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*Disposition of Excess Weapon Plutonium
in Deep Boreholes*

Site Selection Handbook

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Los Alamos
NATIONAL LABORATORY

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*Grant Heiken
Giday Woldegabriel
Richard Morley
Harry Plannerer
John Rowley*



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Los Alamos
NATIONAL LABORATORY

Los Alamos, New Mexico 87545

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by

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ABSTRACT

One of the options for disposing of excess weapons plutonium is to place it near the base of deep boreholes in stable crystalline rocks. The technology needed to begin designing this means of disposition already exists, and there are many attractive sites available within the conterminous United States. There are even more potential sites for this option within Russia.

The successful design of a borehole system must address two criteria:

- (1) how to dispose of 50 metric tons of weapons plutonium while making it inaccessible for unauthorized retrieval, and
- (2) how to prevent contamination of the accessible biosphere, defined here as the Earth's surface and usable groundwaters.

The required time frame for this isolation cannot be specified at this time, since it is unclear which regulations might be applied (National Research Council, 1992). However, consideration of the half-lives (Lide, 1995) of ^{239}Pu (2.4×10^4 yr) and its fissile daughter uranium (7×10^4 yr), indicates that a projection as far as possible into the future would be useful. This can be carried to an extreme, and is brought into better perspective when events on equivalent past timescales are compared to future events (Chapman and McKinley, 1987). The nonretrievability requirement is easily met by the emplacement design and the extreme depth. Two key performance issues must be examined:

- (1) whether there is migration to the biosphere, and
- (2) the processes involving siting and the selected natural systems.

The borehole system uses mainly natural barriers to prevent migration of plutonium and uranium to the Earth's surface. Careful site selection ensures favorable geologic conditions that provide natural long-lived migration barriers. These conditions include deep, extremely stable rock formations, strongly reducing groundwaters (brines) that exhibit increasing salinity with depth, and most importantly, demonstrated isolation or noncommunication with the biosphere for millions of years. Isolation is the most important characteristic; the other conditions are chiefly those that will enhance the potential of locating and maintaining the isolated zones. The expected site will probably be located on the craton in very old Precambrian crystalline rocks, most likely the center of a granitic pluton. The site will be located in a tectonically stable area with no recent volcanic or seismic activity and will be situated away from tectonic features that might become active in the near geologic future, such as intracratonic uplifts or plate boundaries.

PART I ENGINEERED SYSTEM DESCRIPTION

The engineered part of the borehole system consists of one or more boreholes drilled to a nominal design depth of 4 km; the plutonium is emplaced in the lowermost 2 km. The exact depths will depend on detailed downhole examination of the yet-to-be-selected site. The drilling system will be designed to be as noninvasive as possible to minimize formation damage — and therefore damage to the desirable isolating properties. A canisterless system will be used, consisting of the plutonium wastefrom loaded into drillpipe. The system differs from other radwaste designs in that it does not rely on a long-lived canister to delay the release of the wastefrom to the borehole environment. Survival times for most canister materials are thought to be short when compared with history of the surrounding rocks, so common drill pipe is used for emplacement purposes only. The pipe is expected to rapidly corrode away under the downhole conditions, scavenging any available oxygen as it corrodes. The pipe will be surrounded by a bentonite/aggregate backfill to provide an additional hydraulic barrier with mechanical strength. The wastefrom will be either some form of plutonium oxide or synrock. Synrock is a plutonium-doped synthetic ceramic that has the mineral structure of a zirconolite and is extremely stable over geologic timespans. The plutonium oxide is functionally insoluble in reducing conditions and performs almost as well under oxidizing conditions. The plutonium will decay into uranium over time, gradually changing the plutonium oxide into uranium oxide; the synrock should be unaffected by the decay. Finally, a series of plugs and seals will be emplaced throughout the emplacement zone to provide mechanical separation and retard or prevent any vertical transport. The upper half of the hole will be designed as a massive series of isolation seals to prevent direct release to the accessible environment.

Another potential feature being considered is the addition of large amounts of depleted uranium to the backfill. This will provide isotopic dilution of uranium as it increases from alpha decay of the plutonium. The question raised by this approach is: if the plutonium is immobile, what would happen if the depleted uranium migrates away before the plutonium decays significantly? Natural analog studies of "fossil reactors" may help constrain the relative migration rates.

Because experience with man-made materials is limited to short timespans, emplaced materials and seals will be chosen to either be or mimic natural substances that have an observed performance history for geologic timespans. These materials may include natural bentonite backfill, rock plugs sintered in place with rock melting tools, the zirconolite wastefrom, and specially formulated cements.

Definitions

Pluton: Includes all intrusive igneous rocks, usually a mass of more silicic magma (e.g., granite, granodiorite, diorite) intruded into the shallow (less than 20 km depth) Earth's crust. Plutons associated with concentric dike systems may have underlain a caldera at the Earth's surface; these are commonly associated with large volcanic fields also at the surface. Map scale ranges from tens to hundreds of km². In map view, these range from nearly circular to oval, to polygonal (where there is strong structural control of the shape).

Batholith: Large, intrusive bodies with steeply dipping walls, covering hundreds to thousands of km², composed of overlapping silicic plutons. The growth of a batholith can span millions of years.

Craton: "A part of the Earth's continental crust that has attained stability and has been little deformed for a prolonged period" — AGI Glossary.

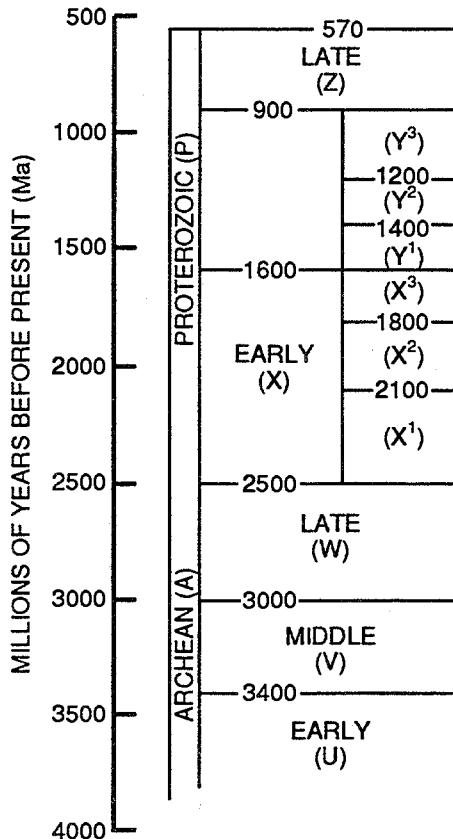
Archean: Time period from >3.4 to 2.5 billion years before present (Fig. 1).

Ga: Giga-annum — a billion years.

Proterozoic: Time period from 2.5 to 0.57 billion years before present (Fig. 1).

Phanerozoic: Time period from 0.57 billion years before the present to the present (Fig. 1).

Fig. 1. Decade of North American Geology time scale for Precambrian Rocks. The subdivisions of the Early and Middle Proterozoic have recently been adopted by the US Geological Survey (adapted from Reed et al., 1993). It is the plutonic rocks emplaced during these times that will be targeted for site evaluation.



