AN ESTIMATION OF THE STATISTICAL DISTRIBUTION OF
FAULTING IN SELECTED AREAS AND THE DESIGN OF
AN EXPLORATION MODEL TO DETECT THESE FAULTS

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A Final Research Report

Submitted to

Lawrence Livermore Laboratory

Livermore, California 94550

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San Jose, California 95192

November 1977

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1 EXECUTIVE SUMMARY

Selected sites in the United States have been analyzed geomathematically as a part of the technical support program to develop site suitability criteria for High Level Nuclear Waste (HLW) repositories. Using published geological maps and other information, statistical evaluations of the fault patterns and other significant geological features have been completed for 16 selected localities. The observed frequency patterns were compared to theoretical patterns in order to obtain a predictive model for faults at each location. In general, the patterns approximate an exponential distribution function with the exception of Edinburgh, Scotland--the control area. The fault pattern of rocks at Edinburgh closely approximate a negative binomial frequency distribution. The range of fault occurrences encountered during the investigation varied from a low of .15 to a high of 10 faults per square mile.

Faulting is only one factor in the overall geological evaluation of HLW sites. A general exploration program plan to aid in investigating HLW repository sites has been completed using standard mineral exploration techniques. For the preliminary examination of the suitability of potential sites, present economic conditions indicate the scanning and reconnaissance exploration stages will cost approximately \$1,000,000. These would proceed in a logical sequence so

that the site selected optimizes the geological factors.

The reconnaissance stage of mineral exploration normally utilizes "saturation geophysics" to obtain complete geological information. This approach is recommended in the preliminary HLW site investigation process as the most economical and rewarding. Exploration games have been designed for potential sites in the eastern and the western U.S. The game matrix approach is recommended as a suitable technique for the allocation of resources in a search problem during this preliminary phase.

2 INTRODUCTION

The Lawrence Livermore Laboratory is conducting a study: "Technical Support in the Development of Nuclear Waste Management Criteria," for the U.S. Nuclear Regulatory Commission. In developing a basis for site suitability criteria, one concern has been the possibility of overlooking an important geological feature that might contribute to the release of nuclear materials to the biosphere. Some of this concern can be addressed by considering the exploration/evaluation techniques whose use can minimize the possibility.

The San Jose State University Foundation contracted with the Laboratory to consider the general problem of geological exploration to evaluate high-level nuclear waste repository sites in order to develop bases for criteria to aid in the evaluation process. Certain specific items of the exploration process have been considered such as faulting, the selection of exploration tools--i.e., allocation of resources--, and the cost of exploration.

The report is divided into six chapters. The topics covered include an outline of geological exploration, a statistical study of faulting, and a section describing exploration economics--including the exploration game. An additional section is concerned with the fault statistics in the selected areas. The investigation was limited by the time

available and by an uneven quality and quantity of available data in the areas investigated.

3 THE EXPLORATION

3.1 Planning

A detailed plan is necessary for the geological exploration and evaluation of HLW sites. The exploration program will not only be concerned with the discovery and outlining of suitable sites, but will also provide management with some of the information necessary for construction of the repository facilities and acquiring the needed land.

The exploration manager must plan the exploration strategy in terms of his objectives. Some of the problems to be answered in the planning include: (1) the type of terrain desired for the HLW sites, (2) where will the terrains be found, and (3) the technique utilized to select the terrain. The solutions to these problems depend on the geological parameters of the terrains solicited, the availability and utilization of well qualified geological personnel, and present land use patterns. All available data and every aspect of the problem must be scrutinized in order to develop a meaningful plan and formulate useful concepts.

3.2 Program structure

An exploration program may be considered to consist of scanning, screening, and project stages with the type of decisions differing in each. This general approach would be followed in almost all cases of geological problem-solving

and is well suited to the HLW site selection process. However, the details of the specific program would vary with the particular target solicited and the ultimate objectives of the program. The selection of HLW sites would be similar to mineral exploration and site evaluation in the construction industry, but it would also have some basic differences dictated by its own specific requirements.

3.2.1 Scanning or reconnaissance stage

The scanning or reconnaissance stage for HLW sites will require a literature search and an aerial geological investigation. The fault study--in section 4.2--conducted by the author constitutes a portion of a scanning exploration program. In general, the reconnaissance stage would involve selecting potential areas on the basis of the presence or absence of significant geologic features. The locations selected would then be evaluated and the best of them would be subjected to additional exploration.

3.2.2 Screening stage

The screening stage for HLW sites will require a preferred sequence of airborne and ground studies along with office analysis of the data. The particular studies include a variety of airborne geophysical techniques and remote sensing. These data can be evaluated and specific targets delineated. Follow-up ground investigations consisting of geological and geophysical mapping would then be utilized to

evaluate and rank preliminary site choices. The author has designed an exploration program for two different locations. A game matrix has been outlined for the allocation of exploration resources at the screening stage. The cost of the exploration program has been estimated using current economic indices. Selected locations meeting predetermined site requirements could then be subjected to the detailed phase of exploration involved in the project stage.

3.3.3 The project stage

Ultimately, the HLW site selection program will be at the project state--which will require detailed ground geophysical and geological surveys, diamond drilling, and soil and rock mechanical investigations. Again at this level, decisions concerning the exploration will be conducted by senior exploration personnel based upon extensive professional experience. A quantified approach may also be used in support of the general program and this will include sequential analysis, graphical probability functions, and game theory; these various mathematical systems may be used to estimate the general level and variety of exploration required. However, they will not replace the traditional exploration approach because they are still at the experimental level of development. All possible exploration techniques should be utilized in the site selection and evaluation process. These are discussed in Chapter 5.

4 FAULTING

4.1 Summary

Faults and faulting must be considered when selecting an HLW site. Faults are a potential hazard because they represent earthquake generating features and also because they may increase the permeability of the location--thus facilitating the migration of HLW materials. A consideration of faulting should be completed before making the actual site selection.

The results of the investigation at this point are preliminary, but several hypotheses may be formulated concerning the data and possible applications. Each area has a unique fault population with its own distinctive statistical parameters. The fault densities vary from a low of about 0.147 to 10.03 faults per square mile; Edinburgh, the control location, has a density of 2.64 faults per square mile. Fifteen of the locations investigated have fault densities of 2.64 or less; nine of these display fault densities of less than one fault per square mile. The Nevada Test Site--with a mean of 10.03 faults per square mile--has the highest incidence of faults.

In general, the results should be used with caution; they represent a preliminary estimate of the minimum number of faults that will be encountered in the region in question. The measured fault intensities for some of the locations

were undoubtedly too low because of the inadequacy of the data. The locations of eastern Montana; San Juan County, Utah; Coconino, Arizona; and Grant County, Oregon are all in this category. Central Connecticut and eastern Tennessee include data for two geological provinces and thus may not constitute a completely valid sample--and thus their results are not completely reliable. The investigation of eastern Pennsylvania utilized a different scale map and a different size unit cell; the results were undoubtedly too low for this region and should not be compared with the results of the other areas.

In general, the fault frequencies are exponential in character; however, the Edinburgh region has a distinctive negative binomial distribution for its observed faults. Since Edinburgh has been studied in greater detail, the other locations may also have negative binomial fault distributions--thus there may be more faults waiting to be discovered at each locality.

4.2 Fault occurrence statistics

The statistics of fault occurrences at 16 selected geological locations were computed and analyzed. This is part of a general program to determine the variation in fault density between different areas in order to select the site with a minimum exposure to faulting. The quantitative data for estimating the probability parameters of the distribution patterns were obtained from published geological maps of

each area. The possible significance of the distribution patterns was analyzed.

The distributions analyzed were obtained from available published geological maps of various locations. The locations are presented in Table 1; and were selected to present dispersed geographical sites throughout the United States. They were selected to represent a wide variety of geological and geographical settings. The amount of published data available varied widely from one location to the next--San Juan County, Utah has forty published geological maps whereas some of the other areas have only 10 or less. The quality and completeness of data also varied widely between locations--some maps were of the reconnaissance variety and others were the results of more exhaustive analyses and thus represented complete knowledge. Detailed results are presented in Chapter 6.

