UNITED STATES DEPARTMENT OF INTERIOR

GEOLOGICAL SURVEY

# Exploration of Crystalline Rocks for Nuclear Waste Repositories: Some Strategies for Area Characterization

by

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## ABSTRACT

A general strategy for the exploration of crystalline rock masses in the eastern United States for the identification of potential sites for high-level radioactive waste repositories has been generated by consideration of the Department of Energy (DOE) Siting Guidelines, available information on these crystalline rocks, and the capabilities and limitations of various exploration methods. The DOE has recently screened over 200 crystalline rock masses in 17 states by means of literature surveys and has recommended 12 rock masses for more intensive investigation including field investigations. The suggested strategy applies to the next stage of screening where the objective is to identify those potential sites that merit detailed site characterization including an exploratory shaft and underground study.

The DOE Siting Guidelines are reviewed to determine the types of information that are both important and suitable for collection prior to site characterization; that is, the area phase of exploration, in the terminology used by DOE in the screening process. The single most critical need for information concerns the issue of whether or not the hydrology of a potential site can be adequately characterized. There is almost no information on hydrology at repository depths in the areas being screened by DOE.

Early in the exploration of an area, a preliminary delineation of the regional and local ground water flow systems should be made. The locations of fracture zones, faults, shear zones, large dikes, large inclusions of country rock in intrusive rocks, and major changes of rock type need to be determined to begin to characterize the hydrologic system and to avoid such features, if possible, in siting the repository. Major fracture zones are significant conduits for water flow in some areas as shown by a summary of deep holes and excavations in the eastern United States and Canada. Details of these holes and excavations, which unfortunately are very limited in number, are presented in an Appendix. The survey of deep holes shows that subhorizontal fracture zones will probably be present in the subsurface in most areas, but these zones appear to be widely spaced below depths of 200 m.

Exploration methods that may be used at the area phase include reconnaissance hydrology, remote sensing, geologic mapping, seismic monitoring, mineral resource studies, potential field geophysics, electrical and electromagnetic techniques, active seismology, drilling, borehole logging, core studies, sampling for hydrochemistry, hydrologic testing, and *in situ* stress measurements. Three phases of exploration are suggested:
1) reconnaissance, which makes use of existing information and includes reconnaissance hydrology, remote sensing, and potential-field geophysics;
2) surface study, which involves detailed ground studies of low cost, such as surface water and spring sampling, geologic mapping, potential-field geophysics, electromagnetic methods, and mineral resource potential studies; and 3) drilling, which directly investigates hydrologic conditions at depth by means of numerous logging and testing techniquyes. The first two phases have high potential for discovering steeply dipping fracture zones and faults; but if subhorizontal fracture zones and faults are present, they may be detectable only by drilling. This uncertainty regarding the presence of subhorizontal fracture zones at a site dictates a drilling strategy in which the number,

extent, and depth of such zones are delineated as early as possible in the exploration program; encountering them unexpectedly at a late stage could be a serious problem. Depending on the distribution of subvertical and subhorizontal fracture zones, a multilevel repository may be more feasible than a single level one.

# INTRODUCTION

The U. S. Department of Energy (DOE) Crystalline Repository Project has as its goal the identification of several potential sites for disposal of high-level nuclear wastes in mined geologic repositories in crystalline rocks. To this end, DOE has evaluated crystalline rock bodies in 17 states in 3 regions in the Eastern United States: the North Central (Lake Superior) Region, the Northeast Region (Northern Appalachians including the Adirondack Mountains), and the Southeast Region (Southern Appalachians) (fig. 1). This screening based on literature surveys of pertinent information on all crystalline rock bodies of sufficient size tentatively identified 12 areas in 7 states for detailed study (U.S.DOE, 1986). The screening utilized criteria and methodology for both geologic and environmental factors that were developed in a series of workshops with participation of the states involved (U.S. DOE, 1985). These and subsequent screening criteria must be consistent with DOE's Guidelines for Recommendation of Sites for Nuclear Waste Repositories (U.S. DOE, 1984) which are required by the Nuclear Waste Policy Act of 1982 (NWPA). The level of information that has been available in the region-to-area screening stage is much less than will be available at the time of site recommendation, when additional exploratory work will have been done.

The DOE was planning field studies to further evaluate the selected areas, which range from 200 to 3000 square km in area when in May, 1986 it announced an indefinite suspension of work in the 12 areas although it plans to continue technology development for the Crystallilne Repository Project. The objective of the field studies that were planned was to identify those areas and portions of areas most likely to contain suitable volumes of rock for high-level nuclear waste repositories. Thus, following the region-to-area screening, which was based on published information only, and prior to the recommendation of sites for detailed site characterization (including a shaft and underground workings), there is an area phase of exploration involving field investigations to identify specific sites with the best potential for hosting a licensable repository.

There are great many things one must know about a site by the time it is proposed for licensing. Thus, there are many possible studies that could be made during the area phase. However, the primary purpose of this phase is to reduce the amount of geography under consideration and identify specific sites for detailed investigation. Consequently, it is most important to address those factors that have serious potential for either disqualifying the site or rendering it relatively unfavorable. If there is a weak link in the chain, one wishes if possible to find it at this stage before the expenditure of appreciable resources. Investigations which are essentially confirmatory in nature can be deferred until the site characterization stage.

Because there are a great many studies and types of information that could be collected at this phase, it is important to have a rationale or logic for exploration. This requires that one develop a clear concept of what features one hopes to find as well as those features which one wishes to avoid. Then one can identify the methods and tools that will be most useful in searching for or identifying such features. With a knowledge of the methods and tools, their costs in time and money, the significance of the information, and the uncertainties attached to it, one can develop possible exploration strategies; that is the sequence of investigations and their scheduling. The choice of strategies will vary with the resources and time available for exploration and the risks one is willing to accept in selecting sites for detailed study on the basis of limited information.

This document discusses strategies for reconnaissance and field investigations, including the early phases of drilling, to provide geoscience information on the areas under consideration. A complete Area Characterization Plan, to be developed by DOE with involvment of the states within which the areas to be studied are located, will outline all of the investigations to be carried out in the area phase including their cost and scheduling. Here, we provide input for the Area Characterization Plan by discussing what we believe to be the most important issues that need to be addressed in this phase and suggesting methods for their resolution. This report is not intended as a complete outline of area phase geoscience investigations, however.


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## INFORMATION NEEDS DERIVED FROM DEPARTMENT OF ENERGY GUIDELINES

The DOE Guidelines for Recommendation of Sites for Nuclear Waste Repositories (U.S.DOE, 1984) provide the starting point for evaluating information needs. Only the post closure guidelines will be considered here as these are the ones which relate to the capability of the geology and hydrology to isolate the waste. The guidelines are generic in nature and, aside from occasional references to the unsaturated zone, apply to all types of host rocks. Our concern here is in applying the guidelines to crystalline rocks and identifying the kinds of information that are best assembled at the area phase. Information needs that are better met in the site characterization stage are not discussed in detail. The guidelines are discussed by the general topics that they address rather than individually.

### Geohydrology

The guidelines for geohydrology (960.4-2-1) include the pre-waste-emplacement ground-water travel time from the disturbed zone to the accessible environment, the ability of the geologic repository to isolate the waste, the extent to which the hydrology of the site can be characterized and modeled, and the quality of the water along the flow path from the disturbed zone to the accessible environment.

The ground water travel time from the disturbed zone to the accessible environment is mentioned both under favorable conditions and disqualifying conditions. It is a favorable condition if the travel time is more than 10,000 years (960.4-2-1(b)(1)), and a disqualifying condition if it is less than 1,000 years (960.4-2-1(d)) although exceptions to this disqualifying condition may be permitted by the Nuclear Regulatory Commission at the time of liscensing. In order to develop values for the travel time, a sufficient understanding of the hydrology of the rock mass in which the repository is to be placed must be achieved. In addition, travel times will depend on a characterization of the surrounding rock between the repository and the accessible environment as well as an adequate understanding of the regional hydrologic flow system.

Techniques for the characterization of the hydrology of fractured crystalline rocks are currently under development and will require considerable testing. Should the rock mass contain planar features of different permeability from that of the rock mass, they would further complicate the characterization. Thus, the condition mentioned under Potentially Adverse Condition 960.4-2-1(c)(3): "The presence in the geologic setting of stratigraphic or structural features - such as dikes, sills, faults, shear zones, folds, dissolution effects or brine pockets - if their presence could significantly contribute to the difficulty of characterizing or modeling the geohydrologic system," is especially significant in crystalline rocks. Such features would require additional drill holes to determine their hydrologic properties, and it would be preferable in the area phase to try to identify zones where they are absent.

Potential Adverse Condition 960.4.2-1(c)(2), "The presence of ground water sources suitable for crop irrigation or human consumption without treatment along ground water flow paths from the host rock to the accessible environment," will also need to be addressed and will require basic hydrologic information obtainable only by drilling. With a few exceptions, groundwater sources in crystalline rocks are predominantly in the upper few tens of meters. If a well does not produce within some reasonable depth, it is usually abandoned and drilled at another location nearby in hopes of hitting a more transmissive set of fractures. A potential for upward flow from a repository to the shallow ground water systems used for crop irrigation or human consumption should be avoided and will have to be carefully evaluated during area and site characterization. At depth, the accessible environment is defined by regulations of the Environmental Protection Agency (EPA) (U.S. EPA,1985) as the lithosphere lying beyond a controlled area which may extend at most 5 km from the boundaries of the emplaced waste.

Favorable condition 960.4.2-1(b)(4) deals with expected hydraulic conductivities and gradients at repository depths. These properties will begin to be determined by drilling and testing during the area/location stage.

The remaining hydrologic conditions are of much less significance in crystalline rocks: Favorable Condition 960.4-2-1(b)(2) and Potentially Adverse Condition 960.4-2-1(c)(1) which both relate to the nature and rates of future hydrologic processes and their effect on the performance of the repository will need to be addressed, but require no information that is not already available relating to the advance and retreat of glacial ice, the rise and fall of Pleistocene sea levels, and general uplift of the land surface.

Unfortunately, there is only limited information on hydraulic properties of crystalline rocks at depth. There is no way at present to predict the permeability and abundance of open, water-bearing fractures at depths in any particular locality. Unlike the potential repository areas in salt, which are well understood generically because of past petroleum exploration, very few large bodies of crystalline rock have been drilled to repository depths; that is, 300-500 meters. The exceptions are crystalline rocks that contain mineral resources, but ore deposits are anomalies which will have to be avoided in repository exploration. Consequently, their past exploration offers little guidance to fracture distribution in masses of unmineralized crystalline rocks.

The total number of drill holes to such depths in the three regions under consideration from which useful information can be obtained is probably no more than one-half dozen. Information bearing on the abundance and hydrologic properties of fractures is very uneven among these holes; it is impossible to draw any firm generalizations. However, these holes permit speculation about what may be encountered at depth and will be discussed subsequently.

## Geochemistry

Geochemical characteristics of a site, according to the guidelines (960.4-2-2), should be those which would not affect or would favorably affect the ability of the natural system to isolate waste. Application of most of the geochemical guidelines will require information on the geochemistry of the ground water and the host rock at depth. Such information will not be available until boreholes have been drilled to repository depths, cores obtained, and the ground water sampled.

Characterization of both the regional and local groundwater flow systems may be greatly aided by information on groundwater chemistry. Isotopic and chemical analyses offer the possibility of determining residence time and relative age of the groundwater with depth, sources of dissolved constituents, existence of rapid flow paths, redox status, corrosion potential to cannisters, identification of different aquifer systems, sorptive capacity for radionuclides, and reactivity to backfill materials.

Geochemistry also involves characterization of the host rock. Although the primary mineral assemblages in crystalline terrains will probably be fairly constant with depth, the mineralogy and age of fracture-fill assemblages may change with depth in a regular fashion providing clues about water flow paths and rock-water interactions in the past.

## Rock Characteristics

The siting guidelines for rock characteristics (960.4-2-3) refer to thickness and lateral extent of the rock mass and physical and engineering properties of the rock relating to mineability and thermal properties. Unless they are heavily fractured, crystalline rocks in general are very strong and will probably present no problems in terms of mining and construction of a repository, unless relatively unusual conditions of in situ stress are encountered. While this is unlikely to occur, the in-situ stress conditions should be investigated once drill holes are available.

Favorable Condition 960.4-2-3(b)(1), "A host rock that is sufficiently thick and laterally extensive ..." will require that estimates of the size and thickness of the rock mass be made from geophysical studies corroborated by boreholes in a few places.

## Climatic Changes

The siting guidelines on Climatic Changes (960.4-2-4) are primarily concerned with whether likely climatic changes, as indicated by climatic conditions during the Quaternary Period, will adversely affect waste isolation by changes in the hydrologic system. Climatic changes may also induce changes in rates of erosion and deposition, which are considered in the following siting guidelines.

Climatic changes may result in increased or decreased precipitation and evapotranspiration, continental glaciation, and change in sea level. Such changes may, in turn, induce changes in erosion and deposition and boundary changes on the ground-water flow regimes, such as increased or decreased recharge, changes in discharge level in response to stream aggradation, or degradation and changes in sea level. Climatic changes are generally of a cyclic nature and consequently climatically induced boundary changes that produce no permanent physical changes in the flow system are also cyclic.

Continental glaciation would impose changes in hydrologic boundaries of the aquifers greatly different from present conditions, as well as physically perturbing the geologic framework of the flow system. Cyclic recurrence of continental glaciation would therefore cause fluctuating, but non-replicative, changes in the ground-water flow regime.

Clearly, the effects of climatic changes need to be assessed, but the hydrologic system must first be sufficiently well known that the additional effects of postulated climatic changes can be evaluated.