The key performance question, stated previously, is: Can the borehole system effectively isolate the wastes from the accessible environment for millions of years? This can also be expressed as: If an isolated system can be found, is it possible to emplace the waste without disturbing the natural isolating features, and will these features continue to provide isolation for an equivalent geologic timespan? These questions immediately spawn several other obvious performance questions, such as:

- Can the system really contain the wastes forever?
If not, how long is the actual containment period?
- Under what scenarios, both expected and abnormal, can a release occur, and what is the magnitude and timing of the release?
- If a release occurs, will it reach the accessible environment, in what amounts, and with what effects on the biosphere?
- ^{239}Pu decays to ^{235}U — what effect does this have on the borehole system and natural transport phenomena?
- Are there any credible scenarios leading to criticality, and if so, how would a criticality event affect isolation?
- Even if there is never a release, how does the system evolve over time?

A complete performance assessment scenario development is beyond the scope of this document (see, for example, Rechard, 1995). However, the above simple questions should be sufficient to examine the types of natural features required to achieve adequate performance of the borehole. The borehole-siting effort is designed to locate and evaluate these features.

PART 2

SEARCH FOR APPROPRIATE DISPOSAL SITES FOR SURPLUS FISSILE MATERIALS

I. Plutonic Rocks of Stable Cratons

A Very Deep Borehole for disposition of Surplus Fissile Materials (VDB-SFM) site consists of the ideal combination of:

- (1) crystalline rock at the surface or within 1 km of the surface,
- (2) a region that is tectonically stable,
- (3) an area located away from population centers, and
- (4) a region not near international borders ("near" = 200 km).

At an ideal site for borehole disposition of surplus fissile materials (SFM), it must be demonstrated that there is no fluid movement from the bottom of the borehole at a depth of 4 kilometers and there will be no significant migration over the next million years. (For definitions of the terms used in this discussion, see Fig. 1).

An ideal area for a VDB repository is on the Canadian Shield, a large, tectonically stable area of "basement" rocks exposed by glaciation of a craton (stable continental mass). The shield continues into the northern United States, where it is exposed over large areas or is buried by a relatively thin sedimentary cover over even larger areas of the US. Plutonic rocks within the shield area are excellent targets because of their relatively uniform nature. Large plutons (tens of kilometers wide) appear to be no more than 10 km thick. If a repository is sited within a pluton that has been deeply eroded, it might be possible to drill through the pluton's base, especially if a drillsite is located near its margins. If more information is required on pluton geometries before siting a repository, there are well-exposed analogues in northern Ireland, Nigeria, and Peru that could be studied. Whole plutonic-volcanic complexes that have been tectonically rotated 90° and then eroded to expose geometries are accessible in Canada, southern Arizona, and Saudi Arabia.

Plutonic rocks are emplaced as the magma body rises buoyantly, either by ductile deformation of surrounding rocks, ingestion of blocks of surrounding rocks, or both. Once emplaced and when any surface volcanic activity ceases, these large masses of silicic magma cool slowly. Cooling to ambient crustal temperatures can take several million years. The resultant product is a coarsely crystalline rock that is strong except where fractured by faulting or in the near-surface (upper 1 kilometer of the Earth's crust). Rocks surrounding the plutons and even the pluton tops (after solidification) can be fractured brittlely, but most fractures are filled with secondary minerals deposited by short-lived geothermal systems.

A. Location

About 90% of the conterminous US is underlain by Precambrian Rocks, which make up the continental crust (Reed and Harrison, 1993). Exposures of these rocks are found over about 10% of the US, but large areas of the "basement" are covered by less than 1 km of sedimentary and volcanic rocks.

Numerous 1.5- to 1.3-Ga granite-rhyolite plutonic complexes have intruded the older Proterozoic continental crust of the US (Fig. 2a; Van Schmus *et al.*, 1993). These authors based their reconstruction of the Precambrian basement on outcrops and cuttings and cores from several thousand drillholes across the central US (Fig.2b; Van Schmus *et al.*, 1993). Seismic reflection surveys also support proposed widespread granite-rhyolite provinces across the central US (Pratt *et al.*, 1989); these authors also propose that the rock sequences may be as thick as 11 km.

Within the Midcontinent of the US, between the Rocky Mountains and the Appalachian Mountains, there is an approximate area of at least 2,600,00 km² of accessible Precambrian basement within 1 km of the surface or at the surface (Fig. 2c). This is a large resource that could be used for deep storage. A summary of the distribution of Precambrian basement is given here.

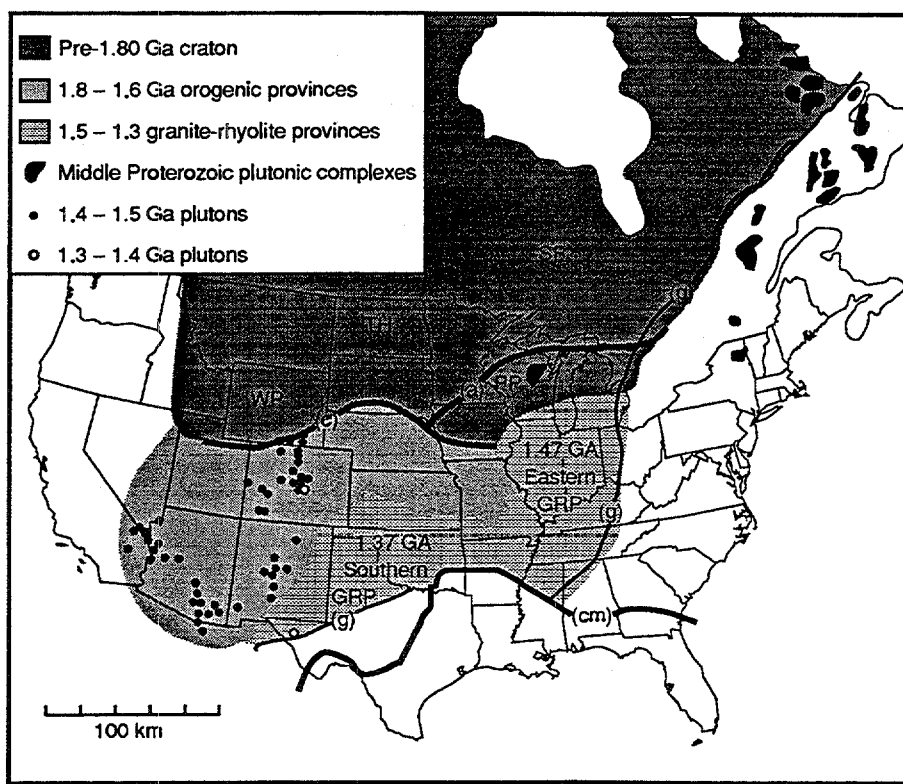


Fig. 2a. Distribution of Middle Proterozoic granite-rhyolite provinces — 1.5- to 1.3 Ga (billion years) intruded into older Proterozoic crust and Middle Proterozoic anorthosite massifs in North America. SP, Superior province; WP, Wyoming province; TH, Trans-Hudson orogen; PP, Penokean orogen; (a) edge of Archean craton in the Great Lakes area; (c) Cheyenne belt; (g) Grenville-Llano front; (cm) late paleozoic continental margin (from Van Schmus *et al.*, 1993).

Fig. 2b. Map of the Midcontinent region of the US, showing drillholes that have reached basement rocks. Many of the data from Fig. 2a were derived from samples collected in these drillholes (from Van Schmus *et al.*, 1993).