A limited amount of previous geostatistical investigations has been completed. These include applications of statistics to distribution of mines (Slichter, 1959), valuation of mineral deposits (Journal, 1975), interpretation of geochemical anomalies (Koch and Link, 1970). Previous studies on the general application of statistics to uranium exploration have been completed for the Atomic Energy Commission (Mickey and Jespersen, 1954). The U.S. Bureau of Mines has conducted extensive investigations into the applications of statistics and probability to the mineral

TABLE 1

Comparisons of Statistics of Fault Occurences at
Selected Geological Locations

Location	Mean (Faults/Square Mile)	Variance	Range
1. Edinburgh	2.64	6.10	14*
2. Eastern Montana	0.06	0.16	7
3. San Juan County Utah	0.73	3.46	22
4. Grant County Oregon	0.74	1.47	7
5. Nevada Test Site	10.03	267.22	239
6. Karnes County Texas	0.15	0.15	3
7. Sweetwater County Wyoming	0.26	0.54	6
8. Coconino County Arizona	0.45	1.32	15
9. Keweenaw County Michigan	0.52	0.83	6
10. Western Massachusetts	0.23	0.40	7
11. Bonneville County Idaho	2.12	5.46	12
12. Valencia County New Mexico	1.36	6.65	14
13. Central Connecticut	1.44	13.34	14
14. Eastern Tennessee	1.01	1.98	14
15. Kern County California	1.27	5.65	28
16. Eastern Pennsylvania	0.10	1.00	59**

* These represent upper limits for each unit cell, the lower limit was 0 faults in each case.

** The unit cell for Pennsylvania was 58.4 square miles.

industries (Becker, 1964 and Hazen, 1961).

Previous investigations (Kock and Link, 1970 and DeGeoffroy and Wignall, 1971) have shown that some geological features such as orebodies have a negative binomial distribution and are thus predictable. The results of this investigation suggest that faults may also have a negative binomial distribution and thus be predictable (i.e., they are non-random features produced by geological processes). The observed frequency distributions for the 16 locations are presented in graphical form in Appendix B; and in tabular form in Appendix D.

Several potential applications of fault statistics are evident and include utilization in the design of the exploration program and estimation of site stability. If faulting is a consequential item, then the fault statistics may be used in a qualitative sense to select sites. The fault data may also be used to compute earthquake probabilities and hazard functions for the estimation of foundation safety, and may possibly be utilized to outline seismic zones for building codes or insurance programs.

4.3 Future work

The author recommends that additional work should be completed to define the nature of the fault frequencies and to obtain the frequency distributions for other potentially significant geological features such as caves or dikes. A more detailed analysis of fault frequencies should

be completed for the regions of the Nevada Test Site, the Michigan "copper country", and Edinburgh, Scotland. Locations that have been extensively mapped and investigated would be suitable for this type of analysis because all of the faults have probably been discovered. Similar investigations are suggested for caves in regions such as Hawaii, the Nullabor Plateau of South Australia, and the Mammoth Cave, Kentucky area. An investigation of the ring dikes of Mull or Arran, Scotland might also be warranted.

5 EXPLORATION ECONOMICS AND A GAME MODEL

5.1 Introduction

A game matrix has been designed to represent the various exploration techniques. This innovative approach was utilized in order to select an optimum exploration program with a reasonable allocation of exploration effort (Von Neumann and Morgenstern, 1944). In many different situations, simplified games have proven to be useful decision models for more complex situations in industry or nature. As the objective of an exploration program is to obtain complete knowledge concerning the subsurface conditions (i.e., site geology and soil mechanics characteristics), the game was determined with the same objective as nearly as possible. It seems reasonable that the objective should be to maximize the discovery of significant anomalies. The size of the exploration program was limited by the law of diminishing returns--i.e., when new outlays for obtaining information no longer increase or decrease the value of the game, no additional dimensions are warranted.

5.2 Game criterion

In designing this game for the allocation of exploration effort, the author selected the anomaly function as the single valued criterion to optimize. The cost of exploration is not of primary concern compared to the problem of deter-

mining the geological structure and potential safety of the underground storage facility. The various geophysical anomalies expected for potential HLW repository sites in the western and eastern sites were calculated and then equated to each other, utilizing an anomaly rating scale. These numbers were then used as the coordinates (or payoffs) in the exploration game and a solution of the game was obtained. The choice of a suitable criterion and the representation of the conflict situation by a simplified mathematical model are problems that limit applications of game theory to geological problems (Shepard, 1966).

In designing a game, it is necessary to choose a criterion in the shape of a value function to be optimized. Several possible criteria have been utilized for games traditionally. The minimax criterion (Williams, 1966) allows the player to achieve a result equal to the mathematical expectation of the game. During this game, the player assumes that nature is an intelligent opponent and behaves as in a duel. A second criterion choice would apply a coefficient of optimism to the largest and smallest payoffs in the game and ignore intermediate values. A third criterion would be to design the game matrix in terms of the economic costs of all possible outcomes; the player attempts to minimize the costs (Kaufmann, 1968). The criterion of the mean (or average state) may also be used in some cases to design a game. Each of these possibilities was considered but the author selected

the geophysical anomaly as the value function to optimize in the game.

5.3 The Exploration Program

5.3.1 Planning

A geological exploration program was designed for the investigation of the potential HLW repository sites.

The area selected for the search was estimated to be 20 square miles; the cost of the exploration will increase directly with the size of the area to be explored. Station and line spacing were estimated in order to eliminate omitting any potentially hazardous feature that might violate the integrity of the repository. The station spacing used is directly dependent on the measured fault statistics--i.e., locations with greater intensities of faulting would require a closer station and line spacing in order to detect all of the faults. The cost of surveying the entire area using each method was calculated. The magnitude of the expected anomalies corresponding to the selected search techniques were computed for the physical contrast of the model; these anomalies were utilized to formulate numerical indices for the game matrix. Solutions to the game matrix corresponding to the selected geological model were calculated and these were then transposed into actual exploration situations.

A consideration of the possible role of faults in the life cycle of an HLW repository suggests that the model

to use for designing the program would be the smallest significant fault that might be encountered. Faults present three possible types of hazards. They may be the source of earthquakes; they may be potentially high permeability zones; or finally, they may be a factor in the ultimate foundation failure. Each of these items suggest that larger faults are more detrimental to the repository failure than smaller faults. The density of faults (i.e., faults per square mile) at the potential site location would dictate the line and station spacing and the amount of exploration needed to discover all potentially hazardous features. The statistical data indicate that within a single geological province, a uniform density of faults will be encountered. The faults are a direct consequence of geological processes and should vary within a narrow range. These postulates were utilized in outlining the exploration programs.

5.3.2 Calculated geophysical anomalies

Petrological and mineralogical characteristics of the fault models were utilized in estimating physical constants such as density, magnetic susceptibility, and seismic velocities through the fault block. Some of the properties and physical constants include the following: For both models the fault would place conglomerate in contact with shale. The petrological character of the two materials suggests a density contrast of .1 g/cc, a magnetic susceptibility contrast of 10^{-5} cgs units, and an electrical resistivity ratio

TABLE 2
Estimated Geophysical Anomalies for a
Concealed Fault

Exploration Technique	Physical Contrast Assumed	Estimated Anomalies
Gravimetric	.1 g/c.c.	2 milligals
Magnetic	$k=2600 \times 10^6$ cgs	10 gammas
VLF Electromagnetics	100 mhos/meter	A discrete anomaly is possible.
Electrical Resistivity	Resistivity contrast 2	1000 phm-meter
Seismic Refraction	Velocity contrast = 2000 fps.	165 milliseconds
Seismic Reflection	Acoustical impedance contrast = 100	10 milliseconds
Geochemical Prospecting	0	Small halos may indicate concealed faults

of 10. The seismic velocity variation would be 3,000 fps across the fault contact. The fault is concealed beneath alluvium at a depth of 1,000 to 1,500 feet below ground level. The geophysical contrasts for this situation and the resulting anomalies are shown in Table 2.

