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STATE-OF-THE-ART FOR EVALUATING THE
POTENTIAL IMPACT OF TECTONISM AND
VOLCANISM ON A RADIOACTIVE WASTE
REPOSITORY

MASTER

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1. INTRODUCTION

1.1 Concepts and Time Frames For Waste Isolation

Technology is presently being developed in the United States for the long-term isolation of radioactive wastes from the biosphere. Recent research has concentrated on the development of mined repositories at depths of 500 to several thousand feet below the ground surface. Several estimates have been made of the minimum time required for the safe isolation of radioactive wastes, with most estimates falling in the range of 100,000 to 1,000,000 years (Goad, 1979). For such time scales, it is necessary to investigate the potential influence of geologic processes on the integrity of a repository. The potential effects of tectonism and volcanism on a nuclear waste repository and the means of evaluating tectonic and volcanic processes are discussed in this report.

1.2 Prediction of Geologic Processes

Ideally, one would like to predict accurately the tectonic and volcanic activity at a given site for the time period required for waste isolation. To do this, tectonism and volcanism would have to be thoroughly understood, deterministic (as opposed to random) processes, and all boundary conditions of these deterministic processes would have to be known (Kitts, 1977). The processes of tectonism and volcanism are probably deterministic, but extremely complex. Our understanding of these processes and boundary conditions has increased dramatically in the past few decades, but still does not allow very accurate predictions.

Another approach to prediction is to assume that a process is random, and to make probabilistic predictions based on the spatial and temporal distribution of past tectonic and volcanic activity. Probability estimates must be made on a regional data base because the distribution of tectonic and volcanic activity is not random. An assumption inherent in such a prediction is that the phenomenon is stationary, which may be justifiable for geologically short time spans. A major shortcoming of probabilistic predictions is the lack of sufficient records of previous events. The combination of geologic and historic records rarely provides the detail necessary to make probabilistic predictions. The records are particularly sparse in areas of tectonic and volcanic stability where repositories are likely to be located.

1.3 Plate Tectonics

Within the past few decades, the development of plate tectonic theory has given geologists a better understanding of the global distribution of mountain belts, volcanism and seismic activity. According to the theory, the outer shell of the earth consists of a few large, rigid plates that are roughly 100 km thick. These lithospheric plates are underlain by weaker, less-rigid materials of the asthenosphere. Lithospheric plates are in motion, moving at rates on the order of several centimeters per year relative to one another. The driving mechanism for these motions is not well understood; however, most earth scientists agree that convective flow of mantle materials is involved. Most volcanism, earthquakes and deformations occur along narrow belts that coincide with the boundaries of lithospheric plates. The nature of plate boundaries is dependent on the relative motion of the two plates at the boundary; divergent, convergent and transform boundaries are the three possibilities.

Where plates diverge, such as along the mid-Atlantic ridge, new lithosphere is created as partially molten mantle material upwells between the diverging plates. Divergent boundaries are characterized by active basaltic volcanism, high geothermal heat flow, and shallow earthquakes caused by extensional stresses. At convergent plate boundaries one lithospheric plate generally overrides another, and the subducted plate is resorbed into the mantle. Deep sea trenches, shallow and deep focus earthquakes, andesitic and basaltic volcanism, and compressive deformations are common along convergent boundaries. At transform boundaries, lithosphere is not created or destroyed, as plates slide past one another parallel to their common boundary. Shallow earthquakes associated with strike-slip faults are characteristic of transform boundaries.

The interior regions of any plate are more stable than the plate boundaries with respect to seismicity, volcanism and deformation; however, the interior regions of plates are not completely devoid of tectonic instability such as earthquakes, faults and volcanism.

It has been postulated that some mid-plate volcanism is due to isolated thermal plumes ("hot spots") within the mantle (Morgan, 1972). According to this theory, narrow plumes of hot mantle materials rise and spread laterally at the base of the lithosphere. The surface manifestations above a mantle plume would include volcanism, uplift and high heat flow. It appears that mantle plumes are fixed relative to moving lithospheric plates, producing chains of volcanic activity that trace the motion of the plate. The

Hawaiian Island-Emperor seamount chain is a series of basaltic volcanoes that are progressively younger to the southeast. The orientation of these and three other Pacific island and seamount chains appear to define the motion of the Pacific plate relative to the mantle (Fig. 1a). Most other postulated "hot spot" locations are associated with divergent plate boundaries at oceanic ridges, but the Yellowstone area is a notable exception (Fig. 1b).

1.4 Tectonic Setting of the United States

Most tectonic instability in the United States is related to the active boundary between the Pacific and North American plates (Fig. 2). In southern and central California, the San Andreas fault and related strike-slip faults form a transform boundary between the Pacific and North American plates, with a left lateral displacement rate of roughly 6 cm/yr (Atwater, 1970). Numerous shallow-focus earthquakes on strike-slip faults and little volcanism are characteristic of the San Andreas transform system. In southernmost California and the Gulf of California, the transform boundary has a component of divergence. As a result, Pleistocene volcanism, high heat flow and geothermal resources are found in the Imperial Valley (Robinson, 1976). In northern California, Oregon and Washington, the continental margin is a convergent boundary between the North American plate and the Gorda plate, a small plate that lies between the Pacific and North American plates. Seafloor magnetic anomalies indicate that the Gorda and Pacific plates are diverging at a rate of 5.8 cm/yr along the Juan de Fuca and Gorda ridges. The resultant convergence of the Gorda and North American plates is calculated to be approximately 2.5 cm/yr in a NW-SE direction (Atwater, 1970). Tectonic instability along this plate margin is manifest in andesite volcanism of the Cascades and in shallow to medium depth earthquakes. Several large andesite-dacite strato volcanos have formed since the Pleistocene in the Cascade range from northern California to Washington. The base of these strato volcanos consists of large basalt shield volcanos that were constructed in Late Miocene to Pleistocene (Armstrong, 1978). Pleistocene and Holocene eruptions have been confined to the major volcanos, which lie within a few kilometers of a north-south axis along the crest of the Cascade range. Relative to other convergent plate boundaries, the seismicity is low, and deep focus earthquakes are less frequent. The present tectonic framework of the western United States began to take shape in mid Tertiary, when the San Andreas transform began to form, ending a period of continuous subduction along the western boundary of the North American plate.

Maps of recent volcanism (Fig. 3) and recent seismicity (Fig. 4) indicate that large areas of the western United States are tectonically active. The Basin and Range Province is presently char-

acterized by extensional faulting, high regional heat flow, and sparse volcanism (Livaccari, 1979). The tensional nature of the Basin and Range Province is probably genetically related to the formation of the San Andreas transform boundary roughly 20 to 30 million years ago. Present tectonic and volcanic activity is concentrated along the eastern and western margins of the Basin and Range Province (Christiansen and McKee, 1978). The Rio Grande Rift is also a tensional feature that has undergone extension from mid-Miocene to present. It is separated from the Basin and Range Province by the relatively undeformed Colorado plateau. The distribution of these physiographic provinces is illustrated in Fig. 5.

Large volumes of basalt were extruded to form the Columbia River and related basalts from 17 m.y. to 13 m.y. ago. Minor amounts of subsequent intracanyon basalt flows have occurred up until approximately 6 million years B.P. The basalt plateau covers an area of approximately 220,000 km², with basalt thicknesses as great as 1 km (Williams and McBirney, 1979). Individual basalt flows range from 10 m to 150 m in thickness, and may have been separated by intervals of thousands or tens of thousands of years. The basalts were probably extruded from vast upper mantle reservoirs through a series of fissures. Similar extensive flood basalts are found in the Paraná River region of South America and the Deccan plateau of India. Typically, flood basalts are erupted in a relatively short time span, followed by volcanic quiescence. The initiation of the Columbia basalt volcanism coincides with a major change in the tectonic framework of the western United States, namely the development of the San Andreas transform system.

Bimodal rhyolite-basalt volcanism began about 13 million years ago south of the Columbia plateau. From Miocene to present, the bimodal volcanism has migrated to the east toward the Snake River plain and Yellowstone, and to the west toward Newberry volcano in Oregon. Armstrong (1978) proposes a three-phase sequence for each episode of volcanism in the Snake River plain-Yellowstone trend:

1. Eruption of rhyolite, ash, tuff and minor basalt with an associated broad uplift.
2. Eruption of flood basalts with minor rhyolite, associated with subsidence.
3. Large volumes of tuffaceous sediments with some basalt.

Stage 1 is exemplified by current activity at Yellowstone Park, Stage 2 activity is found in the eastern Snake River plain, and Stage 3 is seen in the western Snake River plain. A northeastward migration of volcanism at approximately 4.5 cm/yr is implied by this model, and

age dating of the igneous rocks supports this hypothesis. The motion of the North American plate relative to the postulated Hawaiian mantle plume is calculated at 4.5 cm/yr to the southwest (Smith and Christiansen, 1980). This rate and direction of motion is opposite the migration of volcanic activity in the Snake River plain-Yellowstone trend, thus it appears that the Hawaiian and Yellowstone mantle plumes are both fixed relative to one another, as if they were "anchored" in the mantle. Models have been proposed by Smith and Sbar (1974) and Matthews and Anderson (1973) relating the Yellowstone mantle plume theory to the existence of 2 or 3 sub plates bounded by the Snake River plain, the Inter-mountain seismic belt and the Rio Grande Rift (Fig. 6).

The eastern and central portions of the United States are within the interior of the North American plate, which is continuous from the western continental margin to the mid-Atlantic ridge. There is no recent volcanism and there are relatively few earthquakes and active faults. Infrequent large earthquakes such as the New Madrid, Missouri (1811-1812) and Charlestown, South Carolina (1886) earthquakes occur at great distances from known tectonic boundaries, and are poorly understood (Ekren, 1974). The maximum intensities observed during these two earthquakes are MM XII and X, respectively (Bolt, 1975).

Tectonic and volcanic hazards to nuclear waste repositories are most extreme along the major tectonic boundaries represented by the San Andreas fault system and the Cascade volcanic arc. Large areas of the western United States cordillera are tectonically and volcanically active. Volcanism, seismicity and faulting in the western cordillera are concentrated along the eastern and western margins of the Basin and Range Province, the High Lava Plains-Yellowstone trend and the Rio Grande Rift. The eastern and central United States are within the relatively stable interior of the North American Plate, where there is no recent volcanism and relatively minor seismicity.

Faults, earthquakes, slow deformations of the earth's crust and volcanic activity are all manifestations of large scale tectonic processes that could potentially have adverse impact on the performance of a geologic nuclear waste repository. In the following sections, each of these manifestations will be discussed with regard to (1) the potential impact on a repository and (2) the best available methods for evaluation.

2. EXECUTIVE SUMMARY

Most estimates of the time required for safe isolation of radioactive wastes from the biosphere range from 100,000 to 1,000,000 years. For such long time spans, it is necessary to assess the potential effects of geologic processes such as volcanism and tectonic activity on the integrity of geologic repositories:

- Faults and fracture zones could provide unacceptable hydrologic circulation through the repository.
- Fault movements could displace geologic barriers that are necessary for waste isolation.
- Ground motions associated with earthquakes could endanger waste handling operations, particularly surface operations.
- Vertical tectonic deformation could cause accelerated erosion of geologic barriers overlying the repository horizon.
- Extrusive volcanic flow and ash deposits could pose significant hazards to surface structures at locations relatively close to eruptive centers.
- Igneous intrusion through a repository site could transport radioactive wastes directly to the surface.

Predictions of geologic phenomena can be based on probabilistic models, which assume a random distribution of events. The necessary historic and geologic records are rarely available to provide an adequate data base for such predictions. The observed distribution of volcanic and tectonic activity is not random, and appears to be controlled by extremely complex deterministic processes. The advent of global plate tectonic theory in the past two decades has been a giant step toward understanding these processes. At each potential repository site, volcanic and tectonic processes should be evaluated to provide the most thorough possible understanding of those deterministic processes. Based on this knowledge, judgments will have to be made as to whether or not the volcanic and tectonic processes pose unacceptable risk to the integrity of the repository. This report describes the potential hazards associated with volcanism and tectonism, and the means for evaluating these processes.

New and existing faults and fracture zones provide potential pathways for the migration of groundwater through the repository. Also, faulted and fractured rock poses engineering problems during

excavation; however, mining technology is capable of solving such problems. Displacements along new or existing faults through the repository could breach the geologic barriers that provide isolation for the waste.