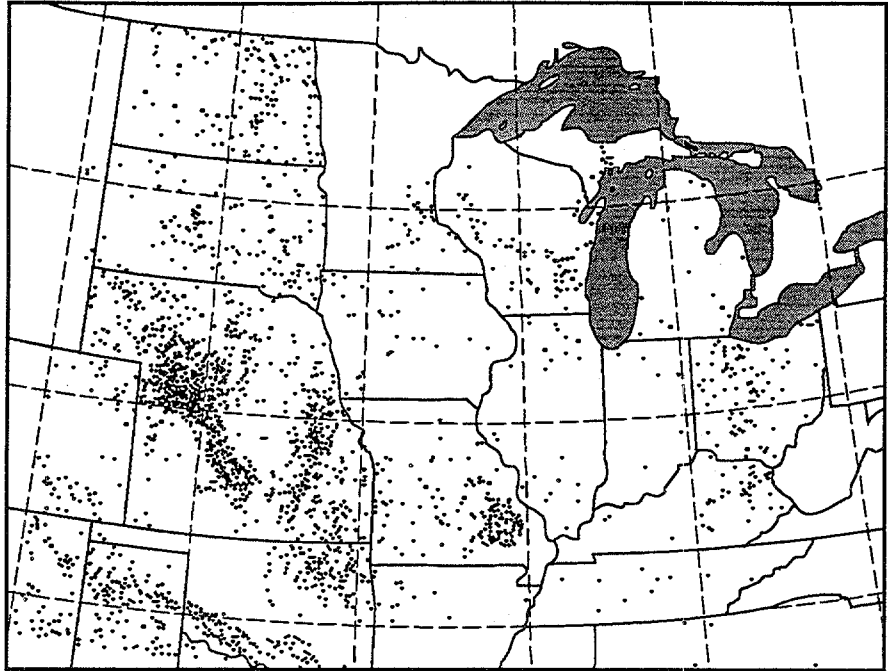
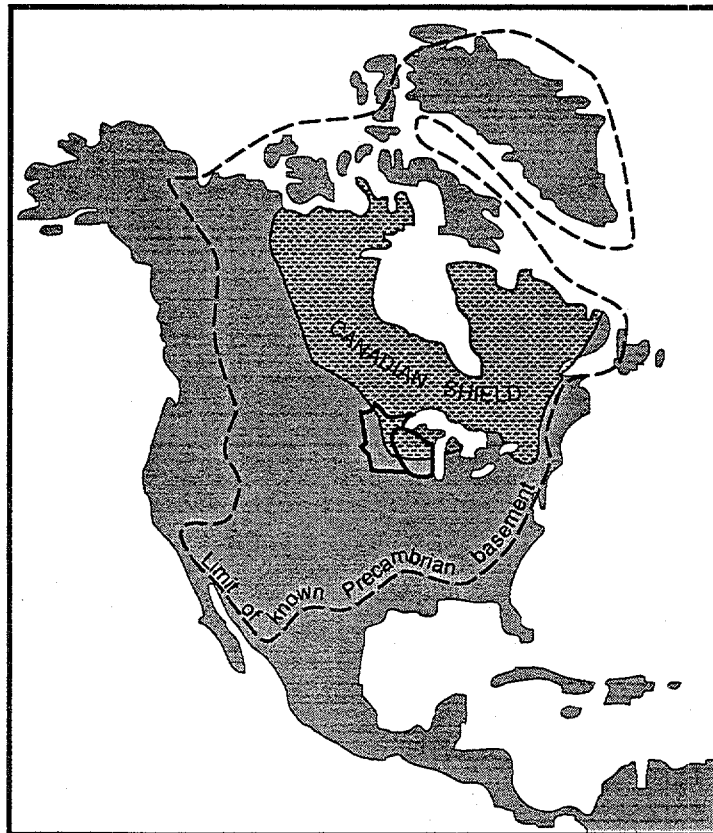


Fig. 2c. Outcrops of Canadian Shield (dashed) and limits of known Precambrian crystalline basement rocks, identified in outcrops or drillholes (from Sims *et al.*, 1993).



1. **New England and Upstate New York.** Large areas of moderately stable, crystalline rock are exposed across much of upstate New York, New Hampshire, and Vermont. The southern part of this area is densely populated, and the northern part is near the Canadian border. South-central Maine and the Adirondack Mountains of New York meet the criteria, but there are few federal facilities with site control. There is a surprising amount of tectonic activity in upstate New York and across central New England.

2. **Appalachians.** Although the rock types are appropriate, there is considerable topography, and there are population concentrations in this area. There are also abundant coal, oil, and natural gas resources within and parallel to the mountain range. However, there are numerous federal facilities within areas with appropriate rocks in Tennessee and Mississippi.

3. **Central Midwest.** There are surface exposures of crystalline basement rock that are appropriate. Some of the rocks in central Arkansas and southeastern Oklahoma might be appropriate and underlie some guarded federal facilities. Of particular interest are the Wichita Mountains magmatic province of southern Oklahoma and the Llano uplift of central Texas.

4. **Northern Midwest.** Large areas of Wisconsin and Minnesota would be perfect for repository sites (crystalline rocks, isolation, tectonically stable) and can be located at least 200 km from the Canadian border. However, much of the area that fits these criteria is wilderness. Again, there is a paucity of guarded federal facilities. The Black Hills of South Dakota would work as a repository site, especially if some of the old mining areas could be isolated and guarded.

5. **Rocky Mountains.** In this area, running from the Canadian border to central New Mexico, there are countless potential sites. Many of them are in mountainous areas that are completely isolated, tectonically stable (few earthquakes), and far from either the Canadian or Mexican borders. There are high plateaus and valleys that would qualify if topographic relief is a problem. Much of the land belongs to the US Government and most is managed by the Department of Interior or the Department of Agriculture. Some of the areas are national parks, monuments, and/or wildlife refuges. There are military bases scattered throughout the region. As some of them are decommissioned, they could be developed as repository sites (either mined or deep boreholes).

6. **Basin and Range.** There are many guarded federal facilities within this isolated part of the US. Basement rock crops out in many of the mountain ranges across Arizona, Nevada, and Utah. The region, with some exceptions (Phoenix, Tucson, Salt Lake City, and Las Vegas) is isolated, with very few people. Most of this region is a great distance from any

international border. Much of the needed information on tectonic stability is being acquired, in detail, by the Yucca Mountain Project. This region is ideal for closer scrutiny in the search for a repository site.

7. **Pacific Coast and the Sierra Nevada.** One of the largest regions of the US with outcrops of crystalline basement rock runs from the Mexican border near San Diego through southern California and the length of the Sierra Nevada. There are also blocks along the coast south of San Francisco and across the California-Oregon border. A great deal of the southern exposure is within or flanking densely populated urban areas or rapidly growing developments. The region is also very unstable tectonically; the San Andreas fault runs through the middle of it. Most of the Sierran Block is either tectonically unstable or locked up in national parks, monuments, and wilderness areas. Near the northern end, the Reno urban area is growing fast.

