source mechanism, such as size orientation, stress drop, duration; by the geologic structure at the source, along the transmission path and at the receiver; and by the elastic properties along the path. Special experiments can be planned to investigate any of these parameters that may be of particular concern to siting studies.

4.0 SEISMOLOGICAL ANALYSIS TECHNIQUES

The compilation of seismicity data, both historical and instrumental, the operation of seismographic monitoring networks, and the performance of special field experiments all result in a data base that can be used for many purposes beyond the initial objectives. Often the design of monitoring networks or field experiments provides data suitable for other seismological studies. The sections following describe briefly the more common analysis techniques that may be applicable to precharacterization and site characterization studies. The list is not exhaustive. Descriptions only are given because these analysis techniques range widely in their application, resolutions and reliability, and they do not have a base time or base cost.

4.1 Hypocenter Revision

Normal operation of an earthquake monitoring network includes the routine and timely determination of earthquake locations. Pater, special studies may improve the seismic velocity model relative to that originally used. These improvements may be the result of refraction surveys, gravity data, inversion of travel times along with other geophysical data, and identification of lateral variations. Sometimes for larger shocks, additional data become available from stations outside the monitoring network. Spectral studies or waveform synthesis studies may provide depth constraints on some shocks. With these improved tools as they may be available, earthquake locations may be recomputed in order to reduce the uncertainties in their coordinates. These recomputed locations then permit improved tectonic interpretations of the seismicity.

4.2 Velocity Model Studies

Crustal refraction profiles are one aspect of velocity model studies and were described in Section 3.3. Similar travel time curves can sometimes be synthesized from the seismic monitoring data. Quarry or construction blasts in and near the monitoring network provide checks on the applicability of the velocity models. A good model should lead to locating well-recorded blasts at their known origin points within the uncertainty of the solution. In a more formal procedure, arrival times of seismic phases may be used in various inversion techniques to estimate corrections to the velocity model. Systematic residual times (observed time minus computed time) for stations can be studied for each station to derive time corrections that represent local velocity effects. Residuals from teleseismic earthquakes can sometimes be interpreted in terms of deep-seated velocity structure in the crust.

4.3 Fault Process Studies

If an earthquake is well recorded, first-motion polarities of the P waves can be used to determine the nodal planes of an equivalent, double-couple source model. Clusters of smaller shocks can be used to determine "composite mechanisms". Two complimentary planes are obtained as possible attitudes of the fault plane; when geologic trends are clear, one of the planes can usually be chosen as the preferred solution. Even if the choice of preferred solution is ambiguous, the general orientation of the principal stress axes is indicated. These indications must be considered general because most earthquakes probably occur on pre-existing fault surfaces rather than along failure planes ideal for the imposed stress orientation. Variations in stress orientation are important in developing a tectonic model to describe the seismic setting of the study areas and to evaluate tectonic structures (faults) that may be potential earthquake sources.

The spectra characteristics of seismic waves can be interpreted in terms of source theories to estimate parameters of the earthquake source mechanism. The spectra are also affected by geologic structure at the source, along the travel path and at the receiver. For each earthquake recorded digitally, P-wave spectra can be computed for a time window including the initial P-phase arrivals.

Care must be taken to avoid inclusion of later phases because the spectra can be considerably distorted. When the S-wave can be clearly identified and appears uncontaminated by other arrivals, S-wave spectra can be computed also. Source model theory provides a convenient interpretation of the spectra by relating seismic moment to the long-period spectra density level, and source dimension to the corner frequency at which spectral densities begin to fall off as a function of increasing frequency. Stress drop can then be computed from the measured quantities. As a practical matter, computed spectra often do not fit the theoretically predicted shape, and several disrupting factors can be demonstrated such as crustal structure effects.

Further understanding of faulting process can be gained by constructing synthetic seismograms to match the observed seismograms. This modeling process involved adjustments to values representing the crustal structure, the orientation of the fault rupture and the dynamics of the fault rupture. Typically, this analysis is limited to larger earthquakes, about magnitude 5.5 to 6 and larger, treating seismic waves at frequencies of about 1 hz and lower. The high-frequency character of small shocks would dramatically increase the computational burden and the required detail in the crustal models.

4.4 Seismotectonic Interpretation

The final step in characterizing the seismic setting of a potential radwaste storage site is to correlate the occurrence of earthquakes with tectonic structures and describe the regional tectonics. Ideally, this correlation would delineate the active source areas for earthquakes and lead to a clearcut evaluation of the seismic setting and potential seismic hazards. The amount of seismicity actually observed historically and during instrumental monitoring will greatly influence the degree of reliable correlation possible. Also, any seismic monitoring study is a "one-sided" experiment in the sense that observed seismicity can point to active tectonic structures, but a lack of seismicity does not prove a structure is incapable of generating future earthquakes. A broad understanding of the geology and tectonics, both local and regional, is a necessary complement to the seismicity data for interpretation of the seismic setting. The tectonic analysis will permit an evaluation of potential earthquake source structures based on the seismicity distribution, tectonic history, stress orientation and source parameters.

4.5 Recurrence Estimates

Recurrence relationships express the rate of earthquake occurrence as a function of earthquake magnitude. The relations may be developed for regions, tectonic zones, or even particular faults. The value of recurrence estimates lies in their use in determining the probabilities that various levels of strong ground motion will affect a particular site. Several mathematical models have been proposed, and the truncated log-linear model is perhaps the most widely used: $\log N(M) = a - bM$ where $N(M)$ is the number of earthquakes of magnitude M or greater. A maximum magnitude is used to truncate the relation. Recurrence studies evaluate the sesimicity data to determine the best estimates for the equation constants so that the relation can be extrapolated to very rare events. Other studies deal with alternative mathematical models of the earthquake distributions, the maximum earthquake to be assumed, or with the distribution of maximum earthquakes is sequential, short time periods.

4.6 Attenuation Studies

A functional description of the attenuation of seismic energy as it propagates is needed for two primary purposes: local calibration of earthquake magnitude scales and prediction of ground motion levels at a site caused by earthquakes in the region. Attenuation can vary from area to area and local studies are needed to measure the attenuation or justify the use of relations developed for other areas. The attenuation of propagating seismic phases can be measured using amplitude data from regional and local monitoring networks. The attenuation of a strong ground motion is slightly different physically because the ground motion peaks may be caused by different kinds of seismic phases at different epicentral distances. If variations in strong ground motion have not been carefully observed in the study region, careful analogy may have to be drawn from similar regions.

4.7 Site-Specific Ground Motion Studies

Assessment of regional seismic hazards will identify potential earthquake sources, and an attenuation relationship will predict average levels of strong ground motion at a particular site. But actual ground motion experienced will be modified by conditions at the site. Measurement and analysis must consider the effects of any significant soil column overlying competent bedrock. For radwaste sites, an important consideration will be the attenuation of surface wave energy as a function of depth. Generally, subsurface facilities will experience lesser shaking than the surface handling facilities. Both modeling and theoretical studies can be applied to these problems.

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