Golder Associates
CONSULTING MINING AND GEOTECHNICAL ENGINEERS

SCOPING STUDY OF SALT DOMES, BASALTS AND CRYSTALLINE ROCK AS RELATED TO LONG TERM RISK MODELING FOR DEEP GEOLOGIC DISPOSAL OF NUCLEAR WASTE

Distribution:

34 copies - Lawrence Livermore Laboratory,
Livermore, California

6 copies - Golder Associates,
Kirkland, Washington

"Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore Laboratory under contract number W-7405-ENG-48."

P.O.# 8770703

S77308

November 1978

TABLE OF CONTENTS

SECTION	TITLE	PAGE
1.0	INTRODUCTION	1
2.0	GENERAL SITE SUITABILITY CONSIDERATION	1
3.0	SALT DOMES	4
3.1	GENERAL	4
3.2	SITE SUITABILITY CHARACTERISTICS	4
3.3	SUMMARY	6
4.0	BASALTS	7
4.1	GENERAL	7
4.2	SITE SUITABILITY CHARACTERISTICS	8
4.3	SUMMARY	10
5.0	CRYSTALLINE ROCK	11
5.1	GENERAL	11
5.2	SITE SUITABILITY CHARACTERISTICS	11
5.3	SUMMARY	14
6.0	CONCLUSIONS AND RECOMMENDATIONS	15
	APPENDIX A - SALT DOMES	
A.1	GEOLOGY	A-1
A.1.1	General	A-1
A.1.2	Salt Dome Intrusion and Rate of Deformation	A-2
A.1.3	Anomolies in Salt Mines	A-5
A.2	HYDROLOGY	A-8
A.2.1	General	A-8
A.2.2	Special Features in Salt Mines	A-10
A.2.3	Salt Dome Dissolution	A-12
A.3	SPECIFIC SITES	A-13
A.3.1	Tatum Salt Dome	A-13
A.3.2	Hydrology	A-15
A.4	POTENTIAL RELEASE PATHWAYS	A-17

SECTION	TITLE	PAGE
APPENDIX B - BASALT		
B.1	GEOLOGY	B-1
B.2	HYDROLOGY	B-2
B.3	SPECIFIC SITES - COLUMBIA RIVER PLATEAU	B-4
	B.3.1 General	B-4
B.4	SPECIFIC SITES - SNAKE RIVER PLAIN	B-11
	B.4.1 General	B-11
	B.5.2 Idaho National Engineering Laboratory	B-12
B.5	POTENTIAL RELEASE PATHWAYS	B-14
APPENDIX C - METAMORPHIC AND INTRUSIVE IGNEOUS ROCKS		
C.1	GEOLOGY	C-1
	C.1.1 General	C-1
	C.1.2 Metamorphic Rocks	C-1
	C.1.3 Intrusive Igneous Rocks	C-3
	C.1.4 Shear Zones in Metamorphic Rocks	C-5
C.2	HYDROLOGY	C-8
C.3	SPECIFIC SITES	C-12
	C.3.1 Precambrian Shield Rocks	C-12
	C.3.2 Appalachian Region - Savannah River Plant Site	C-16
	C.3.3 Batholiths - Western United States	C-22
C.4	GENERIC BATHOLITH MODEL	C-29
APPENDIX D - REFERENCES		

LIST OF TABLES

Table Number	
I	SUMMARY OF SITE SUITABILITY CHARACTERISTICS
A-1	DATA ON UPLIFT RATES IN SALT DOMES
A-2	DATA ON DISSOLUTION OF NORTHEAST TEXAS SALT DOMES
A-3	HYDROLOGIC DATA FROM TATUM SALT DOME
C-1	PERMEABILITY OF METASEDIMENTS FROM MARQUETTE MINING DISTRICT, MICHIGAN

LIST OF FIGURES

Figure Number	
A-1	SALT DOME BASINS AND DOMES IN THE GULF COAST REGION
A-2	DIAGRAMMETRIC DEVELOPMENT OF A SALT STRUCTURE
A-3	DIAGRAMMETRIC ILLUSTRATION OF SALT-DOME RELATIONSHIPS
A-4	TOTAL DISSOLVED SOLIDS IN GROUNDWATER IN THE WILCOX GROUP SANDS AT PALESTINE AND KEECHI SALT DOMES
A-5	TOTAL DISSOLVED SOLIDS IN GROUNDWATER IN THE WILCOX GROUP SANDS AT BULLARD, BROOKS AND WHITEHOUSE SALT DOMES
A-6	SOUTHWEST-NORTHEAST SECTION THROUGH TATUM SALT DOME
B-1	SCHEMATIC SECTION THROUGH A BASALT FLOW SHOWING TYPICAL COOLING STRUCTURES
B-2	COLUMBIA RIVER BASALTS (STIPPLED) IN THE NORTHERN PART OF THE COLUMBIA RIVER PLATEAU
B-3	GENERALIZED CROSS SECTION OF THE PASCO BASIN IN COLUMBIA RIVER BASALT
B-4	SNAKE RIVER PLAIN
C-1	PRINCIPAL AREAS OF INTRUSIVE AND METAMORPHIC ROCKS AND THICKNESS OF SEDIMENTARY ROCKS IN THE UNITED STATES
C-2	RELATION OF WELL YIELD TO WELL DEPTH IN 239 CALIFORNIA WELLS IN CRYSTALLINE ROCK
C-3	IDEALIZED MODEL OF FLOW PATTERNS IN METAMORPHIC AND IGNEOUS ROCKS
C-4	TYPICAL CROSS SECTIONS OF REGIONS OF CRYSTALLINE ROCK MASSES
C-5	TYPICAL PART OF CRYSTALLINE APPALACHIANS IN NORTH AND SOUTH CAROLINA
C-6	GENERALIZED CROSS SECTION OF THE SAVANNAH RIVER PLANT SITE
C-7	SIERRA NEVADA BATHOLITH
C-8	PIKES PEAK BATHOLITH COMPLEX
C-9	GEOLOGIC MAP AND SECTION OF VASQUEZ TUNNEL

SCOPING STUDY
OF
SALT DOMES, BASALTS, AND CRYSTALLINE ROCKS
AS RELATED TO LONG-TERM RISK MODELING
FOR
DEEP GEOLOGIC DISPOSAL OF NUCLEAR WASTE

1.0 INTRODUCTION

The purpose of this study is to provide a preliminary geotechnical data base sufficient to initiate the development of Long-Term Risk Models (LTRM), for salt domes, basalt and crystalline rock, and identify technical issues requiring additional investigation.

The report is organized to provide general brief comments on each rock type in the text while presenting the detailed data base information in the Appendices. The data base includes both general and site specific geologic and hydrologic information.

There is sufficient information to begin the development and analysis of LTRM for salt domes, basalt, and crystalline rock.

2.0 GENERAL SITE SUITABILITY CONSIDERATIONS

For the purpose of this report, we have defined six major categories for evaluating suitable sites. These categories are listed below with comments on the desirability of site characteristics. Some characteristics may be desirable in one category and undesirable in another.

1. Topography: A site with gentle topography and minor relief is desirable.

2. Geographic Setting: The site should be in an area which is sparsely populated and unlikely to become densely populated in the near future. If possible, the site should be near current waste stockpiles. The site should not have significant recreational value.

3. Geologic Setting: Optimum geologic characteristics include:
   a. Tectonic stability.
   b. Simple and predictable geology.
   c. A thick, uniform and continuous host rock of low permeability with minimal fractures.
   d. Minimal geologic flaws such as faults and other anomalies.
   e. Minimal tectonically induced stresses.

4. Hydrologic Setting: Optimum hydrologic characteristics include:
   a. Minimal regional surface waters such as streams and lakes.
   b. Low rainfall, deep groundwater table.
   c. Site not subject to flooding.
   d. Predictable hydrology.
   e. Host rock with low permeability and low water content.
   f. Minimal horizontal gradients and little or no vertical gradients.
   g. Little or no circulating ground water at depository depth.
   h. Low groundwater velocities.

i. Long distance to groundwater surface discharge areas.

j. Groundwater conditions which facilitate shaft construction and operation.

k. As related to nuclide retardation and canister corrosion, nonsaline ground water is desirable. However, in terms of groundwater resource potential, saline water is desirable.

5. Mechanical and Chemical Rock Properties: Optimum host rock mechanical and chemical properties include:

a. Host rock of low solubility.

b. Uniform and predictable mechanical behavior.

c. High strength.

d. Maximum creep which promotes healing of fractures in terms of retrievability and stability, a rock with minimal creep behavior is desirable.

e. Thermally stable both mechanically and chemically.

f. High thermal conductivity.

g. High nuclide retardation both in the host rock and surrounding formations.

h. Mechanical properties which tend to minimize existing and potential fracturing.

i. No adverse chemical reactions with waste.

6. Natural Resources: The host rock and general repository area should have minimal natural resource potential. Specifically:

a. The host rock itself should not be a valuable resource.

b. The repository vicinity should not contain prolific freshwater aquifers.

c. The repository site should contain minimal existing boreholes, underground openings, and abandoned or active wells.

d. The repository vicinity should contain minimal existing and potential underground natural resources.

3.0 SALT DOMES

3.1 General

There are several areas containing salt domes in the United States. The most important of these is the Gulf Coast which contains over 300 salt domes. Salt domes have intruded upward through thick sequences of sediments. Their cores are slender plugs of almost pure halites. Their sizes and shapes vary, but they generally average 2 to 3 miles in diameter and are often more than 5 miles high. Salt dome emplacement is not well understood, and it may be difficult to demonstrate long-term stability, particularly under the influence of the waste heat.

The salt plug may be effectively impervious and contain no circulating ground water. However, the surrounding thick sedimentary deposits contain prolific aquifiers which often constitute important agricultural, industrial, and domestic water supplies.

Data base information on salt domes is included in Appendix A.

3.2 Site Suitability Characteristics

Based on our available information, the general site suitability characteristics of salt domes include:

1. Topography: Gulf Coast salt domes are in areas with low relief.

2. Geography: Salt domes are often near population centers.

3. Geologic Setting:
   a. Salt domes are in areas of relative seismic stability.
   b. The geology is relatively simple within the salt plug. The geometry of the dome and locations of boundary shear zones or other potential anomalies are complex and difficult to predict. Outside the dome, the geology is very complex.
   c. The salt plug is a thick and uniform formation.
   d. The salt plug is essentially pure halite (NaCl), but can contain some anomalies as discussed in Appendix A.1.3. Except for boundary shear zones, those anomalies are probably isolated features which may not seriously impact waste containment.
   e. Current information, as discussed in Appendix A.1.2, indicates that salt dome movement probably would be too slow to affect waste containment seriously. However, it may be very difficult to demonstrate this, especially with respect to the heat effect of the waste.

4. Hydrologic Setting:
   a. Gulf Coast salt domes are poorly located with respect to surface hydrology. They are in areas of high rainfall, abundant surface water, high flood potential and shallow groundwater table.
   b. Current data indicate that the interior of a salt dome is effectively impervious and contains no circulating

ground water. Water contained as brine inclusions is probably less abundant than in bedded salt, on the order of 0.02 percent.

c. Outside the dome, groundwater conditions are undesirable with numerous prolific aquifers. Shaft construction and operation may be difficult because of these aquifiers and weak ground. Long-term shaft sealing will be very important.

5. Mechanical and Chemical Properties:
   a. A major drawback of salt is its high solubility.
   b. Salt has relatively low strength and a high creep potential, particularly at elevated temperatures. This is undesirable in terms of depository stability, but desirable as related to healing any induced fracturing.
   c. Salt has high thermal conductivity.
   d. Brine inclusions will migrate toward the canister due to its heat. This may not be a major problem due to low flow rates.
   e. Salt has very low nuclide retardation.
   f. Salt is corrosive and may reduce the useful life of the canister.

6. Natural Resources: Salt dome areas contain major oil and gas reserves as well as major groundwater supplies and are commonly riddled with drill holes. The salt itself is also a resource; thus, salt domes are very poor candidates with respect to natural resources.

3.3 Summary

Salt domes have the best of some site characteristics and the worst of others. Salt domes are probably the least permeabl and most uniform of potential host formations. They also exhibit creep behavior which would minimize fracturing. On the other hand, they are highly soluble and surrounded by aquifers. They are also in populated areas and are associated with major oil and gas reservoirs.

Potential nuclide release pathways are discussed in Appendix A.5. The only release pathways appear to be related to flaws such as shafts or boreholes.

The primary data base areas needing further investigation include:

1. Prediction of current and future salt dome movement, especially as related to heat effects of the waste.

2. Determination and predictability of salt dome geometry and locations of potentially permeable boundary shear zones.

3. Determination of the longevity of shaft seals and potential rates of solution of salt through flooding of shafts.

4. Study of the natural resource problem including locating abandoned drill holes.

4.0 BASALTS

4.1 General

Basalt regions consist of complex interlayered basalt flows and interflow sediments consisting of clays, silts, sands, and gravels. The Columbia Plateau in the northwestern United States covers over 200,000-square miles with an average thickness of about 3,000 feet. The Snake River plain in central Idaho overlies another thick succession of basalt. Typical flows are approximately 100-feet thick with a range of a few feet to more than 200 feet. Although the flow surfaces are generally strongly jointed, the interior of some of the thicker flows have been found to be massive with few joints. The jointed basalt zones and coarse interflow sediments have high hydraulic conductivities and are prolific aquifers below the water table.

Data base information on basalts is included in Appendix B.

4.2 Site Suitability Characteristics

Based on our available information, the general site suitability characteristics of basalts include:

1. Topography: Basalt plateaus are generally areas of gentle relief, although they are rugged near erosional features such as canyons.

2. Geography: Much of the Columbia Plateau is sparsely populated. Close proximity to the Hanford Reservation which contains more than half of the nation's military nuclear waste is also an advantage.

3. Geologic Setting:
   a. Basalt plateaus are areas of moderate tectonism.
   b. In general, the geology is predictable with each major flow being areally extensive and continuous.
   c. Although many flows are thin and/or strongly jointed, thick sections of massive, essentially joint-free basalt do exist.
   d. Possibility of future volcanism should be considered.

4. Hydrologic Setting:
   a. Generally, rainfall is low, the groundwater table is deep, and limited surface water exists.
   b. With proper site investigation, groundwater predictability should be good due to horizontal continuity of major layers. However, groundwater flow patterns in deep basalt zones are not well understood at this time due to a lack of available data.
   c. Groundwater flow through basalts is primarily through fractures. Thus, relatively high groundwater velocities could occur.
   d. Thick, massive basalt flows should have very low hydraulic conductivity, on the order of 10^{-7} to 10^{-9} cm/sec.
   e. Freshwater aquifers can exist both above and below any potential depository basalt flow layer. This is a disadvantage of basalt.
   f. Groundwater gradients are expected to be relatively small with little if any vertical component. Distances to natural discharge areas can be very large for properly selected depository locations.
   g. Shaft sealing during operation should not be a serious problem because of competent ground. Shaft sealing after decommissioning will be very important.

5. Mechanical and Chemical Properties: In general, basalt has excellent mechanical and chemical properties. It has high strength and is thermally and chemically stable. However, it does have relatively low thermal conductivity and, because of its high strength, is subject to fracturing

without rehealing. The rock will be subject to excavation (blast) induced fracturing not specifically related to stress concentrations because of its high mechanical strength and brittleness. Nuclide retardation through fractures in basalt is not well understood.

6. Natural Resources: Groundwater potential may represent the primary natural resource in basalt areas. Commercial concentrations of mineral resources are rare in basalt.

4.3 Summary

Basalt has many excellent site suitability characteristics relating to its geologic predictability, areal continuity, low hydraulic gradients, low permeability in massive flows, high strength, insolubility and lack of mineral resources. The Columbia River basalts are located in sparsely populated and arid regions. Proximity to the existing Hanford Reservation is also an advantage. The primary disadvantage of basalts is the potential existence of freshwater aquifers above and below the depository layer.

Potential nuclide release mechanisms are discussed in Appendix B.5.

The primary data base areas needing further research include:

1. Groundwater flow patterns, including recharge and discharge areas in deep basalt zones.

2. Joint patterns and joint properties as related to basalt flow depth, thickness, chemistry, weathering and potential joint filling.

3. Fracture flow behavior, including the validity of using conventional Darcy flow relationships.

4. The hydrologic properties of joints and how these properties might be altered by temperature and/or stress changes.

5. Data on nuclide retardation in fractured basalt.

6. Evaluation of potential thermally induced water flow.

5.0 CRYSTALLINE ROCK

5.1 General

For the purposes of this report, crystalline rock is a general term meaning any intrusive igneous rocks and/or medium to high-grade metamorphic rocks exhibiting little or no foliation. Figure C-1 in Appendix C shows the areas of these rock types in the United States. These include: Precambrian shield rocks in Minnesota, Michigan and Wisconsin; crystalline basement rocks of the Appalachian Mountains extending from Alabama to Maine; large granite batholith areas in the western United States including the Sierra Nevada batholith in California, the Pikes Peak batholith in Colorado, and the Idaho batholith; and small isolated granite bodies throughout the western United States.

Data base information on crystalline rock is included in Appendix C.

5.2 Site Suitability Characteristics

Based on our available information, the general site suitability characteristics of crystalline rock include:

1. Topography: Generally, the shield area and portions of the Appalachian area have gentle topography while the western batholiths occur in areas of rugged topography.

2. Geography: Generally, western batholith areas are more sparsely populated, but local low population densities can be found in shield and Appalachian areas.

3. Geologic Setting:
   a. The western batholith areas and Appalacian region are areas of moderate to high seismic activity. The shield is an area of low seismic activity.
   b. At the fringes of a granite intrusion, the geology can be very complex with significant fracturing and alteration. However, within the intrusion the gross geology should be uniform and predictable.
   c. Generally, metamorphic crystalline rocks occur in geologically complex areas. Premetamorphic features such as contacts or compositional changes may occur. Folding and metamorphism may have produced joints, faults, shear zones and open foliation. The gross geology of metamorphic crystalline rocks is variable and a more intensive exploratory effort would be required for site selection than is necessary within intrusive rock.
   d. Large intrusions of crystalline rock represent continuous formations which are an ideal geometry for a depository host rock.
   e. Fractures at shallow depth and/or along the fringes of an intrusion are numerous but decrease with depth toward the interior of the intrusion.
   f. The majority of our current knowledge of the detailed geology of crystalline rocks relates to shallow formations and/or areas containing mineral resources. These

resources generally occur at the fringes of intrusions where the geology is very complex and significantly different from the uniform interior of a granite intrusion.

4. <u>Hydrologic Setting</u>:
   a. Generally, crystalline rocks occur in areas of high rainfall with numerous streams and lakes.
   b. Groundwater tables are generally shallow within crystalline rock masses.
   c. Unfractured crystalline rocks have very low hydraulic conductivity on the order of 10^{-9} cm/sec. and low porosities on the order of 1 to 3 percent.
   At shallow depths and/or at the fringes of the intrusion, permeable fractures are common producing low to moderate rock mass permeability. With increasing depth, the fractures tend to close or are nonexistent. At depths exceeding a few thousand feet, extensive areas of crystalline rock may exist which contain very few permeable fractures.
   d. In metamorphic crystalline rocks the presence of permeable features such as fractured zones, open foliation and contacts will determine groundwater flow behavior.
   e. Since flow is confined to fractures, groundwater flow velocities can be relatively high.
   f. Shallow zones of active water circulation occur in crystalline rocks. The extent of these zones and the nature of the circulation depend on rainfall, surface topography and permeability. Below these zones, groundwater movement may be sluggish or nonexistent.
   g. Although small volumes of well water can be pumped from shallow, weathered zones in crystalline rocks, prolific aquifers seldom occur. Aquifers may be nonexistent at depth.

5. Mechanical and Chemical Properties: In general, crystalline rocks have favorable mechanical and chemical properties. These rocks have high strength and thermal and chemical stability. However, they do have relatively low thermal conductivity, and because of high strength, are subject to fracturing without healing. The rock will be subject to excavation (blast) induced fracturing not specifically related to regional stress fields. Nuclide retardation through fractures in crystalline rock is not well understood.

6. Natural Resources: Mineral resources are frequently located in crystalline rocks along contact zones, in veins, faults and in other complex geologic environments. However, the interior of granite intrusions probably contain few, if any, known mineral resources. Except for shallow wells, crystalline rocks do not contain any groundwater resources.

5.3 Summary

The favorable characteristics of intrusive crystalline rocks are their gross geologic uniformity and areal extent, low permeability and porosity, possible lack of circulating groundwater, high strength, lack of aquifers, and minimum potential mineral resources. The primary disadvantage is fracturing, which could result in high groundwater velocities. Because of the inherently variable structural nature of metamorphic crystalline rocks, a greater exploratory effort will be required to locate suitable sites than would be required for sites in areas of intrusive crystalline rock. Possible rugged topography (western batholiths) and proximity to population centers (Appalacian and shield areas) are also drawbacks, but could be minimized through proper siting.

Potential nuclide release mechanisms are discussed in Appendix C.5.

The primary data base areas needing further investigation include:

1. Groundwater flow patterns in crystalline rock, including an evaluation of possible stagnant groundwater depth using techniques such as isotope analysis.

2. Fractures and fracture properties as related to geologic environment and depth.

3. Fracture flow behavior including the validity of using conventional Darcy flow relationships.

4. Hydrologic properties of fractures and how these properties might be altered by temperature and/or stress changes.

5. Nuclide retardation in fractures.

6. Thermally induced water flow.

6.0 CONCLUSIONS AND RECOMMENDATIONS

Table I - Summary of Site Suitability Characteristics, is based on the available information and the above discussions. It presents an entirely subjective rating of the site suitability characteristics of salt domes, basalts, and crystalline rocks. The table also indicates the level of available information for each category. We have made no attempt to rate each rock type since the current information indicates that all three types may be suitable.

As related to the development of LTRM, the primary problems and areas requiring further work include:

1. Salt Domes: The current data indicate that there would be *no* flow paths out of an unflawed repository in a salt dome. The primary nuclide release processes would probably be related to salt dissolution. Thus, the modeling effort should concentrate on rates of natural dissolution, dissolution around boreholes and shafts, and release pathways associated with these solution features. Salt dome movement, either natural or induced by the waste heat, must also be evaluated.

2. Basalt and Crystalline Rock: The groundwater flow patterns in deep basalt or crystalline rocks are poorly understood. A hydrological modeling program in conjunction with additional field data is necessry to develop a defendable flow path model. An evaluation of fracture flow behavior, particularly with the sparsely fractured rock should be performed.

Additional research areas were discussed in previous sections.

Respectfully submitted,

GOLDER ASSOCIATES

Robert L. Plum

David L. Pentz

TABLE I

SUMMARY OF SITE SUITABILITY CHARACTERISTICS

Characteristic	Salt Domes		Basalts		Granites	
	Merit	Level of Information	Merit	Level of Information	Merit	Level Inform
Topographic Setting	Excellent	Excellent	Good	Excellent	Variable	Excel
Geographic Setting (Population Densities)	Poor	Excellent	Good	Excellent	Variable	Excel
Geologic Setting						
Tectonic Stability	Good	Good	Poor	Good	Variable	Good
Complexibility & Predictability	Poor outside of dome Good within dome	Fair	Good	Good	Good	Good
Extent of Host Rock	Excellent	Good	Good	Good	Excellent	Good
Anomalies	Good	Fair	Good	Good	Fair	Fa.
Hydrologic Setting						
Surface Hydrology	Poor	Excellent	Good	Excellent	Poor	Excel
Depth to Water Table	Poor	Excellent	Good	Excellent	Poor	Excel
Permeability of Host Rock	Excellent	Good	Fair to good	Fair	Good	Fair
Circulation of Groundwater	Excellent within dome Poor outside dome	Fair	Fair	Poor	Good	Poor
Existence of Aquifer	Poor	Good	Poor	Good	Excellent	Good
Mechanical/Chemical Properties						
Solubility	Very poor	Fair (rates of dissolution)	Excellent	Excellent	Excellent	Excel
Nuclide Retardation	Very poor	Fair	Fair	Poor	Fair	Poor
Uniformity (Predictability)	Fair	Fair	Good	Good	Good	Fair
Strength	Poor	Good	Excellent	Good	Excellent	Good
Fracture Potential	Excellent	Good	Poor	Fair	Poor	Fair
Thermal Conductivity	Excellent	Good	Fair	Good	Fair	Good
Thermal Stability	Poor	Fair	Excellent	Good	Excellent	Good
Chemical Stability	Fair	Fair	Good	Good	Good	Good
Natural Resources						
Lack of Mineral Resources	Poor	Good	Excellent	Good	Good	Good
Lack of Groundwater	Poor	Good	Poor to Fair	Good	Excellent	Good

APPENDIX A - SALT DOMES

A.1 GEOLOGY

A.1.1 General

There are more than 300 salt domes distributed throughout the Gulf Coast Province of the United States as shown in Figure A-1. This discussion is confined to Gulf Coast Salt domes although salt domes do exist in other areas of the United States.