B. Granitic Pluton Sizes

We want a disposal site to be close to the center of a pluton, where the rock is most homogeneous; therefore, we need to determine the size and shape of the pluton targeted for drilling. From a plan (map) view, plutons come in all shapes and sizes — from circular bodies with a diameter of less than 10 km (Area = 80 km²) to, for example, larger plutons exposed in the Peruvian batholith with dimensions of 45 x 15 km (675 km²; Meyers, 1975). Collectively, overlapping plutons can make up a batholith with a surface area of several thousand square kilometers. A spectacular view of plutonic rocks and the rocks through which they were intruded is shown in Fig. 3a, which is a satellite image of the plutons of the Pilbara craton, Western Australia (from Reed *et al.*, 1993). This image is included here because it has excellent exposure and shows the shape and size of plutons on a craton.

The actual thicknesses (depths) of plutons are still controversial and hypotheses abound. Hamilton and Meyers (1967) proposed that the plutonic bodies that made up the Boulder batholith of Montana were about 5 km thick. Somewhat thicker plutons (5 to 7 km) were inferred by Osberg *et al.* (1978) within the White Mountains of New Hampshire on the basis of gravity measurements and heatflow data. In contrast, Francis and Rundle (1976) proposed that the plutons below the Andean Plateau were as thick as 30 km.

Because of the wide variety of tectonic and petrogenetic conditions for plutonic rocks it is possible that the many interpretations of original thickness are all correct. Determining the actual volumes of these bodies would require some idea of thickness, which can be modeled on the basis of setting and geophysical properties. Published information on plutons indicates that volumes can range from as little as 400 km³ to more than 20,000 km³.

The classic study of plutons made by Buddington (1959) classified plutons by depth of emplacement or depth at which the magma was generated: Catazonal (9.6 to 20 km); Mesozonal (6.5 to 9.6 km), and Epizonal (from 6.5 km to the surface) and by where the plutons intruded into the volcanic rocks that had erupted from the same plutons. Each zone has distinctive fabrics and petrological characteristics.

C. Pluton Shapes

Field-based models indicate that silicic magma bodies rise buoyantly through the Earth's crust and may assume the shape of a very tall balloon, tapered slightly toward the bottom (much like a salt diapir). This shape is particularly evident to depths of about 10 km. However, the shape may be strongly altered by the environment into which the pluton is being emplaced. Within a strongly extensional environment, plutons follow the lines of joints and faults, which in turn are controlled by the regional stress regime. In map view, plutons range from nearly

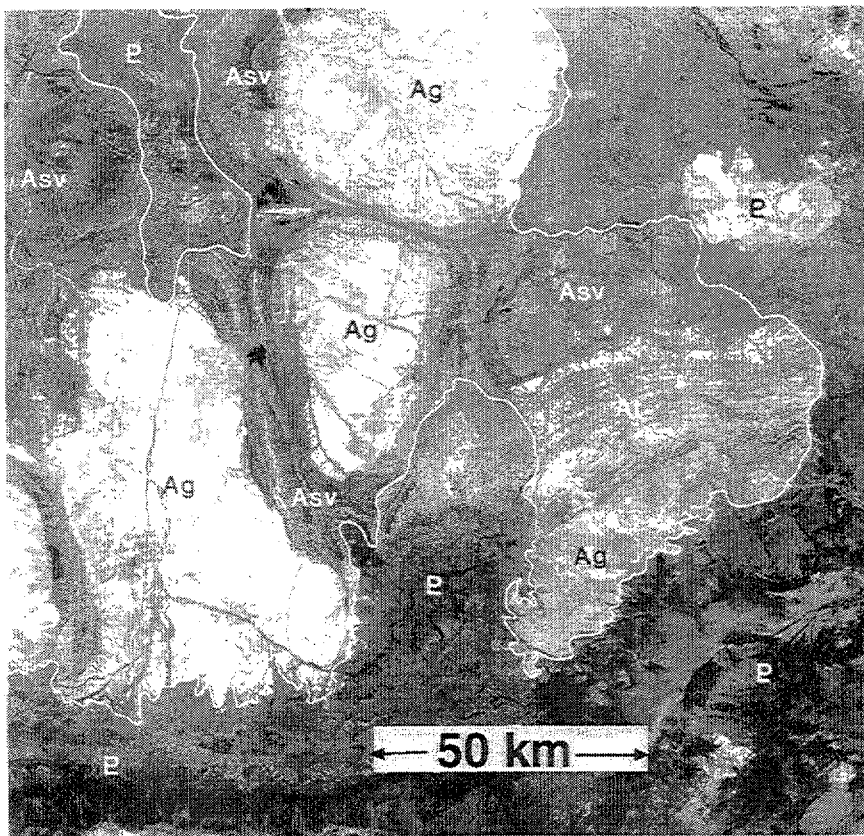


Fig. 3a. Landsat image of the eastern part of the Archean Pilbara craton, Western Australia. Composite granitic plutons (batholiths) are separated by tightly synclinal metamorphosed sedimentary rocks and volcanic rocks (Asv) with similar ages. The batholiths (Ag) consist of tonalite, granodiorite, quartz monzonite, and granite with ages of 3.45 to 3.30 Ga. Also between the plutons are metamorphosed sandstone and siltstone (At). Lying unconformably on plutonic rocks and associated metamorphic rocks are Proterozoic sedimentary and volcanic rocks (PL) (from Reed *et al.*, 1993).

circular to irregular ovals broken by multiple faults. Epizonal plutons, closest to the surface and any associated volcanic rocks, may also be surrounded by thick ring dikes (Figs. 4a and 4b).

Batholiths, composed of multiple, overlapping plutons, are mostly elongate ovals, with the long axis parallel to plate margins. Examples include the Sierra Nevadan batholith and the Peruvian batholith. All shapes are present in the ancient granite-rhyolite provinces of the North American craton, as the craton represents the products of billions of years of continental crust formation.

Pluton size and shape are very important in this project because boreholes should be sited close to the center of a pluton rather than near the edges where a variety of rock types and considerable heterogeneity would be encountered.

D. Fabric and Texture of Plutonic Rocks

For the borehole disposal site, we would select the most homogeneous portions of a pluton; therefore, we must study the fabric and texture of rocks being drilled. In outcrops of plutonic rocks, it is often (but not always) possible to map textures and fabrics that change systematically throughout; these are the products of the flowage history and interaction with wall rocks when the mass was still liquid or partly liquid. In some plutons, these fabrics may control later brittle fracture shapes and orientations. When a plutonic rock is sampled by drilling, it may be possible to use the variations in phenocryst size, groundmass (if finer grained), and orientation of phenocrysts as well as the inclusions of unmelted wall rock (size and orientation) to determine the drillhole's location within the pluton. This approach must be accompanied by geophysical surveys, such as gravity and aeromagnetism, to locate the pluton's borders. Some of the basic fabrics and textures to be evaluated are discussed below.

1. Primary flow structures. If there has been a long residence time during crystallization of a magma body, larger phenocrysts could have been separated by settling within the fluid, producing layered rocks within the pluton. The basic controls are phenocryst mass, viscosity of the magma, gravity, and any thermally driven circulation within the magma body. Near the surface of a pluton, where some of the melt may have been erupted, there may be linear orientations of phenocrysts and lithic inclusions. There may also be linear fabrics near pluton walls, where cooler (and more viscous) magma is deformed by drag (Balk, 1937, is a classic monograph on this subject).