## Erosion

Siting guidelines for erosion (960.4-2-5) refer to establishing siting depths such that erosional processes at the surface will not lead to an increase in radionuclide release from the repository. It seems very unlikely that high erosion rates will be a significant factor. Obviously, in regions which have been glaciated, the likelihood of glacial deepening of existing valleys needs to be considered, but this is not likely to be significant in terms of a repository placed 300 or more meters below the present surface. Should future glaciers cover the area of interest, they would probably continue to cover it for tens of thousands of years, making the region totally uninhabitable for that period of time. Lowering of sea level would increase erosion rates in the northeast region for crystalline rocks near the coast, but as they are relatively resistant to erosion, this is unlikely to be significant.

However, as noted in the discussion of "Climatic Change", erosion and aggradation may affect the ground-water flow regime and the rate of radionuclide release and transport by changing the boundary conditions on the flow system.

In projecting the likelihood of potentially adverse effects of erosional processes, the guidelines again, as for climatic changes, consider conditions during the Quaternary Period to be an appropriate basis for evaluation.

## Dissolution

The guideline on dissolution (960.4-2-6) is intended to apply to those rocks, such as rock salt, that may undergo significant volume reduction as a result of dissolution. The complex dissolution and precipitation reactions involving little volume reduction that have occurred in crystalline rocks are better considered under the guideline for Geochemistry (960.4-2-2).

## Tectonics

Evaluation of an area with regard to the guidelines for tectonics (960.4-2-7; 960.5-2-11) requires consideration of those processes operating during the Quaternary Period. In the areas of crystalline rocks under consideration in the eastern United States, the Quaternary record is very limited. However, compared to the western third of the U.S., there is relatively little tectonic activity in the Eastern United States. The Lake Superior region is especially stable and relatively aseismic. The causes of earthquakes are little understood along the east coast. While some areas appear to be more seismic than others according to the historic record, the record itself is too short to draw conclusions for long periods of time.

There are three principal seismological phenomena that must be considered in the geological characterization of prospective repository sites: 1) strong vibratory ground motion; 2) ground rupture due to faulting; and 3) ground failure and liquifaction. Careful siting should keep the possiiblity of ground rupture, ground failure and liquifaction to a minimum. The main seismological issue will be the capability of a site to wihtstand strong ground motion and will require a seismic hazard analysis in which the probability of excedance of peak ground acceleration at the site is computed for specfied return periods.

All three regions are experiencing uplift at low rates. However, this uplift or tilting is generally on a regional scale and does not appear likely to present any potentially disruptive processes or events. Uplift in the North Central Region is due to isostatic rebound following deglaciation and is decreasing.

With a few very minor exceptions, these regions have had no igneous activity in at least the last 60 million years since the Mesozoic era. Landslides that could potentially create large-scale surface water impoundments are local features that should be readily identifiable. While every attempt should be made to identify faults as possible hydrologic pathways or barriers, significant new information on the tectonics is unlikely to be developed during the characterization of most areas. Descriptions of the tectonic setting during the area phase will primarily rest on existing regional information acquired over many years.

## Human Interference

The potential that a site might have for generating activities by future generations (960.4-2-8) that could affect waste isolation will have to be addressed on a site by site basis.

Crystalline rocks may contain metallic ores of various types. With the exception of some types of large low grade mineral deposits, known mineral resources are relatively rare and occupy a very small percentage of the areas underlain by crystalline rocks. Areas of past mining and known resources have been considered in the regional screening phase and should eliminate most of the potential for encountering such features. Consequently, there is a relatively low probability of encountering mineralization in any area. However, samples and cores from drill holes should be routinely checked for signs of mineralization.

There will remain the possibility that future evaluation of the crystalline rock mass itself may make it a target for deep exploration for undiscovered resources sometime in the future. An elaborate system of permanent markers and records will be used to record the location of the repository; and as has been noted often, societies with the technical capability for deep drilling will almost certainly be aware of its existence. Although the risk of future inadvertent intrusion or disruption of the hydrologic system is small, the likelihood of such intrusion can also be minimized by the proper choice of rock type. The Technical Criteria for siting and constructing repositories of the Nuclear Regulatory Commission (NRC) (U.S.NRC, 1983) state that the following is a potential adverse condition: "60,122(c) (17) The presence of naturally occurring materials, whether identified or undiscovered, within the site, in such form that: (i) Economic extraction is currently feasible or potentially feasible during the foreseeable future; or (ii) Such materials have greater gross value or net value than the average for other areas of similar size that are representative of and located within the geologic setting."

An assessment of undiscovered resources at the site and comparison with other parts of the geologic setting must rely in part on geologically based ore deposit models which compare a given geologic setting with the geology of other areas known to contain certain types of mineral deposits.

Ground Water Resources (960.4-2-8-1(6)(5)) were used as a screening factor in the region to area screening where compilations of data were available. Because in many areas such compilations were not available, this is a factor which should be further addressed at the area stage by evaluating local well data. This factor will need to be still further evaluated once hydrologic drilling and testing begins. Although crystalline rocks are not commonly the sources of large volumes of ground water, some municipalities do rely on deep wells in crystalline rocks for their water supplies.

## Conclusions

In the foregoing sections, we have discussed the DOE guidelines in a general way indicating what to us are the most significant issues that need focussed attention at the area phase of exploration. These sections are not a formal all-inclusive listing of each issue that must be addressed. Such a listing will eventually have to be prepared by DOE and will include non-geological as well as earth science-related issues. It should be apparent that issues related to some guidelines can be resolved by compilations and analysis of information from the literature; others will require studies during the area phase of exploration; and still others will require site-specific, intensive subsurface exploration methods to be fully resolved. Before we address the specific information needs of the area phase, it would be helpful to look at a generalized model of the geohydrologic features of a rock mass of the type to be explored.

## A MODEL FOR AN EXPLORATION STRATEGY

In order to determine the best use of resources in the area phase of exploration, it is helpful to have conceptual models of the sorts of features that make up the subsurface of a crystalline rock mass both on a regional and area scale. Such conceptual models can be generated from existing information and reasonable extrapolations. They will, of course, be updated as exploration proceeds. They provide a context for determining information needs at this stage of exploration and for determining priorities.

"Crystalline rocks", as defined by DOE for the nuclear waste repository program constitute a relatively broad and diverse group, ranging from granitic and mafic intrusions to gneisses of high metamorphic grade. Consequently, our conceptual model must be a very broad and general one. Because our primary concern here is the movement of ground water through such a rock mass, we will focus on this aspect and features that relate to it.

### Regional Ground-Water Flow

Regional hydraulic gradients and the direction of ground-water flow are determined mainly by topography and the distribution of recharge and discharge zones. The flow distribution is affected by the permeability fabric of the rocks. In crystalline rocks interstitial permeability is commonly extremely small and permeability of the rock mass is due to individual fractures, fracture sets, and fracture zones. The frequency, orientation, location, length and width of these features govern the details of flow in crystalline rocks, but the broad features of the regional flow system probably are controlled largely by topography.

In a relatively homogeneous earth, or one that is simply layered, the ground-water flow regime may consist of regional, intermediate, and local ground-water flow systems as suggested by modelling studies such as those of Toth (1962) and Freeze and Witherspoon (1966) and illustrated in figure 2. In a local flow system, discharge areas are immediately adjacent to recharge areas, and ground water circulation is relatively shallow. Regional flow systems involve relatively deep circulation, extending over many kilometers and containing several local systems. Intermediate flow systems have characteristics between those of the regional and local flow systems (fig. 2). Whether water flow in crystalline rock terrains, which contain complex structural discontinuities with a variety of orientations, can be divided so simply into regional, intermediate and local flow systems is not known at this time. In figure 3, one possible configuration of the flow systems within a major watershed in crystalline rocks is shown on the assumption that significant subhorizontal discontinuities are present and govern the flow between major recharge and discharge areas. Location of a repository in the recharge area of the regional flow system would provide an environment in which it would be unlikely that radionuclides would be transported to the biosphere.

## Water flow in crystalline rocks

The main conduits for water flow in crystalline rocks are fractures, fracture zones, shear zones, and lithologic discontinuities (Gale 1982). Fractures are by definition discontinuous in their own planes. They can form a network that will allow fluid flow if their ratio of length to spacing is large. Fracture zones are defined as zones of closely-spaced and highly-interconnected discrete fractures that measure from less than a meter to tens of meters in width and are generally filled with broken and crushed rock. This broken material may or may not be embedded in a clay matrix. Shear zones tend to be continuous throughout large parts of the rock mass, but may be either more or less conductive than the rock mass, depending on filling materials, cementation, age, and stress. Large-scale shear zones can extend for tens of kilometers but their hydraulic properties can vary considerably over such distances (Gale, 1982).

Fractures and fractures zones - The following generalizations about fractures and fracture zones have been derived from a survey of deep holes and excavations in the three regions under considertion for a crystalline rock repository. Summaries of these holes and excavations are provided in the Appendix. They were drilled or dug for a variety of purposes, none being to completely characterize the subsurface hydrology of a site. Therefore, the information available from them is of varying degrees of usefulness. In each list of generalizations the progression is from greater to lesser degrees of certainty.

With respect to fractures,

1. They occur at all depths.
2. Many occur in clusters or fracture zones.
3. In some holes, fracture orientations are consistent throughout the hole; in others they are not.
4. Fracture orientations may or may not be consistent between holes as close as 1 km and between the surface and the subsurface.
5. Fractures may be absent over depth intervals as large as 100 m.
6. Subhorizontal fractures are most abundant near the surface but occur at repository depths.
7. Open, water-bearing fractures decrease dramatically in number and aperture with depth but may occur at repository depths.
8. The number and extent of water-bearing fractures is unrelated to the density of all fractures.

With respect to fracture zones,

1. Subhorizontal fracture zones form significant water-bearing units on parts of the Canadian shield in Canada and in parts of the Southeast Region. Available information does not rule out their importance elsewhere.
2. There is no apparent limit on the depth of subhorizontal fracture zones, but they are widely spaced below 200 m.
3. Many subvertical fracture zones are water-bearing at the shallow depths to which they have been drilled.
4. Fracture zones are very complex in detail. Parts may be tightly cemented; others may contain significant void space; water flow may occur as much in small openings as in large.

5. Many fracture zones are the sites of extensive rock alteration indicating that water flowed in them at one time. Uranium has commonly been redistributed in such zones.

The hydraulic conductivity of both fractures and fracture zones decreases with depth in an irregular way (Snow, 1970; Brace, 1980). Although individual fracture zones may have relatively high conductivities, the mean of the conductivity distribution decreases by one to two orders of magnitude in the first 100 meters. Compilations of hydraulic conductivity values measured at five sites in Sweden indicate a consistent decrease in the mean of the conductivity with depth (Swedish Nuclear Fuel Supply Company, 1983).

Fracture zones have the potential to dominate ground water flow within a crystalline rock mass as they appear to do at the site of the Underground Research Laboratory (URL) under construction by the AECL in Manitoba. There, three gently-dipping zones of subhorizontal, intense fracturing, 10 to 15 m thick, can be traced between adjacent boreholes. The two upper zones crop out at the surface and extent to depths of 200 and 400 m under the URL site. The third zone has been encountered at dephs of 400 m (Davison, 1985). After extensive drilling, the general pattern of water movement within the zones has been defined, but they are very complicated in detail (Davison, 1985).

A zone of interlacing fractures averaging 22 m in thickness and dipping at least $25^o$ at a depth of 400 to 600 m dominates the hydrology in the crystalline rocks locally under the Savannah River Plant near Aiken, South Carolina (Marine, 1984, p. 60).

The role of subvertical fracture zones in the total hydrologic picture is less clear than that of the subhorizontal ones. Water may be moving up a subvertical fracture zone that connects two subhorizontal fracture zones at the Whiteshell Nuclear Research Facility, Manitoba (Green and Soonawala, 1982). Subvertical fracture zones are the locus of spring discharges in some places; enhanced yields of water wells located along subvertical fractures zones have been noted frequently (Parizek, 1971; Snipes, 1981; Socha, 1983; Cressler and others, 1983; Frape and others, 1984).

Major fracture zones should be avoided to the extent possible in siting a repository because of their relatively high hydraulic conductivities, their complex hydrologic properties, and their tendency to be the locus of potential water supplies. Relatively deep, subhorizontal fracture zones that contain brines are not potential water supplies and, consequently, a less adverse condition than shallower, fresh water bearing zones.

Subhorizontal fracture zones probably cannot be identified from geologic mapping alone because the low-angle of intersection with the topography produces an irregular outcrop pattern and the fractured rocks are more susceptible to erosion than the unfractured ones. Surface electromagnetic and seismic methods, properly calibrated and with appropriate processing for the near-surface environment, may be able to detect such zones; research to determine if this is the case deserves a high priority. Evidence for the presence of such zones at the Whiteshell Nuclear Research Facility was found in the seismic records after their presence was indicated by drilling (Green and Mair, 1983).

Traces of subvertical fracture zones may show up as prominent lineaments on remote imagery. Some subvertical fracture zones contain resistant minerals such as quartz and form positive features (Snipes, 1981); but many others are weaker than the surrounding rocks and have no outcrop expression. Where a regional joint set is parallel to the direction of the lineament, there is a strong suggestion that the lineament is the expression of a zone of more intense fracturing with the same orientation (Nur, 1982). Relatively inexpensive electrical and electromagnetic prospecting methods should be useful in detecting water filled, subvertical fracture zones.

Faults and shear zones - Much of the discussion above concerning fracture zones also applies to faults and shear zones. As noted by Gale (1982) and Davis (1982), the hydraulic conductivity of faults and shear zones may actually be less than that of the adjacent unfaulted rock. Major faults should probably be avoided in the area-to-location screening, however, because their properties are difficult to characterize without underground workings and may change along strike. Faults which bring into contact contrasting rock types are frequently the location of enhanced well yields in crystalline rocks of some areas (Cressler and others, 1983).