The magnitude of the potential geophysical anomalies were calculated¹ for the hypothetical buried fault. A gravimetric anomaly of two milligals was calculated for the density contrast of .1 g/cc. A magnetic anomaly of 1 gamma was estimated for a susceptibility contrast of 10^{-5} cgs. A resistivity anomaly of approximately 1,000 ohm-meters was estimated for the hypothetical model. A seismic refraction anomaly of 165 milliseconds would result from the contrast of 3,000 fps and a fault throw of 1,500'. A large reflection anomaly would potentially occur from this situation. An electrical resistivity anomaly might also arise because of the contact and the resistivity contrast.

The theoretical anomalies were used to estimate coordinates (or payoffs) for the exploration game. The anomalies were rated on a scale of one to ten; with ten being an excellent anomaly and one being a poor or weak anomaly. This is a qualitative solution based upon the author's experience and concept of anomaly magnitudes. These ratings represent a type

¹The calculation of geophysical anomalies is covered in most geophysics textbooks, such as "Introduction to Geophysical Prospecting" by Milton Dobrin.

of search effectiveness and are presented in Table 3.

5.4 The exploration game

The search effectiveness estimate of each technique was then used to construct the exploration game which was represented by an eight by three matrix. The eight rows in the matrix represent the various possible search techniques and the three columns correspond to the presence or absence of faults. The techniques selected for exploration include magnetic, gravity, seismic refraction, electromagnetic (VLF), geological mapping, electrical resistivity, seismic reflection, and subsurface investigations. The various techniques were selected in order to obtain a complete geological picture of the site location. The exploration game is shown in Figure 17.

A solution to the game model consists of odds of about 0:1:0:0:0:1:1:1 and indicates that the exploration should consist of gravimetric, electrical resistivity, seismic reflection and subsurface investigation techniques. If the game matrix were reduced to an eight by two conflict situation with the third column (ambiguous fault situation) omitted, then the seismic refraction technique would be the dominant solution. The solutions suggest that the other search techniques--magnetics, VLF electromagnetics, and geological mapping should be utilized only on a reconnaissance basis.

A more precise determination of exploration strategies and resource allocation could be estimated when the exact location for a HLW repository site is selected. Each province

Texas have been analyzed statistically to determine the fault densities. The region is about 100 miles south of San Antonio near the Gulf of Mexico and has had extensive oil production. The maps analyzed consisted of 7 preliminary geological quadrangles--based partially on geophysical investigations--of the GP series and are listed in Appendix C. The geology is similar on all of the quadrangles and is characteristic of the Gulf Coast region south of the Balcones fault zone.

The area is characterized by Tertiary sedimentary and volcanic rocks and numerous oil deposits and some uranium deposits. The sedimentaries include clay, siltstone and sandstone. The volcanic rocks are tuff and small sections of porphyry and vesicular lava.

The results of the investigation indicate that the region has an average fault density of 0.147 faults per square mile; and the observed faulting frequencies essentially approximate an exponential probability distribution. The data are presented in Table 1. The results are considered only a preliminary estimate of the fault statistics, because only a limited amount of data were available for the analysis of this region.

6.2.7 Sweetwater County, Wyoming

About 14 geological quadrangles of the region of Sweetwater County, Wyoming have been analyzed to determine the incidence of faulting. The area analyzed--about 735

Counties. The region is part of the Basin and Range physiographic province and displays its characteristic geology.

Numerous mines are indicated on the various geological maps.

The exposed rocks include igneous, metamorphic and sedimentary types ranging in age from Precambrian to Recent. The igneous rocks in the region include basalt, tuff and intrusives of granite, aplite and pegmatite. The sedimentaries includes dolomite, limestone, shale, quartzite, landslides and alluvium. Some Precambrian metamorphics including quartz-mica, schist, amphibolite and gneiss were also recorded in parts of the area. Normal faults, thrust faults and structural lineaments (from photographs) were included in the analysis. Some of the rock units are extensively fractures (they were mapped as faulted rocks) and display as many as 235 faults per square mile.

The results of the analysis indicate that the region has an average fault density of 10.03 faults per square mile; the fault occurrences closely approximated an exponential distribution. The range of faulting encountered varied from 0 to 235 faults per square mile. The occurrence of intense faulting in some parts of the region suggest that a mixed or compound population may be present. These anomalously high values were discounted in the analysis. Table 1 shows the results of the statistical investigations.

6.2.6 Karnes County, Texas

The fault occurrences of a region in southeastern

border. The maps analyzed consisted of six geological quadrangles and these are tabulated in Appendix C.

The location is part of the juncture of the high lava plains and the basin and range province of Oregon. The exposed rock units range in age from Triassic to Recent. The rock types include igneous extrusives--such as basalts, andesites, rhyolite, tuff, and breccia--and intrusive diorite porphyry. A variety of sedimentary rocks is also present including conglomerate, greywacke, shale, and limestone. Numerous recent deposits such as glacial material, river gravels, and landslides are also present.

The results of the statistical study indicate the region has an average fault density of 0.399 faults per square mile, and the faulting occurrences closely approximate an exponential frequency distribution. The range of faulting encountered varied from 0 to 7 faults per square mile. Table 1 shows the results of the investigation. However, these results are only tentative because the amount of data were minimal and the region is at the juncture of two geological provinces.

6.2.5 Nevada Test Site

The faults in the region of the Nevada Test Site were analyzed statistically in order to determine the nature of the fault population. The area is in southern Nevada in close proximity to Las Vegas and includes 27 geological quadrangles--1,905 square miles in Nye, Lincoln, and Clark

analyzed is in eastern Montana near the North Dakota border. The maps analyzed consist of 14 geological quadrangles. The location is on the western edge of the Williston basin.

The exposed rocks range in age from Cretaceous to Recent. Rock types include sedimentaries such as sandstone, quartzite, shale, coal, and several varieties of glacial deposits. The region analyzed has been extensively glaciated and the bedrock is known for only about 30 percent of the locality; therefore, igneous rocks were not indicated on the maps analyzed. Normal faults and tension fractures (joints) were the significant structural features shown on the maps.

The conclusions of the study of this area indicate that the region has a fault density of 0.0612 faults per square mile. The faulting closely approximates an exponential distribution. The range of faults throughout the area is from 0 to 7 faults per square mile--Table 1 shows these data. These results are only a preliminary estimate because the amount of bedrock exposures are limited (only 30% of the area) and only 14 maps were available for the study.

6.2.4 Grant County, Oregon

A statistical analysis of the available geological maps of Grant County, Oregon was completed to determine the incidence and frequency of faults. The region investigated is in eastern-central Oregon about 100 miles from the Idaho

and the results may change when a detailed geological investigation is completed. The quadrangles are all of the same geological province, and the 2,000 square mile area is considered a valid geological sample. The location is characterized by deposits of Jurassic, Cretaceous, and Tertiary sedimentary rocks including types such as shale, siltstone, sandstone, conglomerate, and fanglomerates. A limited amount of Tertiary igneous rocks have been recorded throughout the region and these include laccoliths, stocks and dikes of diorite porphyry. Some of the observed structural features include high angle faults and circular faults around sedimentary collapse structures. The geology is characteristic of the Colorado Plateau.

The results of the analysis indicate that the region of San Juan County, Utah has an average fault density of 0.727 faults per square mile, and the faulting probabilities closely approximate an exponential distribution. The range of faulting observed was from 0 to 22 faults per square mile. These data are presented in Table 1. The results are considered to be only a preliminary estimate because the geological maps used for the analysis were only reconnaissance in nature.

6.2.3 Roosevelt County, Montana

The fault occurrences of a portion of Roosevelt and Daniel County, Montana were analyzed statistically in order to determine the nature of the fault population. The region

6.2 The Areas Analyzed

6.2.1 Edinburgh, Scotland

The region of Edinburgh, Scotland has a mean fault content of 2.64 faults per square mile and the fault probabilities closely approximate a negative binominal distribution. Edinburgh is in southeastern Scotland bordering on the North Sea; the map that was analyzed is sheet 32 of the Geological Survey of Great Britain. The map is a detailed picture of bedrock geology and is large enough to constitute a valid example.