The assessment of these potential hazards requires knowledge of the present distribution of faults in and near the repository, as well as knowledge of the displacement history of these faults. At the ground surface, faults can be located by geologic mapping, topographic analysis and aerial photograph interpretation. Sub-surface drilling and borehole logging can be useful in the identification of fractures and faults at depth. Seismic reflection methods can delineate subsurface fault structures, but only if reflectors are offset or terminated by the fault, or if the fault plane itself is a shallow dipping reflector. Other geophysical methods such as seismic refraction, gravity, magnetics, and electrical resistivity may yield anomalies on a traverse of a fault structure, but the interpretation of such anomalies has inherent ambiguity. No exploration program could guarantee the location of all faults and fracture zones in the vicinity of the repository, and a high probability exists that undetected minor faults and fracture zones will be encountered during construction. Flexibility in the layout of rooms and pillars within the repository would help to minimize the intersection of fracture zones with the repository. In dry rock formations, such as salt, radar reflection methods can be used to detect water-bearing faults ahead of the mining face.

Information concerning the timing, direction and amount of previous fault displacements aids in estimating the potential effects of these faults on a waste repository. The amount of displacement on a fault can be estimated, if an offset feature can be correlated from both sides of the fault. The direction of displacement can be inferred from slickenside striations on fault surfaces and from drag structures adjacent to faults. Dating of geologic materials that predate or postdate fault motions provides upper and lower bounds on the timing of movement. Carbon-14, Potassium-40 and Rubidium-87 are the most common isotopes used in radiometric dating. ^{14}C is applicable to materials younger than approximately 50,000 years, ^{40}K is applicable to materials older than 100,000 years, and ^{87}Rb is applied to materials older than 100 million years. Fission track dating is an indirect radiometric dating technique for minerals containing sufficient quantities of Uranium-238. Materials older than 3 million years have been dated with this technique. Several other more qualitative methods of dating geologic materials exist, and many of these are rate processes that require calibration by radiometric dates.

Linear patterns of microearthquake epicenters, as defined with seismograph arrays, can define active fault zones such as near New Madrid, Missouri. Present motions on active faults can also be monitored geodetically or with creepmeters placed across the fault; however, these measurements require fairly long observation periods.

Experience in mines and tunnels indicates that earthquake ground motions could cause only minor superficial damages to the underground excavations of a repository. After waste is emplaced and the repository is backfilled, these damages would be inconsequential. Surface waste handling facilities and mine shaft openings would experience more severe ground motion, and the design of these structures would have to comply with seismic criteria similar to those developed for nuclear power plants.

Slow vertical tectonic uplift could cause accelerated erosion, possibly breaching geologic barriers to waste migration. Geodetic leveling and tide gage data indicate that current uplift and subsidence rates are on the order of several mm/year in tectonically stable regions, and up to several cm/year near tectonic boundaries. Systematic errors in leveling data could be significant, but their magnitude is not presently known. Geologic evidence indicates that long-term vertical crustal movements proceed at much slower rates than those observed in leveling and tide gage surveys. The two types of data are compatible, if movements are episodic or oscillatory. If a present uplift rate of 5 mm/yr were held constant for 1,000, 10,000 or 100,000 years, resulting net uplifts would be 5, 50 and 500 meters, respectively. For increasingly long time spans, it becomes less and less likely that the scale of net movement will be as large as indicated by extrapolation from present rates of movement. Also, the toxicity of the nuclear waste would be decreasing with time. Vertical tectonic movements are judged a minimal hazard, except along tectonic boundaries where large uplift rates occur.

Extrusive volcanic deposits (lava flows, pyroclastic flows, mudflows, and ash) potentially threaten surface waste-handling facilities of a repository during their relatively short operational lifespan. After the repository is backfilled and sealed, extrusive volcanism would probably not have significant adverse effects on waste isolation. For extrusive volcanism, the time span of potential hazard is on the order of a hundred years, several orders of magnitude shorter than the time spans over which significant change in the distribution of volcanism can be observed in the geologic record. Extrusive volcanic hazard zones can be delineated based on the extent of recent (Quaternary) volcanic deposits.

Igneous intrusions could conceivably transport waste directly to the biosphere, and are a potential hazard to waste isolation until waste is reduced to nonhazardous levels, a time span estimated at 100,000 to 1,000,000 years. The possibility of volcanic intrusion occurring outside of Quaternary volcanic centers should be considered. The risk of intrusive volcanism at a potential repository site can be evaluated by assessing regional tectonic models and geothermal and geophysical data that may indicate the existence of magma at depth. The High Lava plains of Oregon and Idaho, the eastern and western margins of the Basin and Range Province and the Rio Grande Rift are zones of high seismicity and volcanism that may be boundaries between semi-independent lithospheric plates.

Characteristic earthquakes accompany the movement of magma, and may help in the location of subsurface magma reservoirs. Also, anomalous propagation characteristics of seismic waves through molten or partially molten regions of the earth's crust and upper mantle can be used as evidence for the location of magma chambers. Magma chambers may also produce magnetic and gravity anomalies. There is a large range of possible interpretations for gravity and magnetic anomalies, and these methods should only be used as supplemental evidence in an investigation of a potential magma body. Measurable surface deformations accompany the movement of magmas within crustal reservoirs. Most measured deformations have been on the flanks of active volcanos, but doming has been measured over a suspected magma body approximately 20 km deep in the Rio Grande Rift.

Measurements of conductive heat flow may provide a useful tool for the detection of areas of relatively high risk with regard to future igneous intrusions. Large scale regional anomalies may outline zones of weakness and tectonic boundaries, and localized heat flow anomalies may indicate the presence of magma at depth. Regional heat flow anomalies are associated with plate boundaries along the Cascade volcanic arc and the San Andreas fault system. Generally high heat flow along the Snake River Plain-Yellowstone trend and along the Rio Grande Rift could indicate crustal magmatic thermal sources and a higher risk of intrusion in these areas. A zone of high heat flow across northern Nevada appears to be associated with intrusive thermal events of Miocene age, as no present crustal magmatic sources are known. Small scale local heat flow anomalies may indicate the presence of shallow crustal magmatic reservoirs. A large, abrupt heat flow anomaly which occurs over the Yellowstone caldera is the best example of such an anomaly. Where magmas do exist at shallow crustal levels, there is likely to be significant heat loss through hydrothermal convection, which would inhibit quantitative modelling of conductive heat flow anomalies.

In summary, four aspects of tectonism and volcanism have been examined for their potential impact on repository performance and for the available means of evaluation:

- Faults
- Seismic Ground Motions
- Vertical Tectonic Movements
- Volcanism

Active faults and faults that provide unacceptable hydrologic communication with the repository must be avoided. Geologic environments that are free of active faults and have few minor existing faults are relatively common. No present day exploration program could guarantee the location of all faults or fracture zones prior to excavation. Repository design and layout should be flexible to deal effectively with faults or fractured zones, should they be encountered during construction.

Underground, seismic ground motions are not as severe as motions at the surface, and only minor damages would be anticipated in the mined openings of a repository. The design of surface waste handling facilities will be more critical with regards to seismicity. Technology exists to design structures such as nuclear power plants to withstand earthquake ground motions in areas of moderate and, in some cases, high seismicity. Seismic ground motion criteria would be a dominant factor in the site screening process only in regions of concentrated high seismicity.

Geologic evidence indicates that in most areas of the United States long-term rates of vertical tectonic movement would not be sufficient to alter the containment capability of a nuclear waste repository. Along major active tectonic boundaries, the long-term rates of vertical movement could have an adverse impact on a waste repository, and must be considered as a screening criterion for potential sites.

Areas in which it is probable that volcanic processes would have significant impact on a waste repository site are limited to well-defined belts of Quaternary volcanism. Sites near these belts should be located such that extrusive volcanic deposits from Quaternary volcanic centers would not compromise the safety of surface waste handling facilities. The potential for igneous intrusion during the time period required for waste isolation must be evaluated based on regional tectonic models and geophysical and geothermal data. In regions distant from any belts of Quaternary volcanism, one does not need to consider volcanism as a siting criterion.

3. FAULTS

Faults and joints are planar discontinuities resulting from fracture of rock masses. In most cases, the stresses that cause the formation of faults and joints are directly related to large scale tectonic processes. Faults have displacement parallel to the fracture plane, and joints do not. Minor faults consist of only one or a few fractures that are not extensive and across which little displacement has occurred. Large faults may consist of a zone several hundred meters wide that is pervasively fractured. Along some faults, or portions of faults, the fault is in constant motion (creep) and, along other faults, large episodic displacements are separated by periods of little or no movement.

The largest recorded episodic displacement of the San Andreas fault was 5 meters in the 1906 San Francisco earthquake. Large episodic vertical displacements have been observed during major Alaskan earthquakes. A maximum uplift of 13 meters and a maximum subsidence of 2 meters were associated with the 1964 earthquake in Prince William Sound (Plafker, 1975). Creep rates along the central and extreme southern sections of the San Andreas fault in California are on the order of several centimeters per year. The Garlock fault is a subsidiary fault associated with the San Andreas system and its motions have been estimated at 7 mm/yr and 1 cm/yr (Clark, 1974; Pavoni, 1971). The largest fault displacements and displacement rates in the United States are found along the major tectonic boundary represented by the San Andreas system. There are several other less active fault systems in the western United States; however, displacement documentation is generally lacking.

There is very little evidence of recent fault displacement in the central and eastern United States. In the New Madrid, Missouri region, seismic reflection profiles indicate normal faults that correlate to zones of high historic seismicity (Zoback, et al., 1979). The youngest sediments offset by the faults are of Eocene age. Displacement along the faults increases with depth, implying that movements have occurred along the faults since the Cretaceous. Seismic reflection profiling of the Charlestown, SC seismic region has revealed structural evidence of buried faults, but historic earthquakes do not appear to correlate to any specific structure (Schilt, et al., 1979). The Clarendon-Linden fault system in western New York State consists of a 5 to 15 km wide zone of steeply dipping reverse and normal faults that offset Precambrian and lower Paleozoic rocks. Historic earthquakes have occurred along this zone; however, no surface faulting has been found that is associated with the historic earthquakes (Fakundiny, 1978). The potential impact of a fault on the performance of a nuclear waste repository is dependent on the hydrologic behavior of the fault and on the history of fault motions.

3.1 Potential Effects on Repository

3.1.1 Hydrologic Effects

The primary adverse effect that open fractures could have on a waste repository is that they represent potential pathways for the migration of groundwater through the repository. The degree to which faults or joints will change the gross permeability of a rock mass is dependent on the rock types; the nature of the fault zone; and the spacing, orientation and intercommunication of the fractures.

In carbonate rocks, fractures are known to dramatically increase the permeability, probably as a result of dissolution and widening of fractures by groundwater. In karst regions of Hungary, it was found that 85 to 100% of all water flowing into underground mines was flowing in through faults and associated fracture zones (Tettamanti, 1967). Wells installed along a fault in crystalline igneous rocks in Sweden produced much higher yields (5x to 8x) than wells in adjacent unfractured bedrock (Davis and Dewiest, 1966). The bulk of groundwater movement through rhyolites and tuffs in a portion of the Nevada Test Site occurs through joints and faults (Blankennegel and Weir, 1975). A fracture zone may not contribute significantly to the gross permeability of the rock mass if deposits of minerals such as calcite, silica, or zeolites effectively cement the fractures. Many faults are filled with gouge, which can also reduce the permeability of a fault. In general, however, fractures will tend to increase the gross permeability of low-permeability rock types such as those presently being considered for nuclear waste repositories.

Fractures affect the permeability of rock masses to depths of several thousand feet (Ekren, 1974). The brittle elastic behavior of rocks near the earth's surface changes to more plastic behavior at depth. Plastic deformation, or creep, of rock can heal fractures and reduce fracture permeability. At the depths considered for geologic nuclear waste repositories in crystalline rock types, such as granite and basalt, no reduction in fracture permeability would be expected due to creep. Geologic evidence and mining experience indicate that at depths of several hundred meters rock salt and some shales are characterized by plastic behavior over long time spans. The time-dependent fracture healing process would be difficult to quantify as it is a function of fracture geometry, physical rock properties and stress conditions. Due to plastic deformation, fracture permeability in rock salt and some

shales could be expected to decrease with time after fracture formation, and fewer open fractures are likely to be encountered during excavation.