Major faults are one of the geologic factors used to screen potential areas in the region-to-area phase of exploration. Those areas selected by this screening are less apt, therefore, to contain major faults than other areas of crystalline rocks. However previously unrecognized faults may come to light during area studies or site characterization.

Lithologic Discontinuities - Lithologic discontinuities of some type are certain to occur within the repository host rock and will have to be carefully studied. Within plutonic rocks, limited data suggest that discontinuities formed at high temperatures, such as aplite or pegmatite dikes or contacts between different plutons of a botholithic complex, are less apt to be water bearing (Stone, 1984; Hoag and Stewart, 1977) than those formed by intrusion of magma into relatively cool host rock such as diabase dikes within older granitoid rocks (Nystrom, 1976). Within metamorphic rock sequences, drill hole data from depths shallower than 100 to 200 m indicate that the contacts between contrasting rock types tend to be water bearing (Cressler and others, 1983), but it is possible that such contacts would be closed and free of fluid at repository depths.

Modeling Water Flow through Fractured Rocks - Although detailed modeling of ground water flow cannot begin seriously until site characterization, some consideration of the data needs and preliminary models can be made in the area phase. Modeling ground water flow through crystalline rocks presents problems because although theories of fracture flow have been developed, they have been little tested in the field and the types and amount of information needed to model such flow are not well established. Under some conditions, fractured media can be treated as a porous medium equivalent. Techniques for determining where these conditions exist have recently been developed by Long and others (1982).

Although crystalline rock bodies are generally not layered in the sense of having well-defined hydrostratigraphic units, they contain more water-bearing fractures and fracture zones near the surface. Consequently, the hydraulic properties for the subsurface at repository depths will be quite different from those for the near-surface portions of a rock mass. At repository depths, the bulk permeability may be very low with few open water-bearing fractures. Under such conditions, treatment of the crystalline rock as a porous medium would be inappropriate (Witherspoon and others, 1983). Since it would be impossible to characterize every individual fracture, flow through such a fracture network would have to be treated stochastically. Statistical representations of fracture density, orientation, length and aperture would be constructed from the best available data and used in conjunction with Monte Carlo techniques to generate various portrayals of of the water-bearing fracture population.

It may be possible to model some portions of the regional ground-water flow system as an equivalent porous medium; however, the regional system in the vicinity of the repository should contain very few fracture zones and these would have to be modeled individually. In some parts of the ground-water flow system where fracture families are water bearing, a dual porosity model may be appropriate.

The input for portrayals of the fracture network around a repository will come eventually from underground excavations, but intelligent guesses about the subsurface distribution of fractures may be possible from limited surface exposures, cores, geophysical logs, and single-hole hydrologic tests in a few boreholes during the area phase. Most fracture networks measured at the surface have fairly regular orientations and a range of spacings. Usually there are at least two preferred directions of fractures in a given rock mass. The combined fracture systems lead to a random distribution of fracture spacings (Priest and Hudson, 1981) in an intersecting network. In some rock masses, a single fracture orientation predominates and the variable spacing between individual fractures leads to a strongly clustered distribution (Priest and Hudson, 1981). Such a fracture distribution might not result in an intersecting network, especially if fracture lengths are short compared to fracture spacing, and might provide a high degree of hydrologic isolation.

## Structural model for a site

The range of hydrologically significant structural features that may be anticipated within crystalline rocks at the scale of a repository is illustrated by the model shown in Figure 4. Major fracture zones control ground-water flow at depth. The various deep holes and excavations inventoried in the Appendix provide the basis for this provisional model.

Where more than one hole has been drilled in a body, they suggest that the range of features shown may be present within a single body; however, it is also possible that a given site will be more or less heterogeneous than the provisional model. Determinations of the range of heterogeneity and the characteristic distances between features are some of the goals of area and site characterization. No dimensions are presented for the model. Their determination is another goal of area and site characterization. The upper zone of weathered rock and numerous open fracture zones grades downward to less permeable rock without a sharp break.

The proposed model is essentially the same as the concepts that have developed for the subsurface of rock masses investigated on the Canadian Shield by Atomic Energy of Canada Limited (AECL), and in Sweden by the Swedish Nuclear Fuel Supply Company (SKBF). In both settings, plutonic and metamorphic rocks are cut by numerous fracture zones along parts of which permeability is relatively high; the solid rock between such fracture zones has very low permeability (Keys, 1984; National Academy of Sciences, 1984). A key question for the crystalline rock program in the United States is whether rock masses in the northern and southern Appalachians and the Adirondacks have the same basic hydrologic properties at depth as those characterized in Canada and Sweden even though they have widely different ages and have undergone different tectonic histories. A firm answer to this question is not possible at this time because no locations in the United States have been characterized to the same level of detail as those in Canada and Sweden. However, information from the holes and excavations that do exist permit the provisional assumption that conditions are similar.

## Conclusions

We conclude that the subjects needing focused study at the area phase prior to intensive site-specific exploration are:

(1) Ground-water hydrology
- a. Recharge areas
- b. Discharge areas
- c. Water table and regional hydraulic potential
- d. Flow anomalies
- e. Definition of regional, intermediate and local flow systems
- f. Ground water resource potential
- g. Ground-water chemistry
- h. Ground-water residence times

(2) Geology
- a. Structures and their hydraulic characteristics, especially
  - 1/ Fracture zones
  - 2/ Faults
  - 3/ Shear zones
  - 4/ Joints
- b. Geometry of potential crystalline-rock bodies
  - 1/ Vertical extent
  - 2/ Presence of large dikes
  - 3/ Large inclusions of country rock
  - 4/ Layering or other compositional differences
  - 5/ Extent of multiple intrusions

(3) Mineral resource potential

Exploration during area characterization could be readily organized into three distinct phases, each distinguished by the nature of the methods to be employed. The first phase would be a reconnaissance one, which makes use of methods and sources of information that do not require people on the ground in the area of interest. The second phase would consist of field studies carried out on the ground. The purpose of both of these phases would be to try to identify possible faults, fracture zones, dikes, or major changes in lithology so that these can be assessed for their hydraulic characteristics and avoided in selecting the specific repository site; in addition, the outlines of the regional flow system would begin to be determined. The third phase would consist of drilling to repository depths and deeper at a potential site to determine what the rocks and structures are like and how readily the hydrology of the site can be characterized. Better definition of the regional flow system could also begin in this phase; however, activities more completly defining the regional system would extend into site characterization.

From the model described above, it appears that fracture zones and faults can be arbitrarily divided into two general groups, subhorizontal or subvertical, although a complete range of attitudes may be present. The first two phases of exploration would provide information mainly on the location of subvertical features and possibly give some indication of subhorizontal ones. The third phase, drilling, would explore for the subhorizontal zones in detail and would begin to provide information on their hydrology. Known subvertical fracture zones could be drilled with appropriately oriented slant holes and their hydrology could begin to be evaluated.

The remainder of this paper discusses these three phases of exploration - reconnaissance, surface study, and drilling - and what methods and strategies one could employ during each phase. Space does not permit a complete discussion of each exploration method; instead, some of the more important aspects relative to an exploration strategy are considered.

## RECONNAISSANCE PHASE

### Reconnaissance hydrology

Hydrologic studies in the area phase of exploration will provide a basis for preliminary evaluation of prospective sites. These data and interpretations would also be necessary input for the succeeding site characterization phase and would provide a basis for planning further studies.

The following steps provide a logical progression for obtaining the necessary information for evaluation of areas and the ultimate selection of potential sites: (1) delineation of recharge and discharge areas; (2) mapping of regional potentiometric surface; (3) identification of regional, local, and intermediate flow systems (figs. 2,3); and (4) definition of hydraulic properties of the flow regime for use in quantitative models. The first two steps and a provisional estimate of step three can be made in the reconnaissane phase using information available from published literature and data files. Evaluation of these data then will provide the basis needed to determine where the analysis should be augmented by additional data collection in the surface study and drilling phases.

Reconnaissance hydrology includes compilation of information from available sources (no field studies) primarily on recharge areas and discharge areas. The general outline suggested below is based on procedures developed by the U.S. Geological Survey program in the Basin and Range province for identifying prospective environments for high-level radioactive waste isolation. The methods are described in Bedinger, Reed, Harrill, and Gates (1985) and applied in the Bonneville region (Bedinger, Reed, and Langer, 1985).

The first step is the identification of discharge areas from topographic maps, remotely sensed imagery, and the records of stream and spring flow. The general outlines of the flow system can then be estimated from water-level maps, the base flow of streams, and chemical and physical quality records of springs and ground water. Then the recharge areas are identified from considerations of topography and water level data in relation to the characteristics of the discharge areas. A tentative distinction between local and regional ground-water flow systems is then possible.

Lines of equal hydraulic potential can be mapped for the regional groundwater flow systems based on the assumption that there is a hydraulic connection between the near-surface hydrologic system and the regional system. Although such a connection may not be present, this a useful initial working hypothesis. If geologic data are sufficient, the geologic and hydrologic data can be combined in flow models, such as two-dimensional cross-section models. The preliminary delineation of flow systems will provide a measure of the length of flow path from a repository to the natural discharge area. The regional potentiometric surface will provide an estimate of the hydraulic head. At this point, time of travel from a potential site to the accessible environment can be estimated, for ranges of hydraulic properties of the rocks. Preliminary models can provide a basis for planning additonal surface studies and test drilling to define the hydrologic framework.

## Remote Sensing

Geological remote sensing techniques involve airborne and spaceborne instruments that measure emitted and reflected electromagnetic radiation (Williams, 1983). Analysis of aerial photographs is included, but potential field methods (gravity and magnetics) are not usually included under the topic of remote sensing and are discussed separately. The power of remote sensing derives from the synoptic view provided by spacecraft or high altitude aircraft and the capability to observe and measure, qualitatively or quantitatively, emitted or reflected radiation over much of the electro-magnetic spectrum.

Almost all of the bedrock types under consideration for radioactive waste repositories in the eastern United States have very limited outcrops. This places a serious constraint on the type and amount of information that can be obtained by remote sensing technology. Bedrock in the North Central and Northeast regions is extensively covered by glacial deposits ranging in thickness from a few meters to several tens of meters. Analysis of remotely sensed imagery will be limited largely to structural analysis. Bedrock in the Southeast region is generally overlain by a thick mantle of soil, saprolite, and colluvium that may indirectly reflect the composition of the underlying bedrock; the vegetative cover is dense over most of the region, however. Some compositional inferences about the underlying rock may be possible from the response of various vegetative types to different parts of the electromagnetic spectrum (Nancy Milton, USGS, personal communication, 1984), but research to determine the lithologic significance of such spectral responses is still in its infancy. In some of the low-relief regions of the Southeast Region, the topographic and structural information which can be derived from remote sensing technology may also be severely limited, because the rate of saprolite formation apparently is very close to the rate of denudation (Pavich, 1985). Linear features, such as weak rock zones surrounding faults or fracture zones, are not etched out by erosion as they are in less humid and cooler regions. Remotely sensed images of such areas tend to be rather bland and featureless. However, in the more rugged parts of the Southeast Region, such as the Blue Ridge and its foothills, there is abundant topographic texture in remotely sensed images which can provide information as to the geologic structure.

The principal systems, which provide remotely sensed images of possible use in area/location characterization, are the Multispectral Scanner and Thematic Mapper (both operating on the current generation of landsat satellite), side-looking airborne radar, side-looking satellite radar, and conventional aerial photography. Emphasis in remote sensing studies should be directed at the extraction of new information from imagery acquired by the Thematic Mapper and Side-Looking Radar and on detailed site-specific studies of Multispectral Scanner data to supplement earlier regional studies (Dutch, 1981; Barosh, 1976; Isachsen and McKendree, 1977; Trask and others, 1977). Acquisition of additional remotely sensed data for the candidate areas should be undertaken only after the analysis of existing data indicates a potential for acquiring useful information and after careful cost-benefit studies.

## Potential-field Geophysics

Geophysical techniques normally referred to as potential-field methods are magnetics and gravity. Airborn radioactivity methods are also included here because the the data aquisition method is similar. The magnetic method is excellent for distinguishing rocks with variations in magnetic properties in areas ranging from a few to many thousands of square kilometers. Data acquisition is accomplished by aircraft flying at altitudes ranging from 100 m to 300 m or more above the ground surface, with lateral flight line spacings from 200 m to several km. Digital recording allows semi-automated processing and production of contour and color maps on a time scale of 6-12 months after data acquisition. For local studies, sophisticated navigation systems must be used, but features as small as a well casing have been detected with low altitude surveys having closely-spaced flight lines.

Magnetic maps reflect spatial differences in magnetic properties of the rocks (including magnetic reversals) and can be used to detect intrusions whose magnetic properties contrast with the country rock (Griscom and Bromery, 1968). Faults in magnetic rock can be detected in many terrains if the magnetic rocks are vertically displaced, or if rocks that have contrasting magnetic properties are thrust over one another (Nelson and Zietz, 1983).

The gravity method is one of the best single methods for determining the overall size and shape of crystalline rock masses (Diment, 1968). It does not normally detect faults and fracture zones on a local scale. The gravity and magnetic methods can be combined in effective ways, using modern computer graphics presentations, to produce informative, synoptic, regional maps. Well-defined linear trends can be targeted for later exploration as possibly significant discontinuities. Airborn radioactivity surveys may assist in locating fractures mineralized with radioactive materials (Joseph Duvall, U. S. Geological Survey, personal communication, 1985).

Gravity and aeromagnetic data are available for all candidate crystalline-rock repository areas, but much of it has quality and resolution that are suitable only for reconnaissance phase studies. These data sets contain a great deal of latent information that can be extracted by combining data sets and preparing derivative maps. Color and shaded-relief presentations allow interpreters to glean much more useful information from a map than does the traditional contour-line presentation. Merged data sets displayed in various formats can lead to the identification of significant discontinuities; producing them takes from a few months to a few years, depending on the size of the area being studied and the heterogeneity of the data sets. These potential-field methods are some of the most effective methods for identifying large-scale compositional or structural features.