A salt dome is a slender plug that has pushed up into the overlying strata, forcing them aside and then seemingly frozen in place. The plug is a more or less vertical column of almost pure halite, but may contain isolated inhomogeneities consisting of potassic salt, sand and clay impurities and minor joint structures. They differ in size and shape but average 2 to 3 miles in diameter and may rise more than 5 miles in height. The circular form was characteristic from the domes' inception.

Peripheral to the salt plug is an enclosing sheath of "sheared salt" which grades away from the plug into "sheared shale." This sheath has been likened to fault gouge as it is generated by the abrasion of the upward moving salt against the adjacent shaley and sandy sediments. A subsequent salt spine, moving up adjacent to the parent plug, may enclose portions of the sheath materials between the two salt bodies. The thickness of the sheared zone is uncertain and variable. Overlying most, but not all, dome salts is a layer of caprock. The upper portion is dominantly calcium carbonate (calcite), while the underlying portion is calcium sulfate (anhydrite) and sulfur.

Most of the south-central United States salt domes have intruded an interlayered sandstone and siltstone sequence of considerable thickness. These beds are typically upwarped around and over the dome and are thinned as they stretch to accommodate the intrusion. Occasional limestone beds are also encountered in this sequence. Overlying the deformed sedimentary sequence are recent sediments consisting of unconsolidated sands, silts and clays of varying thickness.

Normal and reverse faults having a general radial pattern are encountered surrounding the dome.

A.1.2 Salt Dome Intrusion and Rate of Deformation

Historically, there have been two theories on the emplacement of salt domes. The earlier theories all used buoyancy as the prime motivating force of intrusion. Salt is lighter than most common sediments in which domes occur. Thus, buried salt domes can be found by their negative gravity anomalies. The average specific gravity of a dome is about 2.2 compared to the surrounding sediments whose specific gravity ranges from less than 2.0 near the ground surface to greater than 2.5 at depth (Gussow, 1968). The buoyancy effect tends to increase as more material is displaced, and the upward flow will continue as long as the salt remains plastic. The shape would approximate a tear drop or elongated bubble rising through the sediments. This development of a salt dome is illustrated in Figure A-2.

The latest theory uses plasticity and a critical temperature as the driving mechanism. The fact that the density of salt is less than the overlying strata is not a requirement for instability. According to Gussow (1968),

> Increased temperature greatly reduces the ultimate strength of salt and eliminates work hardening. When salt is heated above 400°F (205°C), it becomes soft and plastic and flows indefinitely with a pressure gradient of about 33-100 kg/cm^2 (460-1,400 psi). It is plastic during the entire process of intrusion, and even during extrusion at the surface. Thus, at the time of extrusion, salt can flow by simple gravity, like a "glacier," as long as it remains hot. When buried at a depth of more than 25,000 ft., sedimentary salt becomes mobile because of the high temperature and behaves hydrodynamically; it moves laterally to places of lower overburden pressure, where doming or piercement occurs. Once flow is initiated, it will continue until the supply of salt is depleted or cut off, either by the coming together of the overlying and underlying strata or because additional supplies of salt have not been heated to the temperature necessary to maintain plasticity. The energy impelling the lateral or radial flow to the place of piercement can be attributed only to an imbalance in geostatic load of the overburden, but after piercement occurs, the geostatic load differential and the ever-increasing effect of buoyancy cause the salt to rise rapidly through the overlying strata. Buoyancy becomes an effective force only when the height of the intrusion has increased greatly.

Salt may reach the surface and even flow for short distances. There is no further movement after the original intrusion. Additional sedimentation and burial of the old surface would, however, cause differential compaction of the adjacent strata and draping of the new sediments over the rigid salt mass. These features are suggestive of continued slow dome growth, but Gussow (1968) considers them to be more representative of differential compaction, as illustrated in Figure A-3.

There is considerable evidence that the piercement and growth of salt intrusions is episodic (Netherland, Sewell and Associates, 1976). Domes seem to grow by pushing upward a series of spines and lobes separated by the adjacent shear planes. The rate of movement is not uniform throughout time. According to Netherland, Sewell and Associates (1976) "Domes in the Northeast Texas Basin appear to have grown more rapidly in their early stages and during periods of rapid sedimentation. During periods of emergence and erosion in the basin, the domes probably grew very slowly or became stable." Gera (1972) states that salt deformation is probably at a maximum in the late stages of dome growth when they approach the surface. At this time the buoyancy effects are at a maximum and the resistance offered by the poorly consolidated surface materials is minimal. He goes on to quote flow rates of 0.[illegible] mm to 2 mm per year. Netherland, Sewell and Associates in their study of Northeast Texas salt domes created an "uplift-vs-time" value for the various geologic formations pierced by the six selected domes as shown on Table A-1. They measured the arching of the beds and then divided by the number of years involved. The average annual uplift of the domes during the last 50 million years was computed to be 0.006 mm or about 4 feet per 200,000 years. Differential compaction of the sediments over and surrounding the domes was ignored but would tend only to reduce these values.

Upward growth of a salt dome may be halted by a variety of factors. The rim syncline or the subsidence of the overlying beds can cut off the supply of salt flowing radially to the base of the salt dome. If the overlying strata are very rigid, like limestone, salt may continue to flow for a longer time than if they were more plastic like shale (Gera, 1972). Physical resistance of the overlying strata may create enough drag or be strong enough to resist penetration of the salt dome and so stop the upward movement. When the salt dome reaches the surficial unconsolidated sediments, it tends to lose its buoyancy. This loss may be reflected in lateral spreading rather than further vertical movement. The influence of fresh water may also help to stop the vertical movement of a salt dome. When the salt enters the freshwater strata it is dissolved and a residual dense caprock is created. The caprock may grow downward to the base of the freshwater horizon and seal the salt dome from further dissolution or it may be massive enough to inhibit further growth.

A.1.3 Anomalies in Salt Mines

Salt domes can contain anomalous features within the generally massive salt plug. The following is a discussion of some of the specific features we have observed in salt mines. The mines were in salt domes and were generally located approximately 1,000 to 1,500 feet below ground surface. Our work shows that the mining was done by a room and a pillar operation.

1. Inclusions in the Salt: Two distinct types of inclusions have been noted. Petrographic and spectrographic analyses indicated that the inclusions contained sylvite (KCC) and fine sand grains. The first of these was generally a pink to red color when first mined but gradually changed to dark orange through to yellow with time. In some cases the inclusion was in a distinct vertical or subvertical bed of approximately 6 inches to 18 inches thickness and parallel to the general layering direction. These beds often extended from the floor to the roof of the mine although they were observed in one wall and not in that directly opposite. They were then found in the next adjacent workings. In other cases the only evidence was a general yellow or orange staining in the salt.

   The second type of inclusion was much darker, generally reddish-brown to dark brown. It generally occurred in thin bands 3 or 4 inches wide and followed the layering exactly. There was a general band of dark coloration which in many cases was tightly folded, and within this band were darker round inclusions of fine grained sediments. Sylvite was identified in the samples that were analyzed.

Although the origin of the inclusions is not known, in our opinion they were present at the time the salt was initially deposited.

2. Pressure Pockets: Pressure pockets are large openings which develop in the roof and walls of salt dome mines at the time of blasting. These openings are much larger than can be attributed to the blast itself and are also referred to as blowouts and gas bursts. The origin of these pressure pockets is not known, although they are invariably associated with gas inclusions in the salt. It is possible that they are at least partly due to high, localized stress concentrations, although this has not been verified. They are observed as large and relatively stable openings, generally circular at the mouth and narrowing upward. In a number of cases the edge of the pressure pocket is associated with very closely spaced exfoliation-type jointing. A pressure pocket in the roof of one mine was of corkscrew shape, approximately 10 feet in diameter at the outer edge and extended into the roof for a distance of at least 60 feet. It did not exhibit the closely spaced jointing observed in some other pressure pockets. In our opinion the pressure pockets may be associated with much more porous salt although this has not been confirmed. It is not now possible to predict exactly when and where pressure pockets will be found in the mine. Pressure pockets have only been observed in the roof and never in the floor of any of the salt dome mines, although there is no apparent reason for this.

3. Jointed Salt: An area of jointed salt extending over approximately 600 to 700 feet was observed in one mine. This area appears to be quite unusual and is not well understood. This salt was hard and relatively fine-grained and had a distinct yellow color when illuminated with miners' lamps. It exhibited a distinct audible "ring" when two pieces struck each other, and laboratory strength tests indicated that it was as much as 75 percent stronger than the other salt in the mine.

The joints were generally flat dipping (typically 10 to 20 degrees dip) and spaced approximately 6 inches to 1 foot apart. Typically, they were traced over a distance of 10 to 15 feet. The salt also showed extensive cross-jointing, producing blocks commonly 1-foot wide and 6-inches high. The flat dipping features are almost certainly unrelated to mining activities, although some of the jointing may be related to blasting. The origin of this jointing including the open joint discussed below is unknown.

In one of the headings within the yellow salt zone there was a flat dipping open joint. At the face, the joint had a maximum aperture of approximately 2 feet and was open over a distance of 4 to 6 feet. This joint extended more than 40 feet in the salt behind the face. It resembled an open bedding feature in a sedimentary deposit although the true bedding is vertical and the joint dipped only slightly. The "yellow" salt zone is apparently a relatively narrow steeply dipping band 30- to 40-feet thick, but this has not been confirmed. Petrographic and spectrographic analyses indicated that this salt contained sylvite (KCl) and kieserite ($MgSO_4 \cdot H_2O$). Chemical tests showed that the salt contained over 99 percent halite, although it had a much higher magnesium content than salt in other parts of the mine.

A.2 HYDROLOGY

A.2.1 General

The massive, very pure salt within the plug may be impermeable, and exhibit no evidence of flowing water. Isolated inclusions of brine and hydrocarbons, commonly associated with impure salt, can produce small flows which rapidly decrease in volume and usually stop completely within a few months.

The porosity and permeability of in-situ dome salt is thought to be extremely low, possibly zero, making in-situ measurement of these parameters very difficult. We have attempted to measure the in-situ permeability of salt in a salt dome with inconclusive results. The data appear to reflect salt creep due to the injected fluid pressure rather than any actual fluid flow through the salt.

Laboratory tests conducted by Gloyna and Reynolds (1961) using salt from the Grand Saline dome indicated some permeability through cracks and fissures but none through the crystals. Permeability varied with confining stress and with length of time over which the stress was applied. At the start of the tests intrinsic permeability ranged from 6×10^{-11} to 5×10^{-13} cm^2. It decreased from 3×10^{-11} to less than 10^{-15} cm^2 after 3 to 36 days of stress application. This corresponds to a hydraulic conductivity of about 6×10^{-6} cm/sec to 10^{-10} cm/sec. The average porosity of the samples was 1.7 percent. Hansen (1977) found a water content of 0.02 percent in Jefferson Island salt.

Sheared zones exhibit little or no flow due to the low permeability of the sheared material. Shale sheaths, when present, often act as protective membranes enclosing the salt bodies and isolating them from surrounding aquifers. Shear zones separating spines of movement within the salt body can produce small but relatively steady flows when encountered in mines. Because these flows are relatively steady, the probable source of this water is from outside the salt body. The calcite caprock found overlying many domes is often fractured and water bearing. It can act as a permeable pathway allowing connection between upper aquifers and lower aquifers, which are interrupted by the salt plug. The anhydrite portion of the caprock is relatively impermeable and may form an effective seal over the salt plug if it occurs in sufficient thickness.

Salt domes are surrounded by thick sedimentary deposits through which they have intruded. These sediments contain numerous, productive groundwater aquifers which constitute important sources of agricultural, industrial, and domestic water supplies. Water near the surface is generally fresh but may become saline at depth, particularly near the Gulf Coast where pumping has caused areas of seawater intrusion (Winslow et al., 1957, Harder et al., 1967). Aquifers are generally confined with piezometric heads usually increasing with depth below ground surface. Regionally, horizontal flow is toward the Gulf Coast at gradients of several feet per mile or less, although heavy pumping has caused localized reversals of the normal groundwater flow direction. Recharge of the various aquifers normally occurs at outcrops of the aquifer formations which may be located over a hundred miles away from the salt domes.

Salt domes can affect the local and regional hydrology. Upwelling of deeper waters can take place around some domes or along peripheral faults caused by intrusion of the salt body. This results in salt water plumes within the upper freshwater aquifers and may also cause some depressurization of the deeper aquifers.

Recent sediments contain prolific aquifers. Water from these aquifers is directly recharged by precipitation and is in constant circulation with numerous surface streams.

A.2.2 Special Features Observed in Salt Mines

Several features observed in salt mines are hydrologically significant. Although most salt found in domes is more than 97 percent pure halite, inclusions of impure salt often including brine and/or hydrocarbons have been found usually in distinct zones. These inclusions are commonly associated with boundary shear zones. Kupfer (1974a, 1974b) reports that shear zones may be the result of differential movement of separate spines within a single salt stock. Boundary shear zones, which often contain entrapped sedimentary material, separate spines and can extend completely across a salt stock.

Because of the high solubility of salt, significant water leaks can threaten the stability of a mine in salt. We have observed three types of water leaks in mines in Louisiana salt domes. They include:

1. Short-Duration Leaks: These leaks are relatively common in Louisiana mines. Typically, brine possibly containing hydrocarbons begins dripping from the ceiling after new

workings are opened. Volumes may be significant (i.e., exceed evaporation rate) for several days to a month, after which flow diminishes and generally ceases within 6 months. The larger and more persistent drips are commonly near shear zones. Water was probably introduced into the salt during intrusion into the overlying sedimentary layers and subsequently sealed by recrystallization. Fracturing caused by mining may have allowed connection of the previously isolated brine inclusions.

2. Increasing Volume Leaks: These leaks tap water sources from outside the salt dome. Because there is a large source of fresh water in the surrounding sediments, these leaks can rapidly increase in size and cause flooding of the mine. Miners carefully seal shafts and avoid the outer regions of domes because of potential flooding hazards.

3. Sporadic-Continuing Leaks: These leaks, found in only two Louisiana mines, occur near boundary shear zones. They begin slowly, gradually increasing in volume until stabilizing at a much slower rate. They are normally grouted at this time; however, new leaks develop within several months and the sequence is repeated. The leaks are thought to tap water from an external source which is conveyed slowly along the shear zone. Flows do not rapidly increase because the shear zone acts as a low permeability membrane. The flowing water could dissolve salt and create cavities which may eventually collapse, breaking the membrane and causing flooding. This has not actually occurred to date.

Belchic (1960) describes brine and gas flow from boreholes and newly opened rooms. These fluids, sometimes under high pressures, originate from within the salt body rather than from an external source. Belchic also describes leaks of the short-duration and increasing-volume types. Slow brine drips from the ceiling often form salt stalactites as the brine evaporates upon entering the mine. Many of the slow drips are accompanied by small amounts of hydrocarbon.

A.2.3 Salt Dome Dissolution

Salt dome dissolution occurs when fresh water comes into contact with the salt. The subsurface flowing water will dissolve the salt and carry it downstream in the aquifer or upward toward the surface through fractures. Saltwater plumes down gradient from a dome indicate active dissolution of salt, but it is not known whether the entire surface of the dome is involved or only a very limited zone. Water that comes to the surface over a dome is usually found in saline creeks, springs, small lakes or marshes. It may have flowed from considerable depth along the flanks of the dome ultimately to flow through fractures to the surface. Figures A-4 and A-5 illustrate the relative hydrologic stability of several salt domes with an evident plume from Bullard salt dome and possibly a plume from Whitehouse salt dome.

Caprocks of anhydrite, gypsum, and limestone cover most shallow salt domes. The caprock was probably formed when salt was dissolved by water leaving behind a deposit of less soluble impurities. The thickness of the caprock is a function of the volume of salt dissolved and the amount of less soluble impurities. Generally, the impurities in salt domes constitute less than 3 percent by volume, but 15.3 percent has been recorded at the Hockley dome in Texas (Gera, 1972). The occurrence and thickness of caprock decreases with depth and is normally absent below a range of 3,000 to 5,000 feet. This depth also may be the limit of freshwater bearing strata. Caprock may exist below this depth in older domes which were in contact with freshwater bearing strata at one time but are now buried and in the saline water zone.

The dissolution rate can be calculated from the caprock thickness and the amount of insoluble impurities if it is assumed that all the caprock formed since deposition of the surrounding sedimentary formations. One such formation is the Wilcox, deposited approximately 50 million years ago, which forms a major freshwater aquifer in much of the Gulf Coast region. Netherland, Sewell and Associates (1976) measured the caprock thickness of five salt domes and found a range of 50 to 300 feet of caprock. Assuming 1 percent less soluble impurities and 50-million years dissolution time, the average vertical dissolution rate was 0.031 to 0.183 mm per year or 20 to 120 feet in 200,000 years. Increased content of less soluble impurities would reduce these numbers proportionately. Smith (1976) measured dissolution rates using salinities measured in down-gradient salt plumes from three of the same domes plus the Hainsville dome. He found rates of 20 to 75 feet of salt thickness removed in 250,000 years. The individual results are shown in Table A-2. He noted that increased salinity near salt domes may be the result of either actual salt dissolution or vertical upwelling of saline water around the domes from deeper saline aquifers.

A.3 TATUM SALT DOME

A.3.1 Geology

The Tatum Salt Dome and surrounding area is in Lamar and Marion Counties, Mississippi. Geologic and hydrologic studies in the area were made for the nuclear detonations known as the Salmon and Sterling Events. The following information comes from a report by Taylor (1971).

The Tatum Dome is a salt stock overlain by a caprock. The source of the salt is believed to be the Louann salt bed of Jurassic age. At this location, that bed is about 20,000 feet deep. A section through the salt dome is shown on Figure A-6.

The stock has pierced a section of clays, sands, and sandy limestones from Jurassic to Oligocene in age. Rocks of late Oligocene age are deformed upward but are not pierced. Miocene to Recent rocks over the dome are relatively undisturbed, indicating that there may not have been any movement of the dome since the Miocene.

The salt stock itself is composed primarily of halite. It attains a maximum diameter near the top of about 4,500 feet and may extend to a depth of 20,000 feet. To date, no drill holes have penetrated the full depth of the salt.

The caprock consists, in ascending order, of nearly 500 feet of dense gray anhydrite, 15 feet of white gypsum, and nearly 150 feet of gray calcite. The top of the caprock is about 800 feet below the surface where it exists as a relatively flat plateau with only 20 feet of relief.

The regional dip of the sedimentary rocks is to the southwest at a gradient of 30 to 40 feet per mile. The dip increases with depth. The salt stock locally modifies the regional structure by warping the sediments upward.

A.3.2 Hydrology

1. Surface Water: Mean annual precipitation in the area is about 60 inches with 20 inches of surface runoff.

   Surface water eventually drains to the Gulf of Mexico with Lower Little Creek and its tributaries the major streams in the immediate area. The high base flow of streams is sustained by springs and seeps from underlying Miocene and Recent sedimentary deposits.

2. Ground Water: Aquifers containing fresh water extend from near surface to about 1,400 feet below sea level in the general area of the Tatum Dome and to about 700 feet below sea level over the dome itself (land surface elevation over the dome is about 30 feet above sea level). Some aquifers containing fresh water elsewhere contain saline water in the vicinity of the dome. Figure A-6 is a cross-section through the Tatum Dome showing the designation and approximate position of the various aquifers. These aquifers may be offset or interrupted by faults near the dome, but most of them (except local and surficial aquifers) are regionally extensive.

   The Cook Mountain Limestone (aquifer 5 on Figure A-6) contains saline water (approximately 18,800 mg/liter total dissolved solids) and is not used as a source of water near the dome. Oil field brine has been injected into the Cook Mountain six miles to the southwest, which has resulted in increased heads in the Tatum salt dome area. The limestone of the Vicksburg Group (aquifer) fo rms a brackish (approximately 1,300 mg/liter) artesian aquifer. Piezometric heads are lower than those in the Cook Mountain but higher than those in overlying aquifers. It is probably hydraulically connected with the calcite caprock on the dome. Miocene sediments form several artesian aquifers (aquifers 3, 2, 1 locally) containing fresh water (less than 200 mg/liter), except directly over the dome where aquifer 3a contains some saline water. Regionally these aquifers are lenticular beds that are not easily traced over a large area. Water table aquifers exist in Recent terrace and alluvial deposits. Fresh water from the surficial aquifers contributes to the high base flows of the local streams. Groundwater also occurs in the calcite part of the caprock. This water is under an artesian pressure lower than that in aquifer 4 but higher than aquifer 3. Some hydraulic connection with aquifers 3 and 4 is indicated in the caprock aquifer.

In the area of the Tatum Dome most domestic and stock wells are located in the surficial aquifers, although a few penetrate to the shallow Miocene aquifer. Outside the area, large withdrawals are made from the Miocene aquifers.

3. Water Movement: Recharge to the various confined aquifers takes place at outcrops to the northeast at distances varying from 75 miles in aquifer 5, and 55 miles in aquifer 4, to only a few miles in the shallower Miocene aquifers. Groundwater in the surficial aquifers is recharged primarily from local precipitation.

The regional groundwater flow is downdip or to the southwest. Local withdrawals have modified this regional flow in several aquifers. The important hydrologic parameters measured in the area of the Tatum dome, including horizontal gradients and flow directions, are given in Table A-3.

A.4 POTENTIAL RELEASE PATHWAYS

It is appropriate to investigate a variety of conditions that are likely or possible and which represent potential pathways for the release of depository contents. The following is a partial listing of conditions which require consideration in the salt dome model:

1. Depository-Induced or Related Conditions
   a. Fracture zone around openings: As with bedded salt (GAI 1977a), fracturing around mine opening in the salt is expected to be relatively minor and will probably heal with time.
   b. Shaft backfill and shaft sealing: Similar to the sedimentary bedded salt model.
   c. Density effects of canisters: As with bedded salt, the canisters may migrate through the salt and ultimately reach an environment that increases the rate of waste release. Preliminary studies (Sandia 1977a) indicate that the magnitude of movement will be small (less than a few inches in 1,000 years). Thus, it is doubtful that this effect will be a problem.
   d. Heat-induced diapirism: The heat generated by the waste might affect the balance of forces and initiate movement of the salt dome. Considering the size of the salt domes and the great depth of the source of the salt, it seems doubtful that the relatively small heat source of the depository applied near the top of the dome would induce diapirism. However, due to the present lack of understanding about salt dome diapirism, it may be difficult to prove that depository heat is not a problem.

e. Fluid inclusion migration: Inclusions of brine will migrate toward the heated depository and may become a source of water and pressure. Large brine cavities in dome salt tend to occur in the boundary shear zones and are less frequent than similar inclusions in bedded salt.

f. Thermally induced groundwater flow: Since there is probably no effective source of water within the salt dome, a convection cell would have to develop with inflow down one pathway (such as a shaft) and up another pathway. Such convection could have a serious impact since the incoming fresh water would dissolve the salt. However, since incoming fresh water would quickly become saturated brine, the small thermally induced gradients may be insufficient to overcome the density gradients. The process, however, leads to salt dissolution.

g. Dissolution: Fresh water flowing into shafts and/or boreholes may lead to significant dissolution of the salt and potentially remove sufficient salt to reach the depository. A model to predict cavity growth by dissolution of salt around a borehole indicates that cavities may spread laterally but will be shallow, of the order of several meters for the case considered (Snow and Chang, 1975). Also during resaturation of the depository, the pillars may dissolve, leading to collapse of the roofs and possibly large scale deformations above the depository. Data have been developed by Sandia (1977b) and others to examine the rate of dissolution. Data from dissolution cavities around oil and gas wells may also be useful in evaluating the problem.