3.1.2 Excavation, Mining Effects

Jointed and faulted rock poses engineering problems for the excavation of mined repositories; however, mining technology exists to solve these problems. Avoidance of fault and fracture zones is a site selection criterion of high priority so that few faults and fracture zones would be anticipated.

3.1.3 Effects of Fault Displacements

Displacements along faults through or near to a repository could have an adverse impact on the short-term safety of repository operations as well as on the long-term integrity of the geologic containment. Before the repository is sealed and backfilled, displacement along a fault intersecting the repository could cause local caving, based on tunneling and mining experience (Carpenter and Towse, 1979). After waste emplacement fault displacement could rupture the engineered waste containment, providing direct hydrologic access to the waste form along the fault zone. Fault displacements occur at rates that range from undetectable to several centimeters per year. If these larger rates are considered over the time spans necessary for the safe isolation of radioactive wastes, movements along faults in or near to the repository could be large enough to breach geologic or hydrologic barriers to waste migration. For example, 1 km of offset would result from 100,000 years of displacement at a rate of 1 cm/yr.

The potential adverse impact of active faulting through a repository is very severe, and avoidance of such faults should be a site selection criterion of high priority.

It is a general consensus in the literature of site selection criteria that faults that have had displacements within the Quaternary period (approximately 2 million years ago until present) should not intersect the control zone of a repository (National Research Council, 1978; Nuclear Regulatory Commission, 1979). Also, the potential long-term impact of active faults outside of the control zone should be evaluated. The assessment of faulting hazards at a particular repository site requires knowledge of the distribution of existing faults and the timing and orientation of previous fault displacements.

3.2 Location of Existing Faults and Joints

The location of faults in the vicinity of a nuclear waste repository is critical, as faults are potential hydraulic conduits, and displacements along them could threaten the integrity of a repository. The areal density of faults is quite variable. In a statistical study by Brooke (1977), fault densities were determined for several areas in the United States based on published geologic maps. The highest average density observed was ten faults per square mile in the Nevada Test Site. A low value of 0.06 faults per square mile was determined for Roosevelt County in eastern Montana.

Faults or fracture zones are common geologic features, and no exploration program could guarantee the location of all minor faults and fracture zones within the repository horizon. In several cases, preliminary geologic and geophysical investigations of nuclear power plant sites have failed to locate fracture zones and faults that were revealed by subsequent excavation and construction (Geotechnical Engineers Inc., 1977). Preliminary exploration programs of repository sites are likely to be less effective at fault detection than power plant exploration programs, because of the greater depths involved. Due to the high probability that undetected minor faults and fracture zones will be encountered during construction, repository layout and design should be flexible to minimize fault intersection (Golder Associates, 1979).

3.2.1 Geologic Methods

Faults are easily identified when exposed at the surface, characterized as fractured zones across which relative motion has occurred. In areas of infrequent bedrock exposure, the identification of faults is difficult. Surficial geologic materials such as glacial deposits and alluvial deposits often limit bedrock outcrops to only a small percentage of a given area. Faults create zones of weakness that are often eroded preferentially to form topographic lows, where outcrops are infrequent. Springs and groundwater surface irregularities are commonly associated with faults. Typically, a fault would be identified by a linear topographic depression, with apparent offset determined from outcrops of dissimilar bedrock on opposite sides of the fault.

Subsurface drilling can add a third dimension to geologic mapping efforts. Abrupt changes in rock type, fracturing, gouge, slickensides and secondary minerals are all characteristics associated with faulting that could be detected in a core log. Extensive drilling should not be used in a reconnaissance exploratory program of the repository site, as each borehole creates a potential leakage path for radionuclides. Drilling is suggested,

however, for characterization of discontinuities defined by remote geophysical surveys (Geotechnical Engineers Inc., 1978). Although drilling should be limited, it cannot be avoided as a mapping technique.

3.2.2 Geophysical Methods

Remote exploration of rock masses for fault identification is possible with a wide variety of geophysical techniques. Geophysical surveys are relatively inexpensive and the methods do not alter the integrity of potential repository media. Seismic reflection yields a two-dimensional image of subsurface geologic structure and is particularly useful in the location of faults at depths of several hundred meters where a repository is likely to be located. Other geophysical techniques do not produce images of structure, but anomalies in the data may indicate the presence of buried faults; however, there is inherent ambiguity in the interpretation of these anomalies. In the following sections, each geophysical technique is discussed with regard to its applications and limitations for fault detection.

3.2.2.1 Seismic Reflection

With the seismic reflection method, geologic structure is mapped by measuring the travel times of impulses that travel from a surface source down to a reflecting layer and back to geophones at the surface. A series of reflection recordings are usually made to produce a profile that is similar to a geologic cross section, except that two-way travel time instead of depth is on the vertical axis. Conversion of travel time sections to depth sections is possible with velocity information obtained from well surveys, seismic refraction surveys or from multi-channel reflection surveys.

Reflection profiles are most effective at defining geologic structure in horizontal or shallow dipping sedimentary rocks because of laterally continuous reflecting horizons. At faults, these reflecting horizons are terminated or offset, which makes it possible to identify the fault structure. The edges of reflecting horizons exposed at a fault often produce parabolic diffraction patterns that line up along the fault plane on a reflection profile. If

the dip of the fault plane is shallow, it may show up as a dipping reflection with little resolution of features below the fault plane.

The resolution available on seismic reflection profiles is on the order of the wave length of the seismic signal. Short wave length, high frequency sources offer the highest resolution, but the rapid attenuation of higher frequency seismic energy restricts the depths to which high resolution seismic reflection is effective. Petroleum exploration seismic reflection systems are able to obtain reflections from depths of 20,000 feet. Under ideal conditions, such systems are capable of resolving structural relief to within 10 to 20 feet (Dobrin, 1976). Ash (1974) estimates that vertical offsets of greater than 25 feet in sedimentary rock or other rock types with well defined reflectors should be detectable by seismic reflection methods.

Seismic reflection is the best available geophysical technique for the delineation of subsurface geologic structures such as faults. The method yields the most detail in relatively horizontal sedimentary rocks, but even under ideal circumstances, minor faults with limited vertical offset would probably be undetected. Reflection profiling should be employed to locate as many fault structures as possible prior to subsurface construction.

3.2.2.2 Seismic Refraction

In seismic refraction prospecting, the distance between the source and an array of geophones is large relative to the vertical depth of the survey. Refraction surveys are most effective in horizontal and shallow dipping sedimentary rocks. Refraction surveys do not yield accurate structural pictures, but they do give information about the distribution of seismic velocity with depth. In limited cases, faults can be detected with refraction surveys. Ideally, a high velocity layer such as limestone or rock salt would underlie a low velocity layer in the faulted area. The location and the amount of offset of a vertical or near-vertical fault could be determined from a plot of time vs source to geophone distance (Dobrin, 1976).

Without prior knowledge of the location of the fault structure, it would be impossible to unambiguously infer the existence of a fault from an anomalous refraction travel time curve. Thus, refraction data should only be used to supplement other geologic and geophysical data in fault studies.

3.2.2.3 Radar Reflection

The principle of radar exploration is similar to seismic reflection in that travel times of reflected waves are analyzed to determine the location of discontinuities within a rock mass. Electromagnetic waves of short wavelength are used in radar systems, as opposed to the relatively long wavelength mechanical waves employed in seismic methods. The short wavelengths afford high resolution, estimated at +3 m, but the maximum penetration of most radar systems is on the order of several hundred meters (Geotechnical Engineers Inc., 1978). Faults can be detected by radar exploration if the fault juxtaposes rocks with different electrical properties, or if the fault zone itself has anomalous electrical properties. Radar waves can only propagate through essentially dry geologic materials. Water in excess of one-half percent by volume will render radar methods ineffective (Geotechnical Engineers Inc., 1978).

The radar source consists of a directed beam, and the receiver is located at the source. Within a plane, the direction to a reflector from the source can be determined to $\pm 9^\circ$ (Geotechnical Engineers Inc., 1978). Due to the roughness of geologic discontinuities and the short wavelengths involved, planar features can be detected by radar even if the plane is close to parallel to the beam direction.

The requirement for a nearly dry medium severely limits the possible applications of radar. Remote radar exploration from the earth's surface is not generally possible due to moisture in soils or rock between the surface and target horizons. Radar has found its broadest application in the exploration of rock salt formations from within salt mine workings. Brine cavities,

faults, shale interbeds and other discontinuities have been mapped at distances up to 400 m from the radar source. Radar has also been used in other dry rock types, and, in one case, penetration of up to 330 m was achieved in granite (Geotechnical Engineers Inc., 1978). Radar reflection would be most useful in detection of faults from within the repository horizon during the construction of a geologic repository in salt.

3.2.2.4 Gravity Methods

Gravimeters measure minute variations in the earth's gravitational field due to variations in the density of near-surface rocks. Faults can be detected by gravity surveys if the fault separates rocks of contrasting density. Gravity anomalies are somewhat ambiguous in that a variety of subsurface density distributions can be modelled to produce the same anomaly. Gravity data alone could not uniquely identify a fault structure. Gravity surveys are best used in conjunction with other geophysical methods such as seismic reflection to better define the subsurface density distributions.

3.2.2.5 Magnetic Methods

Magnetic surveys measure lateral variations in the intensity of the earth's magnetic field. Within a limited area, most lateral variations in total field intensity are due to variations in the subsurface distribution of rocks containing minerals of high magnetic susceptibility. Igneous and metamorphic rocks have very high magnetic susceptibility compared to sedimentary rocks, and most magnetic anomalies are related to changes in the structure of basement rocks or local igneous intrusions (Dobrin, 1976). Faults could be detected by magnetic survey if basement rocks or igneous intrusions such as diabase sills were offset by the fault.

Interpretation of magnetic data is similar to the interpretation of gravity data in that each anomaly can be modelled with a variety of subsurface structures and magnetic susceptibility contrasts. Modeling of magnetic anomalies can

be more specific if the magnetic data are combined with other geologic data pertaining to the geologic structure and magnetic properties of the rocks. Therefore, magnetic data are useful in the location of subsurface faults only when the interpretation can be supported by sufficient geologic and geophysical information.

3.2.2.6 Electrical Resistivity

Electrical resistivity is a measure of the amount of current that will pass through a medium under an applied voltage. In rocks, the porosity, permeability, degree of saturation and the chemistry of pore fluids are the main factors that determine the resistivity. The increased fracture porosity and permeability in a fault zone could appear as a region of lower resistivity in a regional survey. Ash (1974) indicates that geologic structures can be investigated to depths of 1000 ft with a surface resistivity survey. Resistivity surveys are of limited usefulness in fault location studies due to the variety of groundwater and geologic conditions that can produce resistivity anomalies.

3.2.2.7 Borehole Logging

Several methods have been developed by the oil and gas industry to supplement core logging information with downhole geophysical measurements. The methods that could be applicable to fault location are: photographic logs, resistivity logs and acoustic logs. Photographic logs are taken with a small camera inserted into the uncased portion of a hole. In zones of low core recovery, where faults would be suspected, photographic logs can help identify fracture density and orientation. Drilling fluid clarity and mud on the sidewalls of the well are problems that limit the usefulness of photographic logs.

Resistivity logs measure the resistivity of formations adjacent to the borehole by measuring potentials associated with natural or induced currents. The resistivity in fractured zones would be less than in unfractured zones, due to increased porosity, permeability and water content, although conditions other than high fracture density can produce similar resistivity profiles.

Acoustic logs and other borehole seismic methods measure the velocity and attenuation of compressional and shear waves in rocks adjacent to the well. Attenuation of seismic waves can be up to 10 to 20 times higher in fractured zones as opposed to unfractured zones (Ash, 1974). Acoustic log data cannot uniquely identify fault zones, as bedding plane laminations and lithology differences can produce similar attenuations.

3.2.3 Aerial Photographs and Remote Sensing

Faults or fractures often appear as lineaments on aerial photographs or remote sensing images. The anomalous tonal qualities that tend to outline fault traces are the result of changes in topography, groundwater conditions, soil type and vegetation. These changes can be very subtle and oftentimes lineaments which are obvious on aerial photos or remote sensing images are not detected in surface geologic investigations. Lineament interpretation should be used as a guide to outline areas that require further geologic and geophysical fault investigations as not all lineaments are due to the presence of faults.