The highest priority should be given to early assembly and interpretation of existing potential-field data sets for candidate areas. Any adverse conditions that can be revealed by magnetics and gravity should be discovered as early as possible. Additional aeromagnetic data could be acquired in the reconnaissance phase if necessary. Ground magnetics and additional gravity data can be obtained in the surface study phase. As exploration focuses on successively smaller areas, it is important to acquire denser and more accurate potential-field data for each area. With a uniform data set over a local area, data processing and derivative map production can be done in a few months.

## SURFACE STUDY PHASE

### Hydrologic Studies

The provisional hydrologic models developed in the reconnaissance phase can begin to be upgraded with the collection of field data prior to actual drilling. The data to be collected include: low-flow stream and spring discharge; hydrochemistry of streams and springs; chemical and hydraulic data from existing wells that may not have been available during the earlier phases of exploration; and the isotopic composition of ground water from existing boreholes and springs.

### Geologic Mapping

For the areas to be investigated in the area phase, detailed geologic maps at a scale of 1:24,000 or 1:100,000 should be prepared and should include the following information for all outcrops:

a. Outcrop location and extent
b. Rock types, internal contacts, petrography
c. Alteration
d. Fracture orientation, spacing, length, filling aperture, and roughness.
e. Foliation and layering
f. Fracture zones
g. Faults and shear zones
h. Indications of mineralization

For some of the rock masses, much of this information is already available at the scale indicated; for example, the Orogenic Studies Laboratory at Virginia Polytechnic Institute and State Univeristy has in its files such information on many of the Acadian and Alleghanian plutons of the southeast. Similar detailed studies exist for some bodies in the other two regions. Every effort to locate such existing data sources in State and federal surveys and in universities should be made before undertaking new studies. Field studies and advice by workers familiar with the region and area should be sought out and made use of whenever possible.

Information on fractures is most likely to be lacking even for those bodies for which relatively detailed studies exist. This information will have to be obtained directly. Discontinuity scanline survey methods (Brown, 1981) should be applied uniformly in the three regions. Most of the rock bodies are so limited in exposure (a few percent outcrop at best) that there will be unavoidable uncertainty as to the representativeness of such data, even when every outcrop is measured. Fracture abundance, spacing, and characteristics may also be quite different at depth than they are at the surface. Nevertheless, this data is relatively easy to obtain and can provide the initial basis for chracterizing the rock mass and assessing potential repository performance.

The regional geologic setting of each area should also be addressed in this phase. Much of this information can be compiled from existing small-scale maps. Where deposits of appropriate age are present, there should be a thorough search for faults with Cenozoic offset such as those shown on compilations by Howard and others (1978) and Prowell (1983). Such faults should be trenched and studied for evidence of Quaternary offset.

## Seismic investigations

Contemporary seismic hazards analysis combines actual seismological data (which form the bulk of the seismic description of a region) with various hypotheses and theoretical models which represent the seismic character of the region. The seismological data are used to 1) identify seismic source zones; 2) estimate recurrence rates in individual source zones; 3) identify mode and sense of faulting, source parameters, and orientation of principal stress components; and 4) develop attenuation models. The reliability of seismic hazards analyses is directly related to the quality and quantity of seismological data available and the reasonableness of models and hypotheses. Thus activities under this heading should include the compilation and comprehensive reevaluation of previously observed seismic data, collection of new seismological data, and testing of hypotheses and models against other geological data.

Preliminary locations of seismic source zones and estimates of recurrence rates are often possible by evaluation of historical earthquake catalogs, earthquake histories, and other previously published material. The historical data sets generally cover long time spans and often are the only pre-instrumental evidence of activity in areas of infrequent seismicity. In addition, early instrumental seismic data can sometimes be used to provide improved earthquake locations and magnitudes. The usefulness of such material, however, is frequently limited because older seismic data are inherently less complete and less accurate than similar data acquired by modern seismic networks. Thus uncertainties in earthquake locations, magnitudes, and intensities have to be evaluated and completeness of the historical catalogs estimated before a hazard analysis is even attempted In certain areas of the northeast, southeast, and central U. S., regional networks have operated for a decade or more. The catalogs of these networks provide a valuable characterization of regional seismicity.

New seismic data of high quality may be acquired by the establishment of a seismic network designed to monitor the contemporary seismicity of the region around the proposed repository site and may supplement an existing regional network A properly designed and operated network can provide seismic data which supplement and correct some deficiencies in earlier or historical seismic data sets. For example, earthquake locations and magnitudes determined by a seismic network customarily are much more accurate than locations and magnitudes in the historical catalogs. A network catalog will usually be complete to several magnitude units smaller than a historical catalog and therefore, after several years, yield significantly improved and detailed seismicity maps that may permit the association of seismicity with active faults. Although small magnitude earthqeuakes do not in themselves constitute a hazard, they may be used to pinpoint the location and rate of larger magnitude shocks. Further, determination of nodal planes and source parameters from digital seismic data can yield important data on focal mechanisms and state of stress in the region. Analysis of spectra and peak amplitude data will yield improved estmates of magnitude values and assist in developing local ground motion attenuation curves.

Design and operation of new seismic networks in the eastern and north-central U. S. will require the application of state-of-the-art technology because the region is not tectonically active as is the western U. S., in many areas seismicity is infrequent and sparse, and quiet sites for seismic stations are hard to find. Digital data acquisition and automated detection algorithms will be essential. Broad-band and downhole instruments may be required in difficult sites and special signal processing may be required to extract seismic data from noisy data channels.

## Mineral resource potential

The rock masses that have been chosen by region-to-area screening will probably be free of any major known mineral deposits inasmuch as proximity to known resources was a screening factor in selecting areas for detailed study. Also, areas within approximately 3 km of deep mines and quarries (100 m or more in depth) will have been disqualified from consideration (U.S. Department of Energy, 1985). Investigations of the rock masses to search for previously unknown mineral deposits will involve a combination of rock sampling, stream sediment sampling, and geophysics. In order to compare the mineral resource potential of a body with that of other rock masses and with that of the surrounding terrain, information on the following subjects is required for each rock mass:

a) For felsic plutons
   1. Mineralogy and chemical composition.
   2. Formation by anatexis or derived from mantle?
   3. Estimated depth of emplacement.
   4. Multiple intrusions and cross-cutting phases -- veins, pegmatites, greisen.
   5. Chemical interactions with country rock; skarns; composition of country rock.

b) For mafic plutons
   Differentiation history with emphasis on cumulates.

c) For metasedimentary gneisses
   1. Indicators of exhalations-- i.e., layers rich in Fe, Mn, B, Ba.
   2. Alumina rich enclaves indicative of past alteration and fossil geothermal systems.

Detailed information on petrology and rock compoosition is not available for every body (Wones, 1980). To provide a complete assessment of mineral resource potential, investigations of granitoids should insure that the mafic minerals are properly identified - whether biotite, hornblende, or both - and that primary muscovite or other phases indicative of peraluminous composition are noted.

## Potential-field geophysics

New more detailed ground-based gravity and magnetic surveys tailored to the needs of the repository program for specific rock bodies can be instituted at this phase of the exploration.

## Electrical and electromagnetic methods

Electrical and electromagnetic (EM) methods are used to study the electrical structure of the Earth. Electrical properties (conductivity or its reciprocal, resistivity) are controlled by numerous factors, such as: lithology, porosity, permeability, temperature, fracture density and orientation, and chemistry of pore fluids. Conductivity of earth materials ranges over six orders of magnitude or more; thus many geologic contacts involve large conductivity contrasts, and the resulting electrical anomalies are readily detected.

Generally speaking, electrical methods are more sensitive to anomalous conductors than to anomalous resistors. Fortunately, conductive targets are likely to be most interesting from the perspective of radioactive waste isolation. High temperatures, fractures, and porous remnants of sedimentary rocks that have been folded into crystalline rocks, for example, all have relatively high conductivity, and therefore constitute good exploration targets within low conductivity crystalline rocks.

The depth resolution of electrical methods varies with the particular technique, but is equal to or better than that of gravity or magnetic methods. Lateral resolution is a function of the spacial wavelength of the anomalous electrical response, which is a direct function of the depth of burial.

Almost no electrical data have been systematically collected over crystalline rock areas in the eastern United States. Specific structures have been studied, but those are not of interest for nuclear waste studies. A broad array of electrical methods is available for application to all phases of the crystalline repository program. An incomplete list of suggestions follows:

a. Magnetotelluric (MT) study of regional crustal trends, deep crustal electrical anomalies, depth to bottoms of allocthonous plutons, etc. The MT method uses natural EM fields, and can function in a relatively high density of cultural features (pipes and power lines). Probes as deep as the base of the crust.
b. Audio-frequency magnetotellurics (AMT) probes the upper crust to depths of a few kilometers. Regional to subregional studies can define smaller structures or anomalies that transect individual plutons. Sensitive to regional hydrologic conditions.
c. Time-domain EM (TDEM) can probe to depths of several hundred meters, and is useful for defining trends or structures within plutons or in overlying rocks. Fracture systems, if they are filled with clay or conductive fluid, are good exploration targets for TDEM. TDEM is a particularly useful method for working near cultural features.
d. Airborne EM (AEM) methods can probe to about 100 meters, and are useful for rapid reconnaissance in the early part of the area/location stage. AEM systems may be configured for a resistivity mapping function or for delineation of conductive, near vertical fractures.
e. Self potential methods have been used to measure the effects of subsurface water flow as leakage from dams and hydrothermal fluid flow. These methods may provide a unique way of addressing fluid flow within fracture zones.

A period of experimentation and trial will be necessary early in the surface exploration phase to determine the best mix of methods for outlining targets for later drilling. Examples of integrated exploration strategies utilizing a variety of electromagnetic methods in conjunction with drilling are available in publications from the Swedish KBS program (Swedish Nuclear Fuel Supply Company, 1983) and the Canadian experimental program (Sinha and others, 1985). Peter Haney (U.S. Geological Survey, unpublished data) has surveyed the application of surface electromagnetic methods to the detection of shallow fractures in connection with shallow land burial of toxic and radioactive waste.

## Seismic Methods

Seismic methods utilize elastic waves to sense properties of the Earth. Observations can be based on manmade signals, as in conventional seismic reflection and refraction surveys; the signals can be either explosive or vibratory in nature. Natural signals can be used to sense delay or attenuation of teleseismic waves (waves from distant earthquakes). Seismic studies using manmade waves are notable for their capability to respond to small geologic features at depth; resolution degrades much more slowly with seismic methods than it does with potential field or electrical methods, as attempts are made to look deeper into the Earth.

Classical seismic reflection and refraction methods are normally used only in areas where the earth approximates a layered situation such as sedimentary basins. However, with modification they have the potential for detecting significant structures and variations of rock properties within a crystalline rock mass. There has been mixed success to date in the Canadian program of exploration of study areas in efforts to correlate the results of seismic reflection studies with results from core drilling (Green and Soonawala, 1982).

Seismic methods have been much more frequently applied in sedimentary environments than in crystalline environments. Relevant seismic data are likely to be available, therefore, only in areas where crystalline rocks are associated with sedimentary structures that form traps for petroleum. The main exception to this rule is the recent results obtained from deep crustal reflection profiling experiments. These are limited in coverage, and do not show well the structure of the uppermost rocks. These profiles are highly useful, however, for determining the depth extent of plutons.

## DRILLING PHASE

With this phase of investigation, we finally reach the primary concern; what are the hydrologic conditions at repository depths? In the early stages of this phase, emphasis will be on proving up a sound body of rock at proposed repository sites and on making a preliminary determination of site hydrology. As the drilling phase progresses, it will be necessary to refine further the hydrology of the site as well as to obtain a reasonably complete picture of the regional flow system which forms the boundary conditions for water flow through the repository volume.

What are the most likely unfavorable features to be encountered by drilling? Most subvertical fracture zones or faults should already have been detected by investigations during the reconnaissance and surface study phases, which are most effective in finding steeply dipping features. New information from drilling will therefore be most likely to discover previously unknown subhorizontal fracture zones although additional subvertical features will probably be found.

### Drilling strategy

Because significant subhorizontal fracture zones at repository depths may be undetected by surface exploration and geophysical methods, a single hole gives a great deal of information, especially since such zones can hardly be missed by a vertical drill hole. Thus, a strategy that could markedly increase the chances of finding a repository-size block of ground while avoiding subhorizontal fracture zones would be to drill a single hole at a number of areas first and then proceed to drill more holes at those areas which had the fewest such zones.

If sites can be found with no or relatively few subhorizontal fracture zones in the inital hole, at least two additional drill holes should be drilled close enough to the first hole to be certain of obtaining two additional intersections on each zone and thus of establishing their general strikes and dips. Once these have been established, it should be apparent whether there is a good possibility of avoiding these features by adjusting the lateral or vertical position of the repository to provide sufficient rock volume between the possible repository and the fracture zones. If additional subhorizontal fracture zones are encountered in these drill holes, then one may begin to question the wisdom of continuing at this site; however, one may wish to repeat the process of establishing strike and dip of the new fracture zone or zones, and again try to move a sufficient distance from them. We know little about the lateral extent of such zones and consequently must assume that they extend indefinitely until they intersect one another, subvertical fracture zones, faults, or the surface. It is also possible that they may die out laterally with new ones developing in an en echelon pattern.

Because the dimensions of a single level repository would be approximately 2 by 3 km, this approach requires that one select a sufficiently large area for initial studies that one can move the potential repository perhaps as much as 2 km in any direction from the initial drill hole, should unfavorable conditions be encountered. This indicates that the block of ground selected should be at least 10 km in diameter with the possibility of locating the repository anywhere within that area. A more restricted area can, of course, be chosen but this reduces the possibility of relocating the repository to avoid unfavorable features encountered in the first few drill holes.