2. Existing Geologic Conditions

   a. Boundary shear zones: These more permeable zones within the dome may exist in close proximity to the repository facilities. All of these zones may not be detected. Water could flow down (or up) a shaft, through the depository, through a small thickness of salt, and hence up (or down) the boundary shear zone.

   b. Geometry of the Dome: Salt domes are complex structures. The external surface is deeply convoluted. For the salt dome, these convolutions are filled with clay shears salt, and other sedimentary debris. The consequences of being too close to the edge of the dome could be serious, as an immediate discharge of nuclides to the adjacent aquifers may be possible. The heat and potential deformation around the depository could disturb the salt between the depository and the edge of the dome and lead to further deterioration of the clay sheath sealing the salt from the surrounding aquifers. Ideally, the site investigation both prior to and during depository construction will minimize this problem.

   c. Gas, oil and brine-filled voids: These will occasionally be encountered in the mining and usually are related to the boundary shear zones.

3. Future Geologic Conditions

   a. Dissolution: Some salt domes are imperfectly isolated from circulating ground water. Such domes gradually dissolve, and a "salt plume" is detectable in the groundwater down-gradient. However, it may be difficult to prove that a specific salt dome is not dissolving now nor will dissolve in the future. Estimates of the potential range in rates of dissolution are critical. A recent study (Smith, 1976) of salt dome dissolution in northeast Texas indicates that less than 30 meters of salt would be removed from the top of the dome in 250,000 years. Thus, natural dissolution may not be a serious problem.

b. Movement: Salt domes are structures formed by the movement of salt. Some domes are possibly still moving. New spines may be developing adjacent to existing domes. Data on the rate of movement and the potential for movement recurring after the dome has stabilized are very limited. Investigations of this problem at a specific salt dome in Louisiana (Thoms, et al. 1977) concluded "...tectonic movement of the dome may be so small that crustal movements due to other natural effects may tend to dominate." Based on very limited information, it appears that the rate of movement might be too slow to affect the depository during at least its critical containment period (some 400 years).

4. Man-induced Waste Release Pathways

a. Oil and gas wells: Salt domes form traps for oil and gas in the sediments surrounding the dome. These traps are the targets of energy companies' exploration efforts.

b. Mining: Salt is a mineable commodity. A future salt mine may encroach upon the repository.

c. Undetected boreholes: For more than a century salt domes have been the focus of considerable exploratory activity for salt, sulfur, oil and gas. Many holes have been drilled in search of such resources and only some of these have been recorded and/or plugged. Surface evidence of the holes may have been long since concealed; there is, therefore, a finite probability of the repository encountering or just missing an undetected borehole. The consequences of this require consideration.

TABLE A-1

DATA ON UPLIFT RATES IN SALT DOMES[1]

(After Netherland, Sewell & Associates Inc., 1976)

Stratigraphic Interval	Geologic Age (Million Yrs)	Interval Time (Million Yrs)	Deformation in mm						
			BULLARD	KEECHI	MT. SYLVAN	PALESTINE	STEEN	WHITE HOUSE	Average
Post-Wilcox	50	50	.003	.012	.003	.010	.005	.004	.906[2]
Wilcox-Midway Groups	65	15	.024	.028	.031	.043	.026	.035	.031
Upper Cretaceous	98	33	.022	.018	.014	.029	.017	.018	.0 0
Lower Cretaceous	135	37	.049	.038	.054	.026	.049	.047	.044
Upper Jurassic	149	14	?	?	?	?	?	?	.193[3]
Total Time	149	149							

(1) Indicated by deformation of adjacent stratigraphic units.

(2) "Uplife-vs-time" value of .006 mm. per year is equivalent to .000019686 feet per year, or approximately 3.9 feet for a 200,000-year period.

(3) Estimated from regional study: uplift associated with growth of salt pillows.

TABLE A-2

DATA ON DISSOLUTION OF
NORTHEAST TEXAS SALT DOMES

(After Smith, 1976)

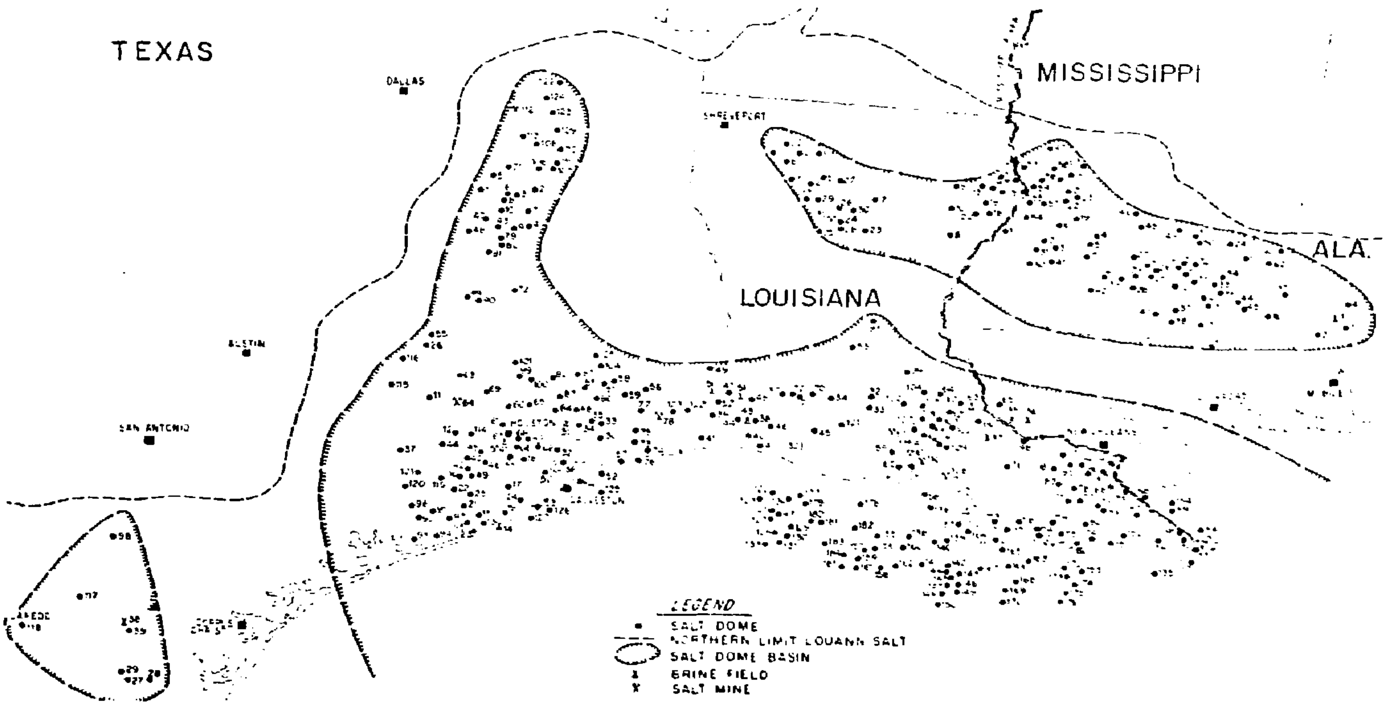
Salt Plume in Overlying Aquifers	BULLARD Dome	HAINESVILLE Dome	STEEN Dome	WHITEHOUSE Dome
Area	2mi x 300 ft	3mi x 730 ft	2mi x 300ft	2.6mi x 300ft
Permeability	50 gpd/ft^2	50 gpd/ft^2	50 gpd/ft^2	50 gpd/ft^2
Groundwater Gradient	2.5 ft/mi	2 ft/mi	3 ft/mi	3 ft/mi
Salinity	5250 ppm	7000 ppm	2000 ppm	5250 ppm
Area of Upper Part of Dome	3.0×10^7 ft^2	1.46×10^8 ft^2	2.2×10^7 ft^2	2.2×10^7 ft^2
Inferred Thickness of Salt Removed in 250,000 years	75 ft	60 ft	50 ft	20 ft

TABLE A-3

HYDROLOGIC DATA FROM TATUM SALT DOME (Taylor, 1971)

Aquifer	Hydraulic Conductivity (cm/sec)	Porosity	Gradient	Rate of Movement (m/yr)	Direction of Movement
1	2.6×10^{-3}	.30	.0004	1.2	southwest
2a	4.4×10^{-2}	.30	.0001	4.6	northeast
3a	3.3×10^{-3}	.30	.00002	.02	northeast
4	1.6×10^{-3}	.25	.00002	.03	southwest
5	4.7×10^{-4}	.25	.00005	.03	southwest

Project No. Reviewed Date



(Le Fond, 1968)

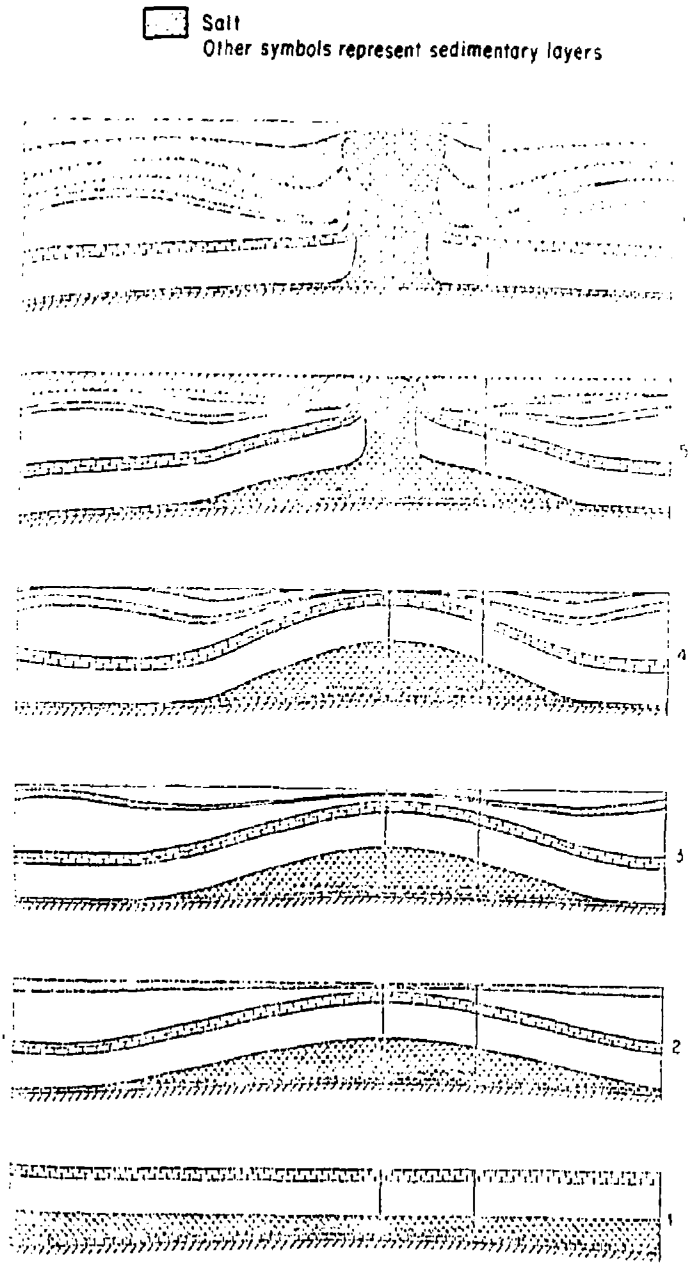
Note: The numbers (referred to in Le Fond, 1968) represent specific salt domes

SALT DOME BASINS AND DOMES IN THE GULF COAST REGION

Figure A-1

DIAGRAMMATIC DEVELOPMENT OF A SALT STRUCTURE (GERA, 1972)

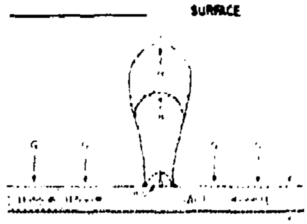
Figure A-2



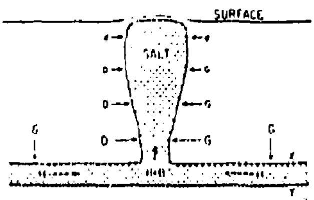
DIAGRAMMATIC ILLUSTRATION OF SALT-DOME RELATIONSHIPS (Gussow, 1968)

Figure A-3

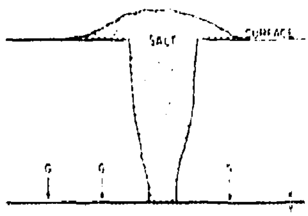
1. Initial tensional radial fracture pattern above a low-pressure point is followed by a peripheral fracture in brittle rocks, and by salt intrusion



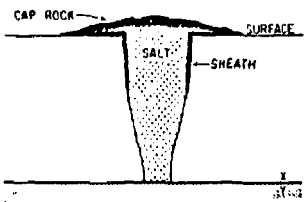
2. Illustrating progressive growth of salt dome and pressure diagram



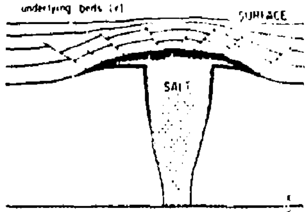
3. Diameter of salt dome may widen with height due to reduction of geostatic load and decrease in density of intruded sediments



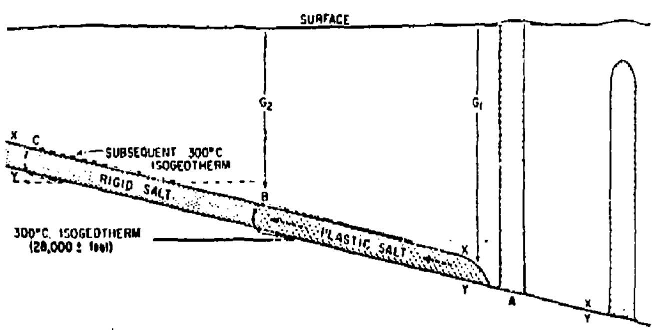
4. Relationship after salt supply is exhausted. Salt continues to flow until supply is exhausted. Extruded salt forms a mountain and associated glaciers. Flow ceases when overlying beds (X) come to rest on underlying beds (Y)



5. Extruded salt removed in wet climates leaving insoluble materials (chiefly anhydrite) as a cap rock. With geologic time, a sheath of anhydrite forms in the zone of solution and groundwater circulation



6. Post-intrusion sedimentation buries cap rock and new load causes compaction of adjacent sediment and differential drops of sediments over salt dome

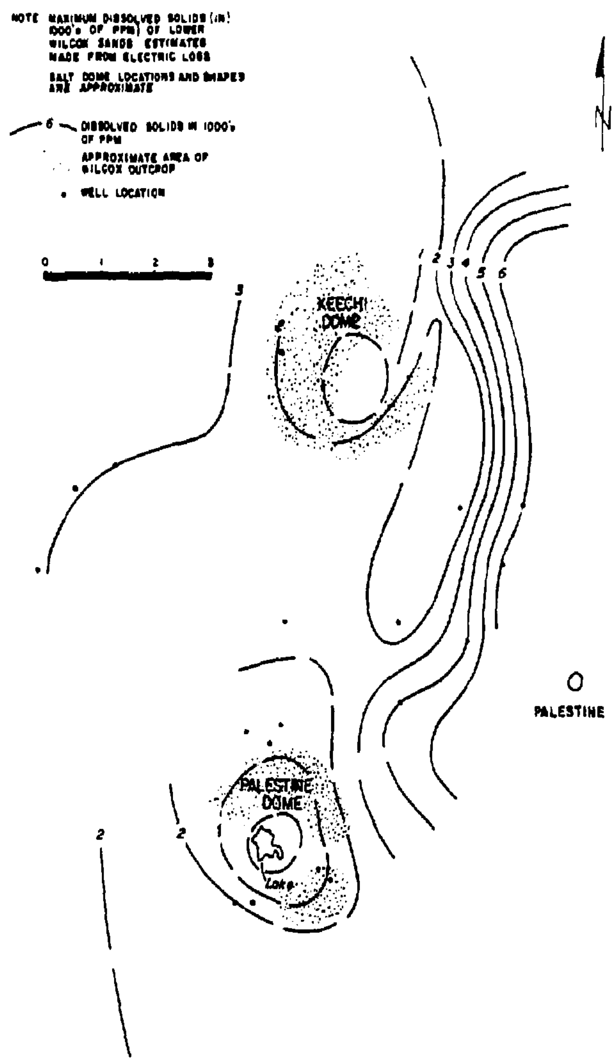


7. Diagramatic section illustrating successive positions of heat front as an evaporite section is buried to greater depths. The 300°C isogeotherm bends up in the salt section because the thermal conductivity of salt is more than twice that of most sedimentary rocks. Diapirism has already occurred at A and is about to occur at B. C is a future position which will result with greater burial. Plastic flow occurs because the geostatic load of G_1 is greater than of G_2. (Note: dip greatly exaggerated.)

Project No. ??/203 Reviewed JK Date 10-78

TOTAL DISSOLVED SOLIDS IN GROUNDWATER IN THE WILCOX GROUP SANDS AT PALESTINE AND KEECHI SALT DOMES (Smith, 1976)

Figure A-4

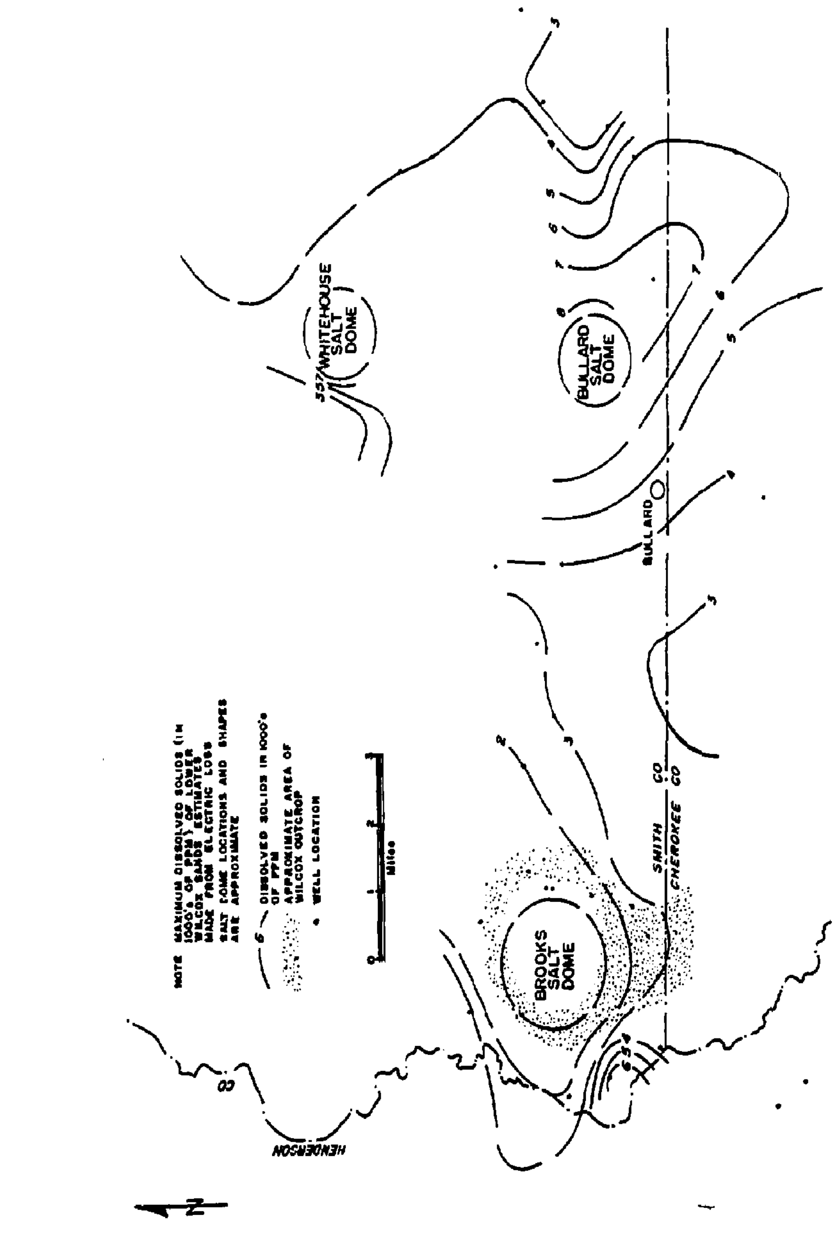


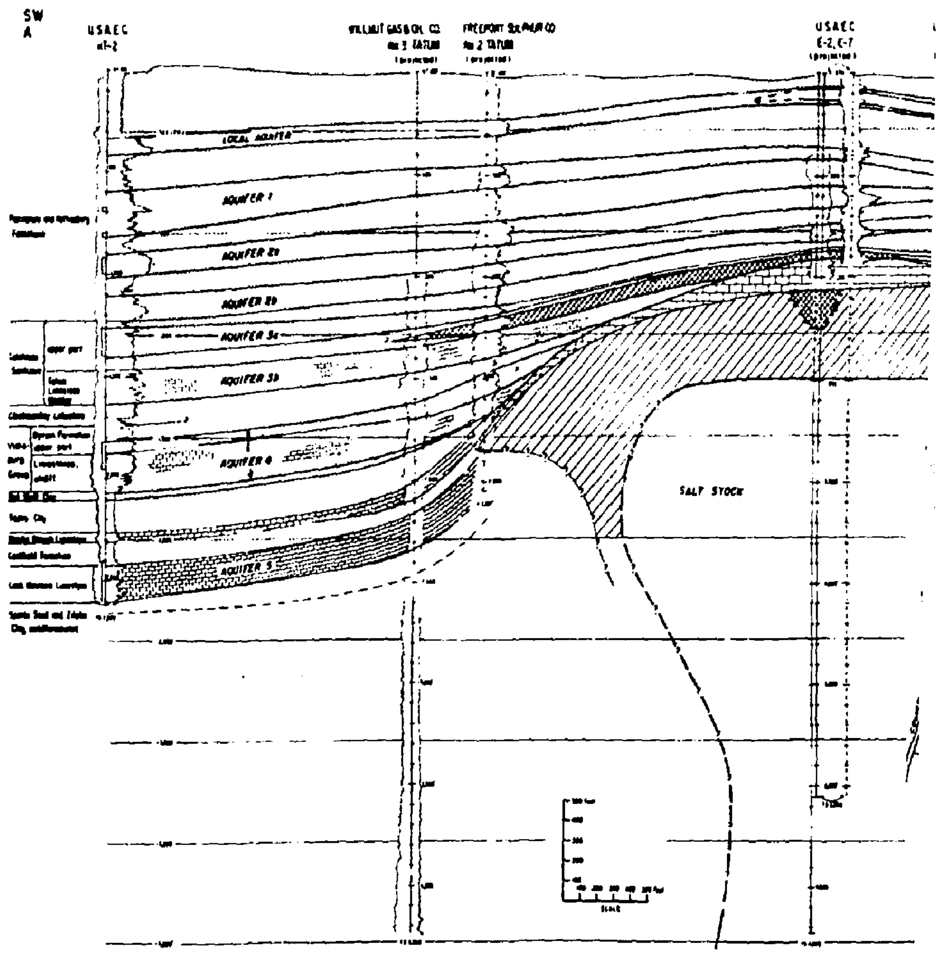
Project No. 773024 Reviewed J.A. Date 12-78

Golder Associates

TOTAL DISSOLVED SOLIDS IN GROUNDWATER IN THE WILCOX GROUP SANDS AT BULLARD, BROOKS AND WHITEHOUSE SALT DOMES (Smith, 1976)

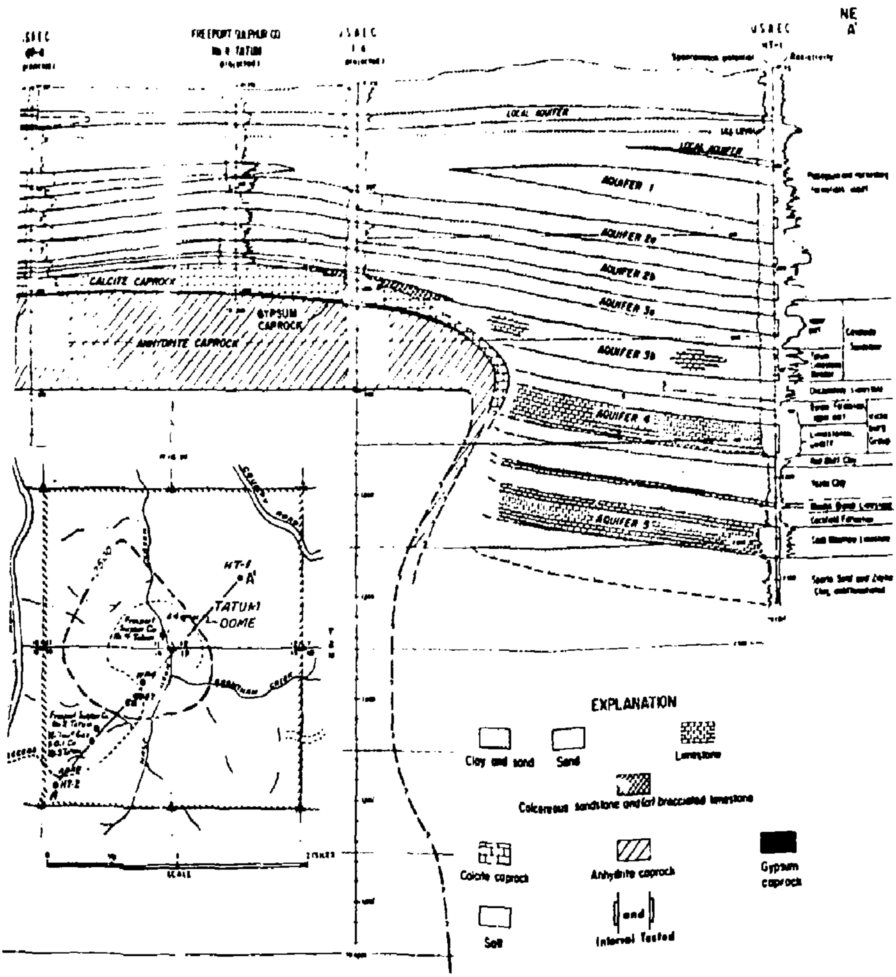
Figure A-5




SW
A
USAEC
HT-2
WILLMUT GAS & OIL CO.
No 1 TATUM
(projected)
FREEPORT SULPHUR CO
No 2 TATUM
(projected)
USAEC
E-2, E-7
(projected)
LOCAL AQUIFER
AQUIFER 1
AQUIFER 2a
AQUIFER 2b
AQUIFER 3a
AQUIFER 3b
AQUIFER 4
AQUIFER 5
SALT STOCK

SOUTHWEST -

Figure A-6



NORTHEAST SECTION THROUGH TATUM SALT DOME

2

(R.E. Taylor, 1971, USGS VUF-1023)

APPENDIX B - BASALT

B.1 GEOLOGY

Flood basalts, or plateau basalts, cover large areas of the northwestern United States. They form the Columbia River Plateau covering approximately 200,000 square miles of eastern Washington and northern Oregon and the Snake River Plain covering a large portion of south-central Idaho. A more detailed description of these basalts can be found in McKee (1972). Old plateau basalts, some of which are now folded and metamorphosed, are found in many other areas of the United States, but are not considered in this report.