Conventional aerial photographs record reflected visible light, whereas remotely sensed images can record radiation from other frequency bands such as infrared and microwave. False color images convert recorded nonvisible radiation to a usable form within the visible spectrum. Infrared images are more sensitive to surface moisture variations than are standard aerial photographs, and, in some cases, they have been used with more success than conventional photographs in fault location (Sabins, 1974). Sophisticated remote sensing systems have multispectral scanners that digitally record radiation from several discrete wavelength bands. Computer processed images are capable of discriminating different rock types that are known to have a characteristic radiation frequency distribution (Kahle and Rowan, 1980). Geologic mapping based on these images would help to further define the nature of lineaments.

Side looking aerial radar (SLAR) uses a radar radiation source at the aircraft, and images are created from recorded reflected radiation. The radar method is very effective at detecting lineaments that are perpendicular to the radar scanning direction, and flight plans should be oriented to take advantage of this. Radar images tend to define more geologic structures in vegetated terrain than do conventional aerial photographs (Sabins, 1974).

In a program to detect faults and fracture patterns at a potential repository site, aerial photographs and remotely sensed images should be utilized in a reconnaissance stage to determine lineaments that would require in-depth geologic and geophysical investigation.

3.3 Defining Fault Motions

A major concern in the evaluation of hazards posed by faults is the potential for future displacements. Analysis of geologic structure within the fault zone and dating of materials adjacent to faults helps reveal the nature and timing of previous displacements. Present movements can be inferred from earthquakes detected with seismograph networks and from geodetic strain measurements. Assessment of the risk of future displacements on existing faults and the potential for new fault development is based on what can be learned of past and present fault displacements.

3.3.1 Measuring Previous Fault Displacements

The determination of the direction and amount of displacement along a particular fault is possible if one can measure the displacement between two originally contiguous points. However, when a planar feature such as a particular sedimentary layer is offset by a fault, there is a 180 degree range of possible displacement directions, and only a minimum value can be assigned to the amount of displacement (Fig. 7a). The direction and amount of displacement can be determined if a linear feature such as the intersection of planar features (for example, a dike and a sedimentary layer) is offset by a fault (Fig. 7b). The displacements measured by such means represent the amount of displacement that has occurred along the fault since the formation of the offset feature. Features that were formed some time after the initiation of faulting, such as young dikes and erosional surfaces, do not provide measures of total fault displacement.

Polished striated surfaces known as slickensides are common along fault planes. All such striations were originally thought to be caused by abrasion during fault movement (Billings, 1972); however, in some cases, the striations are due to parallel growth of elongate crystals, such as quartz (Hobbs, et al., 1976). Studies by Durney and Ramsey (1973) reveal that the orientation of the fibrous crystal growth is parallel to the direction of fault displacement. Bent crystals have been found on fault planes, presumably caused by a change in the direction of displacement. Regardless of the origin of the

slickenside striations, their orientation is parallel to the fault motion that caused them.

Most slickensided surfaces contain small steps facing in one direction and oriented roughly perpendicular to the striations. The fault surface will feel rough to the touch if the steps oppose the movement of the fingers, and a smooth feeling will result if the fingers are passed in the opposite direction. Most field evidence indicates that the fault motion relative to stepped slickensided surfaces is as shown in Fig. 8a (Billings, 1972). In triaxial tests at low confining pressure on limestone, Paterson (1958) has shown that the steps can be oriented opposed to fault motion as in Fig. 8b. Tija (1964) found field evidence of steps similar to those created by Paterson in the lab, although such field evidence is uncommon.

Deformation of planar features adjacent to faults, or fault drag, can be another indicator of the sense of displacement on a fault. Fig. 8c shows fault drag structures relative to the direction of fault displacement. Drag is probably due to deformation prior to fault rupture, but it could also be due to frictional drag as the name implies.

3.3.2 Dating Previous Fault Displacements

To determine the timing of fault activity, geologic materials in the vicinity of faults have been dated by various methods. Based on structural relationships, it is possible to determine if the dated material predated, postdated or coincided with fault movement. It is most common for the age of a fault to be expressed in terms of upper or lower bounds from dating of materials that pre-date or postdate motions. As an example, a dated sedimentary layer that is offset by a fault or fractured by joints places a bound on the oldest possible age of fault or joint activity. On the other hand, an intact dated igneous intrusion that cuts across a fault or joint set places a lower bound on the most recent fault or joint activity. The most widely accepted and accurate age dating techniques are based on radiometric decay processes. Most other dating techniques are qualitative assessments of biologic or geologic rate processes that require calibration with radiometric dating techniques.

3.3.2.1 Radiometric Methods

The radioactive decay process can be used as a geologic clock to determine the age of materials, provided the following conditions are met:

- The present concentration of the radioactive isotope can be measured.
- The relative concentrations of the radioactive isotope and its daughter isotope can be estimated at the time of mineral or molecule formation.
- The mineral or molecule has remained a closed system, i.e., changes in the relative amounts of the radioactive and stable daughter isotopes are due to radioactive decay only.
- The decay rate for the unstable isotope is known.

Three radioactive isotopes have been used in the majority of fault dating studies for nuclear reactor sites: ^{14}C , ^{40}K and ^{87}Rb . Another isotopic age dating method that holds promise for fault dating is ^{238}U fission track dating. Other isotopic dating techniques exist, but the four methods mentioned above are most commonly applied to fault studies and will be described in the following section.

Carbon 14 is a relatively short-lived isotope with a half life of roughly 5730 years (Faure, 1977). A relatively constant ratio of ^{14}C to ^{12}C is maintained in the earth's atmosphere and in living plant or animal tissue. After death, new ^{14}C atoms are not added to the tissue, and the concentration of ^{14}C decreases with time due to radioactive decay. The concentration of ^{14}C in fossil plant or animal tissue is compared to the concentration of ^{14}C in living tissues to determine the relative age of the fossil tissue. Due to the relatively short half life of ^{14}C , accurate age determinations are possible up to roughly 30,000 to 50,000 years, although recent developments in analytical techniques may make it possible to make age determinations up to 100,000 years (Grootes, 1978; Muller, et al., 1978).

A potential source of significant error in the ^{14}C method is the contamination of the sample with younger organic material such as intruding tree roots (Hamilton, 1965).

Carbon 14 age dating was used in the geologic investigation of faults near the WPPSS 3 and 5 nuclear power plant sites in Washington state. In an area near the site, deformed and faulted Tertiary bedrock is overlain by undeformed silty sands and sandy gravels. Organic materials from within the undeformed sediments yielded ^{14}C ages of 10,000 years to greater than 50,000 years, which placed lower bounds on faulting in the Tertiary bedrock (Washington Public Power Supply System, 1974). Another example is from near Augusta, Georgia where organic material from a displaced horizon above the Belair fault has been ^{14}C dated at approximately 2,000 years, which implies very recent offset along this fault (South Carolina Electric and Gas Co., 1977).

Another isotope that is commonly used for radiometric dating is Potassium-40. When a potassium bearing mineral crystallizes, trace amounts of the radioactive isotope ^{40}K are bound into the crystal lattice. Increasing amounts of ^{40}Ar created by the decay of ^{40}K will be trapped in the crystal; thus, the ratio of $^{40}\text{Ar}/^{40}\text{K}$ is a measure of the time elapsed since the crystallization of the mineral. Argon is an inert gas that can diffuse out of minerals in the solid state. The diffusion rate is higher at elevated temperatures, and some metamorphic events may cause the release of all ^{40}Ar , resetting the ^{40}K - ^{40}Ar geologic clock. Minerals such as muscovite and biotite that are resistant to diffusion of ^{40}Ar at low temperatures are sought as samples for K-Ar dating. The half life of ^{40}K is approximately 1.3 billion years, and the application of the K-Ar dating technique is limited to minerals older than approximately 100,000 years (Dott and Batten, 1976). The largest uncertainty associated with the K-Ar method is the extent of argon diffusion, which will cause apparently younger age dates. Errors associated with argon diffusion are difficult to quantify, as a record of the sample's thermal history would be required.

The age of faulting in Piedmont bedrock at the Summer nuclear plant site was bracketed by K-Ar age determinations on faulted granodiorite and on zeolite minerals deposited hydrothermally in the fractures (45 $\pm$ 5 m.y.) (SCEGC, 1977). The 45 m.y. date may be significantly younger than the actual age, due to argon diffusion from the zeolite minerals. Potassium/argon dates from fractured granodiorite and breccia in the fault zone yielded ages of approximately 230 m.y., which probably predates fault motion. In a K-Ar study of fault gouge at the North Anna power station, gouge materials were interpreted to represent a mixture of parent rock minerals and weathering products (Dames and Moore, 1973). Dates determined for the fault gouge materials were not believed to accurately represent the time of faulting. Authigenic minerals such as glauconite have been used for K-Ar dating of sedimentary rocks, but their occurrence is rare, and the results have been unreliable (Dott and Batten, 1976). Age determinations from deformed glauconite-bearing shales at the Watts Bar nuclear plant site were approximately 390 m.y., which is considerably younger than stratigraphic estimations of the age of the shales (approximately 530 m.y.) (Tennessee Valley Authority, 1976). Argon loss during subsequent low-grade metamorphism was cited as the probable cause of the discrepancy.

Another isotope commonly used in geochronology is Rubidium-87. Potassium-bearing minerals like micas will include trace amounts of ^{87}Rb during crystallization in substitution for potassium ions. Once locked in the crystal structure, steady decay of ^{87}Rb to ^{87}Sr will decrease the ratio $^{87}\text{Rb}/^{87}\text{Sr}$, which is used as a measure of the mineral's age. The Rb-Sr method is generally applicable to rocks that are older than 100 million years, and the half life of ^{87}Rb is approximately 5 billion years (Dott and Batten, 1976). Particularly in the dating of younger rocks, it is necessary to know how much of the observed ^{87}Sr content is original, and how much is due to decay of ^{87}Rb . Estimates of the original $^{87}\text{Rb}/^{87}\text{Sr}$ ratio for a certain mineral and rock type can be made by analyzing specimens of

similar mineralogy from recent igneous rocks. For older rocks, the original ^{87}Sr content is not as important as it becomes less significant in comparison to ^{87}Sr generated by ^{87}Rb decay. The Rb/Sr method is most commonly applied to igneous and metamorphic rocks, but applications to sedimentary rocks have been made (Faure, 1977). Whole rock specimens of shale are analyzed for Rb/Sr ratios, and the assumption is made that the detrital and authigenic minerals in shales form at approximately the time of deposition. Persistent detrital minerals like micas may remain intact from erosion to deposition, and increase the apparent Rb/Sr age of the shale. At the Summer nuclear reactor site near Augusta, Georgia Rb/Sr as well as K-Ar dates were determined for specimens of granodiorite encountered in the excavations. Both analyses yielded ages of approximately 300 million years, lending confidence to the results of both methods (SCEGC, 1977).

Fission-track age dating is another recently developed radiometric technique that has found application in fault dating studies. Uranium ^{238}U spontaneously decays through a lengthy series of unstable isotopes to a stable daughter product, ^{206}Pb . When ^{238}U is bound in a mineral, fission products tear through the crystal lattice, creating discontinuities or "tracks." With the aid of chemical etching, the tracks can be seen and counted under a microscope. The ratio of natural fission tracks to fission tracks induced by bombarding the sample with thermal neutrons is a measure of the age of the specimen. Fission tracks will anneal at elevated temperatures, so that tracks can be erased by metamorphic events. If thermal metamorphism has occurred in the history of the crystal, this ratio reflects the time elapsed since the most recent thermal event. The half life of ^{238}U is 4.5 billion years, but the fission track dating method can be applied to rocks as young as 3 million years, providing the ^{238}U concentrations are high enough in a particular mineral (Hamilton and Farquhar, 1968). Zircon, apatite, natural glasses and hornblende are minerals that have favorable concentrations of ^{238}U .

The fission track dating method has been applied to epidote, a common hydrothermal mineral in faults and fractures. Fission tracks in epidote remain stable up to temperatures where the mineral itself becomes unstable, thus age dates are probably representative of the time of crystallization (Bar, 1974). Bar determined the ages of epidote samples from two faults to be 11 to 32 million years and 103 to 120 million years. These ages were in agreement with geologic evidence for the age of faulting.