2. Contacts with wall rocks ("country rock"). Contacts of plutonic rocks with surrounding rock units range from sharp, through veined (abundant angular clasts of the wall rock) to permeated (gradational). Large blocks of country rock ingested by the pluton might also be

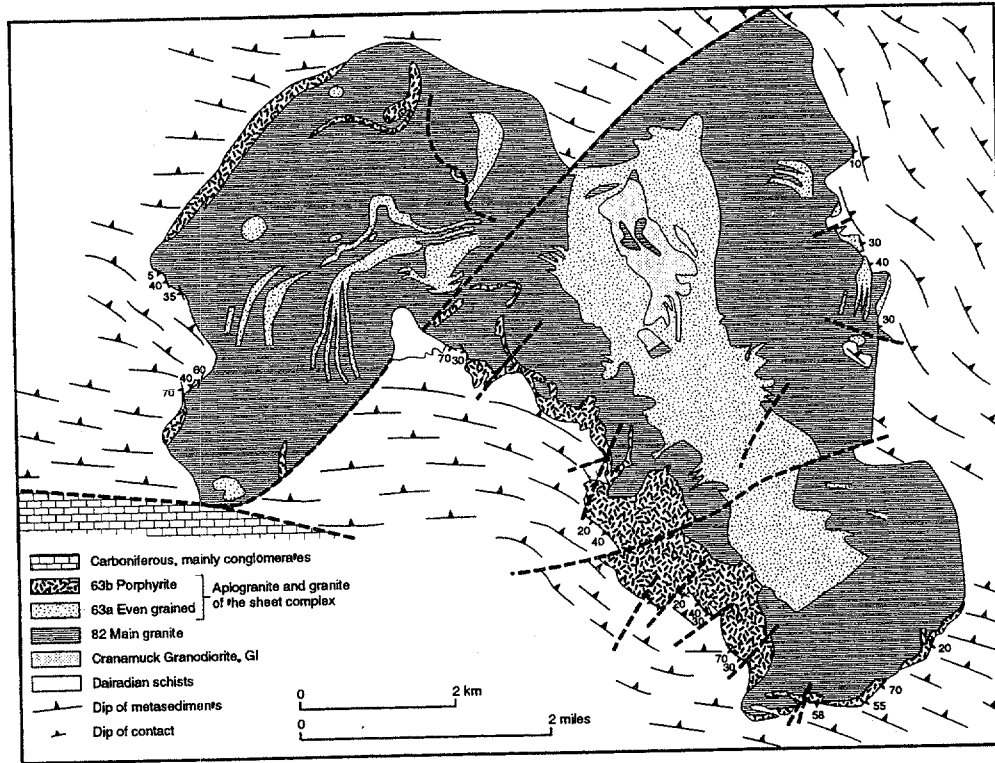


Fig. 4a. Simplified map of the Barnesmore Pluton in Northern Ireland (from Pitcher and Berger, 1972).

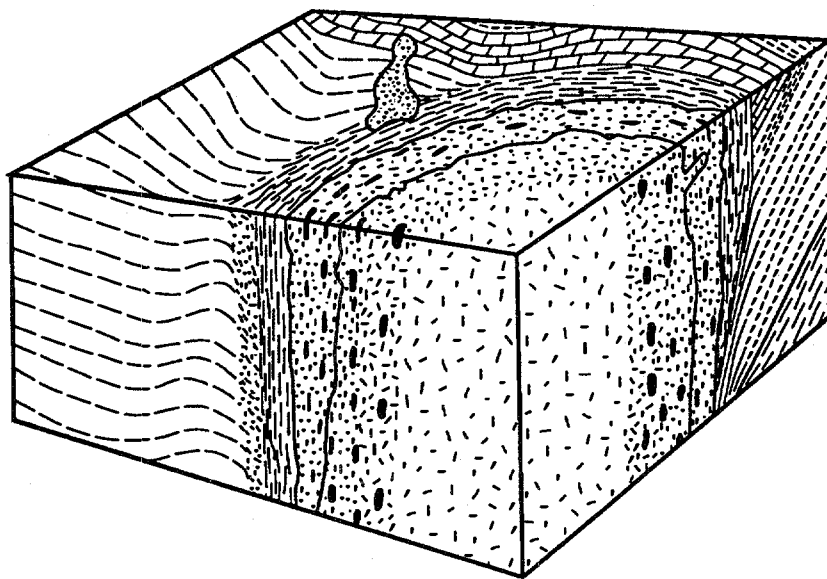


Fig. 4b. Simplified block diagram of the northwestern portion of the Ardara Pluton, Northern Ireland, showing compression and deformation of rocks adjacent to the pluton. Inclusions along the pluton borders are progressively flattened. Minerals near the pluton margins are aligned to produce distinctive textures. (Adapted from Pitcher and Berger, 1972.)

encountered, causing confusion about the location of the boundary. (This problem emphasizes the need for continuous core drilling.)

3. **Post-emplacment shearing and flow.** Late in a pluton's history, continued movement of a solid or partly solid mass may result in the original igneous texture being sheared and recrystallized, which produces a distinctive linear fabric.

Interpretation of fabrics, as well as petrologic data, must be accomplished by an expert who has examined the field relations of these rocks in analogous outcropping plutonic rocks.

E. Geophysical Signatures

The search for Precambrian plutons overlain by sedimentary rocks would begin with regional geophysical surveys. Comprehensive regional geophysical surveys have been conducted for most of the conterminous US. Along with data from thousands of boreholes (mostly oil wells), these data give an idea of the structure and composition of the Precambrian basement. Wherever there are holes drilled into basement rocks, there is the possibility of heat flow measurements — surveys that complement the primary techniques of gravity and magnetic surveys. The magnetic and gravity signatures are dominated by the rocks of the upper crust, which are the target of this project.

The densities and magnetic susceptibilities of granitic plutons are considerably different from those of surrounding metasedimentary and metavolcanic rocks, which makes it possible to identify the plutonic rocks by using integrated geophysical surveys. These contrasts are evident in cross-sections and gravity and magnetic anomaly profiles across the Lake Superior region (Fig. 5; Sims *et al.*, 1993).

Within an area of interest, major structural discontinuities (or the lack of them) can be delineated by reflection/refraction seismic surveys. Most of the more detailed structure within the upper 10 km of crustal rocks can be studied with this technique.

F. Petrological and Geochemical Properties

Once a potential disposal site is identified, the plutonic rocks of that site must be characterized chemically and petrologically to (a) evaluate the degree of interaction between rocks and fissile materials, and (b) search for evidence of past rock/water interactions. Granitic rocks are variable in their compositions and textures. Mineralogical, textural, and structural variations are useful features that can be used to interpret pluton configuration as well as igneous and tectonic history. Petrogenetic information encoded in discrete mineral assemblages reveals magmatic and post-magmatic processes and source regions. The physical features of these minerals, their textural relations within the rock, and the chemical

compositions provide important information for understanding the occurrence and origin of granitoid rocks. Mineralogical compositions can be determined by point-counting coarse minerals in hand specimens, petrographic methods, and x-ray diffraction analysis. Systematic petrographic description is an important first step in classifying and mapping rocks in the field or from drillcores. Such studies establish the groundwork for systematic and detailed geochemical and geochronological analyses to understand the history of evolution of granitoid rocks.