The location is characterized by Middle to Late Paleozoic sedimentary and igneous rocks. The numerous sedimentary rock types include types such as limestone, shale, coal, sandstone, and conglomerate; the igneous rocks of the region include extrusives such as basalt, dolerite, picrite, and techenite. Several volcanic plugs occur throughout the locality. The region is part of the Midland Valley of Scotland (Macgregor, 1948).

6.2.2 San Juan County, Utah

The fault occurrences of a region in southeastern Utah were analyzed statistically. The area is located at the Colorado border about 250 miles southeast of Salt Lake, and includes most of San Juan County. The maps analyzed consisted of 36 geological quadrangles in the MF series tabulated in Appendix C. The maps are of a preliminary nature,

The formulae tested for fitting the observed areal fault distributions included the Poisson, exponential, and negative binomial. Several other distributions were tried and found to be non-suitable and were therefore rejected. These formulae are defined in most standard statistics books (Hald, 1952). A control area was needed to test the experimental technique and to supply the definitive frequency distribution for faults from the other areas investigated. Any location with complete geological knowledge would fill this requirement.

6.8.1 Control area

Edinburgh, Scotland, was selected as the control area for the investigation. It has been studied since the start of the nineteenth century and it is also the locale for extensive mining activities. It represents a more complete state of geological knowledge than any location available to the author. The main difficulty in formulating the statistical model of faulting of any geological province is that all of the faults are not known; for that reason Edinburgh, which did not have the problem, was utilized to formulate the definitive frequency distribution of faults in one geographic region.

(New England) joints and some metamorphic structures were counted as faults. Anything that would change the rock permeability was tentatively classified as a fault. Also, faults that intersected several cells were counted more than once--but this seems reasonable as large faults probably involve more episodes of faulting in their formation and should be weighted more heavily in computing the statistical constants.

No prior evidence of a similar geostatistical investigation of structural features has been located by the author; however, statistical studies of ore deposit distributions have been completed by several authors, (Slichter, Dixon, and Meyer, 1962) and (Kochanč Link, 1970). So a general statistical approach was used for the investigation. The difficult problem was in determining the best value of the free parameter for the frequency distribution formulas tested. The total number of fault incidences in the region and the total number of cells containing at least one fault, when each are large (and different) numbers, forms a suitable basis for determining the free parameter in the distribution formulae. The quotient of these two numbers was used for the significant characteristic of the observed distributions:

$$q = \frac{\text{incidences of faulting}}{\text{number of cells with 1 or more faults}}$$

6 AREAL INVESTIGATIONS

6.1 The experimental model

The areal distribution of faulting patterns was reduced to a one-dimensional case--the time and expense involved in a two-dimensional analysis was not warranted at this preliminary stage of analysis. Each geological area was divided into equal squares or cells (using a grid overlay), and then the number of faults intersecting each cell was counted. The cells were then classified with respect to their content in faults. It was desirable to have areas large enough that they contained several hundred cells (this was the case whenever the necessary data were available); the cells at the same time were selected large enough that each contained several faults (from 0 to 10). The cell size used was 1 square mile whenever possible (for the convenience of comparing fault statistics of different areas. The above described procedures do not account for the three dimensional aspect of faults or their genetic occurrence in stages and preferred directions--in accordance with stress distributions; but the procedure that was used is considered a suitable technique for classifying and comparing faulting occurrences of different areas.

The word "fault" may have a variable meaning. The author has included everything indicated as a fault on the published maps. However, in some locations (southwest) circular structures were also counted as faults and in other areas

features such as faults and concealed cavities. The "completeness of the search" rather than the cost of the exploration program should determine the optimum selection of exploration techniques. The approach outlined will probably give 100% of the geological situation. The line and station spacing for gravimetric, magnetic, electrical resistivity, and VLF electromagnetic exploration should be at intervals of 500 ft. and 100 ft. respectively in the central area at the potential site location and at intervals of 1000 ft. and 200 ft. throughout the remainder of the 20 square miles. It is suggested that the patterns used be rectangular in order to avoid any bias or abasing. At least 12 drill holes are recommended in order to present a complete third dimension picture of the subsurface situation; eight drill holes are suggested for the 5 square mile central location and the remaining 4 holes should be placed around the perimeter of the 20 square mile exploration zone. About 500 line-miles of seismic and 1000 line-miles of aeromagnetic exploration--each completed on a rectangular grid--would also be required for the exploration program.

Table 4
Current Geological Exploration Costs* for HLW Repository
Sites

Exploration technique	Current cost
1. Airborne Magnetic and Radioactive	\$ 55,000
2. Seismic Exploration (Refraction and Shallow Reflection)	\$252,000
3. Geological Mapping and Drill Hole Exploration (14 drill holes)	\$250,000
4. Gravimetric Exploration	\$ 55,000
5. Magnetic Exploration	\$ 40,000
6. VLF Electromagnetic Exploration	\$ 20,000
7. Electrical Resistivity	\$134,000
8. Well Logging	\$ 30,000
9. Geological Management	<u>\$ 75,000</u>
Total Exploration Costs	\$911,000

the approximate cost for an HLW repository site investigation. The listed exploration tools are suggested by the author for the program and include saturation geophysics coupled with detailed surface and subsurface geological investigations. This approach to the problem will probably yield a complete geological picture--including the presence on any hazardous

*These costs represent competitive bids obtained by the author from consulting geophysicists and exploration companies during October 1977.

FIGURE 17
The Exploration Game

Player	→	Nature			
↓					
A					
Exploration Team	Exploration Technique	HLW Site Investigation--Screening Stage Of Exploration			Strategies
		Fault Present	Fault Not Present	Ambiguous Situation	
	Magnetic	2	1	0	
	Gravimetrics	5	3	2	
	Seismic Refraction	10	5	1	
	VLF Electromagnetics	2	0	0	
	Geological Mapping	1	1	0	
	Seismic Reflection	5	3	2	
	Electrical Resistivity	5	3	2	
	Subsurface Investigation	2	2	2	

and individual site will have its own unique geological character and thus present a special exploration problem. An alternate approach to the exploration would be to outline the program qualitatively based upon established techniques and utilize senior geological personnel to formulate and execute the search plan.

5.5 Exploration economics

The cost of completing an exploration program for an HLW repository site would be about \$1,000,000. This was estimated using current prices for exploration in the Western and Eastern U.S. The costs would include all preliminary work through the reconnaissance and screening exploration phases. The author suggests that an area of 5 square miles be investigated in detail and this central area should be expanded to include about 20 square miles that will be explored at about $\frac{1}{2}$ the station spacing of the central location. The nine different search techniques should assume a logical sequence with evaluations at selected points in the program so that the exploration may be terminated before the HLW repository is constructed--if a hazardous condition is encountered during the preliminary phase of the exploration. The exploration costs would vary from \$20,000 for VLF electromagnetic investigation to \$252,000 for seismic investigations. A complete list of current exploration costs is shown in Table 4.

The exploration costs will obviously increase with the inflationary cycle. However, the total below represents

TABLE 3

Search Effectiveness of Exploration Techniques
Used for Concealed Fault Mapping

Search Technique	Effectiveness Faults Present	Effectiveness Faults Not Present	Indeterminate Situation
Gravimetric	5	3	2
Magnetic	2	1	0
Seismic Refraction	10	5	1
Seismic Reflection	4	2	0
Electrical Resistivity	5	3	2
VLF Electromagnetic	2	0	0
Geological Mapping	1	1	0
Geochemical Mapping	1	0	0
Subsurface Investigations	2	2	2

* The effectiveness is based upon an arbitrary rating scale of 1 to 10, with 10 corresponding to an excellent anomaly and 1 representing an anomaly that is just discernable.

square miles--is in southwestern Wyoming near the Colorado border and consisted of maps in the GQ and MF series; these are tabulated in Appendix C. The maps were not all contiguous; however, they are representative of one geological province and are considered a valid sample. The geology is similar on all of the quadrangles and is typical of the Green River Basin.