3.3.2.2 Residual Soils and Weathering Profiles

Qualitative estimates of the age of surficial geologic materials can be useful in fault dating if a stratigraphic relationship is established between a fault and the surficial materials. Residual soils and weathering profiles develop slowly, the exact rate of development being primarily dependent on the bedrock type, climate and vegetation. In some cases, the rate of soil development for a particular area has been calibrated with radiometric and other dating techniques. In large areas of the southwest United States, calcium carbonate is precipitated from downward percolating groundwater to form a "caliche" zone at depth in the soil profile. The rate of caliche accumulation was calibrated by Machette (1978) using K-Ar and other age dating techniques. Based on this method, Machette assigned dates ranging from 20,000 years to 400,000 years for faulting episodes on a specific normal fault in the Basin and Range Province.

Saprolite is a reddish residual clay soil formed in humid climates from a wide variety of bedrock types. Saprolite soil profiles have been used only qualitatively to assess the age of faults. At two nuclear power plant sites, Watts Bar in Tennessee and WPPSS 3 and 5 in Washington, unfaulted saprolite soils have developed in faulted materials near the surface (WPPSS, 1974; TVA, 1976). Saprolite up to 100-ft-thick has developed in basalts beneath a relict erosion surface near the WPPSS 3 and 5 site. Oxidation in the bedrock extends to depths of 200 ft below the erosion surface. Faults displace the basalt bedrock, but do not displace the saprolite or relict erosion surface. The age of the saprolite soil was estimated to be greater than 2 million years, which postdates the most recent faulting of the basalt.

At Watts Bar, saprolite and a relict erosion surface have developed on shale. Pleistocene gravels overlie the saprolite and neither is offset by faults in the shale (TVA, 1976). The saprolite profile and erosion surface were probably developed during a Pleistocene interglacial stage or earlier, and faulting predated this development.

The age of Pleistocene surficial deposits is often estimated for fault dating studies. Drastic changes in climate, sea level and environments of deposition during glacial stages makes identification of glacial deposits fairly easy. The timing of Pleistocene glaciations is well documented in North America, especially the most recent Wisconsin stage with the help of ^{14}C dating. Analysis of stratigraphic relationships between glacial deposits and faults can yield useful qualitative information about the Quaternary history of fault motions.

For example, within four miles of the San Onofre, California nuclear power plant site, several faults displace Pliocene sedimentary rocks. These, in turn, are overlain by undeformed Pleistocene gravel terrace deposits associated with higher sea-level stands. Based on geologic evidence, the age of the gravel terrace, thus the youngest possible age of faulting, has been estimated at greater than 120,000 years (Southern California Edison Co., 1977). Gravel deposits known to correlate to the Orting glaciation of Puget Sound 700,000 to 540,000 years ago are not offset by underlying bedrock faults near the WPPSS 3 and 5 site (WPPSS, 1974). Weathering of the top 25 to 50 ft of these gravels probably occurred during an interglacial stage 540,000 to 320,000 years B.P.

3.3.2.3 Other Methods

Several other dating techniques have been applied to fault chronology studies, but their use has been limited in comparison with the methods described in the preceding sections. The concepts and applications of some of these other dating techniques are summarized below.

- Paleontology - The relative ages of fossiliferous sediments can be determined by correlating the fossil community to a stage in the evolution of life forms. The sequence of evolution has been correlated to an absolute time scale by radiometric dating methods. Paleontology is particularly useful for the dating of older sedimentary rocks, as evolutionary changes are more pronounced over long time spans. Paleontology would be of little use in defining the age of Quaternary deposits.
- Palynology - Palynology is the study of pollens, spores and their distribution. Pollens and spores that are found in sedimentary deposits indicate past vegetation and, therefore, past climates. This can provide relevant data in identifying the approximate age of Quaternary, and, particularly, Pleistocene deposits (Webb, et al., 1980).
- Paleomagnetism - In the past, the earth's magnetic field has undergone long-term changes in orientation and intensity, including polarity reversals. These changes are recorded in the orientation and magnetization of minerals crystallizing within rocks at that time. If the orientation and remanent magnetization of minerals in a rock of unknown age are compared with the established time scale of paleomagnetic variations, an estimate of the rock's age can be made.
- Tephrochronology - Explosive volcanic eruptions can spread continuous ash layers for several hundred kilometers downwind of the volcano. The ages of these layers are often known from radiometric or other dating techniques, and the dated layers provide unique marker beds of wide distribution (Porter, 1978). Tephrochronology is particularly applicable to fault dating studies in the Pacific Northwest, where USGS investigators have identified over 25 distinct Quaternary tephra layers associated with Cascade volcanic eruptions (Kittleman, 1979).

- Glass Hydration - Diffusion of water into the surfaces of volcanic glasses causes the formation of a rind of hydrated glass. The hydration rind thickness is proportional to the square root of elapsed time since the formation of the glass (Friedman and Long, 1976). The rate of hydration varies, depending on the temperature and the composition of the glass. For a particular area, the rate of hydration is calibrated with other dating techniques. Once calibration is established, approximate dates can be determined based on rind thicknesses measured in thin section. The method is restricted to fault studies in relatively recent volcanic deposits.
- Amino Acid Racemization - For each amino acid, two otherwise identical mirror image forms are possible. In living organisms, virtually all amino acids are of the L-type and very few are of the D-type, which are mirror images of L-amino acids. After death, a process called racemization leads to the formation of roughly equal quantities of L- and D-amino acids. The process of racemization is time dependent, and the increasing D/L ratio for a particular amino acid is a measure of the age of the tissue (Schroeder and Bada, 1976). Skeletal remains provide the best tissues for dating purposes. The technique is applicable to materials as old as Pleistocene and possibly Pliocene.
- Fluid Inclusions - Fluids are often trapped within minerals that crystallize in fractures from circulating aqueous solutions. It is possible from analysis of these fluids to determine the range of possible temperatures and pressures that existed at the time of crystallization. Based on this range of temperature and pressure, and reasonable values of geothermal and pressure gradients, one can determine the range of depths at which the mineral crystallized (Peck, 1980). The age of the mineral is approximated by assuming a conservative denudation rate and calculating the time required to bring the mineral from its original depth to the earth's surface. There are several sources of uncertainty in this method which can yield only rough estimates of the age of fault activity.

3.3.3 Measuring Present Fault Displacements

The potential for future displacement is very high along faults that are presently active and such faults should be avoided in the siting of waste repositories. Present displacements can be monitored directly by means of strain measurements across the fault or indirectly with measurements of seismic activity.

3.3.3.1 Seismic Studies

Networks of seismograph stations are used to locate and estimate the magnitude of earthquakes. Small scale arrays of sensitive instruments are able to detect and locate micro-earthquakes as small as magnitude 1.0 to 2.0. Such small events are common, even in less seismically active regions. A persistent linear pattern of earthquake epicenters probably indicates the presence of an active fault structure.

A network of 16 seismograph stations capable of detecting magnitude 1.0 earthquakes was established in the New Madrid, Missouri seismic zone (Stauder, et al., 1976). During a 21-month period, 330 earthquakes were monitored, and their distribution revealed a linear zone of concentrated activity (Fig. 9). The location of these epicenters varied from +2 km accuracy to +10 km accuracy near the fringes of the array. Seismic reflection profiles in the vicinity reveal several faults and graben structures that coincide with the bands of seismicity (Zoback, 1979). The faults offset sediments of Eocene to Cretaceous age, but no offsets have been found in Quaternary alluvium. Another seismic zone near Charleston, South Carolina has been monitored with a network of 10 seismograph stations (Tarr, 1977). For the period of 1973 to 1975, a cluster of earthquake epicenters has been defined just northwest of Charleston (Fig. 10). It is unclear whether this concentration of seismic events correlates to a specific geologic structure.

3.3.3.2 Strain Measurements

Horizontal strain measurements have been made across known or suspected active fault zones. Most measurements have been geodetic, but, in some cases, rod or wire strain meters have been employed. The first geodetic strain measurements

were made with optical triangulation surveys. Movements along the San Andreas fault in central California were determined to be 32 to 49 mm/yr with the triangulation method (Savage and Burford, 1972). The recent development of laser-ranging devices such as the geodolite has allowed greater accuracy in strain measurement with trilateration. The standard deviation of geodolite distance measurements is 3 and 8 mm for distances of 1 and 37 km, respectively (Savage and Prescott, 1973). Trilateration data for the central California section of the San Andreas fault yield rates of 28 to 37 mm/yr (Savage and Burford, 1972).

Creepmeters consist of a rod or wire made of invar or stainless steel, suspended horizontally across a known fault between two supports. The sensitivity offered by the rod creepmeters is 0.1 mm, compared to 0.05 mm sensitivity for the wire creepmeters (King, 1977). Goulet, et al. (1978) measured creep of 15 to 25 mm with creepmeters across the faults in the Imperial Valley of California, but allowed that 2 to 3 mm of motion could have been due to temperature effects on the stainless steel wire. Creepmeters were installed at several locations in the central California section of the San Andreas fault. Results indicate a minimum rate of movement of 15 mm/yr, which is less than estimates of movement from trilateration (Lisowski, 1977). The discrepancy could be due to motion on other faults or deformation adjacent to the fault zone, but outside of the creepmeter. Strain measurements are useful for defining motion or the lack of motion across a fault, but require a fairly long observation period.

4. SEISMIC GROUND MOTIONS

4.1 Potential Effects on Repository

Ground motions associated with earthquakes could be expected to affect most repository sites at some time during the life span of a nuclear waste repository. The magnitude and frequency of motions at a given site is a function of the regional seismicity and site specific attenuation characteristics.

Shear wave and surface wave motions are responsible for most damages to structures at the earth's surface (Bolt, 1978). Ground motions below the earth's surface are not as severe, due to the lack of surface waves and surface amplifications of body waves. A thorough investigation by Rozen (1976) reveals that only limited damages have occurred in rock tunnels during earthquake shaking. Most reported damages consisted of surface spalling of rock and cracking of tunnel linings. Serious damages have been restricted to cavings at tunnel portals and actual fault offsets within tunnels (Rosen, 1976; Carpenter and Towse, 1979). In one remarkable Japanese case history, 55% of all houses above a particular tunnel were destroyed during a magnitude 7.0 earthquake. Other than a 2.3 meter offset where the causative fault intersected the tunnel, only minor damage occurred in the tunnel which was 160 m below the surface (Rosen, 1976). During the 1964 Alaskan earthquake ($M = 8.4$) only minor surface spalling occurred in the Alaska Railroad tunnel near Whittier, less than 100 km from the epicenter. The tunnel is 4500 m long and several hundred meters deep in its center.

In a deep geologic repository in moderate or low seismicity regions, only minor surface damages would be anticipated during earthquake shaking. After backfilling of the repository is complete, no adverse effects would result from earthquake ground motions. Surface waste handling facilities and mine shaft openings would be the most vulnerable parts of a waste repository.

4.2 Evaluation of Ground Motions

Earthquake engineering criteria for the surface facilities of a geologic nuclear waste repository would be similar to the criteria developed for nuclear reactors. The seismic design of nuclear reactors is based on the selection of two design earthquakes for a given site (CFR 10 Energy, 1977). The safe shutdown earthquake (SSE) represents the maximum earthquake potential for the site, and the operating basis earthquake (OBE) represents an earthquake that has a reasonable probability of affecting the site during the life span of a nuclear power plant. The plant must be designed to remain functional and shut down safely after an SSE, and must be able to safely continue opera-

tion during an OBE. The studies that are necessary to define these design earthquakes are:

- Regional structural and historical geology
- Location and evaluation of tectonic structures
- Evaluation of the dynamic behavior of geologic materials at the site
- Evaluation of historic seismicity
- Evaluation of seismically induced flooding and water waves

The scope of seismic investigations for surface facilities is quite different from the scope of studies pertaining to the long-term geologic containment characteristics of the repository and will not be treated in further detail in this study.

5. VERTICAL TECTONIC MOVEMENTS

5.1 Potential Effects on Repository

Over the time spans considered necessary for the safe isolation of radioactive waste (100,000 to 1,000,000 years), it is conceivable that the net vertical movement of a geologic repository due to tectonic processes could alter the geologic and hydrologic containment characteristics of the repository. Areas that experience relatively rapid rates of uplift will have accelerated erosion rates, which could, in turn, bring a repository closer to the earth's surface. Tectonic subsidence of the repository would pose less of a problem to the integrity of the repository, and may be desirable (Gera and Jacobs, 1972).