Basalt is a fine-grained, dark rock composed primarily of plagioclase and pyroxene. Silica content as well as the amount of dissolved gas has an effect on the physical character of lava. Magmas with low silica content tend to be very fluid and form relatively thin sheets that travel great distances. Increasing silica content makes the lava more viscous creating thicker, less extensive flows.

Jointing reflects the cooling history of a flow, changing with distance from the vent, thickness of the flow and the nature of the surface covered. Jointing is also affected by whether the flow ponded quickly and solidified from a motionless fluid or whether it continued to creep forward throughout the period of crystallization. The top of a flow cools and solidifies first. Near the source the surface top could be relatively smooth, but becomes brecciated with increasing distance. Dissolved gasses may migrate to the top of the flow and form a vesicular scoria zone. Originally these vesicles may not be interconnected, but brecciation from continued movement will create connected openings. These vesicular zones are found on both the top and bottom of a flow with the top zone being thicker. Columnar jointing proceeds from both the top and bottom of the flow. Thin flows may have interconnected joints from top to bottom. Thick flows can appear as three separate flows. The top and bottom will be columnar jointed and the middle may be massive. The bottom of the flow is affected by the nature of the pre-existing surface. A pillow-palogonite complex is usually formed where the flow enters a body of water or a swamp. This is a mass of rounded lumps of lava with glassy shells. A brick-like baked zone is created in most soils under a lava flow. Lavas covering pre-existing flows may seal the underlying flow surface. The typical cooling structures of a basalt flow are shown schematically in Figure B-1.

B.2 HYDROLOGY

Extrusive igneous rocks range widely in their hydrologic characteristics. Basalts, which usually have relatively low porosities, can form some of the most productive aquifers known.

Porosity in basalt can range from less than 1 percent in the dense center of the flow to 50 percent in the vesicular top (Davis and DeWiest, 1966). Hydraulic conductivity within basalt depends upon the interconnection between the openings. These openings include: a) vesicles, resulting from the escape of gas bubbles, b) breccia zones between flows, c) voids between flows, d) joints caused by cooling, e) lava tubes, f) fractures due to folding, faulting, etc. Layers of sediments between successive flows can form permeable interbeds when they consist of alluvial sands and gravels. When interbeds are formed by silt, clay, or volcanic ash, they can form confining layers. Horizontal permeability is greater than vertical because shrinkage cracks and scoriaceous, brecciated, and cavernous zones are concentrated near flow surfaces and between flows. The massive centers of the flows are generally low in permeability.

Basalt is extremely anisotropic and nonhomogeneous in groundwater flow. Average permeabilities calculated from pump tests in basalt often reflect several very permeable zones contributing the majority of flow with the remainder of the aquifer contributing only slightly. The massive centers of some basalt flows generally exhibit very low permeabilities relative to the high permeabilities exhibited by the vesicular and brecciated tops and bottoms of flows. Ground water can be under confined conditions locally due to fine-grained interbeds or the massive flow centers, but many basalt aquifers are under water table conditions on a regional scale. Pump tests in the Snake River basalt (Walton and Stewart, 1961) yielded storage coefficients from 0.02 to 0.06, all within the range of values indicative of water table conditions. Transmissivities ranged from 1.3×10^4 to 2.4×10^6 $feet^2$ per day and averaged 5.3×10^5 $feet^2$ per day. The average saturated thickness penetrated by wells was 100 feet. This thickness when divided into the average transmissivity yields a very high value of hydraulic conductivity of 1.9 cm/sec. In contrast, the hydraulic conductivity of dense basalt in cores of the Hanford site ranged as low as 4×10^{-9} cm/sec (Atlantic Richfield Hanford Company, 1976).

Recharge of basalt aquifers can originate from several sources. Natural precipitation may percolate downward to the water table, particularly where the basalt flows are tilted from horizontal (Newcomb et al., 1972). Perched water tables are generally small in areal extent and can form where percolating water encounters layers of low permeability. Rivers and streams flowing across basalt can lose water by vertical percolation.

For example, waters from several mountain rivers disappear at the northern edge of the Snake River Plain and flow along permeable zones between flows, eventually reappearing in springs along the walls of the Snake River Canyon (Brown et al., 1975).

Wells in Snake River basalt are important sources of water for agriculture in southern Idaho which is otherwise a relatively dry region. Groundwater usage is less common in the Columbia River basalt in Washington, particularly from deep wells, but increased use in the future is likely.

B.3 SPECIFIC SITES - COLUMBIA RIVER PLATEAU

B.3.1 General

An excellent review of the Columbia River Plateau geology appears in McKee (1972). The following is a brief summary of this dicussion.

The Columbia Plateau is a vast upland built of Miocene to Recent basalt flows. It covers an area of over 200,000 square miles between the northern Rockies and the Cascade Range, north of the Nevada-Utah-California Basin and Range Province. The average thickness is about 3,000 feet with a maximum thickness in the Pasco Basin of over 9,000 feet. The general area is shown on Figure B-2.

Individual flows generally range from a few feet to a few tens of feet thick with some flows exceeding 200 feet in thickness. The source of the basalt was not from a single central vent or series of vents, but from a series of fissures each of which was several miles long. An individual flow was probably fed by several fissures erupting simultaneously. The flows spread almost like water for great distances. According to McKee (1972),

> A recent theoretical calculation suggests that the average spreading velocity of a Columbia River basalt flow may have been 25 to 30 miles per hour.... One unit, the Roza Basalt member, has been traced from Grand Coulee area east to Spokane, south to Pendleton, Oregon, and southwest into the Columbia River Gorge over an area of approximately 20,000 square miles.

These flows sought the lowest places, filling the old valleys and encroaching on the flanks of hills and mountains. In time, the prebasalt topography was buried, and a relatively flat basalt plain was constructed. The Snake and Spokane Rivers have cut through the basalt sequence along the eastern margin revealing at least 2,500 feet of prebasalt topography formed in schists, granites and other pre-Cenozoic rocks.

As the flows spread over this region, they interrupted the drainage, damming streams and giving rise to local lakes and swamps in which sediments accumulated. Because the Miocene climate was considerably more moist than at present, the processes of weathering, erosion and deposition could rapidly transform the initially barren flow top into one of rich soil and abundant vegetation. The landscape that was developed on the top of one lava flow was buried beneath the next flow, creating interlayers of various thickness between basalt flows. When successive eruptions were close in time, the buried surface was relatively smooth and barren consisting only of the slightly weathered treeless surface of the preceeding flow.

B.3.2 Hanford Reservation

B.3.2.1 General

The Hanford Reservation, located in south-central Washington, is underlain by a thick sequence of Columbia River Plateau basalts within the Pasco Basin. The geology and hydrology of the area have been described by several investigators including Walters and Gralier (1960), Newcomb (1959), Newcomb et al. (1972), and Atlantic Richfield Hanford Company (1976).

B.3.2.2 Geology

The Pasco Basin, a cross-section of which is shown in Figure B-3, contains the thickest accumulation of basalt within the Columbia River Plateau. Basalt flows overlay the crystalline basement which is composed of a complex of metamorphic and granitic rocks. The topographic relief on this buried erosion surface may exceed 2,000 feet. Sedimentary rocks may fill valleys underlying the oldest flows.

As discussed in McKee (1972), overlaying the basalts are the lacustrine and fluvial silts with minor sands and gravels of the Ringold Formation which is composed of both sediments and volcanic ash. These materials came from three sources: The Cascades, the Okanogan Highlands, and the northern Rocky Mountains. An eolian deposit of fine sand and silt generally overlies the eroded surface of the Ringold Formation. This deposit is considered to be the equivalent of the eastern Washington, western Idaho Palouse soils. The eolian soils, Ringold Formation and locally even the basalts were eroded by a series of glacial floods. These floods redeposited sand, gravel, and silt. Large erratic rocks and boulders were carried in by ice rafts. The deposits are in flood channels, terraces and hillside veneers.

The most prominent landforms in the region surrounding the Pasco Basin are the anticlinal ridges that began forming about 10 million years ago. The Saddle Mountains trend east-west and border the Basin to the north. They are an asymmetric anticline with a steep northern slope and a gentle southerly slope. Two basalt ridges occur along the western border. They are the Umtanum Ridge and the Yakima Ridge. Both have more steeply dipping northern limbs with part of Umtanum actually being overturned to the south. Below and en echelon to the east of these ridges are the Rattlesnake Hills and the Horse Heaven Hills. Numerous local faults are associated with these structures.

There is little evidence for faults or folds having active movement within the last 10,000 years, but older sediments are truncated and displaced by previous movements. Micro-earthquakes are numerous and frequent, indicating tectonic deformation without present surface disturbance.

B.3.2.3 Hydrology

1. Surface Water: The Columbia River which flows through the northern portion of the Hanford Reservation is the major surface drainage. The Yakima River forms the southern boundary of the area. Other surface water includes two ephemeral streams and various ditches and ponds, most associated with Hanford Reservation activities.

Precipitation at the site averages approximately 6 inches annually. Less than 1 inch of surface runoff occurs. Annual precipitation less than 10 inches is common in central Washington due to the rain shadow caused by the Cascade mountains to the west.

2. Ground water: Ground water is found on the Hanford Reservation in a series of confined aquifers (primarily interbed layers in basalt) overlain by an unconfined aquifer in the sands and gravels of the Ringold Formation (fine sands, silts, and clays with some coarse sand and gravel) and more recent glaciofluvial deposits. The unconfined aquifer extends down to the top of the basalt in some areas and to silt or clay zones within the Ringold in others. Hydraulic conductivity measured from pumping tests in the unconfined aquifer ranges from 1.8×10^{-1} to 7.1 cm/sec in the glaciofluvial sediments, from 3.5×10^{-2} to 3.5×10^{-1} cm/sec in combined glaciofluvial and Ringold sediments, and from 3.5×10^{-4} to 7.1×10^{-2} cm/sec in the Ringold (Atlantic Richfield Hanford Company, 1976).

The uppermost confined aquifers occur in the lower Ringold Formation and sedimentary interbeds of the upper and middle Yakima basalts. They appear to be interconnected to some degree with the overlying unconfined aquifer. The conductivity of several of these interbeds has been measured by packer tests. The Rattlesnake Ridge interbed, a tuffaceous sandstone, had a hydraulic conductivity ranging from 8.8×10^{-5} to 1.1×10^{-2} cm/sec. The Mabton interbed, a sandstone with some gravel, ranged from 7.1×10^{-3} to 2.1×10^{-2} cm/sec. The conductivity of interbed layers is enhanced by the rubbly tops and bottoms of the basalt flows. The more massive and less permeable centers of the basalts act as confining layers (Newcomb et al., 1972).

The Yakima basalts are divided into lower, middle, and upper formations. Piezometric heads in the lower basalt are reported to be the same or slightly lower than those observed in the overlying middle and upper basalts (Atlantic Richfield Hanford Company, 1976). The lower basalt which is encountered at depths of approximately 1,900 feet below surface has been tested in one well to depths of about 4,300 feet below surface (Atlantic Richfield Hanford Company, 1976). Piezometric data within the lower basalt indicates the existence of two distinct aquifer zones. One zone extends upward from about 2,900 feet and the other extends downward from about 3,200 feet. There is approximately 7 feet of head difference between these two zones with the excess head occurring in the lower.

Hydraulic conductivity within the lower Yakima Basalt has been tested both in the laboratory and the field (Atlantic Richfield Hanford Company, 1976). Laboratory tests on five basalt core samples yielded hydraulic conductivities ranging from 6.7×10^{-9} to 2.1×10^{-8} cm/sec. Field tests yielded the hydrologic properties shown below.

Rock	Hydraulic Conductivity - cm/sec	Effective Porosity
Dense Basalt	4×10^{-9} to 1×10^{-6}	.001 to .01
Vesicular basalt	4×10^{-7} to 4×10^{-6}	.05
Fractured, weathered or brecciated basalt	1×10^{-6} to 2×10^{-3}	.10
Interbed	1×10^{-6} to 4×10^{-3}	.20

3. Water Movement: Potential vertical water movement on the Hanford Reservation tends to be upward to the unconfined aquifer from the confined aquifers in the lower Ringold and upper and middle Yakima basalt formations. Evidence from a single well also indicates potential flow from the uppermost confined aquifers downward to the confined aquifers in the lower basalts. The head differential between the uppermost confined and overlying unconfined aquifers is small (usually less than 30 feet) as is the head differential between the uppermost confined and lower confined basalt aquifers (approximately 7 feet).

Vertical water movement at the Hanford Reservation is influenced by the structure of the Pasco Basin. The confined basalt aquifers are recharged near the fringes of the basin. Tilting of the basalt at the surface is advantageous to groundwater recharge because it exposes permeable interflow zones. Water movement is down-dip toward the center of the basin where confining pressure results in a natural upward flow gradient.

The water table in the unconfined aquifer on the Hanford Reservation generally slopes towards the Columbia and Yakima Rivers. The water table responds to river stages within a two-mile belt on either side of the Columbia River indicating a large degree of hydraulic connection between the aquifer and the river (Newcomb et al., 1972).

Regional flow systems within the lower Yakima basalts are not known because of the lack of deep hydrologic information. Several studies indicate the possibility that on a regional scale the Columbia River basalts behave as an unconfined aquifer with localized areas on zones of perched, semiperched, or confined water (Walters and Gralier, 1960, Newcomb, 1959).

B.4 SPECIFIC SITES - SNAKE RIVER PLAIN

B.4.1 General

The Snake River Plain is formed of basalt and rhyolite lavas with numerous interbeds of tuff and sandstone as shown in Figure B-4. The variety of rocks is in contrast to the Columbia River Plateau proper, where basalt is almost the sole rock type. A detailed discussion of the Snake River Plain basalts is given by Schoen (1972), Hamilton (1963) and Morris (1965) among others.

The structure of the plain is poorly known, but the abrupt termination of northwest trending structures by the northeast trending plain suggests a downfaulted graben. The area is cut by a complex pattern of normal faults. These faults have provided pathways for the upwelling of basalt. These basalt flows obscured the pre-existing structures by filling in the low areas and creating a uniform flat surface. These eruptions have continued into very recent times. Some of the latest were erupted within the last few hundred years. Their combined thickness in some areas exceeds 3,000 feet.

Because of the difference in silica content between basalt and rhyolite, there are great differences in the flows. Some of the more fluid lava flows solidified with a smooth or evenly wrinkled surface. Others with more silica were little more than a moving rubble pile which retained a rough, jagged surface. There are many more lava tube caves within the Snake River Group than in the Columbia River Basalt.

B.4.2 Idaho National Engineering Laboratory

The Idaho National Engineering Laboratory (INEL) is located on the flood basalts of the Snake River Plain in southern Idaho. Burial of radioactive waste began in 1952 at a shallow burial ground located on the INEL site.

1. Surface Water: Surface drainage is to the Snake River which eventually joins the Columbia River and flows to the Pacific Ocean. The Big Lost River, which flows within two miles of the burial ground, loses its entire flow by vertical percolation into the basalt. Several other rivers flowing from the mountains in the north also lose their water as they reach the edge of the Snake River Plain. Geologic evidence suggests that the Big Lost River has flooded the burial ground site in the recent geologic past. Barraclough et al. (1976) report that flooding at the INEL burial ground in 1962 and 1969 caused by rapid snowmelt, combined with rain, is estimated to have provided 50 acre-feet of water which infiltrated into the burial ground. Another 100 acre-feet of percolation derived from heavy rains and snowmelts is estimated to have occurred from 1952 to 1970. Dikes were constructed to help alleviate this problem.

   Precipitation on the INEL site, and on much of the Snake River Plain, averages about 8-inches annually. Surface runoff is less than one inch and is probably near zero due to vertical percolation into the basalt.

2. Ground water: The water table of the Snake River Plain aquifer lies approximately 500 to 600 feet beneath the surface at the INEL site. The regional aquifer is a major source of ground water in southern Idaho and is one of the

most productive aquifers of its kind known. It behaves as a water table aquifer when observed by pumping tests (Walton and Stewart, 1961). Hydraulic conductivities measured within the aquifer range from 4 x 10^{-2} to 4 cm/sec in the horizontal direction (Barraclough et al., 1976). Verical permeability is generally lower than horizontal because of layers of massive basalt and fine-grained sedimentary interbeds. However, significant vertical hydraulic conductivity does exist primarily through vertical fractures. On the INEL site hydraulic conductivity measured within a 100-foot thick basalt zone averaged about 0.2 cm/sec in the horizontal direction and about 0.06 cm/sec in the vertical direction. This indicates a horizontal to vertical ratio of 3.3 to 1 at this particular site.

Sedimentary interbeds containing fine-grained material are generally more limiting to vertical water movement than is basalt. Such interbeds commonly form perched water tables in the basalt above them. Vertical hydraulic conductivities measured in cores of sedimentary interbeds near the burial ground ranged from 1.8 x 10^{-10} to 3.5 x 10^{-3} cm/sec which are substantially lower than those measured in basalt.

3. <u>Water Movement</u>: Precipitation and surface runoff generally infiltrate and percolate downward in the partially saturated zone eventually reaching the regional water table within the Snake River Plain basalts. Percolating water can encounter dense basalt zones or fine-grained interbeds which retard vertical movement forming perched water tables above the 500- to 600-foot deep regional water table.

Regional groundwater flow within the Snake River plain aquifer is generally southwesterly at a gradient of approximately

5-feet per mile (Morris et al., 1964). Beneath the burial ground this regional gradient has been reversed due to recharge from the Big Lost River to the west. Except for this local area of northeasterly flow, ground water generally flows southwesterly under the remainder of the INEL site.

Discharge from portions of the Snake River Plain aquifer occurs along the Snake River canyon to the southwest where water flows from voids between basalt flows.

B.5 POTENTIAL RELEASE PATHWAYS

It is appropriate to investigate a variety of conditions that are likely or possible and which represent potential pathways for the release of depository contents. The following is a partial listing of conditions which require consideration in the flood basalt model:

1. Depository Induced or Related Conditions
   a. Fracture zones around openings: The high strength of basalt may necessitate excavation by drilling and blasting, which could result in an extensive fracture zone. Fractures around the shaft could transmit waste to overlying layers, reducing the transit time and possibly changing the waste discharge location. It would also reduce the resaturation time. It may be possible by placing the repository in a zone dominated by downward flow (such as in the regional recharge area) to minimize the effects of fracture zones around the shaft.
   b. Shaft backfill and shaft sealing: The shaft is a potential problem, both in reducing the resaturation time and in becoming a pathway for nuclide release. Because of

the numerous permeable layers and fractured character of the basalt, shaft sealing may present significant construction problems. The effect of poor shaft backfill performance could be minimized as discussed above by placing the depository in an area of downward flow. Multiple shafts spread out over the depository area should also be examined. With sufficient horizontal gradients and very permeable backfill, water may tend to flow down one shaft, through the depository, and exit from another shaft.

c. Fracturing of depository layer: Thermally induced stresses and/or stresses induced by the depository opening may result in increased fracturing of the thin depository basalt layer. This would increase the permeability of the layer, causing a decrease in resaturation time. It would also decrease the nuclide transit time in the layer. However, the nuclide transit time in the depository layer may be relatively small even for the unflawed case.

d. Thermally induced groundwater flow: The thermal gradients around the depository may induce water to flow and, under certain conditions, may develop small convection cells. The magnitude and extent of these gradients will be relatively small and may be sufficient to affect flow only locally. To date, the predicted thermal gradients (GAI 1977b; Sandia 1977a; Parsons, Brinckerhoff, Quade and Douglas, Inc., 1976) have been based only on conduction. The inflow of ground water during resaturation and the potential movement of heated water away from the depository may significantly reduce the thermal gradients. It is also important to consider the relatively short duration of the peak thermal gradients (probably on the order of 100 to 200 years). The potential for convective flow involving multiple shafts and failed boreholes needs to be examined. Long recharge times and/or long canister dissolution times will minimize the effects of thermally induced flow.

2. Existing Geologic Conditions
   a. Faults: The effects of existing faults need to be examined. Due to the brittle nature of basalt, the fault zone may be permeable, although faults through the interbeds may not. However, since the ranges in vertical gradients are quite small, the effect of the fault may be minor.
   b. Geothermal effects: Some naturally heated water is withdrawn from wells proximal to fault lines in the Columbia River basalts. The influence of these geothermal zones on the general groundwater flow patterns and on the performance of a depository needs to be examined. Because of these effects and the potential resource value, sites in close proximity to geothermal zones may be unsuitable for depository development.
   c. Fracturing: Portions of basalt flows are highly fractured and may be quite permeable. Undetected fractured zones within the depository layer may lead to a decrease in resaturation time and early breach of the layer.
   d. Dikes: Dikes or lava-filled cracks may be more or less permeable than the enclosing strata.