The area is characterized by deposits of Tertiary and Cretaceous sediments--essentially the Green River and Wasatch formations. The rock types encountered include limestone, shale, coal beds, and other types of sedimentary rocks.

The results of the statistical analyses indicate that the region has an average fault density of 0.26 faults per square mile, and the frequency distribution essentially approximates an exponential probability distribution. The range of faulting encountered was 0 to 6 faults per square mile. These data are presented in Table 1. The results are only a preliminary estimate because the amount of data available was minimal and some of the geological maps were only reconnaissance in nature.

6.2.8 Coconino County, Arizona

Nine geological quadrangles--listed in Appendix C--of the general area of Coconino County, Arizona were examined to determine the geographical distribution and frequency of faults throughout the area; these data were then statistically analyzed to determine the density and character of the fault

population. The region analyzed--consisting of 1140 square miles--is located in north-central Arizona (and includes the Grand Canyon) in close proximity to Flagstaff. The region analyzed is part of the Colorado Plateau physiographic province.

The exposed rock units are the Grand Canyon section and include rocks of Precambrian, Paleozoic, Mesozoic, and Recent age. The dominant rock types are sedimentary (limestone, shales, and sandstones) with minor amounts of igneous rocks (granites and basalts) and metamorphic rocks also occurring. Some of the maps are of a preliminary variety, based upon photographic analyses or reconnaissance mapping techniques; and the final analysis may change as more complete data become available.

The region has a fault density of 0.45 faults per square mile and the observed fault frequency distribution closely approximates a theoretical exponential distribution. These data are presented in Table 1. The data indicate the region has an apparent low intensity and a medium range (from 0 to 15 faults per square mile) of fault occurrence. However, these preliminary results may change as more detailed investigations are completed.

6.2.9 Northern Michigan

Bedrock geological maps of the Keweenaw peninsula of northern Michigan were analyzed statistically to determine the nature and distribution of the fault population. This

area was selected because a large amount of detailed geological information concerning it is available. Thirteen geological quadrangles were used in the analysis, and include maps in the GQ and MF series, these are listed in Appendix C.

The area is in the Michigan "copper country", has been mined for over 100 years, and the geological data are considered highly precise. The quadrangles are all of the same geological province and are considered to be one sample. The geology is similar on all of the maps and is typical of shield areas. The location is characterized by deposits of Precambrian sedimentary and igneous rocks. The sedimentary rocks include conglomerates, arkoses, and sandstones; the igneous rocks include various lava flows and intrusives. At least one large fault is known to traverse the entire peninsula.

The results of the analysis indicate that the fault density of the area is 0.5161 faults per square mile and the frequency distribution of faults closely approximates a theoretical exponential distribution. The range of faults encountered varied from 0 to 6 faults per square mile. These preliminary results could be improved by expanding the area of analysis to include the entire geological province. The statistical data are summarized in Table 1.

6.2.10 Central Massachussetts

Geological maps of central Massachussetts were examined to determine the geographical distribution and

statistical occurrences of faulting of that region. The maps include 12 geological quadrangles; these are tabulated in Appendix C. The locality is part of the New England Appalachian province and consists of valleys and low mountains bordering the Triassic lowlands.

The exposed rock units range in age from Cambrian to Triassic. Rock types include igneous (granite, pegmatite, quartz veins, and diabase), sedimentaries (conglomerate, arkose, and sandstone), and metamorphics (gneiss, schist, amphibolite, quartzite, argillite, and marble). In addition, the area has been extensively glaciated and numerous glacial deposits are evident throughout the region; however, the analyzed maps are of bedrock geology, and the glacial aspects were not considered relevant to this investigation. Normal faults and joints were evident on the maps and were tabulated for the analysis.

The fault data were tabulated and statistically analyzed. The observed density of faulting is 0.226 faults per square mile. The observed fault frequency data closely approximate an exponential distribution. The total area consisted of 635 cells and the fault density varied from 0 to 7 faults per square mile. Joints were counted as faults because they characteristically were reported to show movement. Table 1 shows the statistical summary for these data.

6.2.11 Southeastern Idaho

Seven geological quadrangles of the general area of

Bonneville County, Idaho were examined to determine the geographical distribution and frequency of faults of that region. The locale is in southeastern Idaho along the Wyoming border south of the Snake River volcanic field. The geological maps used for the analysis are listed in Appendix C. The geology is typical of the central Rockies of southern Idaho.

The exposed rock units include igneous rocks--basalt, rhyolites, tuffs, and breccias, and sedimentary rocks--shale, siltstone, limestone, dolomite, and sandstone. They range in age from Early Paleozoic to Cretaceous for the sedimentaries and include some Tertiary volcanics. Structural features in the region include normal and thrust faults and these were tabulated for the study.

The fault density data were statistically analyzed and are presented in Table 1. The density of the faults is 2.12 faults per square mile and the observed fault frequencies closely approximate an exponential distribution. The total area consisted of 500 square miles and the range of faults varied from 0 to 12 faults per square mile. Some of the maps are of a preliminary variety (based upon reconnaissance techniques) and the results of the analysis may change when more complete data become available.

6.2.12 Central Connecticut

The faulting occurrences of central Connecticut were tabulated and statistically analyzed to determine their density and distribution characteristics. Six geological quad-

rangles totalling 315 square miles were analyzed during the investigation. The maps include the region in and around Hartford, Connecticut and comprise portions of the New England Appalachians and the border of the Connecticut Triassic basin. The maps are tabulated in Appendix C.

The rock types exposed in the area include igneous, sedimentary, and metamorphic rocks of Paleozoic and Triassic age. The sedimentaries include various siltstones, shales, sandstones, arkose, and numerous glacial deposits. The igneous rocks are basalt, diabase, and pegmatite. A region of metamorphic rocks includes several varieties of schist and amphibolite. A zone of extensive faulting exists at the borders of the Triassic lowlands.

The statistical investigation indicated that the fault density is 1.44 faults per square mile, and the fault frequency population approximates an exponential distribution function. The range of faulting varies from 0 to 4 faults per square mile; these data are presented in Table 1. It is doubtful if the area analyzed constitutes a valid sample because it was too small and consisted of portions of two geological provinces. However, the data presented are a preliminary estimate of the fault occurrences of the region.

6.2.13 Central New Mexico

The faulting occurrences of a portion of central New Mexico were tabulated and statistically analyzed to determine the frequency distribution of faults in the region. The area

analyzed consisted of 16 geological quadrangles in the vicinity of Santa Fe, San Miguel, Torrance, and Valencia Counties, New Mexico; the quadrangles are tabulated in Appendix C. The region borders the Colorado Plateau and is essentially a portion of the New Mexico Rockies.

The area includes rocks of Precambrian, Paleozoic, Mesozoic, and Cenozoic age. The sedimentary rocks include shales, siltstone, sandstones, calcarenite, and some recent terrace and pediment deposits. The igneous rocks exposed are basalt and rhyolite. A variety of metamorphics are also present in the region and include gneissic-granite, schist, gneiss, quartzite, and metarhyolite. Many varieties of faults are recognized in the area and include fault zones, normal faults, and reverse faults.

The analysis of the structural data indicated that the region has an average fault density of 1.96 faults per square mile and the fault frequencies closely approximate an exponential distribution. The number of faults varies from 0 to 29 per square mile. The region analyzed included 1,596 square miles. The statistical data are presented in Table 1.

6.2.14 Eastern Tennessee

A region of eastern Tennessee was analyzed to determine the characteristics of the fault population. Thirteen geological quadrangles were available for the analysis and these are tabulated in Appendix C. The region is along the eastern portion of the Nashville dome and is part of the

Appalachian plateau and Ridge and Valley provinces.

The exposed rocks include some of Precambrian, Paleozoic, and Cenozoic age. Sedimentary rocks include shales, siltstones, sandstones, quartzites, conglomerates, limestones, and dolomites. The area analyzed did not have any igneous or metamorphic rocks listed. The faults are of several varieties including normal, tear, and major thrust faults.