Suppose that at one or more sites the first drill hole shows the absence of subhorizontal fracture zones at the depths of interest. Subsequent holes should then be placed at the approximate boundaries of the repository; that is, at the corners of a square, 2 to 3 km on a side. If no unfavorable features are encountered, subsequent holes can be located within the square itself. On the other hand, if any of these subsequent drill holes encounters a significant subhorizontal fracture zone, a strategy to determine the strike and dip of such a feature could be pursued, and the location of the hypothetical repository adjusted accordingly.

How many drill holes will be required? There is no easy answer. In the most favorable circumstances, an absolute minimum of 4 or 5 is needed to begin to sample the site. Prior to sinking a shaft, there should be a sufficient number of drill holes to determine whether the characteristics of the proposed site indicate that the additional expense of an exploratory shaft is warranted. Because of the relatively unpredictable nature of fractures and fracture zones in crystalline rocks, these drill holes should probably be more closely spaced than has been the case in the media examined to date; salt domes, bedded salt, tuff, and basalt. The underground workings developed during the site characterization stage, while useful in providing a sample of the rocks and fractures at the repository level, constitutes only a small fraction of the area of the repository itself. If the exploratory drill holes are too widely spaced, the chances of missing a large fracture zone during the site characterization stage, only to encounter it during the construction stage, could be significantly higher.

The decision to abandon an area will, of course, be a difficult one. The basic problem is that the less one knows about an area (that is, the fewer the drill holes) the better it will probably appear. On the other hand, as the number of drill holes increases, the understanding of the geometry of the fractures and fractures zones increases, and one may be able to locate the repository where it will avoid such features.

## Borehole geophysical methods

Nearly all geophysical methods have been adapted to be performed in boreholes, where the sensor is closer to the exploration target. One method, heat flow, can be done only in a borehole environment. The same limitations exist for borehole application as for surface application of each method, but boreholes provide a means not only to get closer to the exploration target, but to get away from surficial clutter caused by terrain, weathering, and culture.

When boreholes are available, they can be used effectively as locations for seismic sources and sensors--thereby eliminating some of the loss in resolving power that occurs as seismic waves penetrate from and reflect back to the Earth's surface. Fracture systems that intersect boreholes act as acoustic antennas, and their power to capture waves traveling alongside a borehole can indicate the hydraulic conductivity of the fracture.

Standard geophysical logs are obtained in nearly every borehole that is drilled for petroleum or mineral exploration in the United States. The standard logs are:

- o electrical logs (many varieties, self potential including single-point resistance resistivity logs with various electrode spacings, and inductive resistivity)
- o acoustic (P and S wave velocity, tube waves, televiewer (amplitude), and full wave form)
- o radioactive
- o temperature
- o magnetic properties (magnetic susceptibility and magnetometers)
- o fluid resistivity
- o density (gamma-gamma, and borehole gravity)

However, numerous other logs would be relevant to crystalline waste repository exploration. Among these are:

- o fracture logs - acoustic and electrical methods (particularly radar) for studying fractures and their associated fluids and minerals
- o borehole, hole-to-hole, and hole-to-surface seismic and electrical measurements used to probe into the rock mass and investigate inhomogeneities that extend away from the borehole
- o magnetometer logs
- o high-resolution gamma-ray spectrometers, to determine the state of equilibrium among uranium and its decay products (Tanner and others, 1977). Information from such a probe can provide evidence related to previous leaching and redistribution of uranium.
- o acoustic holography, using continuous-wave sources at the surface with a two-dimensional array of sensors that measure amplitude and phase of the received waves. The received wave can be commutationally or optically imaged using single or multiple frequencies. This method appears to be quite effective for locating small "point" reflectors, while ignoring the flat-lying reflectors sensed in common time-domain reflection. Research is needed to develop this potentially powerful method.

## Studies of core

The availability of core will make possible information on mineralogy, geologic variability with depth, and rock homogeniety and continuity. Particularly important will be a systematic study of the fractures encountered. Information recorded should include the orientation of each fracture; thickness; age, mineralogy, and chemistry of the fracture filling; surface markings and characteristics; and degree and type of accompanying alteration. Although painstaking, such observations are necessary for developing a three dimensional model of the fracture system by comparison with surface outcrops, quarries, and underground excavations. An example of a thorough fracture study from cores is provided by Becker (1984). Discrimination among naturally-induced fractures, coring-induced fractures, and handling-induced fractures is discussed by Kulander and others (1979). Early in area characterization, uniform procedures for the logging and descriptions of fractures in cores should be established. Changes in fracture-filling mineralogy with depth may indicate what important dissolution-precipitation processes have functioned in the rock. The distribution of uranium in the host rock and along fractures should also be examined. To some extent, the rock-fracture-fluid system serves as a natural analog of the repository system and deserves careful study. Uranium distribution is an indicator of how this system has functioned in the past. Studies of the sorptive properties of the rock and its fractures can be made from core, and in conjunction with hydrologic tests may provide preliminary estimates of this important property.

Material from cores provides an opportunity for geomechanical testing of material properties in the laboratory. Final design and performance assessment of a repository will require that these data be combined with that from underground in situ tests. However, laboratory data on material properties can be used for preliminary design and may allow discrimination as to which sites are more favorable than others. A useful review of laboratory tests is provided by the Earth Technology Corporation (1985).

## Groundwater geochemistry

The drilling phase of exploration permits updating the water chemistry estimates made in the reconnaissance and surface study phases with more precise measurements of water chemistry, including stable and radioactive isotope data, from depth. A geochemical interpretation of formation waters that is internally consistent with thermodynamic principles and externally consistent with hydrologic measurements and observations can place important constraints on both regional and local flow systems. Water samples, however, are easily contaminated not only with drilling fluids, shallow groundwater, or air, but also by water from different permeable zones at depth. A careful strategy must be worked out as to when and how to sample in coordination with other measurement programs. Experience at the Stripa, Sweden site suggests that it may be necessary to have at least one drillhole at each area solely dedicated to water sampling and geochemical investigations without interruptions from geophysical logging or hydraulic testing until such time as the chemical parameters are considered to be adequately characterized and truly representative (pers. commun. D.K. Nordstrom, U.S. Geological Survey, 1985). Groundwater chemistry in areas studied in both the Swedish and Canadian high level waste exploration programs changes with depth in complex ways; in general, waters become more saline and apparently older with depth (Nordstrom and others, 1985; Gascoyne and others, 1985).

If there are strong differences in the ages of relatively shallow groundwater, say at 300 m depth, these data could be used in the early stages of area screening. Areas with relatively old groundwater at these depths would be favored over those whose deep groundwaters are younger. Groundwater ages might be estimated very shortly after drilling.

## Hydrologic testing

Tests to determine potentionmetric head, hydraulic conductivity, and porosity will be carried out during the drilling phase in most holes. The difficulties of these tests in fractured media of low permeability are well known (Grisak and others, 1985) and widespread research efforts are underway to attempt to resolve them. A good summary of the test methods and results obtained in the Swedish crystalline rock evaluations can be found in the reports of the Swedish Nuclear Fuel Supply Company (1983). The degree to which these methods can be applied in the three regions under consideration in the United States should be determined early in the area phase.

In this phase, it would also be worthwile to conduct a series of tracer tests to evaluate porosity and fluid velocity in the major fracture zones. Single hole tests such as a borehole dilution test could give valuable preliminary data on these features.

## In situ stress

Knowledge of *in situ* stress is needed for the design of the shafts and repository rooms and as an initial condition for hydrologic modelling. Measurements will have to be limited to boreholes in the area phase of characterization. Both overcoring techniques and the hydraulic fracturing method have been used in boreholes, but the latter has been more widely used at repository depths. Research to improve both techniques and to resolve discrepancies between them is underway (for example, Doe and others, 1983). Knowledge of abnormally high or low *in situ* stress should be obtained early in area characterization. Anomalously high stresses may mean that an area is apt to experience earthquakes and may make underground excavations difficult. Anomalously low stresses may indicate that fractures that would otherwise be closed at depth are open and water bearing. Complete understanding of undergound stresses will not be needed until the site characterization phase.

## Depth of Exploration

According to the DOE guidelines, the minimum favorable depth for a repository is 300 meters. Because hydrologic conditions in crystalline rocks generally become more favorable at greater depth, the chances of success should generally improve with depth at any location. The trade off, of course, is that the cost of constructing a repository increases with depth. This manifests itself primarily as the increased cost of constructing deeper shafts. In view of the many uncertainties in the hydrology of crystalline rocks, the added expense of going deeper may well be worth the additional cost as it appreciably increases the chances of success. Thus, the cost of going to 1000 m as opposed to 500 or 300 m must be weighed against the probability of finding fewer water-filled fractures and fracture zones. At the Whiteshell Underground Research Laboratory, Manitoba the spacing between subhorizontal fracture zones increases with depth, suggesting that chances of finding a sufficient volume of rock without such zones significantly increase with depth. In addition, the hydrologic conductivity of the fracture zones is generally lower in the deeper zones. Experience in some mining districts on the Canadian shield suggests that the composition of brines found in deeper zones may indicate a stagnant situation with no connection to surface waters (Kelley and others, 1984).

It would therefore seem desirable to determine the maximum depth at which a repository in crystalline rock could be readily located in terms of economics, engineering, and geothermal gradient limitations, and then proceed to consider that depth as a possibility from the first drill hole. With luck it may be possible to locate a repository at shallower depth, but if unfavorable conditions are encountered at those depths as exploration proceeds, the possibility of going deeper to avoid them could be kept as an alternative by drilling all exploratory holes to well below the maximum repository depth. Thus one could greatly reduce the area needed for for a hypothetical repository by moving it vertically instead of laterally to avoid unfavorable conditions. If unfavorable conditions are encountered at shallow depths as exploration proceeds, the additional exploration costs of deeper drill holes could thus be offset by the reduced number of drill holes needed to move the repository laterally. In conclusion, going deep probably offers the greatest chance of success, and the increased costs may be more than offset by the reduced risk of failure to find a satisfactory site.

There is a good reason for drilling the first series of exploratory holes to depths considerably below the probable depth of the repository. With such holes, one can locate any deep subhorizontal fracture zones which, on moving in an up-dip direction, would intersect the repository horizon from below. Because of the low angle of dip, such an intersection may be a considerable distance from the drill hole. Thus, it would be better to locate such zones as early as possible with relatively deep holes than to encounter them late in the exploration in the middle of the proposed repository.

## Multilevel Repositories

The possibility of developing multilevel repositories has been mentioned from time to time. Crystalline rocks, because of their high strength, would be especially favorable hosts for such repositories. A multilevel repository would offer reduced costs of development and operation because the same shafts and possibly emplacement holes would serve more than one level and the areal extent of each level would be greatly reduced. However, an advantage of much greater significance is that such a repository could be more easily adapted to any limitations of the site imposed by steeply dipping fracture zones or faults. Thus, while a single level repository might require an area of 9 sq kms of rocks without such features, a four-level repository would require only 2.5 sq km provided thermal loadings were within acceptable limits. In addition, the smaller area could be characterized to about the same degree of certainty as the larger with one-fourth the number of drill holes. Alternatively, as the area to be characterized decreases, the same number of drill holes can be more closely spaced and hole-to-hole seismic and radar methods as well as hydrologic testing would allow much more thorough characterization of the potential repository.

In short, a site for a multilevel repository in crystalline rocks should be much easier to identify and less expensive to explore and characterize than a single level one. This conclusion is based on the preceding arguments and needs to be examined with regard to the engineering aspects and hydrologic modeling of such a site.

## SUMMARY

A review of the DOE siting guidelines and development of a conceptual model of the geologic features significant for a nuclear waste repository in a crystalline rock mass indicate that the primary information needs for identifying favorable sites relate to ground-water hydrology and geologic features that affect the flow of ground water. The major technical issue in the area phase of exploration will be whether the flow systems of a potential site and the area surrounding it can be characterized adequately to satisfy the licensing requirements of the Nuclear Regulatory Commission (NRC).

Unfortunately, there is almost no information on the hydrology or hydraulic properties of the rocks at repository depths in the three regions under consideration. The total number of existing drill holes deep enough to provide some useful information is probably less than one-half dozen.

Modeling ground-water flow through crystalline rocks presents problems because, although theories of fracture flow have been developed, they have been little tested in the field, and the types and amount of information needed to model such flow are not well established. It may be possible to model the regional flow system as a porous medium equivalent. However, in the vicinity of a potential repository site and at repository depths, where there should be very few water-bearing fractures and fracture zones, this approach would be inappropriate. Instead, flow through a fracture network would have to be treated stochastically, using statistical representations of fracture density, orientation, length, and aperture developed from boreholes, surface geophysics and limited outcrops. Detailed hydrologic modeling will require data from underground excavations.

Exploration during area exploration could be organized into three distinct phases: a reconnaissance phase, which would not require people on the ground, a field study phase, and a drilling phase. These three phases are progressively more expensive per area of examination and thus present a natural sequence of screening stages.

The reconnaissance phase would consist of reconnaissance hydrology, remote sensing studies, and potential field geophysics (gravity magnetics, and possibly airborne radioactivity). Reconnaissance hydrology would identify discharge areas from information on topographic maps, remotely sensed images and records of stream and spring flow. The general outlines of the flow system can be estimated from water-level maps, base flow of streams, and records of springs and ground water. Then the recharge areas can be identified from consideration of topography and water-level data as related to the discharge areas. At this stage, local and regional groundwater flow systems may tentatively be distinguished. Lines of equal hydraulic potential would be mapped for the regional groundwater flow systems to provide a hydrologic framework into which the geologic characteristics of the rock mass can be incorporated, first from estimates and later from measured data from drill holes.

Remote sensing (satellite imagery, side-looking radar, and aerial photography) provide a rapid means for initial examination of areas of interest, but with a serious caveat: definite conclusions regarding any features observed cannot be made on the basis of remote sensing alone, nor does the absence of features in the imagery mean geologic discontinuities are absent.