Textural relations in granitoid rocks reflect the bulk composition and cooling history of the magma by indicating the kind of minerals that form, the order of their formation, and occasionally the viscosity and diffusion rates. Some of the common textural features applied to granitoid rocks describe crystallinity, grain size and shapes, twinning, zoning, intergrowth, overgrowth, inclusions, etc. All of these features can be determined by the use of a petrographic microscope.

In addition to descriptions of phase assemblages gained from petrographic microscope analyses, phase compositions are determined by sophisticated analytical instruments such as electron microprobe, ion probe, and mass spectrometers as well as the conventional methods of x-ray fluorescence (XRF), inductively coupled plasma (ICP), and instrumented neutron activation analysis (INAA). These compositional data are needed to evaluate and understand the conditions, processes, and

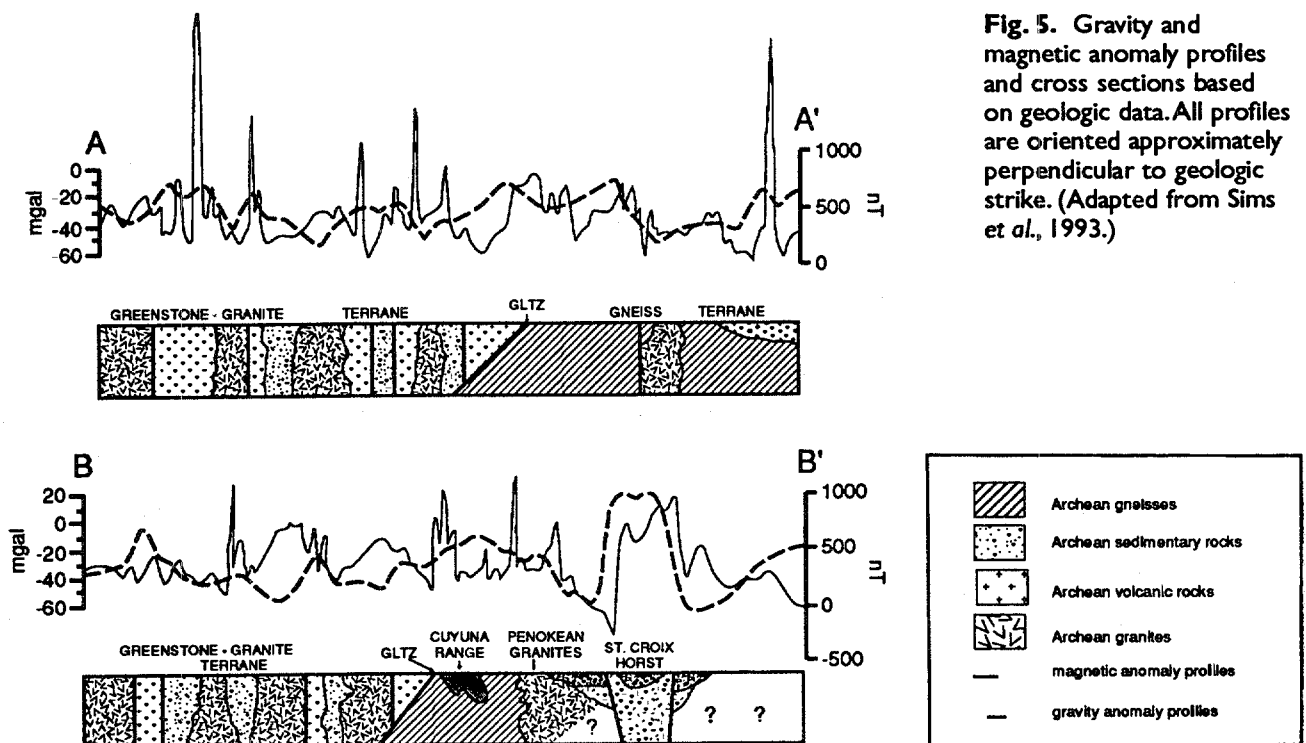


Fig. 5. Gravity and magnetic anomaly profiles and cross sections based on geologic data. All profiles are oriented approximately perpendicular to geologic strike. (Adapted from Sims et al., 1993.)

timing of the evolution of granitoid rocks. Such information includes the general crystallization conditions or compositional indicators (for example, equilibrium or disequilibrium processes), pressure-temperature- f_{O_2} - f_{H_2O} , subsolidus history (that is, processes that occur at temperatures below the stability of a melt phase), and radiometric clock/closure temperature (the age of the last igneous or tectonic activity).

Any understanding of the origins of granitoid rocks will be incomplete without the benefit of geochemical data. According to Clarke (1991), geochemistry represented by elemental, stable and radiogenic isotopes, and geochronology can be used to classify granitoid rocks; establish genetic, spatial, and temporal associations among plutons; understand the process of differentiation; determine the nature of source regions and tectonic environments; establish correlations; measure the degree and style of alteration; and explore mineral resources. Geochemical data are provided in the form of major (>1 wt %), minor (0.1 to 1 wt %), and trace (<0.1 wt% or <1000 ppm) element compositions and stable and radiogenic isotopic ratios. The principal rock-forming minerals in granitoid rocks control the major-element concentrations and normally reflect melt-crystal-fluid differentiation processes and contaminations. Information about source regions of granitoid rocks can be delineated using major elements if the rocks crystallized from primary magma. Trace-element concentrations are dependent on their concentration in the source, the degree and style of partial melting, and subsequent processes. Trace-element ratios in the melt fraction may be identical to those of the source until modified by further differentiation.

Stable and radiogenic isotopes are widely used for petrogenetic and geochronological studies (that is, how the rock was formed and when it was emplaced). Differences in isotopic ratios occur as a result of isotopic fractionations. Measured H, O, and S stable isotopic ratios of granitoid rocks reflect the ratios of the source region, provided that they are not contaminated or re-equilibrated with the host rocks. Like the stable isotopes, radiogenic isotopes (Sr, Nd, Pb) for petrographic studies reflect those of the source region except for wall/rock contamination that may have modified the ratios inherited from the source region. Radiogenic isotopes such as K/Ar and $^{40}\text{Ar}/^{39}\text{Ar}$, Rb/Sr, U/Pb, Sm/Nd are also used for absolute age determinations of granitoid rocks. Relative ages can be established through detailed field studies, but there is no substitute for absolute age determinations that can be used to obtain information about a single pluton or the relationship of spatially related plutons. Geochronology can be used to determine the progression of intrusion, cooling rate, alteration, mineralization, and metamorphism as well as to define the position of the magmatic axis. Multiple field- and laboratory-based geological investigations that combine mineralogical, textural, geochemical, and geochronological methods are essential for understanding the geologic history of granitoid rocks.

On the basis of mineralogical properties (modal compositions of quartz, alkali feldspar, and plagioclase), the granitoid family is generally classified into alkali feldspar granite, syenogranite, monzogranite, granodiorite, and tonalite (Clarke, 1991). Because mineralogical definition limits the range of chemical compositions, the close relationship between mineralogy and chemistry allows a simpler classification that employs the concept of alumina-saturation (molar $\text{Al}_2\text{O}_3/\text{CaO}+\text{Na}_2\text{O}+\text{K}_2\text{O}$). This approach groups the granitic rocks as peraluminous, metaluminous, and peralkaline and helps to map and interpret the evolution and origin of granitoid rocks.