3. Future Geologic Changes
   a. Faulting and tectonically induced changes in fracturing: The suitability of the layered basalts may depend upon maintaining the integrity of the few low permeability strata including the depository layer. Relatively thin

beds of brittle rock will fracture rather than bend when subjected to differential loading or tectonic forces. Since there is active tectonism adjacent to the Hanford site, it seems important to investigate the nature of the result if the depository layer becomes increasingly fractured or faulted.

b. Volcanism: The approximate location of several, but not all, feeder dike swarms is known. Thus, the possibility of a new fissure intersecting the depository should be evaluated.

c. Glaciation: The Columbia River basalts are adjacent to regions covered by glaciers during the Pleistocene. Glaciation significantly alters the hydrology of the entire area.

4. Man-Induced Pathways

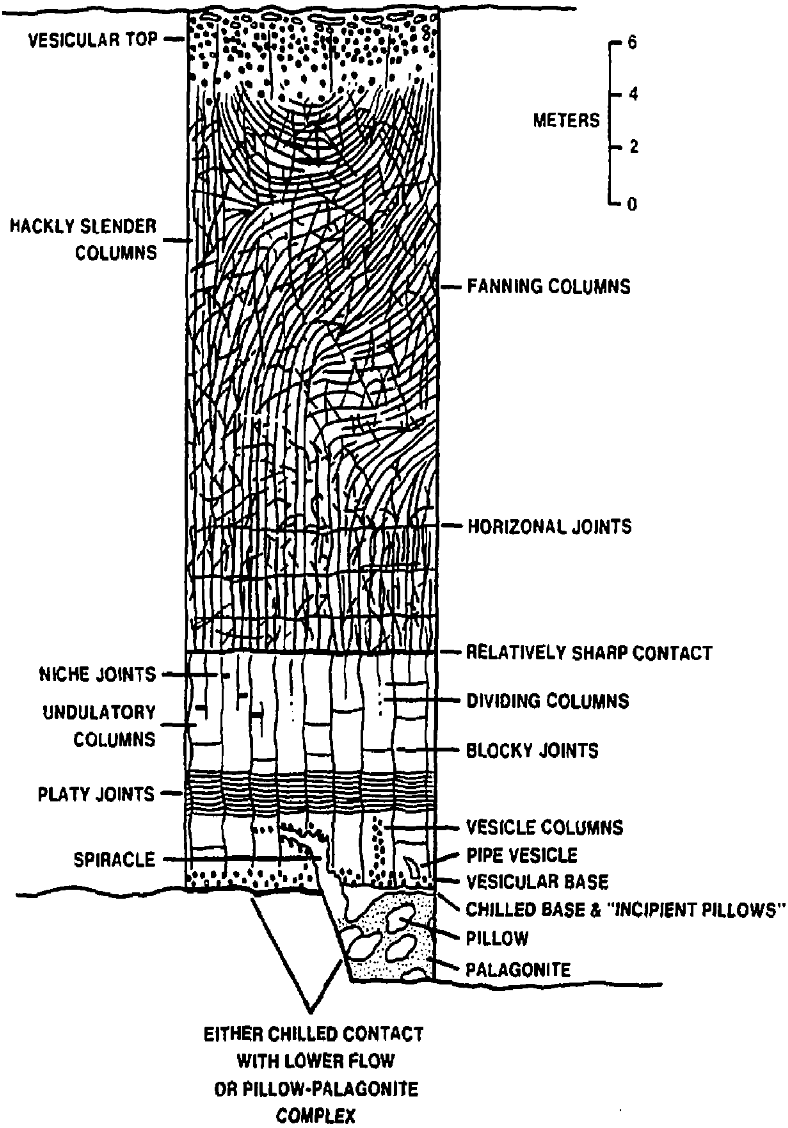
a. Wells: The aquifers within a basalt sequence often contain fresh water. The Columbia River Basalt is in a desert environment, so these sources of fresh water are likely to be tapped eventually. A water well may intercept the hydrologic regime of the depository. Thus, the potential release of waste through wells is a critical factor in determining the suitability of basalts. As discussed in Section 6.4 of our May 1978 report (GAI 1978), the waste will probably escape rapidly from the depository layer (after resaturation and assuming some vertical gradients). Thus, eventual contamination of at least some of the deep basalt aquifers would seem likely.

b. Undetected boreholes and failed borehole seals: Due to small vertical gradients, the effects may be minor. The probability of undetected deep boreholes is lower than in sedimentary basins. There are currently no deep mining activities in basalt.

c. Economic minerals: Placer deposits of economic grade may occur in ancient stream channels between basalt flows. At present we have no exploration technology for locating them. Zeolites and related minerals are found in small concentrations within the vesicles of certain basalts. Additionally, potential ore zones exist in the rocks underlying the basalt which we are presently incapable of finding except by a random drilling program. Thus, problems associated with current and future mines and wells (except of course for water) are considered minimal in basalts.

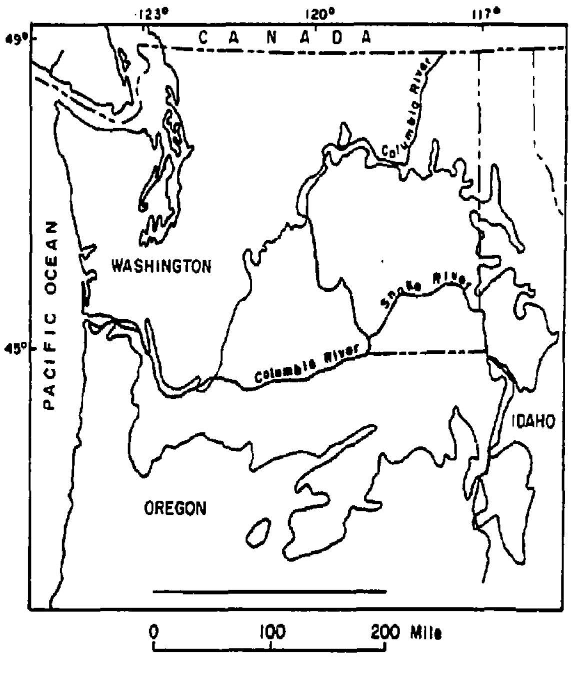
SCHEMATIC SECTION THROUGH A BASALT FLOW SHOWING TYPICAL COOLING STRUCTURES

Figure B-1



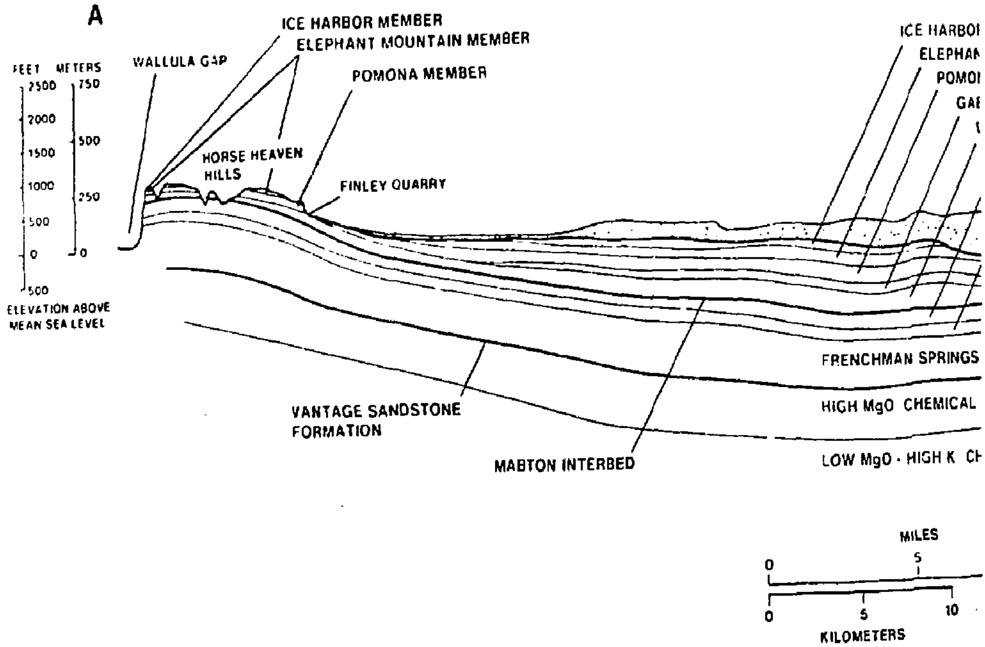
(Atlantic Richfield Hanford Co., 1976)

COLUMBIA RIVER BASALTS (STIPPLED) IN THE NORTHERN PART OF THE COLUMBIA RIVER PLATEAU. (after Waters, 1961) Figure B-2



Project No. 7-9-5 Reviewed Date

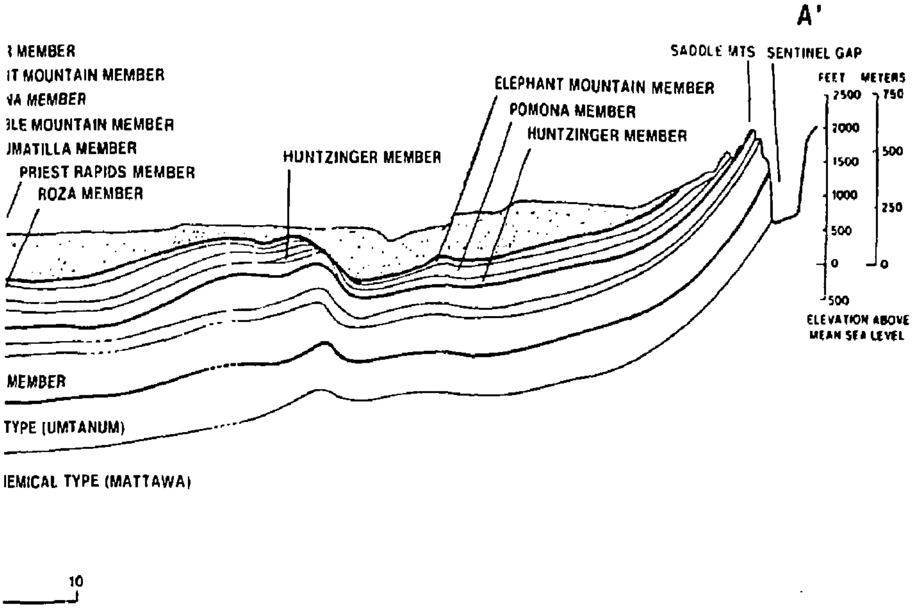
GENERALIZED CROSS SECTION (
IN COLUMBIA RIVER BA



Golder Assoc

IF THE PASCO BASIN
SALT

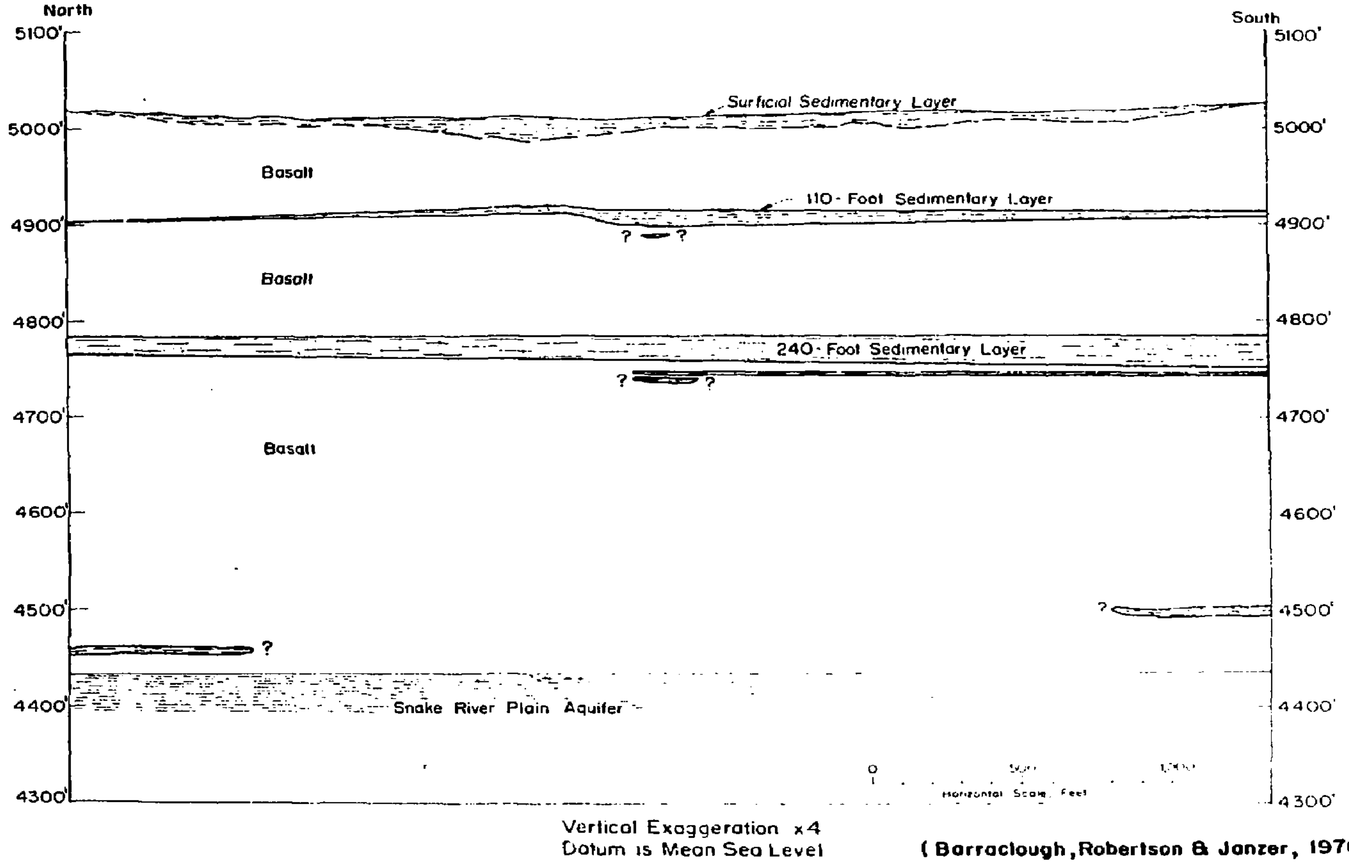
FIGURE B-3



(Atlantic Richfield Hanford Co., 1976)

iates

Project No. 22304 P Reviewed EC Date 11-7-77



(Barraclough, Robertson & Janzer, 1976)

SNAKE RIVER PLAIN

Geologic cross section east to west through the INEL burial ground

Figure B-4

Golder Associates

APPENDIX C - METAMORPHIC AND INTRUSIVE IGNEOUS ROCKS

C.1 GEOLOGY

C.1.1 General

These two families of rocks are discussed together because they have many physical and chemical similarities, even though their origins are quite different. These rocks are composed almost entirely of quartz, feldspar and the mafic minerals in varying percentages. Individual crystals are growth-interlocked, and porosity is as low as can be found in nature. These are also among the strongest rocks mechanically, the most resistant to chemical attack, and therefore, the most durable.

For repository considerations, the major difference between the two families is that metamorphic rocks occur in a significantly more complex geologic environment, tend to be more highly fractured and faulted, and are therefore, more permeable. They also are characterized by foliation which often represents anisotropic weakness.

Figure C-1 shows the distribution of principal areas of intrusive and metamorphic rocks within the conterminous United States.

C.1.2 Metamorphic Rocks

Metamorphic rocks are formed by the transformation of igneous, sedimentary or other metamorphic rocks through the processes of heat, pressure and chemically active fluids which act on the rocks while they are still in the solid state and subjected to deep burial. New minerals and textures are formed and remain stable. There are, thus, innumerable gradations between metamorphic rocks and the original rocks from which they were formed.

Most metamorphic rocks show a thin layering called foliation which is due to the parallel orientation of the constituent minerals. The layers may be relatively coarse bands 1 mm or larger in size as in gneiss or thinner than a sheet of paper as in slate. The foliation appears to record slow pervasive movement within the rock mass. During this movement the original minerals were deformed and slowly recrystallized into new minerals. Thick metamorphic rock sequences frequently contain thin sheared zones parallel or subparallel to the foliation. These zones can be pervious and potentially provide pathways for nuclide transport.

There are often no sharp boundaries between the various types of metamorphic rocks; thus, within a small area, several rock types may occur. Locating a particular metamorphic type at depth may require much more intensive surface and subsurface exploration than either sedimentary or plutonic rocks.

Structural complexity with folding and faulting characterize metamorphic rocks. They are often found in close association with plutonic igneous rocks. Foliated gneiss can grade laterally into massive granite with the same mineral content. Gneisses are similar to granites with respect to physical and hydraulic properties. Only rocks of medium to high metamorphic grade are specifically discussed here.

C.1.3 Intrusive Igneous Rocks

Igneous rocks are formed by solidification from a molten magma. They include intrusive rocks that solidified at various depths within the earth and extrusive rocks that erupted onto the surface. Igneous rocks vary individually in hardness and strength, dependent upon crystal size, mode of eruption and presence or absence of voids. Intrusive rocks solidify beneath the earth's surface in bodies called plutons. The material over them acts as an insulating blanket, causing them to cool slowly.

Crystal sizes range from a fraction of an inch to several feet. These rocks, which consist of granite, granodiorite, diorite, gabbro and other varieties, can generally be regarded as a single rock type from the standpoint of mechanical strength and overall suitability for waste disposal. The intergrowth of crystals gives high mechanical strength and reduces interstitial porosity and permeability.

Batholiths are the largest of the igneous plutons and are emplaced predominantly in mountain belts (for a more detailed discussion of batholiths, see Hamilton and Myers, 1967). They are chiefly granitic in composition without a visible or inferable floor of older rocks. Stocks are small batholiths with less than 40 square miles of outcrop area. Their origin and the time and mechanics of their emplacement have been variously interpreted in geologic literature to explain widely different characteristics. These characteristics generally concern primary flow banding and the interaction with the enclosing rock. The wall rock may be metamorphosed by the emplacement of a pluton. The thickness of this altered zone depends greatly on the temperature of the pluton and the depth of emplacement. Plutons emplaced within about four miles of the ground surface will be of lower temperature and generally will have a smaller alteration zone than those emplaced at greater depth. Several pluton types may be found in a single orogenic belt.

A batholith is not emplaced during a single plutonic event. Numerous intrusions of magma may take place. Some of these events may be forceful, causing fracturing and faulting within the existing pluton. Most of these fissures are filled and sealed by the later fluids. Other emplacements may be relatively quiet with magma filling pre-existing cracks and fissures. Some melting of existing rock may occur. Later uplift generally creates joints and faults unrelated to the original emplacement. Although multiple intrusion creates bodies that differ in mineral content, batholiths may be considered relatively homogeneous in a mechanical sense.

The edge of the batholith is not homogeneous. This altered area is baked, chemically altered, and contains numerous faulted and fractured zones. The geology of these areas is very complex because forceful injection of the magma can displace the country rock creating folds and joints. These features occur in both the country rock and the cooling surface of the pluton itself. Normally, when the pluton is exposed by erosion, these zones are preserved only on the sides of the pluton or in roof pendants. Economic mineral deposits tend to be located in or near these altered zones.

Because most large plutons are found in recent orogenic belts, they are usually topographically high areas. Streams tend to create deep canyons with steep gradients in the durable rock. The areas are subject to the various agents of active erosion while sedimentary basins collect the broken-down byproducts.

C.1.4 Shear Zones in Metamorphic Rocks

Thick metamorphic rock sequences frequently contain thin sheared zones parallel or subparallel to the foliation. Normally, this shearing is located in the weakest layer of the metamorphic rock, often in a schist zone with a high mica content. Such mica-rich zones occur within thick schist sequences and as thin interbeds in the massive metamorphic gneisses and quartzites.

1. Origin: The probable origin of these foliation shears is the differential sliding of adjacent layers during folding. This differential movement would tend to concentrate in the weaker layers consisting of mica schist, chlorite schist, talc or graphite schist, slates or argillites. The massive, thickly-bedded or foliated rocks such as gneisses, quartzites, and marbles, tend to fracture upon folding with the shearing concentrated along one or more of the weak schistose interbeds.

2. Extent: The extent of the shear is dependent on the scale of the fold involved. For foliation shears to extend from hundreds to a few thousands of feet, the extent of the fold limb must be of equal or greater dimensions. Shears associated with small drag folds a few feet in amplitude would be correspondingly small and local in extent.

   Other minor causes of shearing are thrust faulting and rock stress relief. Major thrust faults in metamorphic terrains may terminate in a splay of horsetail shears that resemble foliation shears. Stress relief due to unloading from erosion may also produce minor shearing. This results from movement caused by differences in shear strength and elastic modulus between adjacent beds.

3. Thickness: According to Deere (1973) the typical thickness of a foliation shear is about 1 to 4 inches. Thicker and thinner zones occur but are more rarely encountered. Typically, the thickness of the zone will vary throughout their length. One such seam of contorted, sheared and pulverized biotite schist was found in Rhodesia during the construction of Kariba Dam. The seam occurred in the middle of a 100-foot-thick quartzite sequence. On the flank of a fold the sheared mica schist was about 5 feet thick, but where encountered near the trough of the syncline, it was 30 feet thick (Deere, 1973).

4. Spacing: Because of the great variety of metasedimentary rock types and the diverse stress conditions both regionally and locally to which they are subjected, the spacing of foliation is extremely variable. On the Churchill Falls Hydroelectric Project, Labrador, five foliation shear zones were found in about 6,000 feet of underground workings, giving a true spacing of from 500 to 1,500 feet.

   In the Washington, D.C., Metro, currently under construction along Connecticut Avenue at the DuPont Circle Station, the average spacing is about 25 feet. In some of the New York City tunnels the true spacing (calculated normal to the strike and dip) was found to be in the general range of 100 to 1,000 feet (Deere, 1973).

5. Shear Zone Materials: The weakest material in the shear zone is typically a crushed mica schist gouge. Grain-size analyses of several samples of gouge from the New York City water tunnel No. 3 indicate a moist, plastic, well-graded

mixture of clayey, silty sand (Deere, 1973). Other studies on fault and shear gouge (Howard et al., 1975) indicate that the material commonly contains 5 to 30 percent clay with a widely-variable amount of silt, sand and rock fragments. In the New York Tunnel the most plastic gouge contained montmorillonite or inter-layered montmorillonite-chlorite in the clay size fraction. Less plastic gouges were composed predominantly of vermiculite or inter-layered vermiculite-montmorillonite (Deere, 1973). These clay minerals were most probably formed by the alteration of the primary micas and feldspars in the original rock by heat, pressure and fluid migration at the time of shearing. The clay content may also be increased by near-surface weathering.

In addition to the plastic gouge zone, which may be a fraction of an inch to several inches wide, the remainder of the shear zone consists of partially crushed, sheared and slickensided rock. The gouge layer is usually present on one or sometimes both sides of the shear zone adjacent to the hard rock. Occasionally, the gouge layer or branches of it will occur inside the shear zone. Joints in the hard rock adjacent to the shear zone may also be coated with clay.

6. Hydraulic Conductivity: Because of the clay-gouge material, the foliation shears generally are not permeable in the direction crossing them. The sandy interior of the shear zone as well as the jointed rock zone adjacent to the shear tend to be permeable. Thus, the gouge acts as a dam, but the disturbed zone and the interior crushed zone act as drains parallel to the shear. The hydraulic conductivity

parallel to the shear is expected to be in the range of 10^{-3} to 10^{-5} cm/sec (Deere, 1973).

C.2 HYDROLOGY

Intergranular porosity in solid pieces of fresh metamorphic and intrusive igneous rock is generally less than 3 percent and most commonly less than 1 percent (Krynine and Judd, 1957). Existing porosity is poorly interconnected, resulting in extremely small permeabilities which, for practical purposes, are commonly assumed to be zero. Planar features, including bedding, foliation, cleavage, joints and faults often provide open spaces along which water may move. Such openings are commonly lumped together and referred to as secondary or fracture porosity with the resulting permeability referred to as secondary or fracture permeability. Weathering and decomposition of crystalline rock can also substantially increase porosities and permeabilities. Depths of weathering from 5 to 50 feet are normally encountered; however, the effects may extend to more than 300 feet in regions of intense weathering (Davis and DeWiest, 1966).