Gravity and aeromagnetic data are available for all of the candidate repository areas, but the quality and resolution are suitable only for reconnaissance studies. These data sets can be combined using modern computer graphics presentations to produce a number of derivative maps to identify variations in crystalline rocks resulting from variations in magnetic properties and density. These can be interpreted in terms of the geometry of the rock masses involved and possible discontinuities, such as boundaries of the masses or faults.

The surface study phase would consist of hydrologic data collection and refinement of hypothetical flow models, geologic mapping and ground geophysical studies. Geologic maps at a scale of 1:24,000 to 1:100,000 would be prepared with emphasis on fracture zones, faults and shear zones, joints, alteration, and any indications of mineralization. An evaluation of the mineral resource potential similar to that done by the USGS in assessing the potential of wilderness areas could be initiated. Several types of electrical geophysical methods should be considered for use during this phase, the exact method depending on the geological situation and the information that is sought. Such methods can be most helpful where there is a specific question to be answered, such as the presence of a suspected water-bearing shear zone in an area of limited outcrop. Seismic surveys can provide useful information on inhomogeneities at depth, but relatively few have been run in crystalline rocks where their interpretation is still very much an art.

The drilling phase would focus on determining hydrologic conditions at repository depth; drilling to estimate the characteristics of the regional flow system would also begin. Holes should be designed to allow adequate hydrologic testing and logging at depths of interest. Cores will become available to provide direct information on fractures and fracture zones. An assortment of borehole logs, radar, acoustical televiewers, and flow meters can also be employed to locate fractures and fracture zones and to determine their properties. A variety of tests can be run to obtain hydrologic data on significant fractures and fracture zones; such tests are not routine at this time as experience in hydrologic testing of crystalline rocks in other countries has shown. The updated hydrologic data would then replace or modify the estimates used in the earlier reconnaissance phase of hydrology. Geochemical sampling of ground water, in situ stress testing and geomechanical testing of samples would also be carried out.

Because hydrologic conditions in crystalline rocks generally become more favorable at greater depths, the maximum depth at which a repository in crystalline rock could be readily located should be determined before drilling is started; the added expense of going deeper may well be worth the additional cost if it appreciably increases the chances of success. Depending on the spacing of steeply dipping fracture zones versus that of sub-horizontal fracture zones, a multi-level repository may represent a more reasonable concept than a single-level one. For example, a four-level repository would require one-fourth the area of a comparable single-level repository provided thermal loadings were within acceptatble limits, and the smaller area could be characterized to the same degree of certainty as the larger with one-fourth the number of drill holes.

Initially, a single deep hydrologic hole should probably be drilled at each potential site. The main question to be addressed would be the presence or absence of large sub-horizontal fracture zones which should be avoided in locating the repository. Such zones will probably be difficult to identify by surface methods because of their irregular outcrop pattern. The initial drill hole or holes should be drilled to depths considerably below the probable depth of the repository in order to explore for any deep sub-horizontal fracture zones which, on moving in an up-dip direction, would intersect the potential repository from below. Other things being equal, the absence of sub-horizontal zones would be very favorable. If they are encountered and other factors dictate the continued exploration of the site, their strike and dip should be determined by additional drill holes. With this information, it may be possible to locate the repository where it will not be intersected by such zones. Because of the lack of predictability of fracture zones and other features in crystalline rocks, under the most favorable circumstances the information from four or five deep drill holes near the boundaries of the proposed repository probably represents the bare minimum needed to proceed to a final choice among the sites.

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Figure 1. Index map of the United States showing the location of the North Central, Northeast, and Southeast Regions.

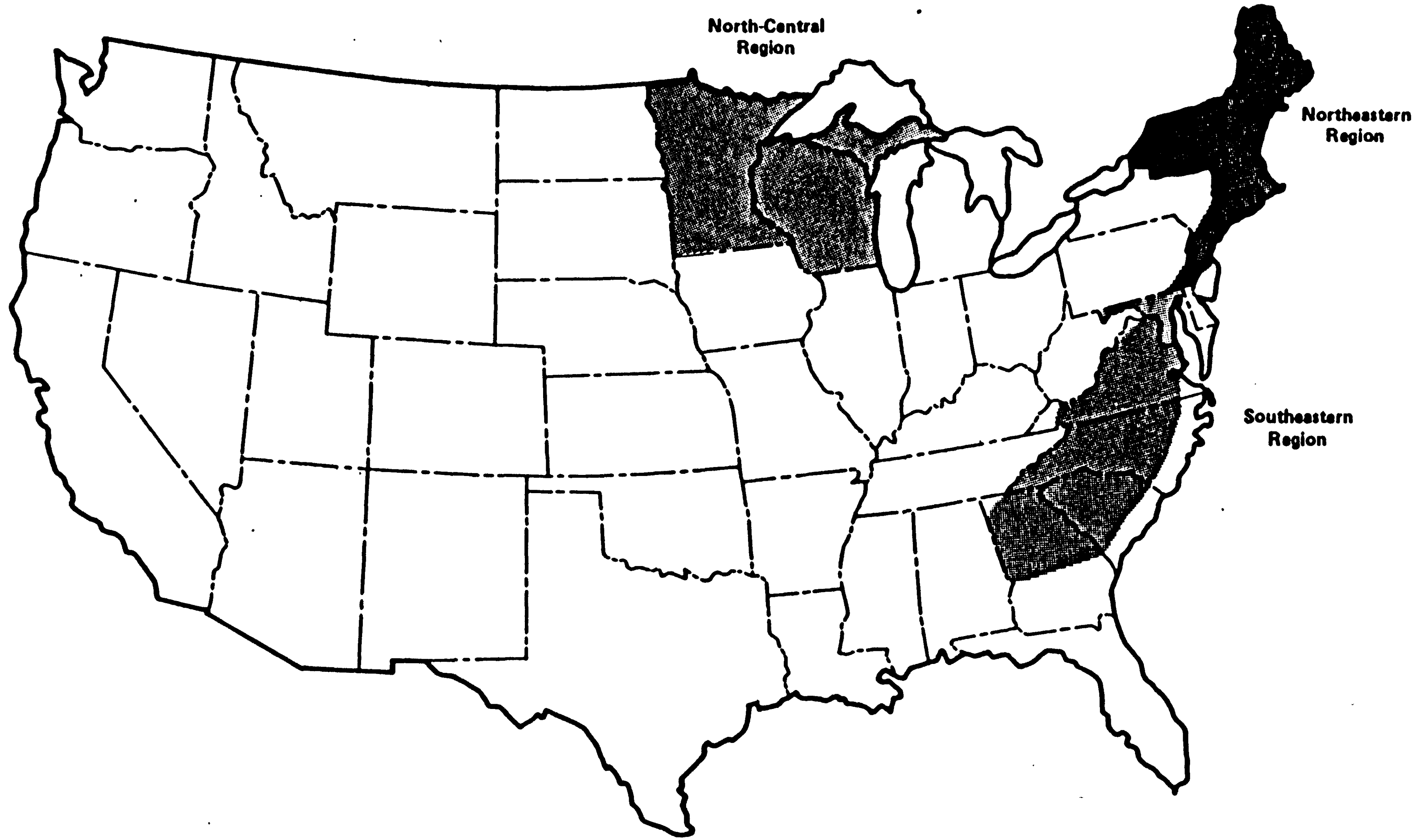
North-Central Region
Northeastern Region
Southeastern Region

Figure 1

Figure 2. Diagrammatic sections showing lines of equal hydraulic head (solid) and flow lines (solid with arrows) for a system in which topography controls regional flow. A. a system with uniform permeability; B. a two-layered system in which the lower part of the section (shaded) is 10 times as permeable as the upper part; C. a system with highly permeable basin fill (shaded) and low permeability consolidated rocks. Local, intermediate and regional flow systems can be delineated in each case (see text). Scale is arbitrary; sections extend from a major discharge zone on the left to a drainage divide on the right.

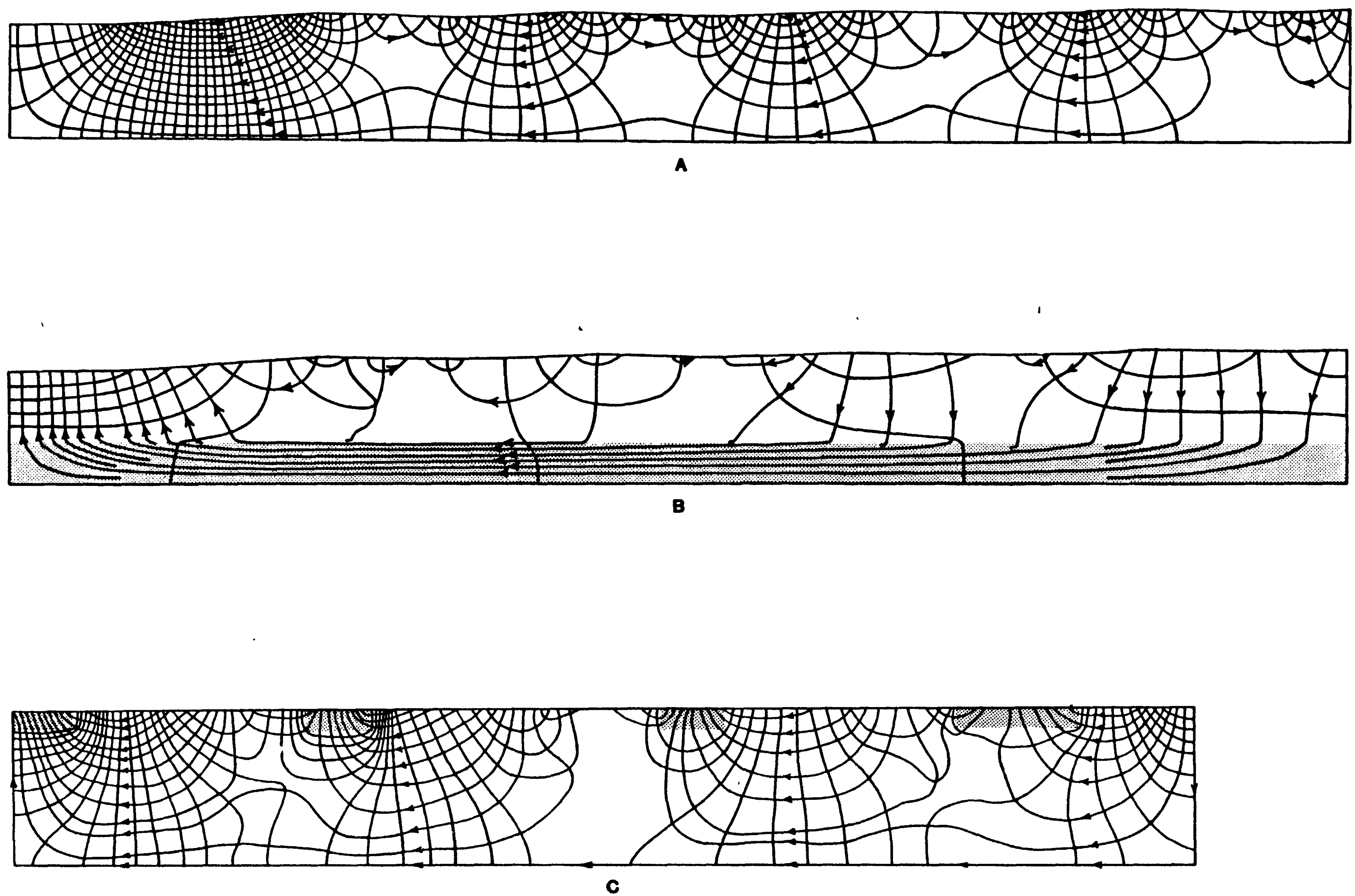


Figure 2

Figure 3. Speculative portrayal of local, intermediate and regional flow systems in crystalline rock terrain in which topography controls regional flow system and major fracture zones and faults control details of flow at depth. In this thrust faulted terrain, subhorizontal fracture zones are assumed to be significant hydrologically. Quite different configurations may be present in other tectonic settings.