5.2 Evaluation of Vertical Movements

Geodetic releveing surveys and tide gage measurements indicate that current rates of vertical crustal movements are on the order of several millimeters per year. These rates, if held constant for 100,000 years, could produce net vertical movements of several hundred meters. In most cases, geologic evidence indicates that long-term vertical crustal movements proceed at much slower rates than those measured with geodetic methods.

5.2.1 Releveing and Tide Gage Measurements

The National Geodetic Survey (NGS), formerly the U. S. Coast and Geodetic Survey, periodically performs leveling surveys of a network of vertical control benchmarks. Elevation differences are measured optically between adjacent benchmarks along survey routes. Comparison of surveys performed over periods of several tens of years reveals broad patterns of elevation change. The rates of change, if averaged over the time span covered by the surveys, are on the order of several mm/yr. relative to a reference benchmark. Provided the measurement errors are not larger than the observed movements, the movements are due to vertical crustal movements.

Brown and Oliver (1976) discuss the errors associated with leveling, and conclude that the observed movements are due to crustal movements. Random error is evident in any releveing profile, but broad patterns (wavelengths of several 100 km) of vertical movement are discernable despite the random noise. Repeated leveling surveys along the Gulf Coast showed similar patterns and rates of vertical movement in successive intervals between surveys (G. Jurkowski, pers. comm.). The

patterns of vertical movement correlate well to regional geologic structure and topography, a fact that Brown and Oliver (1976) cite as evidence that the data represent crustal movements. The degree to which systematic errors affect leveling data is not well understood. In many cases, the observed patterns of vertical movement correlate directly to patterns of topography along the leveling profile. Miscalibration of surveying rods or atmospheric refraction are possible sources of systematic topography-correlated errors (Jackson, 1979; Bomford, 1962).

Long-term changes in mean sea level readings at a tide gage are due to a combination of eustatic sea level changes and vertical movements of the tide gage. Eustatic sea level rise of approximately 1 mm/yr is subtracted from the observed tide gage readings to determine vertical movement of the tide gage (Bird, 1969). Rates of movement determined from tide gages are of the same order of magnitude as those determined from releveling (Brown, 1978). Releveling studies of the eastern United States reveal that the Appalachian Mountains are uplifting at relative rates as high as 6 mm/yr (Brown and Oliver, 1976; Jurkowski, et al., 1979). The trend of uplift is roughly coincident with the topographic pattern of the Appalachians. Relative subsidence is occurring in parts of the Atlantic and Gulf Coastal plains. Some of the observed movements, particularly near the Mississippi Delta, may be due to sediment compaction. In Houston, Texas subsidence rates up to 10 cm/yr accompany water withdrawal (Mead, 1975).

Near tectonic boundaries and active faults, rates of vertical movement can be considerably higher. The famed "Palmdale bulge" near Palmdale, California was observed to have a maximum relative uplift of 0.25 meters between 1959 and 1974, a rate of 17 mm/yr (Castle, 1976). The Palmdale bulge is adjacent to the San Andreas fault in a region where the fault may be locked. The observed uplift at Palmdale exhibits strong correlation to topography, and may actually be the result of systematic error associated with topography (Jackson, 1979). In Japan, rates of vertical movement as high as 10 to 120 mm/yr have been measured in 10- to 15-year intervals preceding major earthquakes (Mescherikov, 1967). Vertical crustal deformation rates near tectonic boundaries can be approximately one order of magnitude larger than rates observed in stable interior regions. The higher rates of movement appear to be confined to narrow belts along major active faults. Releveling across the Rio Grande

Rift near Socorro, NM reveals an elliptical uplift of some 7000 km² (Reillinger and Oliver, 1976; Reillinger, et al., 1979). The maximum relative uplift of 20 cm since 1911 is centered over a crustal discontinuity at approximately 19 km depth. The discontinuity detected by seismic means is believed to be the top of a large magma chamber.

Vertical isostatic adjustments to loads imposed by glaciation, flooding and sedimentation are fairly well documented. Crustal depression of several hundred meters has occurred under the weight of Wisconsin ice sheets in Fenno-Scandia and northern Canada. As much as 500 to 600 meters of rebound has occurred in portions of Fenno-Scandia and an additional rebound of more than 200 meters is expected (Gera and Jacobs, 1972). Current rates of uplift measured with tide gages are nearly 10 mm/yr in the center of the Fenno-Scandian uplift. Loads imposed by glacial Lake Bonneville in Utah created a local depression, and surveying indicates that current rebound rates are roughly 2 mm/year (Bolt, 1975). As the density of water or ice is roughly one-third that of asthenospheric materials displaced during isostatic adjustment, the crustal depression is approximately one-third the thickness of ice or depth of water. Vertical crustal deformations due to future glaciations would be of similar magnitude.

5.2.2 Geologic Evidence

Rates of vertical movement over longer time spans have been estimated from geologic evidence. These rates are consistently one to two orders of magnitude less than current movement rates measured with leveling and tide gages. The Rocky Mountain uplifts have been on the order of 1500 to 3000 meters in the past 15 million years, an average rate of 0.1 to 0.2 mm/yr uplift (Press and Siever, 1974). Tilting rates inferred from terraces and sediments on the Atlantic coastal plain are up to two orders of magnitude less than tilting rates derived from releveing (Brown and Oliver, 1976). Extreme rates of uplift (1.8 mm/yr) are found in the Himalayan foothills, where 1800 m of uplift has occurred since mid-Pleistocene (Gera and Jacobs, 1972).

A large discrepancy exists between vertical movement rates measured over spans of tens of years (releveling, tide gage studies) and rates measured over millions of years (geologic evidence). In tectonically stable

regions, the discrepancy is larger. The two sources of data are compatible, if movements are episodic or oscillatory. If movements are oscillatory, the period of oscillation would probably be less than 1 million years to keep the amplitude of movements within reason (Brown and Oliver, 1976). In studies of oscillatory transgressive-regressive sedimentary sequences in stable continental areas, Sloss and Speed (1974) discovered that the period of these oscillations was often in the range of 100,000 to 1 million years. The transgressions and regressions are probably correlated with subsidence and uplift, respectively. The present rates of movement appear to be on the order of several millimeters per year. If held constant, a rate of 5 mm/yr would produce net movements of 5, 50 and 500 meters over 1,000, 10,000 and 100,000 years, respectively. The magnitude of net movements predicted by constant rates is less likely over longer time spans, due to the episodic or oscillatory nature of movements. Because the toxicity of the nuclear waste would decrease with time, vertical tectonic movements pose a minimal hazard, except where large uplift rates occur along tectonic boundaries.

6. VOLCANISM

6.1 Potential Effects on Repository

For the purposes of this study, the potential hazards of volcanism have been subdivided into two categories: extrusive volcanism and igneous intrusion. Extrusive volcanism poses a threat to surface waste handling facilities during their operational life span of several tens of years but does not threaten the long-term containment of waste after emplacement. Igneous intrusions could adversely affect repository containment for as long as the waste remains hazardous, a time span estimated at 100,000 to 1,000,000 years.

6.1.1 Extrusive Volcanism

Lava flows, pyroclastic flows, mud flows and ash falls are all hazards of extrusive volcanism that could potentially affect a nuclear waste repository. The hazards posed by extrusive volcanism would be greatest during the operating life of surface waste handling facilities. After the repository is backfilled and sealed, extrusive volcanism would probably not have any adverse effects on the containment characteristics of the repository. If a lava flow, pyroclastic flow or large mud flow were to impinge upon the surface facilities of a waste repository, the consequences would certainly be disastrous. Fortunately, with an understanding of the flow processes and geologic mapping of recent deposits, it is possible to site a repository outside of the range of hazardous flow deposits. Extrusive volcanism can be considered in terms of the present distribution of active volcanism, which will not change significantly during the short-term operation of surface facilities. The various types of extrusive volcanic deposits and the extent of potential hazards for each will be discussed below.

The nature of lava flows is primarily dependent on the viscosity of the lava. Lavas that have high viscosity tend to form short, thick flows, and low viscosity lavas can form thin, extensive flows. Magmas rich in silica (SiO_2), such as rhyolites and dacites, tend to have high viscosity and form bulky flows that rarely travel farther than several kilometers from the source vent. Basaltic lavas are lower in silica and are capable of producing extensive thin flows. Individual fissure-erupted basalt flows from the Columbia River plateau are 10 to 65 m thick and cover areas up to 18,000 km² (Williams and McBirney, 1979). Quaternary basalt flows in Iceland reach distances of up to 88 km from the source fissure.

As a magma rises to the earth's surface, pressures within it decrease and gases come out of solution and expand. In more viscous magma, this occurs rapidly as the magma extrudes at the surface, producing explosive eruptions. Fragments of molten and cooling material are blown into the air by expanding gases. This mass of glowing fragments can become fluidized and flow several tens of kilometers. As the pyroclastic flow (nueé ardente) proceeds, cold air is entrained and rapidly expands as it is heated, sustaining the fluid behavior. As the flow loses energy, the hot fragments settle out to form deposits of glass shards that are often fused or welded together. These rock types are known as ignimbrites, ash flows or ash flow tuffs. Their chemical composition is generally close to that of rhyolite or dacite, as these tend to be the more viscous and explosive magmas. Ignimbrite deposits in Yellowstone National Park have individual thicknesses that range from 1 to 10 m and composite thicknesses of 100 to 200 m (Williams and McBirney, 1979). In 1902, two volcanos in the Caribbean erupted and pyroclastic flows took the lives of over 30,000 people. Glowing avalanches on Soufriere volcano devastated the northern end of St. Vincent, flowing distances of up to 20 km from the crater. The entire town of St. Pierre on Martinique was leveled by a pyroclastic flow originating at Mt. Peleé 8 km away. Observations made by persons on ships in the harbor of St. Pierre indicate that the flow traveled with a velocity in excess of 160 km per hour (Bolt, 1975). Pyroclastic flows are capable of traveling up to 30 to 80 km from their source, provided a large drop in elevation is available (Williams and McBirney, 1979). Ignimbrite deposits associated with the formation of Crater Lake in Oregon about 7,000 years ago were found up to 60 km from the crater (Bolt, 1975).

Volcanic mudflows (lahars) consist of flowing mud and volcanic debris and are capable of traveling great distances from their source. Lahars are initiated by various mechanisms such as heavy rainfall, melting of ice and snow or drainage of crater lakes. Mudflows may or may not be hot, depending on the origin of the water and entrained debris. Mudflows frequently form on volcanos that are steep and laden with unconsolidated volcanic debris. The more explosive eruptions associated with silica-rich magmas produce these conditions more often than do basaltic eruptions. Rapid melting of glacial ice

and snow during eruptions of Mount Rainier has produced two lahars in the past 5,000 years that reached the Puget Sound Lowland some 50 to 70 km away (Crandell, 1971). The flow of glowing avalanches across glaciers near the summit of Cotopaxi volcano in Ecuador produced enormous mudflows that traveled at speeds up to 80 km per hour and reached distances greater than 250 km from the crater (Williams and McBirney, 1979). In most cases where lahars have flowed such great distances, they have followed the course of streams and remained very fluid. Mudflow deposits are commonly several meters thick and some reach thicknesses of 70 meters (Williams and McBirney, 1979).

During explosive eruptions, fine-grained volcanic debris (tephra) is blown into the atmosphere to heights of up to 20 km. Winds can distribute the tephra over wide areas before it is deposited. The thickest accumulations containing coarser material are deposited nearest the volcano. During the cataclysmic eruption of Mount Mazama (Crater Lake, Oregon) about 7,000 years ago, thick ash deposits were distributed over a wide area downwind of the volcano. Ash layers 3 meters thick were found over 30 km downwind from the crater, and measurable ash layers are found up to 1000 km downwind. Minor thicknesses of ash deposits would probably not compromise the safety of waste handling facilities; however, thick deposits nearer the source volcano could damage facilities. The thickness of ash that can be tolerated at a repository site will be a function of the structural design of the surface facilities.

6.1.2 Igneous Intrusion

The intrusion of magma into near-surface rocks is another form of volcanic hazard to be considered in the siting of nuclear waste repositories. If an intrusion were to directly intersect a repository, large quantities of hazardous waste could be brought to the surface. Igneous intrusions sometimes reach upper crustal levels and cool without ever breaching the surface. Rocks adjacent to intrusions experience thermal and mechanical changes, as well as increased hydrothermal circulation, all of which would compromise the integrity of a waste repository adjacent to an intrusion. Igneous intrusion is a potential hazard as long as the waste in the repository is hazardous, a time span estimated at 100,000 to 1,000,000 years.