Hydrologic data is generally sparse in metamorphic and intrusive igneous rocks because of their relative unimportance as water-producing formations. This is particularly true at depths in excess of several hundred feet. Water wells seldom penetrate to greater depths because the combined effects of the confinement by the overlying rock, the absence of weathering, and the tendency of fractures to be less common at greater depths result in very low water yields.

Certain regions rely upon metamorphic or intrusive igneous rocks as the only source of water from wells. In these regions, it is important to recognize those features such as faults, fractures, weathering, etc., which tend to improve water yield. Meier and Peterson (1951) cite an example in Sweden where three wells along a fault zone yielded between 70 and 100 gpm, whereas the same rock type in other areas yielded an average of only 15 gpm. Enslin (1943) reports that most of the extractable underground water in intrusive igneous formations in South Africa is stored in basins of decomposed rock. Within such basins a definite water table exists if the decomposed rock is saturated. He reports that waters stored in fractures in unweathered rock are disconnected and too locally confined to form any uniform water table.

Data from relatively shallow wells in metamorphic and intrusive igneous rock is of limited use in projecting hydrologic characteristics at depths of more than several hundred feet. The average porosity and permeability of metamorphic and intrusive igneous rocks decreases rapidly with depth (Turk, 1962; Davis and Turk, 1964; Snow, 1967). This effect is illustrated by Figure C-2 which shows decreasing well yields in crystalline rocks in California. Joints, faults, and other fractures tend to close at depth due to overburden pressures. Rock flowage is not important in most hard rocks within a few miles of the surface, so some openings can exist at great depths (Davis and DeWiest, 1966). Snow (1965), after an extensive literature review, concludes that:

> ...openings (open fractures) in excess of a millimeter are common features of crystalline and some sedimentary rocks. These occur not only in the weathered region, but contrary to philosophical and theoretical treatments of the maximum depth of fracturing, large openings are also at depths to several thousand feet.

Snow does not present all the information necessary to document this conclusion, nor does he discuss the potential for water movement within these openings.

Some data are available from deep borings or mines in metamorphic and intrusive igneous rocks. Such data are usually acquired during mineral exploration and mining. Most ore bodies are located in areas where there has been a greater than average amount of faulting, fracturing, and folding so that hydrologic characteristics of the rock are probably not representative of an average metamorphic or intrusive igneous rock. Porosity and permeability should be lower in less disturbed rocks not associated with mineralization.

Laboratory hydraulic conductivities on unfractured samples of northern Michigan meta-sedimentary and intrusive rocks from boreholes, ranging in depth from a few feet to 2,000 feet, yielded median values generally less than 10^{-8} cm/sec (Stuart, Brown and Rhodehamel, 1954). Davis and DeWiest (1966) compiled the test results in Table C-1. Aquifer tests in the same rocks demonstrated a rock mass conductivity more than one thousand times greater than that of the individual unfractured samples. Aquifer tests further indicated hydraulic conductivities parallel with the strike of the beds which were two to three times the average conductivity. However, these tests were performed over the entire depth of the hole and reflect an overall average permeability. The actual conductivity at depth was not evaluated.

Yardley (1975) after investigating a number of deep mines in Precambrian rocks of the Lake Superior region reports that:

> No evidence of running, seeping, or moving water was seen or reported to us at depths exceeding 3,000 feet. At depths

> of 3,000 feet or less, water seepages do occur in some of the mines, usually in minor quantities but increased amounts occur as depth becomes less. Others are dry at 2,000 feet of depth.

Martinez (1975), after a similar study of mines in igneous and metamorphic rocks in the Maritime Provinces of Canada, writes:

> It seems reasonable to tentatively conclude that mined openings in the rock types investigated (volcanics and sediments metamorphosed to a low or subgreen schist facies and intensely deformed) would provide hydraulic isolation at depths on the order of 2,800 to 3,200 feet below the surface or greater.

These two studies seem to indicate a maximum depth of water penetration in the Precambrian crystalline rocks studied. The possibility exists that some inflow does occur, but is so small that it evaporates and is carried away by the mine ventilation system before it can be detected. Although extremely small inflows, if in fact they do occur, are not significant over short time periods (period of active mining), they may be significant over a duration of thousands of years. Extremely small inflows may be very difficult to measure within an active mine.

There are basic differences between groundwater flow in fractured metamorphic and igneous intrusive rocks and that in layered sedimentary or extrusive igneous rocks. In the latter rock types, ground water is found in permeable aquifer zones which can be confined above and below by less permeable strata. Piezometric heads from one aquifer to another can vary by several hundred feet. Water in fractured metamorphic and igneous intrusive rocks occurs relatively uniformly throughout fractures which provide some hydraulic communication throughout the rock mass. Thus, the piezometric head should not vary greatly vertically within the rock mass. The regional groundwater flow is controlled by the topography and the occurrence of fractures. Recharge occurs near topographic highs and discharge at topographic lows. It is possible for ground water in fractures to become relatively stagnant at depth because of the tendency for fractures to be less frequent and less interconnected (particularly horizontally) with increasing depth. Figure C-3 shows a theoretical model of idealized flow pattern which might be expected in fractured metamorphic or igneous rocks. Confinement can result from overlying sedimentary or, in some cases, decomposed crystalline rock of low hydraulic conductivity, but artesian conditions are generally rare in metamorphic and intrusive igneous rocks (Legrand, 1949).

C.3 SPECIFIC SITES

C.3.1 Precambrian Shield Rocks

C.3.1.1 General

The Canadian Shield extends into Minnesota, Wisconsin and upper Michigan and also lies buried under younger sedimentary strata in eastern North Dakota and northeastern South Dakota.

C.3.1.2 Geology

The Precambrian shield is a broad area of gentle terrain mantled with glacial drift and underlain by Precambrian igneous and metamorphic rocks. The region has some of the oldest rocks on the continent, and though tectonically active at one time is now considered stable. The rocks consist of an old series of highly contorted and metamorphosed clastic sediments and volcanics. The igneous rocks are largely of basaltic composition, and the entire sequence has been intruded by a number of gneissic granite plutons.

These plutons are overlain by a younger series of metamorphic rocks consisting of quartzites, dolomites, slates, and clastic rocks interbedded with lava. These younger rocks include the iron formations of the Lake Superior region and occupy a relatively small part of the total shield area. A thick sequence of basaltic lava flows and sandstones is superposed on the older metamorphics. This sequence, largely located in the Keweenaw Peninsula of Michigan, is locally copper bearing. The lava sequence is tilted 30 to 45 degrees toward the west. Figure C-4A shows a cross section through the Lake Superior shield area.

A body of gabbro about 140 miles long and up to 50,000 feet thick is located along the southwestern shore of Lake Superior. The roots of this pluton probably extend to great depth. Recently, this area has been a target for nickel exploration. Parts of it are in parks and wilderness areas.

Western Minnesota has several granitic plutons. Some are exposed, but most are buried under glacial debris or Pierre Shale. Several quarries near Big Stone, South Dakota, mine the granite for monument stone. Joints must be relatively widely spaced to extract large blocks for monuments.

A belt of quartzite exists in southeastern South Dakota, Southern Minnesota, and Southern Wisconsin. It is divided into two main formations, the Sioux Quartzite and the Baraboo Quartzite. Wells drilled into the Sioux Quartzite in South Dakota produce almost all their water from the glacial till-quartzite interface. Some water comes from fractures and weathered zones in the top 20 feet of the quartzite.

The shield area, while made up of a heterogenous group of rocks, can probably be considered as a more or less homogeneous body for a repository. Tectonically, the region is considered one of the most stable in the nation though earthquakes are recorded periodically. One earthquake trend is along the Keweenaw Peninsula and the other is along the St. Lawrence River. The area is also undergoing uplift from glacial rebound. This is a regional feature and does not seem to affect specific areas individually. The rate is approximately several millimeters per year.

C.3.1.3 Hydrology

1. Surface Water: Three principal surface drainages are present on the shield area. Michigan, northern Wisconsin and northeastern Minnesota drain to the Great Lakes. The remainder of northern Minnesota and eastern North Dakota drain to Hudson Bay with the rest of the shield area draining to the Mississippi River. Precipitation ranges from over 30 inches annually in Michigan and Wisconsin to about 20 inches in eastern North Dakota. Surface runoff decreases from over 15 inches in northern Michigan to about one inch in eastern North Dakota.

   The surface drainage characteristics have been greatly modified by continental glaciation. Numerous lakes and wetland areas are found throughout the shield area where deposits of glacial debris have altered or destroyed pre-existing drainage channels. Most meteoric water circulates within the relatively thin layer of glacial deposits.

Rivers, streams and lakes are constantly fed by groundwater from these surficial deposits.

2. Ground water: Ground water is found in glacial debris over most of the shield area. Glacial aquifers are generally thickest in stream valleys and may be locally confined by interbedded fine sediments. Parts of the shield region which are overlain by consolidated preglacial sedimentary deposits often have extensive groundwater aquifers contained within these deposits.

   The Precambrian crystalline rocks generally contain groundwater only in fractures with amounts depending upon the number, size and permeability of such fractures. These rocks are not usually penetrated by wells since they contain no oil and very little extractable water. Thus, hydrologic data are sparse and characteristics must be inferred from obserations in boreholes or, more commonly, mines.

   Two recent reports include observations made of water inflow into deep mines in the Precambrian Shield rocks in the U.S. and Canada (Martinez, 1975, Yardley, 1975). The findings are summarized by Yardley and Goldich (1975). They found that at depths exceeding 3,000 feet no water was observed, and none was reported by mine workers. One mine at Elliott Lake, Ontario, was reported to have water at that depth in a thrust fault zone, but an adjoining mine with workings about a thousand feet below the thrust fault had no water. The deepest mine visited, the Creighton Mine near Sudbury, Ontario, was dry from the maximum depth of 7,000 feet up to 3,000 feet below the surface. They note that active mining areas contain numerous fractures such as shear zones, faults, and joints, but that these are dry in deep mines despite the fact that extensive mining has created secondary fracturing and permeability in the wall rocks. This implies that areas with less disturbance of the rock should be effectively impermeable. The conclusions of Yardley and Goldich are summarized by these comments:

> At depths between 2,000 and 3,000 feet, some water occurs in some mines; at depths less than 2,000 feet, water commonly occurs in fractures and should be expected.
>
> It seems clear that at depths exceeding 3,000 feet there is very little probability of encountering water-bearing fractures. At depths beyond 5,000 or 6,000 feet, the rock pressures are such that the probability of water entering an underground opening through the rock is exceedingly small. At such depths the particular rock type probably will have little bearing on permeability. Experience in deep mines confirms this general statement.

3. Water Movement: Little information is available relating to water movement in Precambrian Shield rocks. Yardley and Goldich (1975) report that groundwater flow systems may be comparatively short and shallow as inferred from groundwater chemistry data. A relatively shallow groundwater flow system is supported by the lack of inflow into deep mines, even where fractures exist. Computer models of groundwater flow systems (Freeze and Witherspoon, 1966, 1967) may serve as useful tools in further evaluating regional groundwater flow within the Precambrian Shield rocks.

C.3.2 Appalachian Region - Savannah River Plant Site

C.3.2.1 General

The eastern metamorphic belt extending from Alabama to Maine is comprised of folded metamorphic and intrusive igneous rocks. This belt of crystalline rock covers a large area which will differ substantially from location to location in its specific hydrology. Thus, the hydrologic description given below of the Savannah River Plant Site near Aiken, South Carolina is not generally applicable to other regions within the eastern metamorphic belt. The Savannah River site has, however, been extensively investigated with regard to nuclear waste disposal and detailed hydrologic data are available.

C.3.2.2 Geology of the Appalachian Region

1. General: The Appalachian Mountains contain a crystalline complex similar to the Precambrian Shield. The crystalline Appalachians are composed of metamorphic schists and gneisses and of various plutonic rocks. The plutonic rocks are mainly granitic, but some are basic or even ultrabasic. Within this crystalline complex are a series of down-faulted troughs filled with sedments.

2. Paleozoic and Precambrian: These metamorphic and plutonic rocks are structurally very complex. Their pattern on a geologic map is one of swirls and knots as shown on Figure C-5. Foliation usually dips at high angles, but in places it rolls over the crests of domes or arches or dips at low angles over wide areas. The structure indicates plastic flow of the rocks and thickening and thinning of the units with little breaking or faulting. Nearly all the faults of the crystalline area formed after the rocks had been deformed and solidified.

3. Triassic: During Triassic time the Appalachian chain was subjected to a series of great normal faults that produced a narrow chain of fault block mountains bordered by downfaulted troughs. These structural troughs within the crystalline

complex stretch from Nova Scotia to North Carolina. Subsurface evidence has traced similar formations into Florida.

One trough near Newark, New Jersey, has a thickness of sediments probably exceeding 20,000 feet. This trough is about 100 miles long and up to 25 miles wide. The beds dip eastward 15 to 30 degrees against a great fault that bounds the basin on the east. This fault probably had a vertical throw of nearly 3 miles.

The Triassic rocks of the basin are conglomerates, sandstones, siltstones, and shales, with interbedded flows of basaltic lava. The sediments are poorly sorted and irregularly bedded. Sandstones grade laterally into siltstones or conglomerates. The coarsest material is found in the east side of the trough. Thick surface lava flows are found near the middle of the section. Each flow is usually separated by a few hundred feet of sediments. The geology of the other Triassic Fault troughs is in general the same, but the total thickness diminishes to between 1,000 and 3,000 feet in the southern basins.

C.3.2.3 Savannah River Plant Site

At the Savannah River plant site, the major rock units are metamorphic rocks of Pre-Mesozoic age, sedimentary rocks of Triassic age, and the Tuscaloosa Formation of Cretaceous age. Figure C-6 shows a cross section of the site.

1. Crystalline Stratigraphy and Structure: The metamorphic basement complex consists of a steeply dipping sequence of schist, gneiss, and metaquartzite. These have been altered

by igneous intrusion and are partially magnitized. Pegmatite veins occur frequently. The rocks have been sheared, enfolded and recrystallized. The introduction of quartz and feldspar has resulted in a granitoid texture (Bowen et al., 1959).

Numerous planar features occur including relict bedding, foliation, cleavage, joints, and faults. Graded bedding has been identified. Foliation, flow cleavage and shear cleavage generally follow the bedding, but the directions can differ locally. Some foliation always follows lithologic changes in the meta-sediments and concordant contacts of the meta-igneous rocks. Shear cleavage is present where differential movement occurred along preexisting planar features such as bedding. There appear to be three sets of joints. They are parallel, oblique and at right angles to the structural trend. The steeply dipping perpendicular set is the most prominent and prevalent (Bowen et al., 1959).

2. Triassic Trough Sediments: The sedimentary rocks of the Triassic occur across the center of the site. They are in fault contact with the metamorphic complex on their southeast side. These rocks are mudstones, feldspathic sandstones, and conglomerates. The sediments are poorly sorted and have a clay matrix.

3. Erosion Surface Paleosoil: A clay layer immediately overlies the metamorphic and Triassic rocks, but its nature, origin, extent and continuity are not known. (National Research Council, 1972). Exploration has shown that the erosion surface on the triassic and metamorphic rocks has about 150 feet of relief.

4. Cretaceous Rocks: Overlying the clay is the Cretaceous Tuscaloosa Formation. This formation is a sandstone and is a major freshwater aquifer. Above the Tuscaloosa Sandstone are a variety of relatively unconsolidated sands, silts, and clays of Cretaceous age.

C.3.2.4 Hydrology of the Savannah River Plant Site

1. Surface Water: The major surface drainage at the Savannah River Plant is the Savannah River which forms the western boundary of the site. It flows directly into the Atlantic Ocean. Precipitation averages slightly over 45 inches annually with approximately 12 inches per year of surface runoff occurring.

2. Ground Water: The geohydrology of the Savannah River Plant Site has been extensively investigated (Siple, 1964, 1967, Marine, 1967, Webster et al., 1970, National Research Council, 1972). Approximately 930 feet of unconsolidated to semiconsolidated sediments, predominantly sand and clay, form an aquifer overlying the crystalline rock. At the top of the crystalline rock a layer of saprolite, averaging 50 feet in thickness, effectively separates water in the fractured crystalline rock from that in the overlying aquifer. The crystalline . ck is a confined aquifer with a head less than 100 feet below land surface and 20 feet higher than that in the overlying aquifer (Siple, 1964). The water is generally fresh (35-80 ppm) in the sediments overlying the crystalline rock and saline (6,000-7,000 ppm) within the crystalline rock (National Research Council, 1972).

Two types of fractures were indicated by borehole packer tests (Marine, 1967). Small fractures pervade the entire rock mass but yield very little water. Larger fractures found within specific zones yielded substantially larger quantities of water. The deepest boreholes penetrated to about 1,900 feet below the surface with about 1,000 feet of this length in crystalline rock. Some fractures were healed by quartz, calcite, chlorite and zeolite; but open fractures transmitting water were found even at maximum depths penetrated.

Laboratory hydraulic conductivities of the crystalline rock ranged from 10^{-7} cm/sec maximum down to less than 4 x 10^{-11} cm/sec which was the lowest limit measurable. Two-thirds of the conductivities were less than the measurable limit. Of the remaining one-third, the average value was approximately 3 x 10^{-8} cm/sec. Field conductivities from packer tests ranged from 10^{-7} cm/sec to 10^{-10} cm/sec in the poorly fractured zones with an average of 10^{-8} cm/sec. Conductivities in the more highly fractured zones averaged about 5 x 10^{-5} cm/sec (Marine, 1967).

Porosities, as estimated from tracer tests in wells, are about 0.08 percent in the more highly fractured zones and 0.004 percent in the poorly fractured zones (Webster et al., 1970).

3. Water Movement: Vertical flow upward from top of the crystalline rock through the clay (saprolite) layer and to the overlying aquifer is thought to be very slow, estimated at 0.3 feet per year, which is approximately 100 times slower than water velocities within the crystalline rock (National Research Council, 1972) due to the high porosity of the clay.

The horizontal gradient in the crystalline rock is about 3.6 feet per mile, with water flowing westward. Horizontal flow in the overlying aquifer is westward to southwestward at a gradient of about 4 feet per mile.

Recharge to the crystalline rock probably occurs at higher elevations to the northwest of the site. W ter can enter at outcrops of crystalline rock or from the overlying aquifer in areas where the confining saprolite layer is discontinuous or absent.

C.3.3 Batholiths - Western United States

C.3.3.1 General

Several large granitic plutons exist in the western United States. They include the Sierra Nevada Batholith in California, the Idaho Batholith in Idaho, and the Pikes Peak Batholith in Colorado. Many other plutons of large size also exist. Because the geology and hydrology of most of these plutons is similar, only the three batholiths mentioned above are described geologically. Hydrologically, batholiths are discussed in general rather than individually.

C.3.3.2 Geology

1. Sierra Nevada Batholith: The mountains of the Sierra Nevada are about 400 miles long by 30 to 60 miles wide, as shown in Figure C-7. They are contiguous with, but geologically different than, the volcanic Cascade Mountains to the north. They are bounded on the east by the fault block Basin and Range Province and on the west by California's great central

valley. The Sierra Nevada Mountains are a huge block of resistant rocks uplifted by faulting and tilted toward the west. This block is dissected by deep valleys and the higher parts are strongly glaciated. Figure C-4B shows a general cross section through the Sierra Nevada area.

a. Stratigraphy and Structure: The structure is locally complex as numerous granitic plutons were embedded in the earlier rocks in small to large masses. These plutons consist of a whole succession of intrusions of varying shapes and sizes. Each intrusion can be of a different texture and mineral composition, with the younger cross-cutting the older. Nearly all the plutons are cross-cutting and discordant rather than foliated and concordant. They rose as true magmas from the depths to their present levels in the crust, breaking through the strata or forcing them aside (Hamilton and Myers, 1967). Seismic evidence indicates a finite depth of the granites of 20,000 to 30,000 feet. Beneath the granites are metamorphic rocks, probably gneisses, that formed as the wall rocks flowed down and beneath the rising plutons. (Figure C-4B)

b. Fractures: The major recently active faults are along the north, south and eastern borders. Several faults of an earlier tectonic period are located in the northwest part of the mountains. These faults were mineralized and form the Mother Lode Gold Belt. Jointing occurs in at least one area on 50-foot centers for the master joints. Minor joints may be much more variable.

c. Hazards: The Sierra Nevada Mountains are the ultimate recharge area for both the Central Valley and the Owens Valley of California. Several large rivers head in these mountains with steep gradients for both the rivers and their associated subdrainage. Valleys in general are deep with steep sides.

The entire mountain range is in a high seismic risk zone. Numerous small earthquakes epicenter there. The faults along the eastern front are active as some scarps truncate recent alluvial fans. The White Wolf Fault which is part of the Garlock Fault system had active movement in 1952. This fault strikes along the southwestern boundary of the Sierra Nevada Mountains.

Renewed glaciation would affect parts of the mountains. It would increase the valley erosion as they filled with glaciers. Headward movement of the glaciers would also tend to break down the higher parts of the mountains. Glacier melt water would increase the flow of all streams and rivers.

2. Idaho Batholith: The Idaho Batholith is located in the northern Rocky Mountains, mainly in central and northern Idaho, but extending into western Montana. The terrain is characterized by deeply dissected mountain uplands and intermountain basins. Crest levels of the central mountains vary from 7,000 to 12,000 feet. Valleys are mostly narrow and generally are at elevations of 3,000 to 5,000 feet.

   a. Stratigraphy: The batholith consists of virtually structureless granodiorite and quartz monzonite. These rocks underlie two main regions, one in the southwestern part of the area and the other in the northeastern. The rest of the complex consists of schist and gneiss associated with the intrusive rock.

   The intrusive rocks vary in the same way as the rocks in the Sierra Nevada Batholith. There are multiple plutonic intrusions from Cretaceous time to extrusive lava flows in the Holocene.

b. Hazards: The mountains of the Idaho Batholith have many of the same hazards associated with them as the Sierra Nevada Mountains. Both are major recharge areas with numerous streams and rivers in steep narrow canyons. Both would have accelerated erosion caused by glaciation. The Idaho Batholith is, however, not a major seismic area. Thermal springs exist within the batholith indicating a geothermal source of heat or very deep movement of groundwater. Recent volcanism has occurred on its southern border indicating possible future lava flows or renewed intrusive activity.

3. Pikes Peak Batholith: The Pikes Peak Batholith is located in the southern Rocky Mountains in central Colorado as shown on Figure C-8. As in other batholiths, it is a complex of multiple intrusions and folded and faulted metamorphic rocks. Elevations range from 5,000 to 14,000 feet with the higher peaks extensively glaciated. Valleys are narrow and steep sided.

a. Stratigraphy: The rocks consist mainly of a grey-pink, medium to coarse-grained granite. The granite contains occasional dikes and irregular bodies of pegmatite. Large bodies of sugary textured aplite locally cut the granite. Much of the granite shows a crude foliation due to a planar alignment of the mica plates and feldspar laths.

Associated with the granite is a great complex of metamorphic rocks consisting of biotite gneiss, schist and migmatite. Both metamorphic rocks and the granite shown effects of hydrothermal alteration adjacent to faults and veins. In places, zones of intense alteration reach widths of 100 feet or more (Warner and Hornback, 1971). Alteration is particularly intense along fault zones and adjacent to contacts with granite.

b. Structure: Specific structural information was derived from the Vasquez tunnel excavation (Warner and Hornback, 1971). Numerous faults were encountered in the tunnel, especially in its southern part. They were defined as major faults if the width of sheared rock was more than 1 foot and minor faults if the shearing was less than 1 foot. The major faults had cataclastic zones up to 100 feet wide containing gouge and crushed rock with numerous slip surfaces. Many of the minor faults consisted of a single slip surface. Major shear zones as well as a geologic section of the Vasquez tunnel are shown in Figure C-9. A comparison of rock type with minor faults and joints is also shown on this figure.