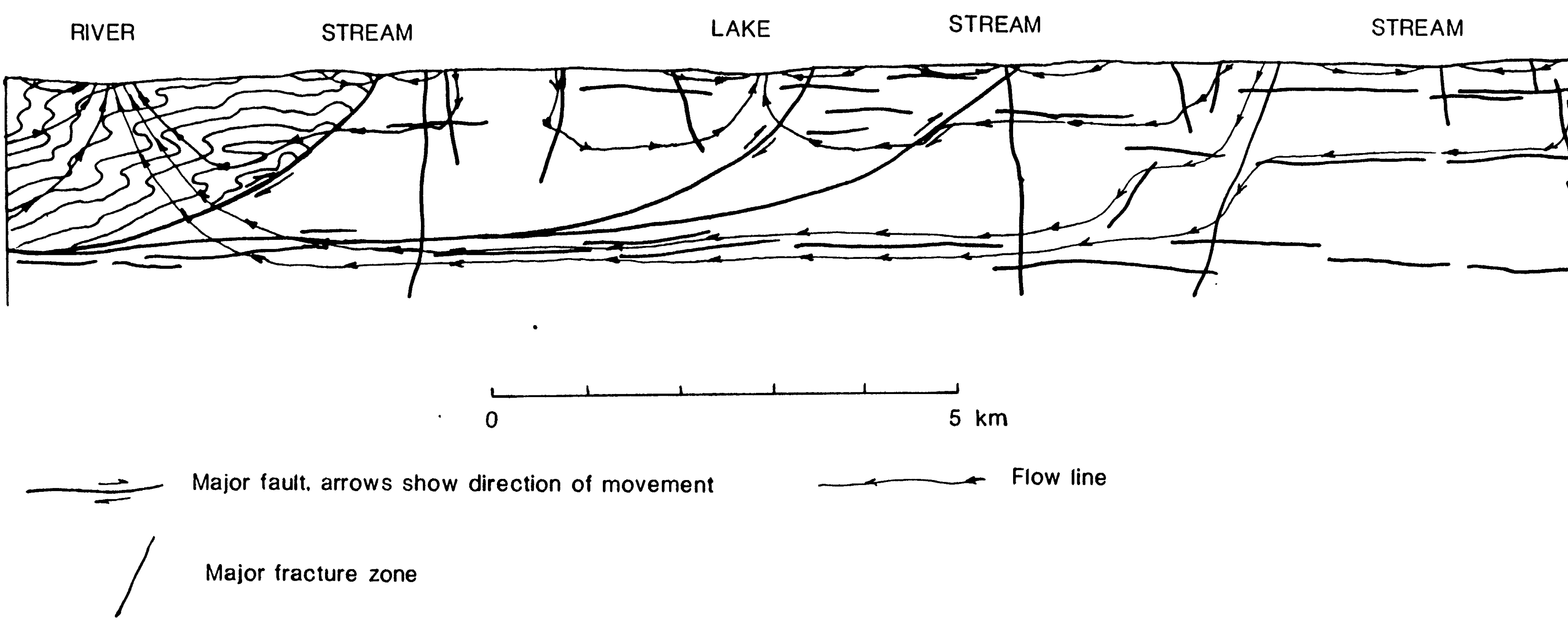
RIVER
STREAM
LAKE
STREAM
STREAM
0
5 km
Major fault, arrows show direction of movement
Flow line
Major fracture zone

Figure 3

Figure 4 Schematic representation of the hydrologically significant elements likely to be encountered at a potential site for a high-level radioactive waste repository in a crystalline rock mass. Heavy solid lines are major fracture zones. Thinner lines are minor fracture zones. No attempt is made to portray individual fractures. Subvertical fracture zones are numerous near the surface becoming less abundant below 30 to 50 m. No scale for the representation is implied. Major subhorizontal fracture zones may occur at any depth or may be absent completely.

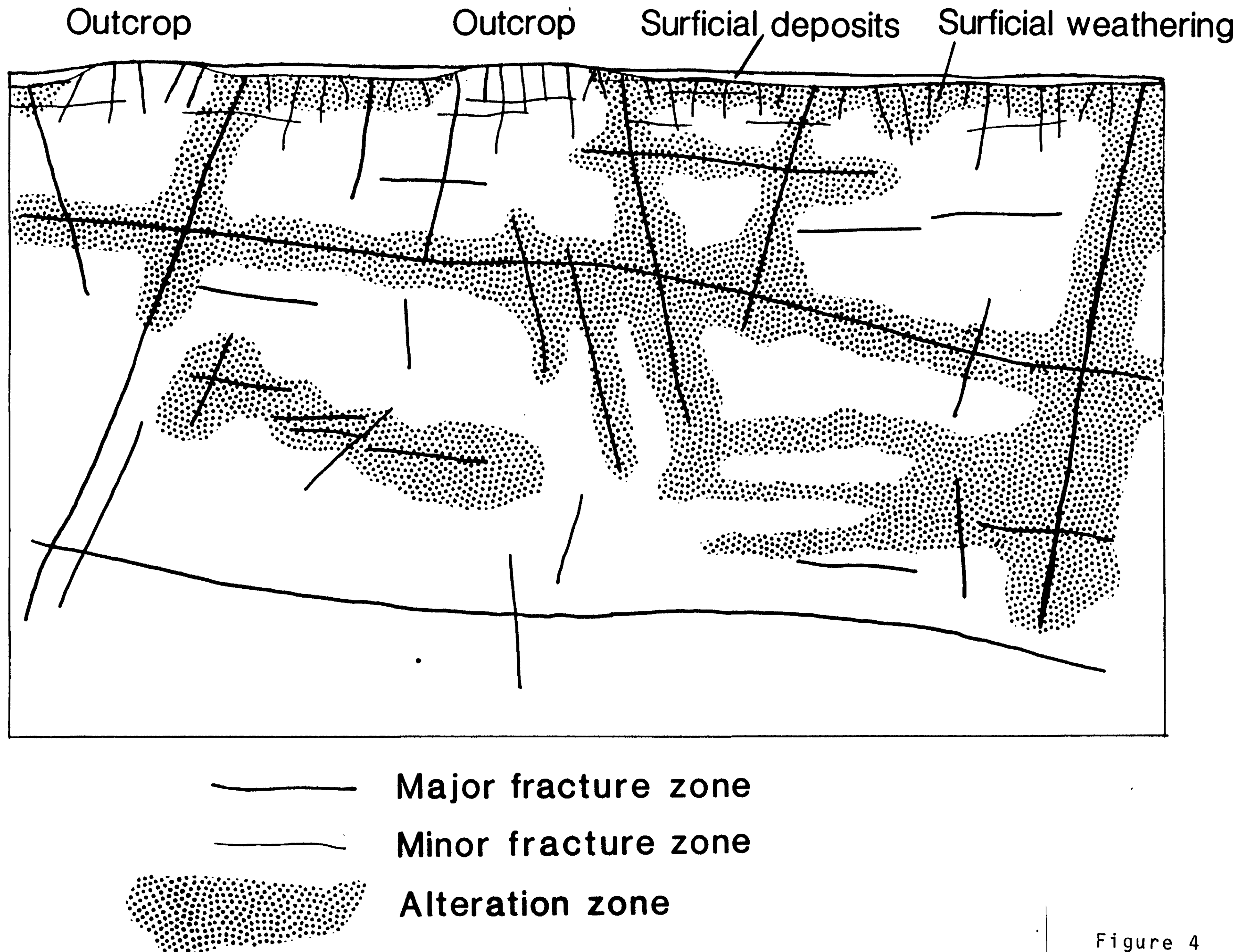
Outcrop
Outcrop
Surficial deposits
Surficial weathering
Major fracture zone
Minor fracture zone
Alteration zone

Figure 4

APPENDIX

# SUMMARY OF INFORMATION FROM DEEP HOLES AND EXCAVATIONS IN THE EAST

## Introduction

Drill holes and excavations to appreciable depths are rare in the crystalline rocks of the North Central, Northeast, and Southeast Regions. Those in which any sort of semi-rigorous hydrologic characterization has been carried out are even fewer. We believe, however, that it is useful to inventory and study in detail the data from available holes and excavations to the extent possible. Generalizations drawn from this survey are summarized in the main body of the report. This appendix provides the basis for them. We discuss data from deep holes in some detail. The information from relatively shallow holes is summarized for a series of holes, e.g. VPI heat flow holes. We include a brief discussion of the Canadian Radwaste Program for the insights it provides to the North Central region.

This compilation is probably far from exhaustive. We would appreciate information leading to additional data from depth in crystalline rocks of the three regions.

## Southeast Region

### Sunshine, Maryland

The Sykesville Formation in northern Montgomery County, Maryland was the site of investigations directed at locating an underground pumped hydro and compressed air storage facility in 1979 and 1980. This rock mass, which at this location is a conglomeratic gneiss of granitoid composition, was under consideration as a site for a high level radioactive waste repository. Three slim holes were drilled to depths of 60, 154, and 992 meters respectively. Severe problems with hole deviation were encountered throughout the operations. The deepest hole was terminated at an angle of $52^{\circ}$ to the vertical at a depth below ground surface of 775 meters (Acres American, 1981). The Sykesville Formation ranges from relatively massive to well foliated and the drill bit consistently deviated to an orientation normal to this foliation.

The fracture density measured in recovered core ranges from 0.3 per meter to 1.0 per meter with some zones of higher density. Many mapped fractures are parallel to the foliation and may have opened up during drillling. No major subhorizontal fractures or fracture zones were encountered (Acres American, 1981).

The permeability coefficient for the more fractured zones encountered is approximately $10^{-12}$ $cm^2$; ($10^{-4}$d) that of the more intact sections of the rock mass is approximately $10^{-15}$ $cm^2$ ($10^{-7}$d) (Acres American, 1981).

## Monticello Reservoir

Two deep holes drilled by the USGS into the Winnsboro plutonic complex to investigate reservoir-induced seismicity near the Virgil Summer nuclear plant at Monticello Reservoir in South Carolina provide insight into conditions likely to be encountered at depth in a crystalline rock mass in this region. The holes (designated Monticello 1 and 2) were drilled primarily to investigate the seismicity; complete geologic and hydrologic characterization was not the purpose. Both wells were drilled to depths of slightly over 1000 m; only a total of approximately 60 m was cored; four measurements of bulk permeability were made over large intervals.

The borehole televiewer was used to measure the density and orientation of fractures throughout both holes. Both the density and the orientation of fractures differ considerably between the two holes and at various depths in each hole individually (Zoback and Hickman, 1982). The density of fractures in both holes is broadly similar to that measured from outcrops of the Winnsboro plutonic complex nearby (about 2 per 5 m), although the density in Monticello 2 (250/500 m) is approximately twice that in Monticello 1 (100/500 m). Secor and others (1982) found considerable variation in the orientations of fractures in outcrops in the vicinity of the two holes. A significant number of fractures in both wells are subhorizontal; about half of the subhorizontal fractures were found in the upper 300 m of each well, although in both wells several subhorizontal fractures were found at depths greater than 1000 m (Zoback and Hickman, 1982).

The wells were drilled with an air hammer rig; and because the holes were not intended to be water wells, no device to measure water quantity was available. Water-bearing zones were identified by the geologist sitting on the well by noting the presence of water in the returns; for some zones a rough estimate of water yield could be made. Five water-bearing zones were noted in Monticello 1 and either 3 or 4 in Monticello 2 (D.C. Prowell, USGS, pers. commun., 1983). There were no water-bearing zones below 630 m in Monticello 1 or below 550 m in Monticello 2. The highest water yields were greater than 500 gpm. Correlation of the water bearing zones between the two wells was not possible because of limited hydrologic testing and logging, although some of the zones occurred at approximately the same depth in the two wells.

Pore pressure measurements indicate that except in two zones in Monticello 2, pore pressures are lower than hydrostatic. This observation suggests that this area is a recharge and not a discharge area. Zoback and Hickman (1982) suggested that the two zones of higher pore pressures in Monticello 2 were due to increased water pressure consequent on filling of the reservoir and implying a hydrologic connection between the reservoir and depths of 300 to 400 m, although this could not be demonstrated conclusively.

To better understand the migration of seismicity with time, Zoback and Hickman (1982) measured the bulk permeability over three relatively large intervals in Monticello 2 and over one interval in Monticello 1 by means of the "slug test" method (Bredehoeft and Papadopolus, 1980). There are numerous uncertainties in applying this method to fractured rock; however, the tests gave reasonably consistent values ranging from $10^{-5}$ to $10^{-3}$ darcy (d) over intervals as great as 330 m. Furthermore, the time between reservoir impoundment and the onset of seismicity can be used to estimate bulk permeability independently according to a theory tested at a number of reservoir-induced seismicity sites. For the Monticello Reservoir area, the calculated bulk permeability according to this theory is also $10^{-3}$d (Zoback and Hickman, 1982). The fact that as of 1979, the seismicity had ceased to migrate away from the original epicenters around the reservoir also led Zoback and Hickman (1982) to conclude that there is no hydraulic connection beyond about 4 to 5 km from the reservoir.

The main conclusions to be drawn from the experience at Monticello Reservoir relative to a strategy for exploration for high level radioactive waste repositories are:

1. In this area, measurements of fracture orientation and density at the surface give a rough indication of overall fracture density but are of no value in predicting either orientation or density at specific depths.
2. Subhorizontal fractures, which cannot be studied at the surface, occur in both wells at depths as great as 600 m and may be water bearing.
3. The bulk hydraulic properties in this area are such that upward or horizontal water movement is probably quite restricted although numerous additional tests would be needed to verify this conclusion.

VPI geothermal holes

During the mid to late 1970s, the Orogenic Studies Laboratory of Virginia Polytechnic Institute and State University (VPI&SU) drilled some 20 holes into exposed and buried plutons of the southeast Piedmont and Coastal Plain as part of the ERDA geothermal program (Becker, 1978, 1984; Bourland, 1978; Farrar, 1977a, b; Speer, 1977). Most of the holes bottomed at about 200 m - too shallow to give direct information about repository depths, yet deep enough to provide some insight into the nature of the rock at depth. The holes were cored and logged geophysically; no hydrologic tests were possible. The VPI&SU reports mention the occurrence of major fracture and alteration zones, but all of the fractures were logged in only one hole, Petersburg 2 (1300 fractures/500 m).

According to the VPI&SU reports, shear and fracture zones and extensive rock alteration are common in the upper parts of most of the plutons that were drilled. The investigators were seeking relatively fresh rock in which to make heat flow measurements, but most of the drill holes, located on the basis of field reconnaissance, encountered substantial thicknesses of altered or fractured rock. Whether intensive surface geophysical measurements could have optimized the locations to a greater extent than was done is not known. The fracture and shear zones range in thickness up to 8 m and encompass masses of brecciated and slickensided rock; vein fillings of feldspar, quartz, chlorite, calcite, zeolites, and fluorite have recemented the original openings. Whether the resulting rock is completely tight is not known. The alteration zones range up to 100 m in thickness. The altered rocks have a greenschist metamorphic facies and are light red, spotted with bright green chlorite and epidote. Most alteration zones occur in the vicinity of fracture zones, but some do not. Spacing between alteration zones ranges from 10 to 75 m. Geochemical evidence indicates that uranium has migrated along at least some of the alteration zones.

A few of the holes showed little in the way of fracture or alteration zones. Core from one hole in the Castalia body had little alteration below 80 m to total depth of 220 m (Farrar, 1977). Two of three cores from the Rolesville are only slightly fractured or altered to total depth of 220 m. A third core is highly altered from the surface to the same total depth (Farrar, 1977).