Such time spans are short enough in geologic terms that only minor changes from the present distribution of active volcanism would be anticipated. Most igneous intrusions in the next 100,000 to 1,000,000 years will occur within regions of Quaternary extrusive volcanic deposits, or along zones of weakness defined by the Quaternary deposits. For intrusions that will occur outside of presently active volcanic centers, there may be precursory phenomena such as heat flow or geophysical anomalies that could be present indicators of future activity.

6.2 Evaluation of Volcanic Activity

6.2.1 Extrusive Volcanism

The hazard posed by extrusive volcanism on a nuclear waste repository is limited to the initial operation of surface waste handling facilities, which is on the order of one hundred years or less. For such a short time span, a fixed areal distribution of active volcanism can be assumed. The hazard of extrusive volcanism can be minimized by avoiding areas that exhibit the potential for extrusive volcanism, based on the spatial and temporal distribution of recent volcanic deposits. A key word in the previous sentence is "recent." There is general agreement in the literature of repository siting criteria to limit volcanism studies to Quaternary (approximately 2 m.y. to present) deposits (ONWI, 1980; NRC, 1979).

The character and timing of eruptions varies widely from one volcanic center to the next, and there appears to be no universal pattern or cycle that can be applied to all volcanos. However, investigations of specific volcanos reveal crude behavior patterns from which qualitative predictions of volcanic activity can be made.

There are two sources of information regarding past volcanic behavior: historic and geologic. Historic records of Mt. Vesuvius in Italy cover almost 2000 years (Fig. 11). Since 1631, Vesuvius has shown cyclic behavior consisting of minor eruptions that gradually build up the summit cone followed by a short, paroxysmal eruption that destroys the summit cone, leaving a large crater (Bullard, 1962). Each cycle lasts from 5 to 38 years and is separated by a quiet interval of roughly seven years. Unfortunately, historic records of U. S. volcanos are too short to determine patterns or periodicity of volcanism.

Stratigraphic analysis in conjunction with various dating techniques helps define volcanic behavior patterns over longer time spans. Lava flows, pyroclastic flows and ash deposits are easily identified and would tend to have clear stratigraphic relationships in the field. Volcanic mudflows (lahars) can be mistaken for glacial deposits or other types of mass movement deposits. Crandell and Mullineaux (1975) list criteria for distinguishing lahars from other types of deposits:

1. Lahars can be continuous for several tens of km, whereas other mass movements are generally less than a few km long.
2. Lahars tend to be graded, with coarser materials at the base.
3. Lahars are often confined to valleys and have fairly flat upper surfaces.

Also, volcanic mudflows would generally be composed of angular volcanic fragments and volcanic ash, whereas glacial deposits would tend to be more varied. Ash deposits from large eruptions are very extensive and can provide an index horizon for regional stratigraphic correlation.

Most of the dating techniques applied to volcanic materials are the same as those utilized in fault age studies. The principles of each dating method are discussed in Section 2.3.2 of this report. The carbon-14 radiometric method is particularly applicable to volcanic deposits due to the abundance of organic materials found in lava flows, pyroclastic flows and mudflows. Carbon-14 dates of wood fragments in pyroclastic flows and lahars have yielded a detailed chronology of the recent behavior of Mt. St. Helens (Fig. 11) (Crandell, et al., 1975). Steam and ash eruptions from Mt. St. Helens began in March 1980, culminating in the largest historic explosive eruption in the contiguous United States on May 18, 1980. It is interesting to note that in 1975 Crandell believed that an eruption of Mt. St. Helens was likely to occur in the next 100 years because dormant intervals in the past 4,000 years have averaged 100-200 years and the volcano had been dormant since 1857. Other radiometric methods such as K-Ar, Rb-Sr and fission-track are applicable to lava flows

and some pyroclastic materials, depending on the mineralogy of the rock. Paleomagnetic studies of minerals within a sequence of lava flows may reveal secular changes, that, in turn, can be correlated to known time intervals. The approximate age of volcanic glasses such as obsidian can be determined from measurements of the thickness of hydration rinds, which develop at a specific rate for a given location. Wood (1977) dated obsidians ranging from 2,000 to 60,000 years old in Mono Craters, California with the glass hydration method. He used a hydration rate of 2 microns²/yr, based on calibration from radiometric dating of local obsidians.

Once the distribution of recent volcanic deposits has been determined, hazard zones can be delineated, assuming that future eruptions will produce volcanic deposits of similar extent. The potential volcanic hazards of two Cascade volcanos, Mt. St. Helens and Mt. Baker, have been assessed by the U. S. Geological Survey with this rationale (Crandell and Mullineaux, 1978; Hyde and Crandell, 1978). In these studies, hazard zones have been defined for the various types of volcanic deposits. Lava flow and pyroclastic flow hazard zones were restricted to the volcano itself and to an extent of up to 15 km from the base of the volcano. Beyond these zones were areas that could probably only be affected by mudflows and floods. These were restricted to narrow belts along river valleys and extended up to 70 km from the volcano for mudflows and 90 km for floods. The existence of man-made reservoirs in some of these valleys accentuates the flood hazard. Zones of tephra hazards are defined based on the prevailing wind directions and previous ash deposits. At distances of 18, 24 and 45 km from Mt. Baker, the potential exists for 35, 15 and 5 cm, respectively, of ash (Hyde and Crandell, 1978). In summary, repositories can be safely sited with regard to extrusive volcanic hazards, if placed outside of the possible range of volcanic flow deposits and thick ash accumulations from Quaternary volcanic centers.

6.2.2 Igneous Intrusion

For extrusive volcanism, the time span of potential hazard was on the order of a hundred years, and the assumption was made that volcanic activity for a hundred year period would be restricted to regions of Quaternary volcanism. The basis for this assumption is that 100

years is many orders of magnitude shorter than the time spans over which significant change in the distribution of volcanism can be observed in the geologic record. Changes do occur in the distribution of active volcanism, and the probability of such an occurrence increases as the length of the time span under consideration increases. Igneous intrusion is a potential hazard to nuclear waste isolation until the waste is reduced to nonhazardous levels, a time span estimated at 100,000 to 1,000,000 years. The possibility of volcanism occurring outside of Quaternary volcanic centers should be considered for the long-term geologic isolation of radioactive waste. The risk of igneous intrusion at a potential site can be minimized by assessing regional tectonic models and evaluating geothermal and geophysical data that may indicate the existence of magma at depth.

6.2.2.1 Tectonic Models

Several investigators have attributed the Snake River plain-Yellowstone volcanic trend to the motion of the North American Plate over a fixed mantle plume (Smith and Sbar, 1974; Matthews and Anderson, 1973). At a rate of 3 to 5 cm/yr, volcanism and uplift would migrate 30 to 50 km to the northeast of the present Yellowstone locus in a million years. New volcanism is most likely to occur along pre-existing zones of weakness such as old plate sutures, failed rifts and older orogenic belts (Sykes, 1978). Old cratonic areas with thick, cool crust are rarely the sites of intraplate volcanism or seismicity. Smith and Sbar (1974) postulate that concentrations of seismicity and volcanism along the high lava plains of Oregon and Idaho, the eastern margin of the Basin and Range Province, and the Rio Grande Rift are indicative of boundaries between semi-independent lithospheric plates (Fig. 6). Some Quaternary volcanic centers are located along these boundaries, and new volcanic centers may tend to develop along these trends.

6.2.2.2 Geophysical Detection

Seismic methods have proven to be very effective in the location of magma chambers. A-type earthquakes are similar to small ($M < 6$) tectonic earthquakes, and are believed to be caused by frac-

turing of adjacent rock during movement of magma within crustal reservoirs (Minakami, 1974b). Swarms of these earthquakes precede some volcanic eruptions by as much as several months. B-type earthquakes are very shallow, small earthquakes that typically have little or no shear wave. These occur immediately prior to and during eruptions, often continuously, and are probably due to magmatic explosions near the crater. For 16 years preceding the cataclysmic eruption of Mt. Vesuvius in 79 A.D., there was a much higher incidence of felt earthquakes near the volcano (Bolt, 1975). Earthquake locations can also be used indirectly to locate magma chambers not associated with present eruptions. Within the caldera at Yellowstone, earthquake focal depths are limited to the upper 5 km, whereas outside of the caldera, focal depths are common at depths of up to 20 km. The lack of lower crustal earthquakes underneath the caldera could indicate the presence of a magma chamber (Smith, 1977).

Seismic waves that propagate through regions with known or suspected magma bodies have anomalous attenuation characteristics. Little or no S-phase and lower amplitude P-waves are common on earthquake seismograms where active volcanos lie between the earthquake and the seismograph station. Machado (1974) and Kubota and Berg (1967) report possible magma chambers to depths of 70 km in Kamchatka and the Alaskan Peninsula, based on seismic wave attenuation. Similar observations of body wave attenuation are consistent with the existence of a shallow magma chamber at Yellowstone (Pitt, 1974). Delays in P-wave arrivals, probably due to slower velocities through molten or partially molten materials to depths of up to 150 km, are also characteristic of seismic waves that propagate beneath the Yellowstone caldera (Iyer, 1974).

In a microearthquake study, Sanford (1977) defined a discontinuity at a depth of 18 to 20 km in the Rio Grande Rift near Socorro, NM. S-P and S-S phases were consistently reflected from

this discontinuity, which revealed a tabular geometry approximately 8 km long and 2 km thick. Sanford concluded that the data imply the existence of a laccolith shaped magma body at depth. Deep seismic reflection profiling across the suspected Socorro magma body also revealed a strong reflector corresponding in depth and extent to the discontinuity defined by microearthquake phases (Krumhansl, 1978).

From measurements of body wave velocities, V_p and V_s , it is possible to calculate Poisson's ratio (ν) (Dobrin, 1976):

$$\frac{V_p}{V_s} = \sqrt{\frac{1 - \nu}{\frac{1}{2} - \nu}}$$

Poisson's ratio is higher in partially molten rock than it is in totally solid rock. Both shear wave and compressional wave velocities are lower in partially molten rock, but shear wave velocity decreases relatively more than compressional wave velocity. Kubota and Berg (1967) calculated Poisson's ratio for various earthquake seismic wave paths in the Alaskan Peninsula, and discovered that higher values of Poisson's ratio correlated with wave paths beneath active volcanos. In a similar micro-earthquake study of the Rio Grande Rift in the vicinity of Socorro, NM, a zone of high Poisson's ratio corresponded to a suspected magma body defined on the basis of reflected S phases from microearthquakes (Sanford, 1977).

During an earthquake, the intensity of ground motion at a given site is partially a function of the attenuation characteristics of the crust through which the seismic waves propagate. If the crust between the epicenter and the site in question has particularly strong attenuation, the felt intensity at the site will be low relative to sites at equal distances in other directions from the epicenter. Analysis of the distribution of intensities associated with historic earthquakes in the Azores reveals zones of low intensities (thus high attenuation) that underlie

active volcanos (Machado, 1974). The zones of anomalous attenuation and intensity are probably due to molten or partially molten materials within the crust.

Known or suspected magma bodies are often associated with broad gravity anomalies. Silicic magma bodies are generally less dense than the surrounding rock, producing lower gravity readings. The magnitude and extent of the gravity anomaly is dependent on the density contrast between magma and host rock, and the depth, geometry and size of the magma body. An infinite number of viable combinations of the above factors can adequately model a specific gravity anomaly. Thus, gravity data is most effective when other geologic and geophysical data are available to place constraints on the densities and geometry involved. A gravity low does not necessarily imply the existence of magma at depth, as only density distributions can be inferred from gravity data. A bouger anomaly of -20 mgal is centered over Mt. Katmai, an active volcano in the Alaskan Peninsula (Kubota and Berg, 1967). Assuming a reasonable density contrast for the type of magma and crust typical of that area, Kubota and Berg found that a spherical low density body at a depth of 3 to 4 km provided a good model of the observed gravity anomaly. Gravity measurements at Yellowstone indicate a broad gravity low centered over the caldera, a minimum of -50 mgals relative to the edge of the anomaly (Easton, 1975). Eaton modeled the anomaly as a tabular low density mass 0.5 to 9 km thick at a depth of several kilometers. A very precise fit to the Yellowstone anomaly was obtained with a complex density model of the upper mantle and crust. The model consisted of an irregularly shaped vertical column of low density material which has a density contrast of 0.2 gm/cc in the upper 30 km, and a contrast of 0.1 gm/cc below that (Smith and Christiansen, 1980).