The fault occurrence data were tabulated and statistically analyzed and the results show a fault density of 1.01 faults per square mile and a fault range of 0 to 14 per square mile. The fault population closely approximates an exponential frequency distribution. The results are considered only to represent a rough estimate because the number and distribution of geological maps did not constitute a complete sample.

6.2.15 Kern County, California

A variety of sources including subsurface data and some surface geological reports of a portion of Kern County, California were analyzed in order to determine the fault occurrence statistics. The data comprise about 21 percent of the county, and some references are tabulated in Appendix C. Some of the data used for the analysis are subsurface maps; all of the fault occurrences were projected onto a horizontal plane and tabulated by the standard procedure. The region is in south central California, and includes the area around Bakersfield.

The geology is characteristic of the central valley of California and the bordering Sierra Nevada Mountains and southern coast ranges. The rocks exposed and encountered in the subsurface work include igneous, sedimentary, and metamorphics of Precambrian, Paleozoic, Mesozoic, and Cenozoic age. The sedimentaries include shale, sandstone, conglomerate, limestone, and dolomite. The igneous types--in the ranges around Bakersfield--include basalt, andesite, and rhyolite extrusives and diorite, monzonite, and granite intrusives. Some metamorphics are present and include schist, phyllite, and metavolcanics. A variety of faults is apparent on the analyzed maps including normal and reverse faults; the major portion of the analysis encompassed a portion of the San Joaquin valley--a large syncline.

The fault density data were tabulated and statistically analyzed and indicate the region has a fault content of 1.27 faults per square mile, and the fault content varied from 0 to 28 faults per square mile. The fault frequency data closely approximate an exponential distribution function. These data are presented in Table 1.

6.2.16 Eastern Pennsylvania

The eastern third of Pennsylvania was examined to determine the geographical distribution and frequency of faulting of that region; the faults on the state geological map were noted and tabulated. The area analyzed is about 11,276 square miles in extent. The general location is in

southeastern Pennsylvania and included portions of the piedmont and Triassic lowland provinces.

The exposed rock units include sedimentary and igneous rocks that range in age from Precambrian to Triassic. The igneous rocks include diabase and basalt dikes, sills and flows; the sedimentary rocks include limestone, shale, sandstone, and conglomerates. The data source is the state geological map of Pennsylvania and this would only show large faults and structural features; more detailed and recent studies may yield a more intense fault occurrence than was noted during this investigation.

The fault density data were tabulated and statistically analyzed and are presented in Table 1. The fault density was calculated to be 5.60 faults per unit cell; the unit cell size is 58.4 square miles. Estimating the fault density for a one square mile cell gives about .096 faults per square mile; this seems much too low. A realistic determination would require repeating the experiment using regular geological quadrangles of the region. The fault frequency data closely approximate an exponential distribution.

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APPENDIXES

APPENDIX A

STATISTICAL FUNCTIONS FOR SELECTED GEOLOGICAL LOCATIONS

The enclosed table shows the first four statistical moments and the kurtosis and skewness of the fault frequency population of the 16 selected geological locations. The following formulae were used for the calculations:

$$M_1 = A = \frac{1}{N} \sum fx$$

$$M_2 = \frac{1}{N} \sum f (x - A)^2$$

$$M_3 = \frac{1}{N} \sum f (x - A)^3$$

$$M_4 = \frac{1}{N} \sum f (x - A)^4$$

$$\text{Kurtosis of distribution} = \frac{M_4}{(M_2)^2}$$

$$\text{Skewness of distribution} = \frac{M_3}{(M_2)^{3/2}}$$

$$N = \sum_{i=1}^n f_i \quad n = \text{number of different groups.}$$

Table 1
STATISTICAL FUNCTIONS OF FAULTING AT SELECTED GEOLOGICAL LOCATIONS

Location	m_1	m_2	m_3	m_4	k	s
1. Edinburgh, Scotland	2.64	6.10	18.61	200.83	5.23	1.36
2. Eastern Montana	0.06	0.16	0.51	1.98	81.91	8.23
3. San Juan County, Utah	0.73	3.46	26.57	314.45	26.27	4.13
4. Grant County, Oregon	0.74	1.47	3.70	16.59	7.71	2.09
5. Nevada Test Site	10.03	267.22	26588.01	4503360.48	63.70	6.09
6. Karnes County, Texas	0.15	0.15	0.16	0.27	12.17	2.80
7. Sweetwater County, Arizona	0.26	0.54	1.53	5.98	20.29	3.82
8. Coconino County, Arizona	0.45	1.32	10.23	140.23	80.12	6.72
9. Keweenaw County, Michigan	0.52	0.83	1.83	7.37	10.68	2.42
10. Western Massachusetts	0.23	0.40	1.08	4.99	31.41	4.29
11. Bonneville County, Idaho	2.12	5.46	17.38	136.97	4.59	1.36
12. Valencia County, New Mexico	1.36	6.65	72.96	1440.11	32.55	4.25
13. Central Connecticut	1.44	13.34	230.21	6052.93	33.99	4.72
14. Eastern Tennessee	1.01	1.98	6.56	55.03	14.10	2.36
15. Kern County, California	1.27	5.65	48.43	764.83	23.94	3.60
16. Eastern Pennsylvania	0.10	1.00	1176.63	50536.17	16.11	2.81

APPENDIX B
OBSERVED FAULT FREQUENCIES

Figure 1. Observed fault frequencies for Edinburgh, Scotland.

Figure 2. Observed fault frequencies for portions of eastern Montana.

Figure 3. Observed fault frequencies for portions of San Juan County, Utah.

Figure 4. Observed fault frequencies for portions of south-central Oregon.

Figure 5. Observed fault frequencies in the vicinity of the Nevada Test Site.

Figure 6. Observed fault frequencies for portions of Kern County, Texas.

Figure 7. Observed fault frequencies for portion of Sweetwater County, Wyoming.

Figure 8. Observed fault frequencies for portions of Coconino County, Arizona.

Figure 9. Observed fault frequencies for portions of Keweenaw County, Michigan.

Figure 10. Observed fault frequencies for portions of western Massachusetts.

Figure 11. Observed fault frequencies for portions of Bonneville County, Idaho.

Figure 12. Observed fault frequencies for the vicinity of Valencia County, New Mexico.

Figure 13. Observed fault frequencies for portions of central Connecticut.

Figure 14. Observed fault frequencies for portions of Kern County, California.

Figure 15. Observed fault frequencies for portions of central Tennessee.

Figure 16. Observed fault frequencies for eastern Pennsylvania.

APPENDIX C

LIST OF MAPS ANALYZED IN GEOSTATISTICAL EVALUATION
OF FAULTING1. Edinburgh, Scotland:

Edinburgh, Sheet 32 of the Geological Survey of Great Britain.

2. Eastern Montana:

Map I-361 Geologic Map of the south half of the Baylor, Larslan West Fork, Police Creek, Kahle, and Lundville Quadrangles, Valley, Roosevelt, and Daniels Counties, Montana by Roger B. Colton, U.S.G.S., 1964.

Map I-362 Geologic Map of the Brockton Quadrangle, Roosevelt and Richland Counties, Montana, by R.B. Colton, U.S.G.S., 1964.

Map I-363 Geologic Map of the Chelsea Quadrangle. Roosevelt and McCone Counties, Montana by R.B. Colton, U.S.G.S., 1963.

Map I-364 Geology of the Cuskers Quad., Roosevelt County, Montana, U.S.G.S., 1963.

Map I-365 Geologic Map of the Hay Creek Quad., Roosevelt County, Montana by R.B. Colton, U.S.G.S., 1963.

Map I-366 Geologic Map of the Oswego Quad., Valley, Roosevelt and McCone Counties, Montana by R.B. Colton, U.S.G.S., 1963.

Map I-367 Geologic Map of the Popular Quad., Roosevelt, Richland and McCone Counties, Montana by R.B. Colton, U.S.G.S., 1963.

Map I-368 Geologic Map of the Porcupine Valley Quad.,
Valley County, Montana by R.B. Colton, U.S.G.S., 1963.

Map I-369 Geologic Map of the Spring Creek Quad., Valley
County, Montana by R.B. Colton, U.S.G.S., 1963.