The numerous shear and fracture zones encountered by the VPI&SU heat flow holes may be part of the eastern Piedmont fault system (Hatcher and others, 1977). Most of the plutons drilled by them are located in its general vicinity. Typically, more faults have been noted in the subsurface in the vicinity of major fault systems than have been mapped at the surface (Healey and Urban, 1983).

## Tirzah propane storage facility

Though relatively shallow at 150 m, this excavation, 7 km east of York, S.C., provides insight into underground conditions in the older metamorphosed plutonic rocks of the Charlotte belt of North and South Carolina. Rocks at the site consist of diorite, leucodiorite, and granodiorite, intruded by mafic dikes, and metamorphosed to amphibolite facies (Butler, 1976). The present mineral assemblage of the plutonic rocks includes epidote, calcite, chlorite, and actinolite, products of metamorphism near the greenschist-amphibolite facies boundary. The rocks have been recrystallized but are not now foliated. Several chlorite-rich shear zones up to 50 cm thick have attitudes which are generally the same as those of the mafic dikes (Butler, 1976). The shear zones are surrounded by alteration zones in the rocks that have been retrograded to assemblages typical of lower greenschist facies. Late stage brittle fractures filled with zeolites and calcite cut the shear zones.

A photograph of part of the cavern taken before filling shows what appears to sound rock cut by numerous fracture planes (Nystrom, 1976). Only a small amount of water is shown on the floor. Pressure tests in zones packed off in test holes at depths of 110 to 150 m indicated small amounts of water flow. Two of the flows occurred at the site of lithologic discontinuities - a quartz vein and a mafic dike - and two occurred at the site of small fractures (Nystrom, 1976).

Greater Atlanta groundwater study

One of the few systematic inventories of water wells in crystalline rock terrains was made in the Greater Atlanta area by Cressler and others (1983). Substantial water production is obtained from rocks of the Inner Piedmont, Brevard zone, and Blue Ridge, including some rock masses which are under consideration for a high level radioactive waste repository. However, all of the production is from depths that are shallower than repository depths.

In all, Cressler and others (1983) studied 1,051 high yield wells - those that supply 20 gallons per minute or more. Some of the highest yielding wells were relatively deep - up to 200 m. Some wells, as much as 300 to 400 m deep, did not have high yields. The high-yielding wells produced water from contact zones, fault zones, stress relief fractures (subhorizontal fractures), subvertical fracture zones, small scale structures that localize drainage, folds that produce concentrated jointing, and shear zones. That such features are good places to look for water supplies in crystalline rocks at relatively shallow depths has long been known. What is significant about the Greater Atlanta study is the importance ascribed to subhorizontal fractures in supplying water from depths as great as 170 m.

The authors note that, contrary to conventional wisdom, a significant number of high yielding wells are located on steep slopes, divides, or topographic highs, some with substantial outcrops of bare rock. These locations did not appear to be the site of subvertical faults or fracture zones, and the authors suspected that the wells might be producing from subhorizontal fractures. To check this hypothesis, they ran sonic televiewer logs in selected high yield wells; the water-yielding fractures in these wells are subhorizontal. Core from two of these wells confirmed the subhorizontal attitude of the openings (Cressler and others, 1983). The authors suggest in addition that numerous other wells are producing from subhorizontal fractures even though geophysical logs and cores are not available to confirm this. These wells were dry during drilling until encountering large volumes of water flow at depths ranging from 60 to 170 m. They were located on saddles, stream divides or the heads of draws and streams. Several produce water from the Lithonia gneiss, a body under consideration for a high level radioactive waste repository, from depths of 40 to 170 m.

Apart from subhorizontal fractures and fracture zones, Cressler and others (1983) found the greatest water yields in the crystalline rocks of the Greater Atlanta area to be from the flinty crushed rock found in major shear zones. Rock masses with contrasting rock types such as schist and quartzite may also be water bearing with high yields at the contacts between them.

## Northeast Region

### Heat flow holes

During the 1950s and 1960s, 18 holes were drilled in the crystalline rocks of New England and the Adirondacks for the purpose of determining heat flow (Birch and others, 1968). The holes were 5 cm in diameter and ranged in depth from 300 to 600 m. In almost all of the holes, egress or ingress of fluid was noted at some time during drilling (W. H. Diment, USGS, pers. commun., 1983). However, systematic studies of hydrology were neither contemplated nor possible at the time.

Cores from three of these holes in storage at Harvard University were examined by G. W. Leo, USGS, in 1984, who provided the following brief summaries:

1. Casco, Maine: near center of Sebago Lake batholith, N. Lat. 44°03', W. Long. 70°37', T. D. 300 m.

Most of the core consists of homogeneous granite with a few pegmatites and mafic dikes. Fractures and alteration zones, apparently related, occur throughout, but there are intervals of unfractured and unaltered rock as much as 60 m thick. Most of the fractures appear to be subvertical below 30 m. Fractures at depth are clustered with a spacing of a few centimeters within clusters. Chlorite is present in many of the fractures.

2. Durham, N.H.: along northwest ridge of Exeter diorite, N. Lat. 43°07', W. Long. 70°55', T. D. 305 m.

The core is abundantly fractured quartz diorite to granodiorite throughout much of its length; there is a 20 m segment near the bottom that is unfractured but which does contain mafic dikes. Subhorizontal fractures are present in the upper 100 m only. Both open and closed fractures were observed with most of the fractures at depth appearing closed or filled with calcite and chlorite. Fractures are clustered. The spacing ranges from 2 cm in fracture zones to several meters for isolated fractures.

3. North Haverhill, N. H., French Pond granite, N. Lat 44°06', W. Long. 72°00', T. D. 240 m.

This rock mass is too small for inclusion in the regional inventory of crystalline rock masses. The core is notable for the abundance of subhorizontal fractures throughout; this suggests that this area in northwest New Hampshire may have a high ratio of subhorizontal to vertical stress.

## Redstone Quarry, N.H.

A 1000 m hole was drilled in the Conway granite at the Redstone Quarry just outside North Conway under the auspices of the Energy Research and Development Agency in 1975 as part of the geothermal program. Nearly complete, 5 cm core was recovered and described in detail, and several logging devices were run in the hole (Hoag and Stewart, 1977). No hydrologic tests were made nor were there any estimates of the water-bearing capacity of any of the rocks encountered. Some water flow at depth was noted (W. S. Keys, USGS, pers. commun. to W. H. Diment).

The hole, spudded in the quarry, encountered four principal members of the White Mountain magma series (Billings, 1956): red Conway granite, green Conway granite, Albany quartz syenite, and a hastingsite-biotite granite. Contacts between the members had shallow dips but were not the site of any more fractures than elsewhere in the hole. In addition, the hole encountered numerous dikes of aplite, fine-grained granite and lamprophyre, mostly with steep dips. The dikes were not the site of increased fracture density (Hoag and Stewart, 1977).

Fractures were mapped throughout the core. Subhorizontal fractures are abundant near the surface, but are less abundant at depth and rare below 100 m. The overall density of subvertical fractures is about the same throughout the hole although there is distinct clustering, varying from .4 fractures/m to .04 fractures/m. Intervals as large as 33 m are without fractures. Because the core was not oriented, detailed information on fracture orientation is not available.

Numerous alteration zones were also encountered at all depths. Some of these coincide with zones of high fracture density and others do not. The thickness of the alteration zones ranged from 1 to 50 m. Albite, chlorite, sericite, and clay minerals are abundant in the alteration zones; and in some, quartz has been removed leaving a system of cavities. Calcite fills some fractures in the alteration zones. Uranium content varies considerably within the alteration zones indicating that there has been transport of that radionuclide within the rock mass.

Hoag and Stewart (1977) concluded that the Conway granite has the physical and chemical properties necessary for the formation of vein-type uranium deposits.

## North Central Region

### Stephenson County, Il.

Two deep holes were drilled into a buried anorogenic pluton in Stephenson County, Illinois, on the north flank of the Illinois Basin in 1979 and 1980, as part of a pumped storage project. The holes, designated UPH-2 and UPH-3 are 1 km apart. Both holes encountered granite under Paleozoic sedimentary rocks at depths of about 600 m, and each penetrated approximately 1000 m of the buried pluton. Both holes were cored. Geophysical logs and hydrologic tests were run in UPH-3 only. The rocks encountered are similar in petrography, age, and geophysical expression to a series of 1400 m.y. anorogenic plutons extending from New Mexico to the Canadian shield (Lidiak and Denison, 1983) including the exposed Wolf River batholith of Wisconsin, which is under consideration for a high level radioactive waste repository.

The rock is mostly a medium- to coarse-grained porphyritic biotite granite; a gneissic granite occurs in the upper 60 m of the buried granite in UPH-3. Cataclastic shear surfaces are present in both rock types.

The fracture distributions in the two holes are similar but not identical (Haimson and Doe, 1983) (500/500 m in UPH 2; 350/500 m in UPH 3). Both cores have a high concentration of fractures around depths of 1300 m. These concentrations could be the expression of a subhorizontal fracture zone that intersects both holes, but such a correlation cannot be firm in the absence of geophysical logs for UPH-2. The lower 300 m of UPH-3 is almost devoid of fractures; considerably more fractures are present in the same interval in UPH-2. Information on fracture orientation is sketchy. The division between subhorizontal and subvertical fractures is not clear in the report of Haimson and Doe (1983). A few of the steeply-dipping fractures in the UPH-3 core could be oriented and their orientations agreed with those of fractures in outcrops and shallow holes to the north in Wisconsin (Haimson and Doe, 1983).

Permeability measurements were made in UPH-3 but are of limited application to the radwaste program because of the great depths. The fracture zone near 1300 m in UPH-3 appears to have a higher permeability than the tight sections above and below it. The value of its permeability measured by different methods ranges from $4.1 \times 10^{-6}$ to $4.7 \times 10^{-7}$ d. A zone of fractures near the top of the granite has a permeability $7.4 \times 10^{-5}$ to $2.0 \times 10^{-5}$d. These values are considerably lower than the measured permeabilities of the upper parts of granites exposed at the surface. Haimson and Doe (1983) ascribe the decrease both to higher stress at depth and to filling and healing of the fractures formed when the granite was near the surface.

Pore fluid eluted from core taken at a depth of 1288 m is predominantly a $NaCl$ and $CaCl_2$ brine (Couture and others, 1983).

### Montello granite

A 200 meter hole was drilled into the Montello granite of south-central Wisconsin as part of an exploration program for the location of energy storage facilities. The Montello granite is not under consideration as the site of a high level radioactive waste repository.

Fracture density ranges from 1.0 to 0.3 /m in the core. Three sets of vertical fractures have orientations similar to those in the Stephenson County, Illinois, deep hole. A fourth set of fractures is subhorizontal. The Rock Quality Designation (RQD) was uniformly high except for a 10-m-zone at the base of the hole (LaPointe and Haimson, 1983). The zone of poor RQD could indicate a fracture zone.

### Canadian Radioactive Waste Program

The Canadian program for handling radioactive waste emphasizes at the present stage investigation of subsurface conditions at five research areas. The program at four sites involves extensive geophysics and deep drilling; at a fifth site, there will be, in addition, an underground research laboratory in which _in situ_ measurements and experiments will be carried out at repository depths. When this program is completed, the Canadians will have an excellent picture of subsurface conditions on the southern part of the Canadian shield. Deep boreholes are too numrous to discuss individually, and we summarize only briefly the major findings at three of the five areas where investigations are most advanced.

The site of the Underground Research Laboratory (URL), 20 km north of Pinawa within the Lac du Bonnet batholith, is the best known of the five sites. The rock at depth is not highly fractured, and most of the fractures logged in the various drill holes are closed. Water flow appears to be dominated by three subhorizontal zones of intense fracturing and alteration. The deepest of these is at 600 m. An intermediate zone at an average depth of 300 m has been extensively tested. Its hydraulic conductivity varies considerably and is as high as $10^{-2}$ cm/sec in some zones and as low as $10^{-8}$ cm/sec in others (C. C. Davison, oral presentation, 17th Information Meeting of the Canadian Nuclear Fuel Waste Management Program, 1984). Hydraulic head distributions indicate that at least the upper and intermediate fracture zones are connected. Water flows from the upper to the intermediate fracture zones. Pumping in one hole is known to have affected the flow in the fracture zone in nearby holes (Keys, 1984). An interesting result of Keys (1984) is that the size of a discrete fracture in the fracture zone does not correlate with the volume of the flow of water. Some of the larger discrete fractures in the fracture zone are apparently extensively filled. There is some concentration of U and Th along the fracture zoness. Uranium series disequilibrium studies corroborate that U has been removed from the rock and has entered the groundwater (M. Gascoyne, oral presentation, 17th Information Meeting of the Canadian Nuclear Fuel Waste Management Program, 1984). Water in the intermediate fracture zone is highly saline (Green and Soonawala, 1982).

Several holes have been drilled in the same Lac du Bonnet batholith to the south of the URL site at the Whiteshell Nuclear Research Establishment (WNRE). Several shallow dipping fracture zones characterize the rock at that site (Green and Soonawala, 1982). However, uranium disequilibrium studies indicate that there has been no migration of uranium or thorium from the rock into the groundwater in the fracture zones (M. Gascoyne, oral presentation, 17th Information Meeting of the Canadian Nuclear Fuel Waste Management Program, 1984).

The Atikokan site is notable in that the rock at the site, a hornblende granite, is intensely fractured both at the surface and at depth. In one hole, 5,000 fractures were logged over 1152 meters of core (Green and Soonawala, 1982). However, most of the fractures appear to have formed shortly after emplacement of the pluton at relatively high temperatures, and most are not water-bearing (Kamineni and Dugal, 1982). The composition of the deep saline waters and uranium disequilibrium studies suggest only minimal water movement at depth (Z. E. Peterman, USGS, pers. commun., 1984).

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