A broad region of low magnetic field intensity is centered over the Yellowstone caldera (Eaton, 1975). One possible explanation of the magnetic low is a large mass of hot rock or magma at

relatively shallow depth. Above the curie temperature, which is approximately 550 to 600° C for most common magnetic minerals, remanent magnetism of rocks is lost, reducing their contribution to the total field intensity. In most of the continental United States, the depth to curie temperatures is 15 to 30 km, but this depth is estimated to be as shallow as 6 km beneath the Yellowstone caldera (Smith and Christiansen, 1980). Magnetic anomalies, like gravity anomalies, cannot uniquely define subsurface magma bodies; however, magnetic data can be used to supplement geologic, geothermal, and other geophysical data.

In many cases, crustal deformations have been observed to accompany the movement of magma in crustal reservoirs. Tiltmeter readings and repeated leveling surveys have documented large upward deformations of volcanos immediately preceding eruptions. Vertical doming of Usu Volcano in Japan began six months prior to an eruption, and the maximum deformation reached +60 m just before the eruption (Minakami, 1974a). Most eruptions of Kilauea on Hawaii are preceded by similar upward deformations that are probably caused by injection of magma into shallow crustal magma chambers. Deformations at Kilauea have been modeled by the expansion of a spherical chamber at various depths in an elastic medium (Machado, 1974). The model provides a best fit to the tiltmeter and leveling observations if the expanding chamber is at depths of 3 to 10 km. Leveling surveys across the Rio Grande Rift near Socorro, NM in 1911 and 1951 show elevation differences defining a 7000 km² elliptical area of uplift (Reillinger, et al., 1979). Maximum uplift in the center of the area is 20 cm relative to the periphery, an average uplift rate of 5 mm/yr for the 40-year interval. The area of uplift is directly above the crustal discontinuity at 18 to 20 km depth which has been interpreted as a possible tabular magma body (Sanford, 1977; Krumhansl, 1978). Elastic models indicate that the shape and profile of the uplift is consistent with an expanding magma chamber at a depth of approximately 18 km (Reillinger and Oliver, 1976). Leveling surveys of the Yellowstone Park area in

1923 and in the 1970's reveal a broad regional uplift of the entire park area at an average rate of approximately 6 mm/yr (Smith and Christiansen, 1980). Within this regional uplift is a localized elongate uplift over the caldera. The maximum uplift is 70 cm (average rate of 14 mm/yr) relative to a benchmark east of the caldera.

6.2.2.3 Geothermal Detection

Heat is transferred from the earth's interior to its surface primarily by the mechanisms of convection and conduction. Near the earth's surface, convection by igneous intrusion and hydrothermal circulation account for significant portions of heat transfer, but these processes are not easily assessed quantitatively. Conduction of heat through sediments and rocks near the earth's surface is a process that can be measured quantitatively, and may be a useful tool in the detection of areas of relatively high risk with regard to future igneous intrusions. In areas where surficial geologic materials are relatively impermeable, hydrothermal convection does not contribute much to the overall heat transfer budget, and conductive heat flow accounts for most of the heat transfer.

Conductive heat flow is equal to the product of the thermal gradient and the thermal conductivity of the medium in question. Vertical temperature gradients near the earth's surface are measured in mines and boreholes, and with soft sediment probes in lacustrine or marine environments. Laboratory tests are run on representative samples of the geologic medium to determine the average thermal conductivity of the vertical section over which the temperature gradient was measured. The geothermal gradient itself does not quantitatively describe conductive heat flow, but it is sometimes used as an empirical indicator of magmatic activity. The average upper crustal geothermal gradient for the earth is approximately 2 to 3°C/100 meters and typical values of continental conductive heat flow range from 1 to 2 HFU (Heat Flow Units) (Press and Siever, 1974).

Temperature measurements for the determination of geothermal gradients must be made at sufficient depth to avoid the influence of seasonal and diurnal temperature fluctuations at the earth's

surface. On land, the surface temperature fluctuations are large, and most measurements must be made in tunnels, mines and boreholes to depths of 100 to 300 meters to eliminate surface temperature effects. Temperature measurements in boreholes are often made soon after the drilling operation is complete, and anomalous temperatures may be recorded due to thermal effects of the drilling operation. Uyeda (1976) monitored temperatures in a borehole for several months after completion of the hole, and concluded that recovery to thermal equilibrium requires a time span up to ten times as long as the drilling operation itself. The recovery time is variable, depending on the drilling methods and fluid circulation, among other factors. Temperature fluctuations on the seafloor and on lake beds are much smaller than subaerial fluctuations, and temperature gradients can be measured with probes inserted only a few meters into soft sediments.

Heat flow studies can be used at two scales to assess the potential hazard of igneous intrusion: regional patterns of heat flow may outline zones of weakness and tectonic boundaries, and localized heat flow anomalies may indicate the presence of magma at depth. Heat flow in the eastern and central United States is fairly constant, averaging roughly 1 HFU (Press and Siever, 1974). Heat flow variations in the eastern and central United States are correlated with lateral variations in the composition of upper crustal rocks (Lachenbruch and Sass, 1977). Roughly 30% of the conductive heat flow measured at the earth's surface is contributed by the radioactive decay of atoms in crustal rocks, the remaining 70% coming from deeper sources. The concentration of radioactive isotopes varies widely among crustal rock types. For example, granitic rocks produce approximately six times as much heat through radioactive decay as do basaltic rocks. Heat flow patterns in the eastern and central United States do not appear to define any large scale zones of weakness or tectonic boundaries.

In general, the western United States is characterized by conductive heat flow in excess of a 2 HFU, and several regional trends are evident (Fig. 12). Trends of high heat flow are associ-

ated with major plate tectonic boundaries along the Cascade volcanic arc, and the San Andreas-Salton Trough transform boundary. Low heat flow of the Pacific Northwest Coast Ranges and the Sierra Nevada is probably associated with the region of cold, descending oceanic lithosphere in modern (Pacific Northwest) and ancient (Sierra Nevada) subduction zones (Blackwell, 1978).

High heat flow is observed along the western margin of the Rio Grande Rift in New Mexico and southern Colorado. Relatively high seismicity and primarily basaltic Quaternary volcanism coincide with the Rio Grande heat flow high. Reiter (1975) postulates that the Rio Grande heat flow anomaly may be due to a system of deep fractures in the lithosphere that allow upward migration of magma to crustal levels. Gravity surveys indicate a positive anomaly across the rift. Density models consistent with the observed gravity anomaly include thin crust over the rift, and possibly tabular mafic crustal intrusions (Decker and Smithson, 1975).

A belt of generally high heat flow parallels the Snake River plain-Yellowstone trend, and the high lava plains of eastern Oregon. This trend correlates directly to the areal distribution of late Tertiary and Quaternary volcanism. Crustal thermal sources, which in some cases such as Newberry caldera and Yellowstone may be magmatic, are the probable source of the regionally high heat flow. Conductive heat flow values in the vicinity of Yellowstone park and along the south-east margin of the Snake River plain range from 3 to 5 HFU (Blackwell, 1978). Along the axis of the Snake River plain, low conductive heat flow is a manifestation of regional groundwater convection. Much of the plain is underlain by an aquifer that is approximately 300 meters thick. Recharge of the aquifer occurs at the eastern end of the plain, and flow is toward the west, where discharge occurs at Thousand Springs in south central Idaho. Flow within the aquifer is rapid enough that virtually no temperature gradient exists within the aquifer (Blackwell, 1978).

Another zone of high heat flow (greater than 2.5 HFU) crosses northern Nevada. Most volcanic activity in this region is from 6 to 17 million years old but there are many active hydrothermal systems. Thermal effects such as high conductive heat flow and hydrothermal activity appear to continue for up to 17 m.y. after the culmination of intrusive thermal events (Blackwell, 1977). The distribution of possible contemporary magma chambers (based mostly on the location of Quaternary volcanic centers) and the locations of known hydrothermal systems are shown in Fig. 13. There are several regions such as northern Nevada that have active hydrothermal systems in the absence of Quaternary volcanism.

Smaller scale heat flow anomalies may indicate the presence of magma within the crust. The best documented case of such a localized anomaly is the Yellowstone caldera. Measurements of heat flow were made in the sediments in Yellowstone Lake. The northern portion of the lake lies within the boundaries of the caldera, and heat flow readings there averaged 15 HFU (Smith, 1977). Outside of the caldera in the southern part of the lake, heat flow average 3 HFU, which is approximately equal to the regional pattern of heat flow. Extremely high heat flow measurements within the caldera are probably indicative of magma or hot crystalline rock within the upper crust. It is not known to what degree these measurements are influenced by the extensive hydrothermal convection systems associated with the Yellowstone caldera (Morgan, 1977). Assuming that conduction is the dominant mechanism of heat transfer, the abruptness of the heat flow anomaly boundary is a measure of the depth to the thermal source. Where magmas do exist at shallow crustal levels, there is likely to be significant hydrothermal effects that will inhibit modeling of the heat flow as a purely conductive system. For this reason, heat flow and geothermal gradient data cannot absolutely prove the existence of magma, but can only be used as empirical indicators.

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PLATE TECTONICS IN THE
WESTERN UNITED STATES
from Seyfert & Sirkin, 1979

Fig. 2

NOTE: Dotted line is 1.5 Heat Flow Unit contour from Fig. 12.
It is not pertinent in the context of this figure.

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DISTRIBUTION AND AGE OF
CENOZOIC VOLCANIC TERRAINS
IN THE WESTERN U. S.
(from Blackwell, 1978)

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Fig. 3

Contours are 1, 2, 3, and 4 or more earthquake epicenters per circular area with radius of 1° of latitude for 1961 through 1967.

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RECENT SEISMICITY IN THE
WESTERN UNITED STATES
(from Christiansen and Mc-
Kee, 1978)

Fig. 4

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TECTONIC PROVINCES OF THE
WESTERN UNITED STATES
(From Christiansen and Mc-
Kee, 1978)

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Fig. 5

NOTES:

- IB - Idaho Batholith
- SRP - Snake River Plain
- CV - Cascade Volcanics
- SN - Sierra Nevada

Arrows indicate relative motions of proposed sub-plates.

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MODEL OF SUBPLATE MOTIONS
IN THE WESTERN UNITED
STATES
(from Smith and Sbar, 1974)

Fig. 6

Fig. 7a Determination of fault displacement from a planar feature.

Fig. 7b Determination of fault displacement from a linear feature (intersection of two planes).

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MEASUREMENT OF
FAULT DISPLACEMENT

Fig. 7

Fig. 8a Slickenside steps oriented with the direction of movement.

Fig. 8b Slickenside steps oriented opposed to the direction of movement.

Fig. 8c Fault drag adjacent to the fault plane.

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SLICKENSIDE STEPS
AND FAULT DRAG

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Fig. 8

NOTE: Circles indicate earthquake epicenter locations, and triangles indicate seismograph station locations.

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SEISMICITY OF THE
NEW MADRID, MO AREA
(from Stander, 1976)

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Fig. 9

SEISMOGRAPH STATIONS

- ☆ 1973 only (temporary)
- ★ 1973-1975 (permanent)
- ★ 1974-1975 (permanent)

EARTHQUAKE EPICENTERS

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SEISMICITY OF THE
CHARLESTON, S.C. AREA
(from Torr, 1977)

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Fig. 10

NOTE: Upper scales mark historical records of eruptions, and lower scales are stratigraphic records of periods of volcanic activity.

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HISTORICAL AND STRATI-
GRAPHIC RECORDS OF RECENT
VOLCANIC ACTIVITY OF FOUR
VOLCANOS (from Crandell et
al., 1975)

Fig. 11

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and Volcanism on a
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CONDUCTIVE HEAT FLOW IN
THE WESTERN U. S.
(from Blackwell, 1978)

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Fig. 12

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and Volcanism on a
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HYDROTHERMAL SYSTEMS AND
POSSIBLE MAGMA CHAMBERS
IN THE WESTERN U.S.
(from Blackwell, 1978)

Fig. 13