Principal fault movement was along planes of foliation with the movement either upward or downward along those planes (Warner and Hornback, 1971). Joints also appeared to be parallel or normal to foliation and were related in orientation to the minor faults (Warner and Hornback, 1971). Joints became irregular in complexly folded metamorphic rocks.

c. Hazards: The area is mountainous and rugged causing the same problems as in other western United States plutons. The geology is locally very complex. Faults and fractures are numerous. Vigorous erosion can be expected with renewed glaciation. The mountains contain the headwaters of several major rivers and are the groundwater recharge area for much of the central United States. Tertiary intrusive activity has cut through the batholith in numerous places with valuable mineralizing solutions, creating veins, stocks, and other economic deposits. It is an area of moderate seismic activity. Deep borehole disposal near Denver reactivated some faults on the Front Range, indicating possible future upward movements. The Rocky Mountains in this area have had at least two major uplifts in the past.

C.3.3.3 Hydrology

1. Surface Water: Batholiths in the western United States generally form rugged mountainous regions receiving abundant precipitation, a large proportion of which occurs as snow. Mean annual precipitation on the batholiths mentioned above ranges from about 15 inches on portions of the Boulder batholith to over 70 inches on portions of the Sierra Nevada batholith. Runoff ranges from 10 inches to 40 inches, respectively.

   Granitic batholiths are often dissected by deep valleys formed by glacial and fluvial erosive processes. Rivers and streams are numerous owing to abundant precipitation and relatively shallow depths to bedrock. Mountainous batholiths are commonly important source areas for major rivers in the western United States.

2. Ground Water: Very little information is available relating to the occurrence of ground water in granitic batholiths. The geohydrology of such areas is relatively unstudied because there is little demand for ground water in mountainous areas with sparse population and abundant high quality surface water resources.

Ground water occurrence in batholitic rocks is controlled by porosity, permeability, structure, topography, and recharge. Ground water is most abundant relatively near surface where porosity and permeability are enhanced by fracturing and weathering. Turk (1962) after examining 239 well records from the Sierra Nevada batholith concluded that 200-300 feet is the practical limit for water-producing wells within the granitic rock. The median yield for all wells was 7.5 gpm and the mean yield was 20.3 gpm. The median depth to water was 40 feet. The most productive zones were within the top 100 feet of rock. Water yield varied with location as well as depth. Of 239 wells, 16.3 percent produced 1 gpm or less. At some localities a layer of decomposed rock up to 70 feet thick provided enhanced porosity and permeability resulting in greater water production.

2. Water Movement: Evidence from a limited number of wells in granitic batholiths indicates poor water circulation at depths greater than 200 to 300 feet. However, the widespread occurrence of thermal springs in batholiths (Waring, 1965) indicates water circulation at moderate or great depths at some localities. Such circulation may occur along deep seated joints or other fractures which provide access to underlying hot rocks.

Assuming there is some continuity and uniformity to fractures occurring in granitic batholiths, it is possible to develop flow systems with topography determining the direction of flow. Flow systems in homogeneous (and some nonhomogeneous, due to layering), isotropic aquifers have been described by Toth (1963) as local, intermediate, and regional in scale and are illustrated in Figure C-3. Similar flow systems modified by fracture patterns may exist within batholiths, although documentation of such systems is not currently available. Theoretical models developed by Toth (1963) and Freeze and Witherspoon (1966, 1967) are of possible use in analyzing these various flow systems.

C.4 POTENTIAL RELEASE PATHWAYS

It is appropriate to investigate a variety of other conditions that are likely or possible and which represent potential pathways for the release of depository contents. The following is a partial listing of conditions which require consideration in the crystalline rock models.

1. Depository-Induced or Related Conditions:
    a. Fracture zones around openings: Similar to the problem in basalt.
    b. Shaft backfill and shaft sealing: Similar to the problem in basalt.
    c. Fracturing of depository zone: Similar to the problem in basalt. Fracturing may not be very important due to the uniformity of the formation. Thus, local increases in fracturing around the depository may not significantly alter the resaturation time or transit time.
    d. Thermally-induced groundwater flow: Similar to the problem in basalt.

2. Existing Geologic Conditions:
    a. Faults: Similar to the problem in basalts. However, faults may be more significant in crystalline rocks since they lack the numerous permeable zones which may effectively intercept flow in basalts.
    b. Geothermal effects: Similar to the problem in basalts.

c. Fracturing (Joints): Batholiths contain characteristic cooling joints which have great persistence and are well interconnected. Such joints tend to be widely spaced. The fracture permeability of such networks is critical and will require further investigation. The problem could be modeled similar to the procedure discussed for basalts.

3. Future Geologic Changes:

a. Faulting and tectonically induced changes in fracturing: Similar to the problem in basalts.

b. New Intrusive Activity: A remote possibility, but one that would have implications for the depository.

c. Glaciation: Many potential crystalline repository sites were glaciated during the Pleistocene.

4. Man-Induced Pathways

a. Wells: Wells exist in the upper fractured zone in many crystalline areas. However, the wells are of small yield and shallow. The occurrence of deep wells penetrating to the level of a depository is very unlikely.

b. Undetected boreholes and failed borehole seals: Similar to the problem in sedimentary models. Like basalts, the probability of undetected deep boreholes is less than that for sedimentary basins, and the consequences may be less due to the limited vertical gradients.

c. Economic minerals: Batholiths are a principal source of economic mineralization, although most of the ore deposits are formed in specific regions in and around the intrusive. If the repository is initially sited to avoid these regions, the prospect of commercial exploitation in the vicinity of the site is remote. Careful evaluation of the mineral potential of the chosen site and its environs is required. In addition, some thought should be given to the distance from potentially mineralized areas that the repository should be located.

Table C-1

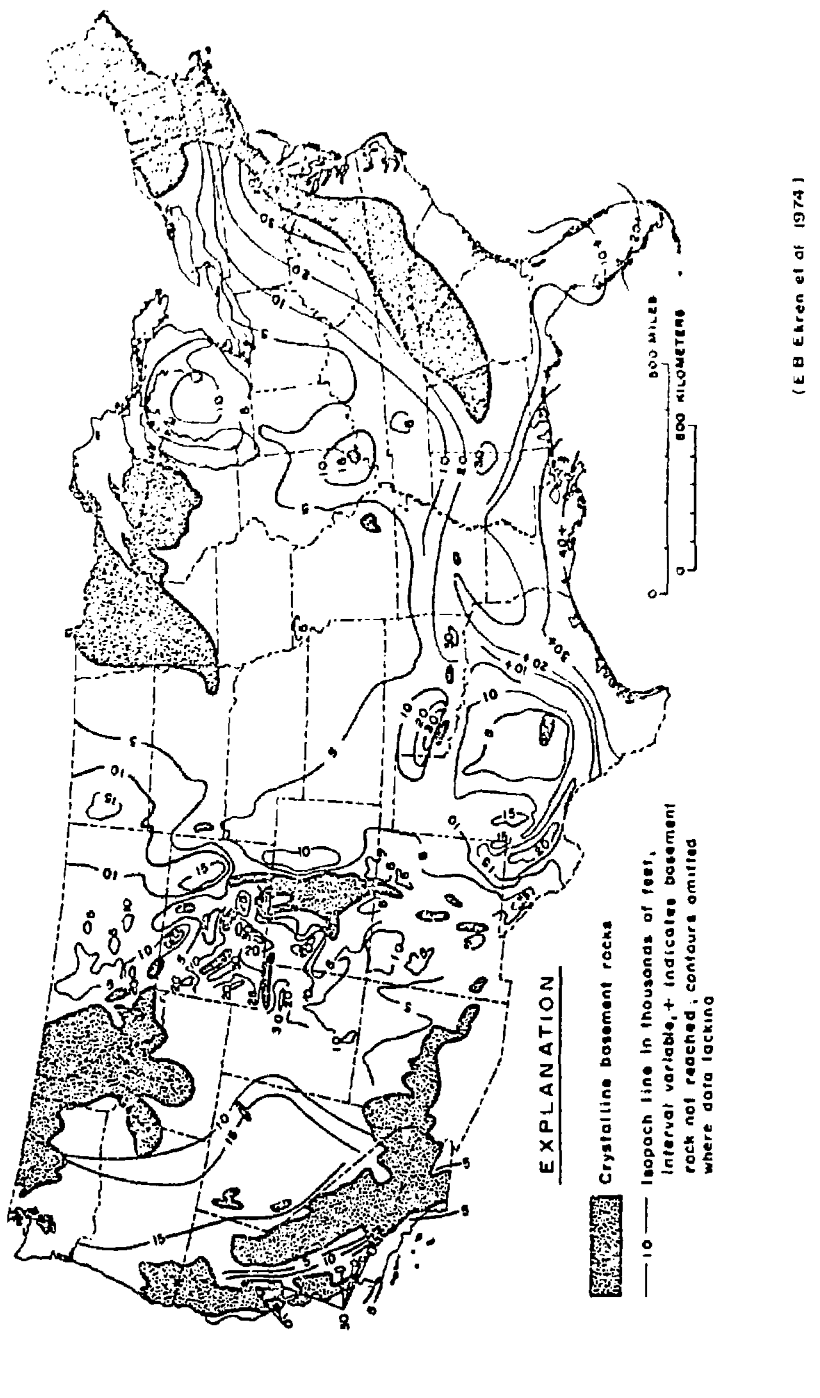
Permeability of Metasediments from Marquette Mining District, Michigan

Rock Type	Number of Samples	Hydraulic Conductivity of Unfractured Samples cm/sec			
		Mean	Median	Maximum	Minimum
Iron Formation and Iron Ore	36	1.6×10^{-6}	6×10^{-9}	3.8×10^{-5}	1.1×10^{-10}
Graywacke	5	3.3×10^{-8}	3×10^{-9}	1.5×10^{-7}	2.7×10^{-10}
Slate	9	6×10^{-9}	1.3×10^{-9}	4.5×10^{-8}	5×10^{-10}
Chert	1	-	1.9×10^{-10}	-	-
Slate with Quartz Seams	1	-	1.8×10^{-4}	-	-
Mica Schist	1	-	2.1×10^{-9}	-	-
Quartzite	1	-	1.9×10^{-9}	-	-
Conglomerate	1	-	2.8×10^{-8}	-	-

(Ref: Davis and DeWiest, 1966 from Stuart, Brown, and Rhodehamel, 1954)

PRINCIPAL AREAS OF INTRUSIVE AND METAMORPHIC ROCKS AND THICKNESS OF SEDIMENTARY ROCKS IN THE UNITED STATES

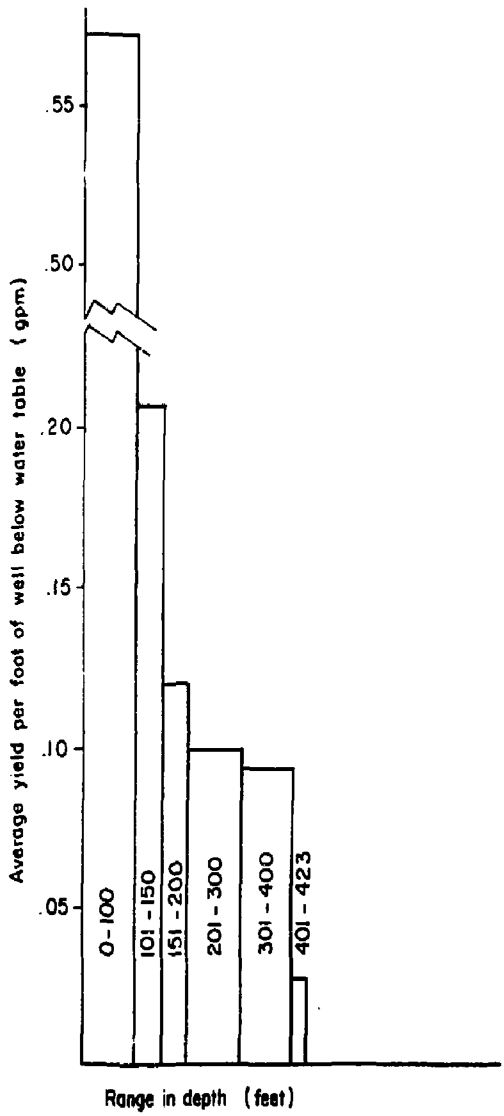
Figure



Project No Reviewed Date

RELATION OF WELL YIELD TO WELL DEPTH IN 239 CALIFORNIA WELLS IN CRYSTALLINE ROCK

Figure C-2



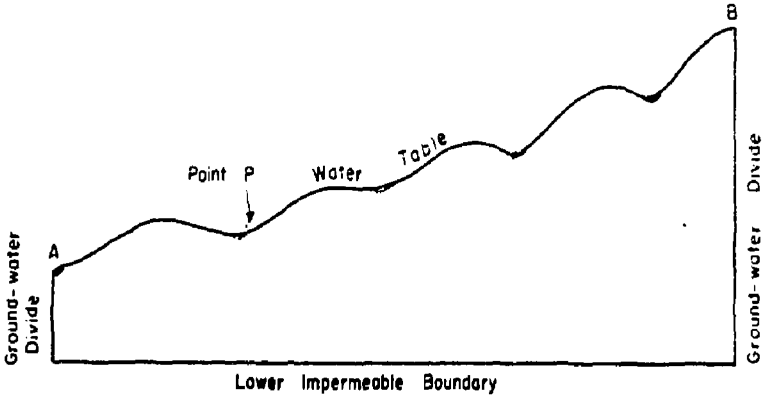
(Ref.: Turk, 1962)

Note: Wells in Sierra Nevada

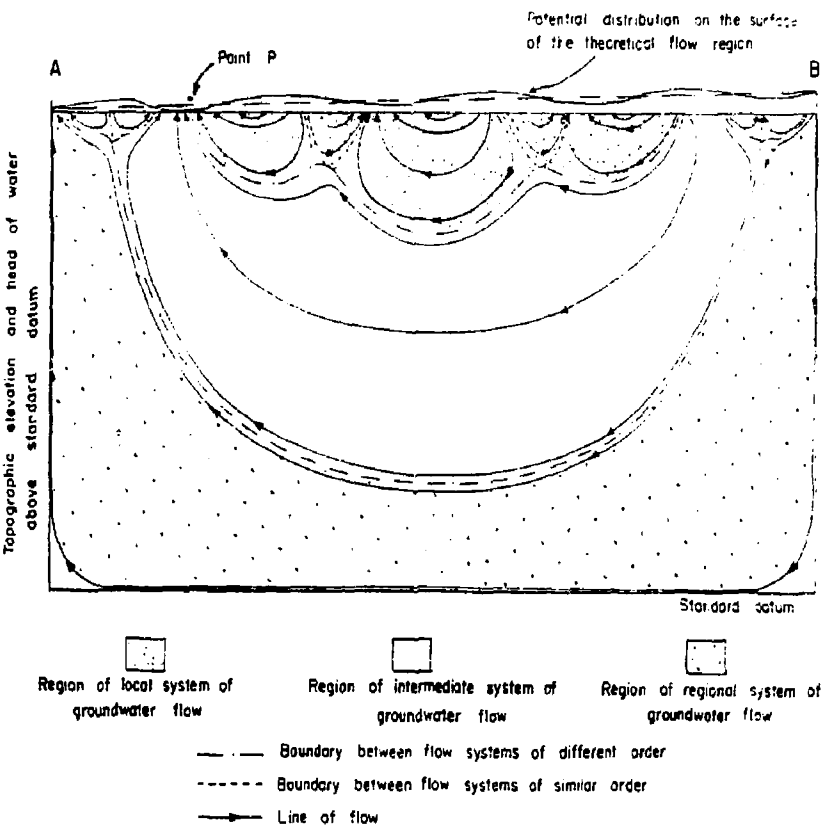
Project No. 77-3... Reviewed ... Date 11-2-77

IDEALIZED MODEL OF FLOW PATTERNS IN METAMORPHIC AND IGNEOUS ROCKS

Figure C-3



a) Cross section showing approximate configuration of water table and right, left, and lower boundary of flow system along line A–B.



b) ***Theoretical flow patterns and boundaries between different flow systems.***

(Modified after Toth, 1963)

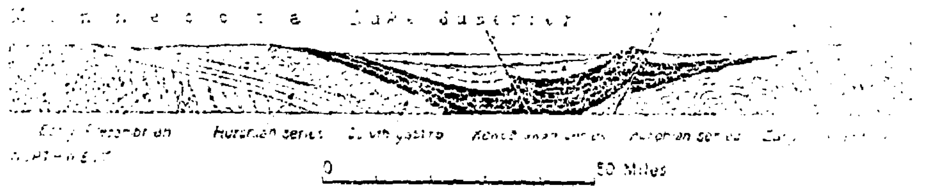
Project No. 773041P Drawn JP Date 11-8-77

Golder Associates

TYPICAL CROSS SECTIONS OF REGIONS OF CRYSTALLINE ROCK MASSES

Figure C-4

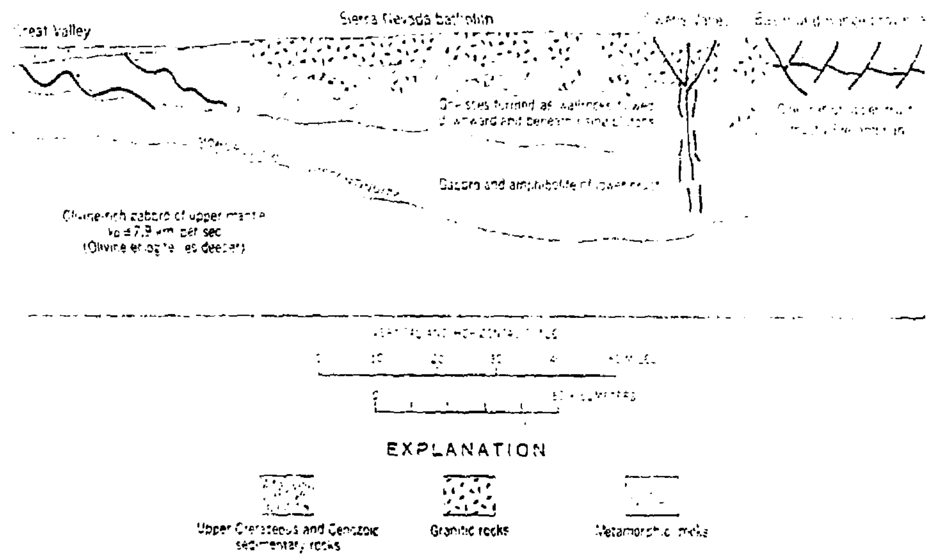
Fig. A- CROSS SECTION OF LAKE SUPERIOR SHIELD AREA



Vertical scale approximately 100,000 feet

(P.B. King 1959)

Fig. B-CROSS SECTION OF SIERRA NEVADA



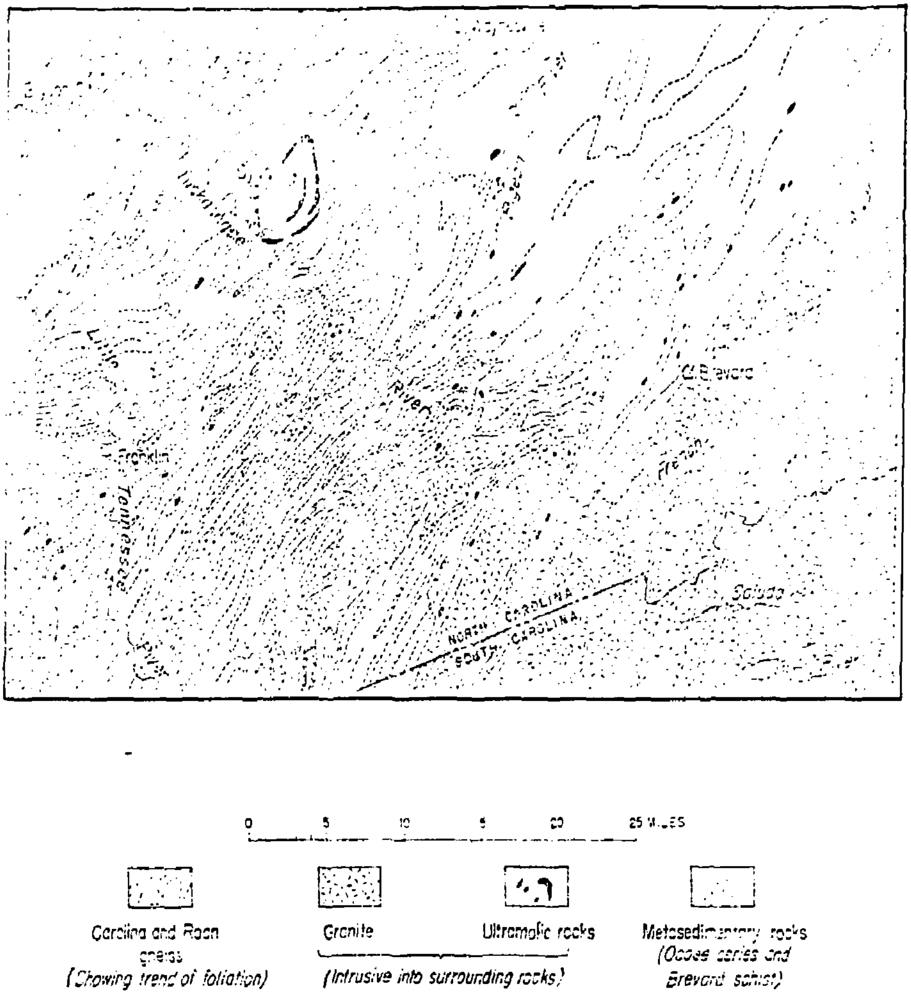
Geologic and crustal section through the Sierra Nevada of California, along the 37th parallel. Adapted from Hamilton and Pakiser (1965). Plutons of granitic magma, melted in upper mantle and lower crust, rose through crust and coalesced at surface to form Sierra Nevada batholith. In the Basin and Range Province, Paleozoic sedimentary rocks moved along bedding-plane thrust faults, then broke into normal-fault blocks.