According to Clarke (1991), peraluminous rocks occur in a general plate tectonic environment of continent-continent collision tectonics that involve a thickened continental crust. The granitic rocks from this kind of setting are characterized by >1 ratio of modal compositions of Al_2O_3 to the combined modal compositions of CaO, Na_2O , and K_2O and a greater content of fluorine when compared with chlorine ($\text{F}/\text{Cl}>3$). Moreover, this rock group contains aluminosilicates, cordierite, garnet, topaz, tourmaline, spinel, corundum, biotite, muscovite, ilmenite, apatite, zircon, and monazite as primary and accessory minerals. These rocks have a range of initial isotopic compositions of $^{87}\text{Sr}/^{86}\text{Sr}$ (0.7050 to 0.7200) and a lower ΣNd ($<<0$). Typical minerals associated with this group of rocks are polymetallic Sn-W-U-Mo-Cu and Be-B-Li-P in aplite-pegmatitic-greisen rocks.

The metaluminous group generally occur in subduction-related continental and island-arc settings. The modal composition of Al_2O_3 is smaller than the combined composition of CaO, K_2O , and Na_2O , but greater than the total of K_2O and Na_2O . Characteristic mineral phases in these rocks are pyroxene, hornblende, epidote, biotite, minor muscovite, magnetite, apatite, zircon, titanite, and allanite. Rocks from this group have a narrower range of initial $^{87}\text{Sr}/^{86}\text{Sr}$ composition (0.7030 to 0.7080) and an initial ΣNd of 0. Typical mineral deposits in this kind of rock are porphyry Cu-Mo.

Unlike the previous group of rocks, the peralkaline granites occur in post-tectonic or anorogenic extension, resulting in intracontinental ring complexes. Generally, the modal composition of Al_2O_3 is smaller than that of the combined composition of Na_2O and K_2O . Fayalite olivine, aegirine, arfvedsonite, riebeckite, and minor biotite are the characteristic minerals; magnetite, apatite, zircon, titanite, allanite, fluorite, cryolite, composition (0.7030 to 0.7120) and a highly variable initial ΣNd are characteristic features of this group of rocks.

Petrological and geochemical studies are important to the deep borehole disposition project because they supply data on rock composition, including sorption properties, age of the rock, evidence for any rock/water interactions and isotopic ages of those interactions, and interaction of fissile materials with the enclosing medium.

G. Structural Properties of Plutonic Rocks: Variation with Depth

Fracture systems in plutons occur in shallow or exposed rocks across the top of an intrusive body (Balk, 1937; Fig. 6). Primary fracture systems associated with the intrusion are most likely filled with secondary minerals in the Precambrian basement rocks that are the target of this project. Open fractures appear to be associated generally with exposed or shallow rock (less than 1 km) and include extensional jointing and exfoliation joints (which are parallel to the ground surface).

Overall seismic velocity increases with depth, reflecting an increasing bulk-rock density, in part because of the decreasing number of fractures in the rock (Fig. 7; Sims *et al.*, 1993).

In their analyses of data from the Swedish 6.6-km-deep drillhole in crystalline basement rocks (Gravberg 1) and from other deep drillholes, the authors of the SKB report (1989) expressed the following view of downhole conditions, which appear to be similar for most boreholes in deep crystalline rocks worldwide.

- The rapid increase in seismic velocity in crystalline rocks with depth within the upper 1000 m and a stable average velocity below 1000 m indicates that there are few open fractures.
- Rock composition is the controlling factor in determining the average velocity, and fracture zones are responsible for low-velocity zones along short intervals.

Long-term changes in conditions at depths of 3 to 4 km are most likely minimal and related to the drilling and fracturing process if there is any artificial hydrofracturing in the well. There are few data from *in-situ* instruments left in deep wells for long periods of time and no data from "long-term" changes. Changes in stress regime related to regional uplift are documented, but only at the surface.

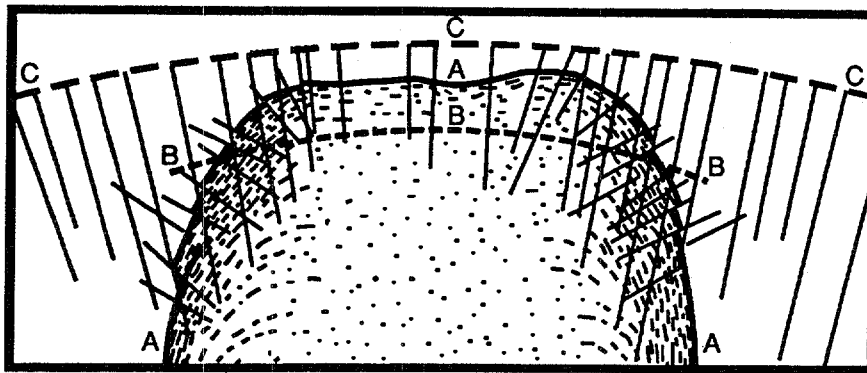


Fig. 6. Superposition of flow-structure and fracture systems in an epizonal pluton. The flow layering, A, is the oldest; next youngest are marginal fissures. Steep cross joints may be oriented perpendicular to the B-arch or to a larger arch, C (from Balk, 1937).

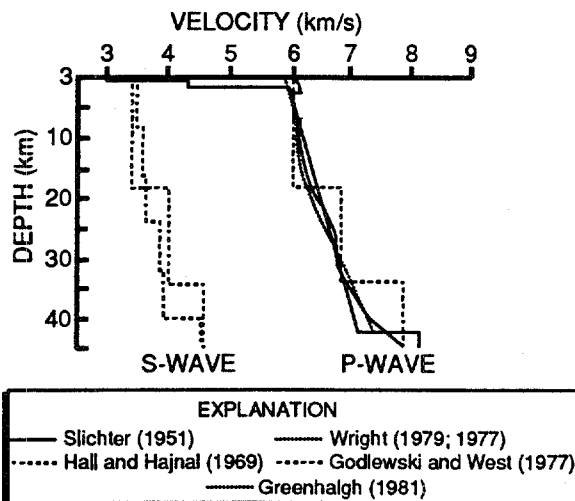


Fig. 7. Seismic velocity vs depth models of the crust in the Lake Superior region (adapted from Sims et al., 1993). Increasing seismic velocities are a reflection of increasing bulk-rock density and decreasing porosity and permeability.

PART 3

EVALUATING THE CONNECTION BETWEEN THE REPOSITORY AND THE EARTH'S SURFACE

I. Fracture Fills, Age-Dating, Evaluation of Past Rock/Water Interactions

At and near the Earth's surface (the upper 1 or 2 km), plutonic rocks are characteristically fractured in the form of joints with no apparent displacements and faults that show some kind of differential movement. Such fractures greatly influence fluid infiltration into the rocks, resulting in alteration and formation of new mineral phases either in a hydrothermal environment or under atmospheric weathering conditions. If the alteration is intense, fractures are sealed by authigenic minerals. Fracture systems can provide information about regional and local fluid circulation that can be used generally to understand heatflow and stress conditions. Fluxes of gases (He, H₂, CH₄, and other organic gases) dissolved in fluids that migrate along fractures can be measured to determine the source regions (for example, mantle and/or deep crustal sources) and can provide information on rate of flux and tectonic activity. In some cases, noble gas abundances in fluid inclusions provide paleo-crustal fluids.