Map I-370 Geologic Map of the Todd Lakes Quad., Valley
and Roosevelt Counties, Montana by R.B. Colton, U.S.G.S.,
1963.

Map I-371 Geologic Map of the Tule Valley Quad., Roose-
velt County, Montana by R.B. Colton, U.S.G.S., 1963.

3. San Juan County, Utah:

Map MF-123 Preliminary Geologic Map of the Mount Peale 1
SE Quadrangle, Montrose County, Colorado and San Juan
County, Utah by W.D. Carter and J.L. Gualtieri, U.S.G.S.,
1957.

Map MF-124 Preliminary Geologic Map of the Mount Peale 1
SW Quad., San Juan County, Utah by Carter & Gualtieri,
U.S.G.S., 1957.

Map MF-139 Preliminary Geologic Map of the Mount Peale 1
NE Quad., San Juan County, Utah and Montrose County, Colo-
rado by W.D. Carter, J.L. Gualtieri, and E.M. Shoemaker,
U.S.G.S., 1958.

Map MF-140 Preliminary Geologic Map of the Mount Peale 1
NW Quad., San Juan County, Utah by W.D. Carter and J.L.
Gualtieri, U.S.G.S., 1958.

Map MF-141 Preliminary Geologic Map and Sections of the
Mount Peale 2 NE Quadrangle, San Juan County, Utah by
G.W. Weir and W.P. Puffett, U.S.G.S., 1960.

Map MF-142 Preliminary Geologic Map of the Mount Peale 2 SW Quad., San Juan, Utah by G.W. Weir and V.C. Kennedy, U.S.G.S., 1958.

Map MF-143 Preliminary Geologic Map and Section of the Mount Peale 2 SE Quad., San Juan County, Utah by G.W. Weir, C.L. Dodson, W.P. Puffett, U.S.G.S., 1960.

Map MF-144 Preliminary Geologic Map of the Mount Peale 3 NW Quad., San Juan County, Utah by G.W. Weir and C.L. Dodson, U.S.G.S., 1958.

Map MF-145 Preliminary Geologic Map of the Mount Peale 3 NE Quad., San Juan Co., Utah by Weir and Dodson, U.S.G.S., 1958.

Map MF-146 Preliminary Geologic Map of the Mount Peale 3 SW Quad., San Juan, Utah by Weir and Dodson, U.S.G.S., 1958.

Map MF-147 Preliminary Geologic Map of the Mount Peale 3 SE Quad., San Juan, Utah by Weir and Dodson, U.S.G.S., 1958.

Map MF-148 Preliminary Geologic Map of the Mount Peale 4 SW Quad., San Juan, Utah by Weir and Dodson, U.S.G.S., 1958.

Map MF-149 Preliminary Geologic Map of the Mount Peale 4 SE Quad., San Juan County, Utah, and San Miguel County, Colorado by Weir and Puffett, U.S.G.S., 1960.

Map MF-150 Preliminary Geologic Map and Section of the Mount Peale 4 NE Quad., San Juan County, Utah, and Montrose and San Miguel Counties, Colorado by G.W. Weir, W.D. Carter, W.P. Puffett, and J.L. Gualtieri, U.S.G.S., 1960.

Map MF-151 Preliminary Geologic Map and Section of the Mount Peale 4 NW Quad., San Juan County, Utah by Weir, Puffett, and Dodson, U.S.G.S., 1961.

Map MF-152 Preliminary Geologic Map and Section of the Mount Peale 2 NW Quad., San Juan County, Utah by G.W. Weir, V.G. Kennedy, W.P. Puffett, and C.L. Dodson, U.S.G.S., 1961.

Map MF-162 Preliminary Geologic Map of the Verdue 2 NW Quad., San Juan County, Utah by I.J. Witkind, U.S.G.S. 1958.

Map MF-163 Preliminary Geologic Map of the Verdue 2 SE Quad., San Juan County, Utah by Lyman C. Huff & Frank G. Lesure, U.S.G.S., 1958.

Map MF-164 Preliminary Geologic Map of the Verdue 1 SW Quad., San Juan County, Utah by F.G. Lesure, L.C. Huff, and Fredrick Stugard, Jr., U.S.G.S., 1958.

Map MF-165 Preliminary Geologic Map of the Verdue 3 NE Quad., San Juan County, Utah by F.G. Lesure, L.C. Huff, and F. Stugard, Jr., U.S.G.S., 1958.

Map MF-166 Preliminary Geologic Map of the Verdue 4 NW Quad., San Juan County, Utah by L.C. Huff and F.G. Lesure, U.S.G.S., 1958.

Map MF-167 Preliminary Geologic Map of the Verdue 3 SE Quad., San Juan County, Utah by L.C. Huff and F.G. Lesure, U.S.G.S., 1958.

Map MF-184 Preliminary Geologic Map of the Clay Hills 2 NE Quad., San Juan Co., Utah by T.E. Mullens, U.S.G.S., 1958.

Map MF-185 Preliminary Geologic Map of the Clay Hills 2
NW Quad., San Juan Co., Utah by T.E. Mullens, U.S.G.S.,
1959.

Map MF-186 Preliminary Geologic Map of the Clay Hills 2
SW Quad., San Juan Co., Utah, by T.E. Mullens, U.S.G.S.,
1959.

Map MF-190 Preliminary Geologic Map of the Elk Ridge 2 NE
Quad., San Juan Co., Utah by R.Q. Lewis, Sr., and R.H.
Campbell, U.S.G.S., 1958.

Map MF-191 Preliminary Geologic Map of the Elk Ridge 2 NW
Quad., San Juan Co., Utah by R.Q. Lewis, Sr., and R.H.
Campbell, U.S.G.S., 1958.

Map MF-192 Preliminary Geologic Map of the Elk Ridge 2 SW
Quad., San Juan Co., Utah, Lewis and Campbell, U.S.G.S.
1958.

Map MF-193 Preliminary Geologic Map of the Elk Ridge 2 SE
Quad., San Juan Co., Utah, Lewis and Campbell, U.S.G.S.
1958.

Map MF-194 Preliminary Geologic Map of the Elk Ridge 3 NE
Quad., San Juan Co., Utah, Lewis and Campbell, U.S.G.S.
1958.

Map MF-195 Preliminary Geologic Map of the Elk Ridge 3 NW
Quad., San Juan Co., Utah, Lewis and Campbell, U.S.G.S.
1958.

Map MF-199 Preliminary Geologic Map of the Elk Ridge 4 NW
Quad., San Juan Co., Utah, Lewis and Campbell, U.S.G.S.
1959.

Map MF-200 Preliminary Geologic Map of the Elk Ridge 1 SW Quad., San Juan Co., Utah, Lewis and Campbell, U.S.G.S., 1959.

Map MF-201 Preliminary Geologic Map of the Elk Ridge 1 NW Quad., San Juan Co., Utah, Lewis and Campbell, U.S.G.S., 1958.

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- Map GQ-455 Geologic Map of the Cane Spring Quad., Nye Co.,
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- Map GQ-456 Geologic Map of the Frenchman Flat Quad., Nye,
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- Map GQ-496 Geologic Map of the Quartet Dome Quad., Nye
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- Map GQ-582 Geologic Map of the Yucca Flat Quad., Nye and
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Map GQ-1002 Geologic Map of the Four J Rim Quadrangle, Sweetwater County, Wyoming and Moffat County, Colorado by H.W. Roehler, U.S.G.S., 1972.

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Map GQ-1077 Geologic Map of the Bull Canyon Quad., Santa Fe County, New Mexico by R.B. Johnson, U.S.G.S., 1973.

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Map GQ-115 Geology of the Knoxville Quad., Tennessee by J.M. Cattermole, U.S.G.S., 1958.