(Hamilton & Myres 1967)

USGS PP554-C

TYPICAL PART OF CRYSTALLINE APPALACHIANS IN NORTH AND SOUTH CAROLINA

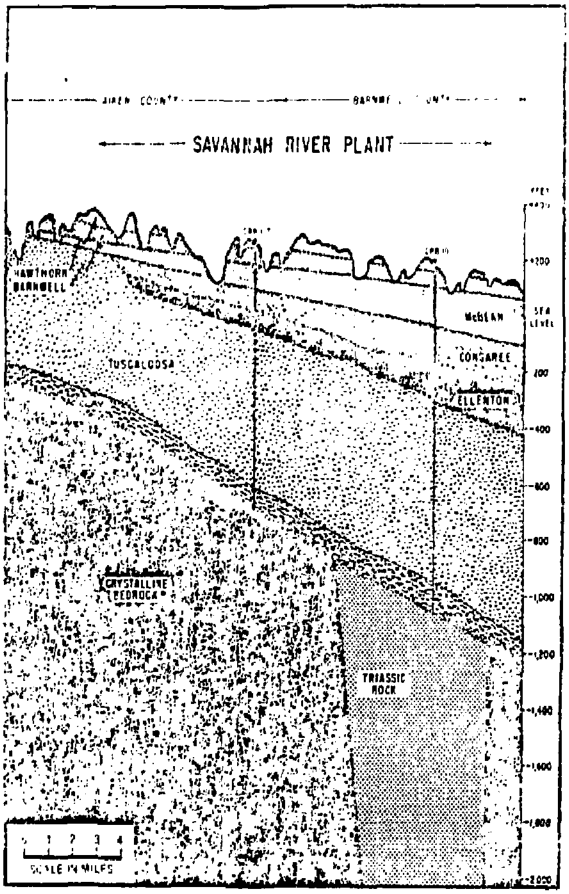
Figure C-5



(P.B. King 1959)

GENERALIZED CROSS SECTION OF THE SAVANNAH RIVER PLANT SITE

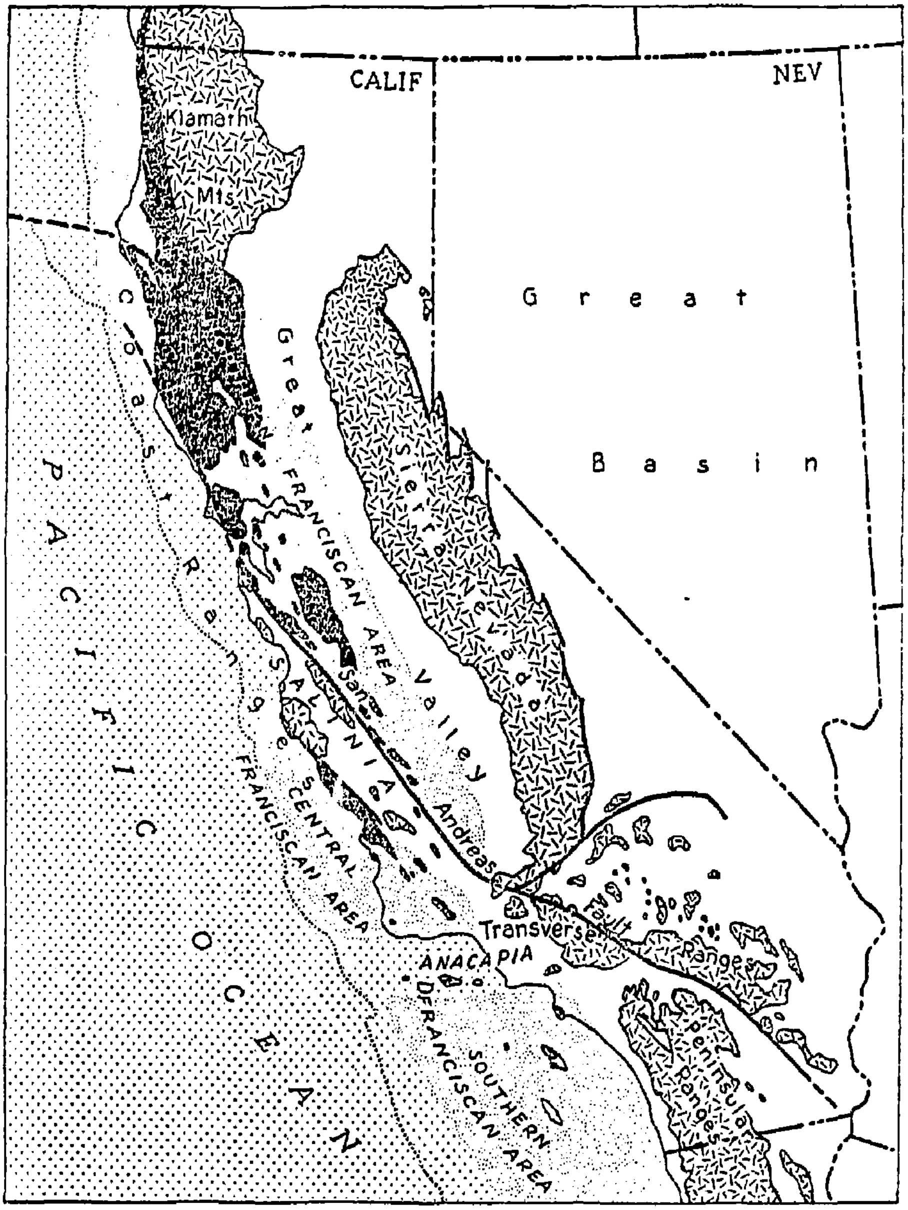
Figure C-6

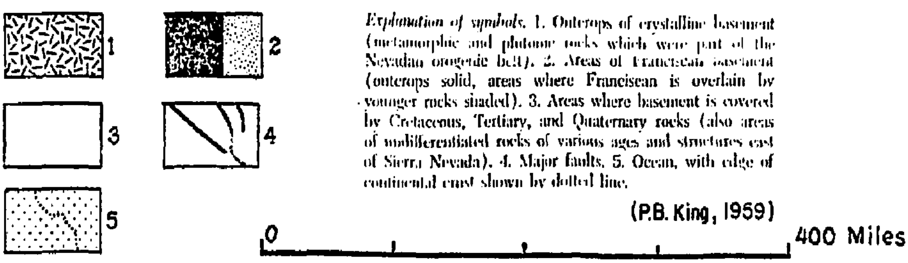


(National Academy of Sciences 1972)

SIERRA NEVADA BATHOLITH

Figure C-7





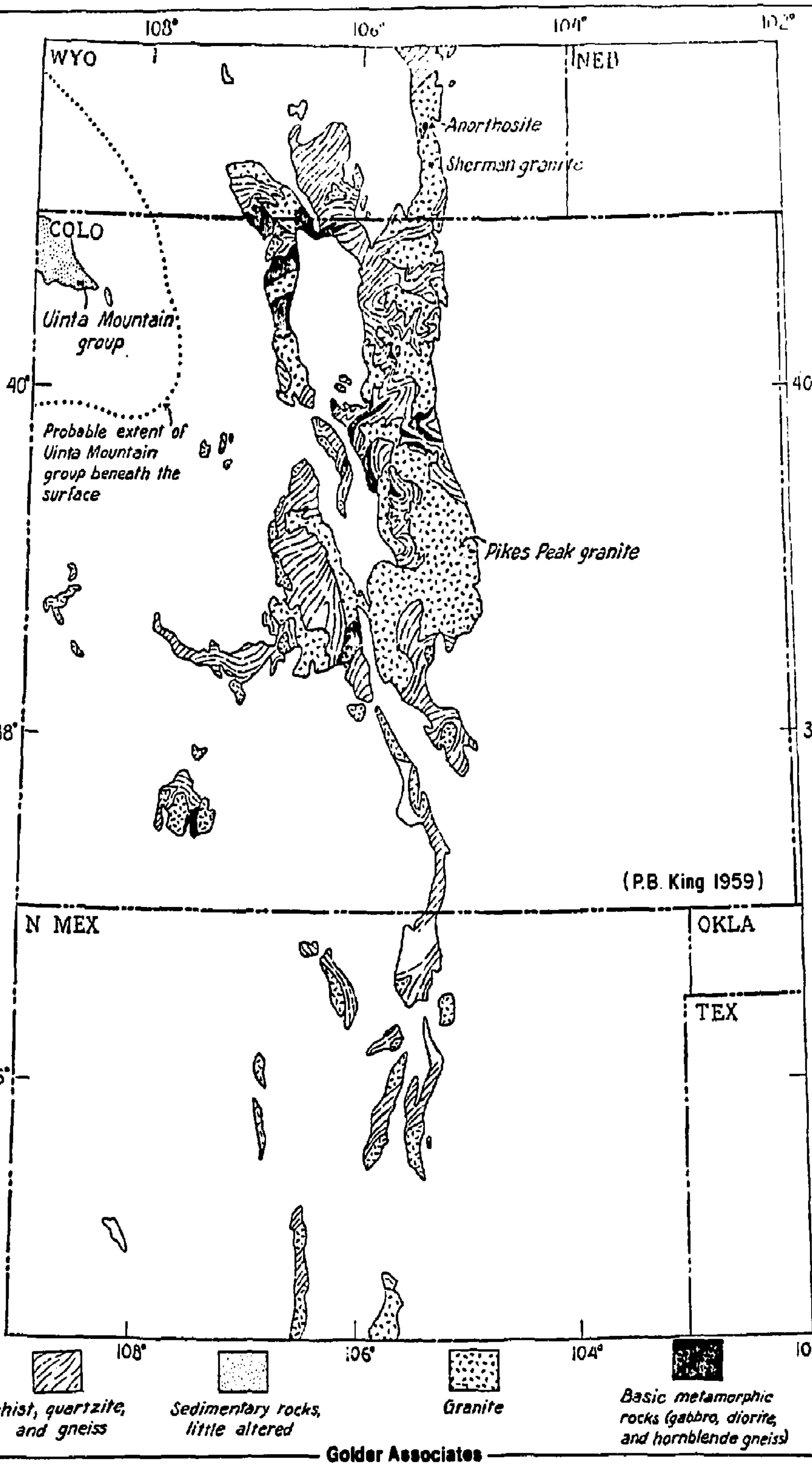
Explanation of symbols. 1. Outcrops of crystalline basement (metamorphic and plutonic rocks which were part of the Nevadan orogenic belt). 2. Areas of Franciscan basement (outcrops solid, areas where Franciscan is overlain by younger rocks shaded). 3. Areas where basement is covered by Cretaceous, Tertiary, and Quaternary rocks (also areas of undifferentiated rocks of various ages and structures east of Sierra Nevada). 4. Major faults. 5. Ocean, with edge of continental crust shown by dotted line.

(P.B. King, 1959)

Project No. 773062A Reviewed: FO Date 11-1-77

PIKES PEAK BATHOLITH COMPLEX

Figure C-8

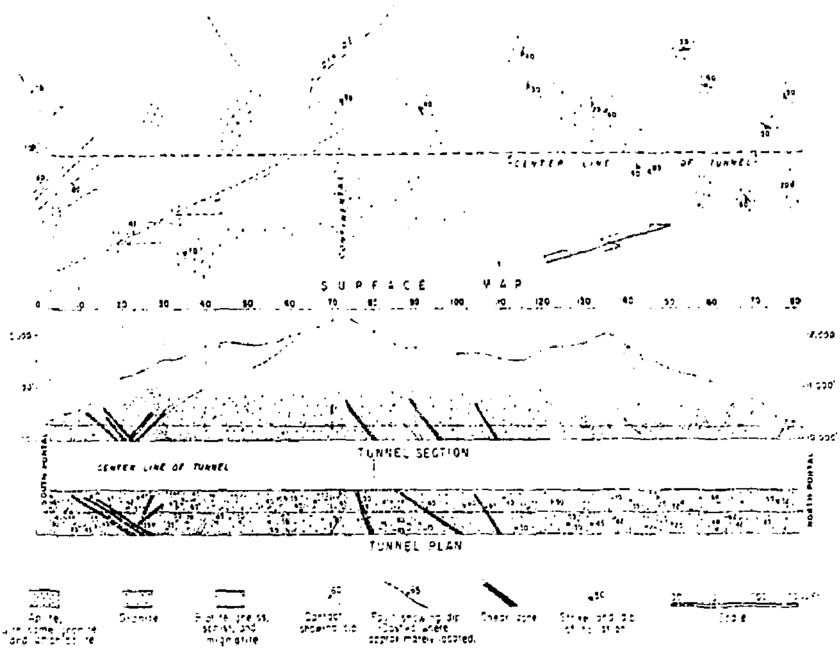


Golder Associates

Project No 773 Reviewed FC Date 11-1-77

GEOLOGIC MAP AND SECTION OF VASQUEZ TUNNEL

Figure C-9



(Warner & Hornback 1971)

Spacing of fractures in relation to lithology, Vasquez Tunnel

Tunnel Segment	Station Interval	Lithology	Distance in feet	Joints	Minor Faults	Joints per 100 ft.	Faults per 100 ft.	Ratio Joints Faults
I	2 + 54 to 28 + 50	Foliated aplite	2,596	42	46	1.62	1.77	0.91
II	28 + 50 to 53 + 50	Foliated granite	2,500	47	69	1.88	2.76	0.68
III	53 + 50 to 92 + 50	Massive granite	3,900	125	60	3.21	1.54	2.08
IV	92 + 50 to 125 + 50	Foliated granite	3,300	151	57	4.58	1.73	2.65
V	125 + 50 to 155 + 50	Biotite gneiss	3,000	89	62	2.97	2.07	1.44
VI	155 + 50 to 181 + 00	Massive granite	2,550	153	54	6.00	2.12	2.83

Project No. 773044P Reviewed RR Date 11-1-77

APPENDIX D - REFERENCES

Atlantic Richfield Hanford Company, 1976. Preliminary Feasibility Study on Storage of Radioactive Wastes in Columbia River Basalts. Vols. I and II. Prepared for the U. S. Energy Research and Development Administration, ARH-ST-137.

Barraclough, J.T., Robertson, J.B., and Janzer, V.J., 1976. Hydrology of the Solid Waste Burial Ground as Related to the Potential Migration of Radionuclides, Idaho National Engineering Laboratory. U. S. Geological Survey Open-File Report 76-471; available from NTIS, IDO-22056.

Belchic, H.C., 1960. The Winnfield Salt Dome, Winu Parrish, Louisiana. In Guidebook of the 1960 Spring Field Trip. Shreveport, Louisiana: Shreveport Geological Society.

Bowen, B.M. et al., 1959. Geological Factors Affecting the Ground Disposal of Liquid Radioactive Wastes into Crystalline Rocks at the Georgia Nuclear Laboratory Site. In 21st International Geological Congress, Section 20, pp. 32-48.

Brown, R.H. et al., eds. 1975. Groundwater Studies. Paris: UNESCO Press.

Davis, S.N. and DeWiest, R.J.M., 1966. Hydrogeology. New York: John Wiley and Sons, Inc.

Davis, S.N. and Turk, L.J., 1964. Optimum Depth of Wells in Crystalline Rocks. Ground Water, Vol. 2, pp. 6-11.

Deere, D.U., 1973. The Foliation Shear Zone - An Adverse Engineering Geologic Feature of Metamorphic Rocks. J. of the Boston Society of Civil Engineers, Vol. 60, No. 4, pp. 163-176.

Ekien, E.B. et al., 1974. Geologic and Hydrologic Considerations for Various Concepts of High Level Radioactive Waste Disposal in the Conterminous United States. U. S. Geological Survey Open-File Report, pp. 74-158.

Enslin, J.F., 1943. Basins of Decomposition in Igneous Rocks: Their Importance as Underground Water Reservoirs and Their Location by the Electrical Resistivity Method. Trans. of the Geological Society of South Africa, Vol. 46, pp. 1-12.

Freeze, R.A. and Witherspoon, P.A., 1966.
1. Theoretical Analysis of Regional Ground Water Flow: Analytical and Numerical Solutions to the Mathematical Models. Water Resources Research, Vol. 2, no 4, pp. 641-656.

Freeze, R.A. and Witherspoon, P.A., 1967.
2. Theoretical Analysis of Regional Ground Water Table Configuration and Subsurface Permeability Variation. Water Resources Research, Vol. 3, No. 2, pp. 623-634.

Gera, F., 1972. Review of Salt Tectonics in Relation to the Disposal of Radioactive Wastes in Salt Formations. Geological Society of America Bull., Vol. 83, No. 12, pp. 3551-3574.

Gloyna, E.F. and Reynolds, T.D., 1961. Permeability Measurements of Rock Salt. J. of Geophysical Research, Vol. 66, No. 11 pp. 3913-3921.

Golder Associates, Inc., 1977a. Development of Site Suitability Criteria for the High Level Waste Repository for Lawrence Livermore Laboratory, Golder Associates, Inc., No. 77300, June.

Golder Associates, Inc., 1977b. Second Report Development of Site Suitability Criteria for the High Level Waste Repository for Lawrence Livermore Laboratory. Golder Associates, Inc., No. 77303, Nov.

Golder Associates, Inc., 1978, Third Report Development of Site Suitability and Design Performance Data Base for a High Level Nuclear Waste Repository for Lawrence Livermore Laboratory. Golder Associates, Inc., No. 77310, May.

Gussow, W.C., 1968. Salt Diapirism: Importance of Temperature, and Energy Source of Emplacement. AAPG Memoir 8, Diapirism and Diapirs, pp. 16-52.

Hamilton, W. and Myers, W.B., 1967. The Nature of Batholiths. U. S. Geological Survey Prof. Paper 554-C.

Hamilton, Warren, 1963. Overlapping of Late Mesozoic Orogens in Western Idaho: Geological Society of America Bull., V74, pp. 779-788.

Hansen, F.D., 1977. Case History. Rock Mechanics Examination of the Jefferson Island Salt Mine: II. Laboratory Evaluation of Strength and Creep Deformation Characteristics of Dome Salt Under Confining Pressure. REISPEC, Inc. Tech. Mem. Rept. RSI-0057. Prepared for Office of Waste Isolation/Union Carbide Corporation/Oak Ridge National Laboratory, Y/OWI/SUB-77/22303/5.

Harder, A.H., Kilburn, Chabot, Whitman, H.M., and Rogers, S.M., 1967, Effects of Ground Water Withdrawals on Water Levels and Salt-Water Encroachment in Southwestern Louisiana: Louisiana Geological Survey and Department of Public Works Water Resources Bull. 10, 56 p.

Howard, T.R., Brekke, T.L. and Houston, W.N., 1975. Laboratory Testing of Fault Gouge Materials. Bull. of the Association of Engineering Geologists, Vol. 12, No. 4.

King, P.B., 1959. The Evolution of North America, Princeton, N. J., Princeton University Press.

Krynine, D.P. and Judd, W.R., 1957. Principles of Engineering Geology and Geotechnics. New York: McGraw-Hill, Inc.

Kupfer, D.H., 1974a. Environment and Intrusion of Gulf Coast Salt and Its Probable Relationship to Plate Tectonics. In Fourth Symposium on Salt. Cleveland: Northern Ohio Geological Society, Vol. 1, pp. 215-225.

Kupfer, D.H., 1974b. Shear Zones in the Gulf Coast Salt Delineate Spines of Movement. Gulf Coast Association of Geological Societies Trans., Vol. 24, pp. 197-209.

LeFond, S., 1968. Handbook of World Salt Resources, Plenum Press.

LeGrand, H.E., 1949. Sheet Structure, A Major Factor in the Occurrence of Ground Water in the Granites of Georgia. Economic Geology, Vol. 44, pp. 110-118.

Marine, W.I., 1967. The Permeability of Fractured Crystalline Rock at the Savannah River Plant Near Aiken, South Carolina. U. S. Geological Survey Prof. Paper 575-B, pp. 203-211.

Martinez, J.D., 1975. An Evaluation of Hydrologic Isolation From Evidence in Mine Openings in Igneous and Metamorphic Rocks in the Maritime Provinces of Canada. Prepared for Office of Waste Isolation/Union Carbide Corporation/Oak Ridge National Laboratory, ORNL/SUB-4415.

McKee, B., 1972. Cascadia. New York: McGraw-Hill, Inc.

Meier, F. and Peterson, S.G., 1951. Water Supplies in the Archae Bedrocks of Sweden. Brussels: International Association of Scientific Hydrology Publication No. 3, pp. 252-261.

Morris, D.A. et al., 1965. Hydrology of Subsurface Waste Disposal, National Reactor Testing Station, Idaho, Annual Progress Report, 1964. U. S. Geological Survey Open-File Report; available from NTIS, IDO-22047, 304 pp.

National Research Council, 1972. An Evaluation of the Concept of Storing Radioactive Wastes in Bedrock Below the Savannah River Plant Site. Washington, D.C.: National Academy of Sciences.

Netherland, Sewell and Associates, Inc., 1976. Geologic Study of the Interior Salt Domes of Northeast Texas Salt-Dome Basin to Investigate Their Suitability for Possible Storage of Radioactive Waste Material. Prepared for Office of Waste Isolation/Union Carbide Corporation/Nuclear Division, Y/OWI/SUB-76/99939.

Newcomb,R.C., 1959. Some Permeability Notes on the Ground Water of the Columbia River Basalt. Northwest Science, Vol. 33, pp. 1-18.

Newcomb, R.C., Strand, J.R., and Frank, F.J., 1972. Geology and Ground Water Characteristics of the Hanford Reservation of the U. S. Atomic Energy Commission, Washington U. S. Geological Society Prof. Paper 717.

Parsons, Brinckerhoff, Quade and Douglas, Inc., 1976. Thermal Guidelines for a Repository in Bedrock. Prepared for Office of Waste Isolation/Union Carbide Corporation/Nuclear Division, Y/OWI/SUB-76/16504.

Sandia Laboratories, 1977a. Thermally Induced Movement of Nuclear Waste Canisters in Salt Formations. Presented at a meeting of the American Nuclear Society, San Francisco, November 29, 1977.

Sandia Laboratories. 1977b. Risk Methodology for Radioactive Waste Disposal in Geologic Media. Draft Report submitted to the U. S. Nuclear Regulatory Commission.

Schoen, Robert, 1972. Hydrochemical Study of the National Reactor Testing Station, Idaho, in Sec. 11, Hydrogeology: International Geological Cong., 24th, Montreal, 1972, pp. 306-314.

Siple, G.E., 1964. Geohydrology of Storage of Radioactive Wastes in Crystalline Rocks at the AEC Savannah River Plant, South Carolina. U. S. Geological Survey Prof. Paper 501C, pp. 180-184.

Siple, G.E., 1967. Geology and Ground Water of the Savannah River Plant and Vicinity, South Carolina. U. S. Geological Survey Water Supply Paper 1841.

Smith, C.G., Jr., 1976. Hydrologic Stability of Salt Domes. Reprint from Proc. of a Symposium on Salt Dome Utilization and Environmental Considerations, Louisiana State U., November 22-24, 1976.

Snow, D.T., 1965. A Parallel Plate Model of Fractured Permeable Media. Ph.D. Dissertation, University of California, Berkeley.

Snow, D.T., 1967. Rock Fracture Spacings, Openings and Porosities. ASCE Seattle Meeting Conf, Preprint 515.

Snow, Richard H. and Chang, Davy S., 1975, Prediction of Cavity Growth by Solution of Salt Around Boreholes, Report No. IITRI C6313-14, Union Carbide Corporation, Nuclear Division.

Stuart, W.T., Brown, E.A., and Rhodehamel, E.C., 1954. Ground Water Investigations of the Marquette Iron-Mining District. Michigan Geological Survey Div. Tec. Report 3.

Taylor, R.E., 1971. Geohydrology of Tatum Salt Dome Area, Lamar and Marion Counties, Mississippi. Vela Uniform Program, Project Dribble. U. S. Geological Survey; available from NTIS, AD-736 691.

Thoms, R.L. et al., 1977. Site Specific Study for Possible Ongoing Salt Dome Movement. In Energy Resources and Excavation Technology: Proceedings of the 18th U. S. Symposium on Rock Mechanics, Keystone, Colorad , June 22-24. Golden, Colorado: CSM Press.

Toth, J., 1963. A Theoretical Analysis of Groundwater Flow in Small Drainage Basins. Geophysical Research, Vol. 68, No. 10, pp. 4795-4812.

Turk, L.J., 1962. The Occurrence of Ground Water in Crystalline Rocks. M.S. Report, Department of Geology, Stanford University, Palo Alto, California.

Walters, K.L. and Gralier, M.J., 1960. Geology and Ground Water Resources of the Columbia Basin Project Area, Washington. Vol. 1 Washington Division of Water Supply Bull. No. 8.

Walton, W.C. and Stewart, J.W., 1961. Aquifer Tests in the Snake River Basalt. ASCE Transactions, Vol. 126, pp. 612-632.

Waring, G.A., 1965. Thermal Springs of the U. S. and Other Countries of the World - A Summary. U. S. Geological Survey Prof. Paper 492.

Warner, L.A. and Hornback, V.Q., 1971. Geology and Engineering Aspects of Vasquez Tunnel, Clear Creek and Grand Counties, Colorado. Bulletin of the Association of Engineering Geologists, Vol. 7, No. 2.

Waters, A.C., 1961. Stratigraphy and Lithologic Variations in the Columbia River Basalt, American Journal of Science, Vol. 259.

Webster, D.S., Proctor, J.F., and Marine, I.W., 1970. Two-Well Tracer Test in Fractured Crystalline Rock. U. S. Geological Survey Water Supply Paper 1544-I.

Winslow, A.G., Doyel, W.W., and Wood, L.A., 1957. Salt Water and its Relation to Fresh Ground Water in Harris County, Texas, in Contributions to the Hydrology of the United states, 1955: U. S. Geol. Survey Water-Supply Paper 1360-F, pp. 375-407.

Yardley, D.H., 1975. Hydrology of Some Deep Mines in Precambrian Rocks. Prepared for Office of Waste Isolation/Union Carbide Corporation/Nuclear Division, Y/OWI/TM-36/21.

Yardley, D.H. and Goldich, S.S., 1975. Preliminary Review of Precambrian Shield Rocks for Potential Waste Repository. Prepared for Office of Waste Isolation/Union Carbide Corporation/Nuclear Division, Y/OWI/SUB-4367/2.