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Appendix D Frequency Distributions of Fault Populations

Area 1. Edinburgh				2. Eastern Montana			
n	N	oP(n)	tP(n)	N	oP(n)	tP(n)	
0	239	.3229	.2163	100	.5263	.5263	
1	261	.2916	.2918	44	.2316	.2493	
2	154	.1721	.1332	27	.1421	.1181	
3	100	.1117	.1041	7	.0363	.0559	
4	45	.0503	.0528	9	.0474	.0265	
5	29	.0324	.0253	2	.0105	.0126	
6	3	.0039	.0117	1	.0053	.0060	
7	7	.0073	.0052	0	.0000	.0023	
8	2	.0022	.0023	0	.0000	.0013	
9	0	0	.0010	0	.0000	.0005	

395 cells
cell = 1 mi²

k = 2.4786

Q = .5390

Negative Binomial
Distribution

2793 cells
cell = 1 mile²

η = 1.90

Exponential Distribution

Appendix D (cont.)
Frequency Distributions of Fault Populations

Area 3. San Juan County, Utah				4. Grant County, Oregon		
n	N	oP(n)	tP(n)	N	oP(n)	tP(n)
0	713	.3294	.3298	333	.5486	.5480
1	160	.2245	.2209	155	.2557	.2477
2	118	.1655	.1481	63	.1039	.1120
3	74	.1038	.0993	25	.0412	.0506
4	38	.0533	.0666	17	.0280	.0229
5	23	.0323	.0447	10	.0165	.0103
6	15	.0210	.0300	2	.0033	.0047
7	12	.0168	.0200	2	.0033	.0021
8	13	.0182	.0135	0	0	.0010
9	4	.0056	.0090	0	0	.0004
N = 1996 cells Cell = 1 mile ² Exponential Distribution q = 3.04				N = 1253 Cell = 1 mile ² Exponential Distribution q = 1.82		

Appendix D (cont.)
Frequency Distributions of Fault Populations

Area 5. Nevada Test Facility				6. Harney County, Oregon		
n	N	oP(n)	tP(n)	N	oP(n)	tP(n)
0	176	.1139	.1191	1255	.9474	.9444
1	197	.1331	.1049	65	.0503	.0525
2	150	.1013	.0924	3	.0015	.0029
3	103	.0696	.0814	1	.0008	.0002
4	105	.0709	.0717	0	0	0
5	82	.0554	.0632			
6	70	.0473	.0557			
7	64	.0432	.0490			
8	64	.0304	.0432			
9	45	.0372	.0380			
10	55	.0277	.0335			
1905 cells Exponential Distribution Cell = 1 mile ² q = 3.40				504 cells Exponential Distribution Cell Size = 1 mile ² q = 1.06		

Appendix D (cont.)
Frequency Distributions of Fault Populations

Area 7. Sweetwater County, Wyoming				8. Coconino County, Arizona		
n	N	oP(n)	tP(n)	N	oP(n)	tP(n)
0	171	.6002	.5998	356	.5570	.5560
1	71	.2492	.2400	166	.2600	.2469
2	24	.0842	.0960	63	.0990	.1096
3	10	.0350	.0384	33	.0520	.0487
4	5	.0175	.0154	12	.0190	.0216
5	3	.0111	.0062	3	.0047	.0096
6	1	.0035	.0025	1	.0016	.0043
7	0	0	.0010	1	.0016	.0019
8						
9						
735 cells Exponential Distribution cell size = 1 mile ² q = 1.67				1140 cells Exponential Distribution cell size = 1 mile ² q = 1.80		

Appendix D (cont.)
Frequency Distributions of Fault Populations

Area 9. Keweenaw County, Michigan				10. Western Massachusetts			
n	N	op(n)	tp(n)	N	op(n)	tp(n)	
0	130	.6429	.6429	189	.6608	.6599	
1	46	.2282	.2296	63	.2203	.2244	
2	18	.0893	.0820	26	.0909	.0763	
3	4	.0198	.0293	4	.0140	.0260	
4	3	.0149	.0104	2	.0070	.0088	
5	0	0	.0037	1	.0035	.0030	
6	1	.0050	.0013	0	.0000	.0010	
7				1	.0035	.0004	
8							
9							
217 cells Exponential Distribution Cell size = 1 mile ² q = 1.56				N = 634 cells Exponential Distribution Cell size = 1 mile ² q = 1.52			

Appendix D (cont.)
Frequency Distributions of Fault Populations

Area 11. Bonneville County, Idaho				12. Valencia County, New Mexico		
n	N	oP(n)	tP(n)	N	oP(n)	tP(n)
0	170	.3283	.3283	337	.3244	.3244
1	110	.2123	.2205	251	.2416	.2192
2	73	.1409	.1481	151	.1453	.1481
3	52	.1004	.0995	111	.1068	.1000
4	38	.0733	.0668	60	.0577	.0676
5	26	.0502	.0449	30	.0289	.0457
6	15	.0290	.0302	30	.0289	.0309
7	15	.0290	.0203	17	.0164	.0208
8	8	.0154	.0091	15	.0144	.0141
9	7	.0135	.0061	14	.0135	.0095
				5	.0048	.0064
500 cells Exponential Distribution				1596 cells Exponential Distribution		
Cell size = 1 mile ² q = 3.05				Cell size = 1 mile ² q = 3.08		

Appendix D (cont.)
Frequency Distributions of Fault Populations

Area 13. Central Connecticut				14. Eastern Tennessee		
n	N	oP(n)	tP(n)	N	oP(n)	tP(n)
0	136	.2336	.2318	406	.5000	.5006
1	43	.1825	.1781	185	.2278	.2500
2	15	.1095	.1368	108	.1330	.1248
3	7	.0511	.1051	69	.0850	.0623
4	8	.0584	.0807	26	.0320	.0311
5	3	.0219	.0620	10	.0123	.0155
6	4	.0292	.0476	3	.0037	.0078
7	5	.0365	.0366	1	.0012	.0038
8	5	.0365	.0281	3	.0037	.0019
9	5	.0365	.0216			
10	1	.0073	.0166			
315 cells Exponential Distribution Cell size = 1 mile ² q = 4.31				819 cells Exponential Distribution Cell size = 1 mile ² q = 2.00		

Appendix D (cont.)

Frequency Distributions of Fault Populations

Area 15. Kern County, California				16. Eastern Pennsylvania		
n	N	oP(n)	tP(n)	N	oP(n)	tP(n)
0	408	.3505	.3500	22	.1294	.1292
1	326	.2800	.2275	19	.1117	.1124
2	141	.1211	.1479	18	.1058	.0979
3	95	.0816	.0961	15	.0882	.0853
4	50	.0430	.0625	12	.0700	.0743
5	37	.0318	.0406	5	.0294	.0647
6	30	.0258	.0264	11	.0647	.0563
7	28	.0241	.0172	11	.0647	.0490
8	15	.0129	.0112	6	.0353	.0427
9	8	.0069	.0072	5	.0294	.0372
10	9	.0077	.0047	3	.0176	.0324
1721 cells Exponential Distribution Cell size = 1 mile ² q = 2.86				200 cells Exponential Distribution Cell size = 58.4 mile ² q = 7.74		

APPENDIX E

THE CALCULATION OF GEOPHYSICAL ANOMALIES

The following formulae were used to estimate the geophysical anomalies that would result from the hypothetical fault model.

1. Gravity anomaly:

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

where g = vertical component of gravity in milligals,

σ = density,

t = throw of the fault,

x = the horizontal coordinate, and

z = the depth of the fault below the ground surface.

2. Magnetic anomaly:

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

where I = intensity of magnetization,

t = the throw of the fault

x = the horizontal coordinate, and

z = the depth of the fault below the ground surface.

3. Seismic refraction anomaly:

$$z = (dt) \frac{V_1 V_2}{(V_2^2 - V_1^2)^{1/2}}$$

where z = the throw of the fault,

dt = the difference in intercept times because of the faulted segments, and

V_1 and V_2 = the seismic velocities in the two media.

The remaining anomalies were estimated by comparing the contrast in physical properties that would result from the fault situation. The seismic reflection anomaly was calculated by using the throw of the fault divided by the seismic velocity. The resistivity anomaly would result because the vertical fault contact would produce a measurable resistivity contrast and the magnitude of the anomaly will be proportional to the ratio of the formation resistivities. The induced polarization and electromagnetic anomalies were estimated by comparing results from known case histories with the assumed fault model.