When fracture-filling minerals are characterized mineralogically, they can provide information about the nature of the fractures, the diagenetic environment, the degree of water/rock interaction, and the time of crystallization and stability of these minerals. Chemical and isotopic compositions of groundwaters in crystalline rocks are used as the source of information for water/rock interactions. In most cases, the chemistry of shallow groundwaters is generally controlled by rock compositions, whereas those from deeper levels are more saline and occur in isolation from the near-surface fluids. The origin of brines in deeper levels of crystalline rocks is not generally well known; however, stable (O and H) and radiogenic (⁸⁷Sr/⁸⁶Sr) isotope compositions are used to reconstruct the geochemical history of such fluids. The concentrations of chemical and stable and radiogenic isotope (O, H, S, U, Rn) compositions of water from fractures indicate the intensity of water/rock interaction and hydraulic connections between different water-bearing fractures. Moreover, the same approach is used to determine the extent of fluid circulation. Oxygen and hydrogen isotope values are also employed to determine the recharge area of the fluids.

Important information about the present thermal state and radiogenic heat generation can be determined from groundwater chemistry. For example, the radioelement (U, Ra, He) compositions of the Stripa (Sweden) granite and groundwaters is much higher than normal. The higher radioelement concentrations in the granite are reflected in the increased contents of U, Ra, and radiogenic gas in the groundwaters

and a higher neutron flux rate. This correlation also indicates greater water/rock interaction. As a result, the U concentration and radiogenic-heat production is about 15 and 4 times (respectively) that of average granites. Moreover, exceptionally high radon concentrations and large amounts of radiogenic helium and argon are present in the groundwaters.

A. Ages and Stability of Fracture-Filling Minerals in Plutonic Rocks

The preferred medium for disposal sites is old, stable rock that has not been affected by fractures or rock/water interactions for at least several million years. This requirement means that all minerals in fractures should be studied to determine their ages.

Fracture-filling minerals in crystalline rocks, if dateable, can be used to constrain the timing of their crystallization. For example, potassium-bearing clays are commonly used to date burial diagenesis, contact metamorphism, and hydrothermal alteration and mineralization through such dating methods as K/Ar, $^{40}\text{Ar}/^{39}\text{Ar}$, and Rb/Sr. Comparison between the isotopic ages of fracture minerals and that of the host rocks can provide information on the age of the fractures. The age and cooling history of plutonic rocks are determined by different dating methods because minerals have variable blocking temperatures in different geologic environments. In deep-seated plutonic rocks that cool slowly, accumulation of daughter elements from decay of radioactive minerals may be delayed until the temperature drops to the blocking temperature, where diffusion of daughter elements is negligible. Thus, a discordance in K/Ar dates may reflect different blocking temperatures, and the rate of cooling can be inferred if the cooling temperatures of the minerals are known. In general, crystalline rocks are dated by the K/Ar, $^{40}\text{Ar}/^{39}\text{Ar}$, Rb/Sr, U-Pb, and Sm/Nd methods for bulk rocks or minerals separates such as potassium-bearing minerals and zircons. Unlike plutonic rocks, volcanic flows and shallow igneous rocks cool rapidly. For example, radiogenic argon begins to accumulate in potassium-bearing minerals as soon as the lavas begin to crystallize.

The rate of uplift and erosion of granitoid rocks are determined by the fission-track dating method. Because fission-track retention varies between minerals, the time since cooling can be measured. Plutonic rocks follow a slow cooling model and, for minerals such as sphene and apatite, higher fission track ages are found. Such information is used to determine the cooling history of rocks, especially when combined with other dating methods. Because the blocking temperature for apatite is about 110°C, it is used extensively to date cooling histories at low temperature. When cooling is caused by uplift and denudation, fission-track ages are used to determine the rate of uplift. Occasionally, thermal overprinting that reaches the blocking temperatures could cause partial annealing and formation of different tracks. The age of the overprinting is also constrained by studying track sizes. Thus, the fission-track dating method provides information about the isotopic age of minerals, rock formation, and the thermal history of the rocks.

B. Applications for Fluid Inclusions in Site Characterization

Fluid inclusions provide an insightful tool for interpreting the fluid history of geologic systems. They are presently the only direct evidence available for characterizing past fluid events in a rock. Historically, fluid inclusions have been used by economic geologists as means for mineral and ore body exploration. An ongoing aspect of fluid inclusion work was to understand and characterize the paleohydrothermal systems present during ore and mineral deposition. The techniques and understanding gained from this study have made fluid inclusions employable in other fields of research, notably geologic site characterizations. Fluid inclusion applications can yield useful information on the composition, origin and general nature of fluids present during mineral growth as well as post-crystallization events affecting the rock.

II. Hydrology of Crystalline "Basement" Plutonic Rocks

In their analyses of data from the Swedish 6.6-km-deep drillhole in crystalline basement rocks (Gravberg 1) and from other deep drillholes, the authors of the SKB report (1989) expressed the following view of downhole conditions, which appear to be similar for most boreholes in deep crystalline rocks worldwide:

- The rapid increase in seismic velocity in crystalline rocks with depth within the upper 1000 m and a stable average velocity below 1000 m indicates that there are few open fractures.
- There are distinct, compartmentalized fluid systems at all depths and a separate fluid circulation system within the upper 700 to 1000 m. Key results from the best-documented wells drilled in crystalline basement rocks are summarized in Table 1 (from SKB, 1992).
- Permeabilities (K) in the Gravberg hole have been measured over 25-m intervals and are highly variable. Joints crossing these intervals can have permeabilities 2 orders of magnitude higher than that of the adjacent rock. Permeability tests must be long-term; short-term measurements provide anomalously high permeabilities. Intact sections of rock measured in Swedish drillholes have permeabilities as low as 10^{-20} m². Permeabilities measured in deep wells are summarized in Fig. 8.
- Salinities of fluids from deep drillholes generally increase with depth below 1000 m (Fig. 9). This is particularly evident in the 12-km-deep Kola Peninsula hole (SKB, 1992). The expected trend of decreasing permeability and increasing salinity with depth is based on a sparse data set. There are exceptions to these trends, such as in the open, fluid-bearing fractures encountered at depths below 2000 m in the Russian deep holes, KTB, and Sancerre-Couy.

TABLE I.
Summary of Findings from Deep Research Boreholes^a

	SC (m)	HS (m)	MHSG (MPa/km)	K (10 ⁻¹⁷ m ²)	TG (°C/km)	BP (m)	PP (%)
USA-8			18		80	minor	
USA-9	817				90		
USA-10	900	1800		0.1	30	1750-3510	+5
USA-11	460				17		
FRG-1			15	0.3	35		+
FRG-2	500	3500			27	0-2500	-10
FRA-1		3200		100			
SWT-1	1050	1326		0.001-10	34		+4
UK-1			12	0.1-6	34	none	+4
URS-1	800	1200		0.01	13/23	major	+4?
SWE-1	1200	>6000	17	1-10	16	1500-TD	0

SC Depth to which water circulation appears to be dominant
 HS Depth to higher salinity water in the crystalline rock
 MHSG Minimum horizontal stress gradient
 K Permeability below 1000 m
 TG Temperature gradient
 BP Depth interval where breakouts are present
 PP Pore pressure above hydrostatic of water column

^a SKB (1989)

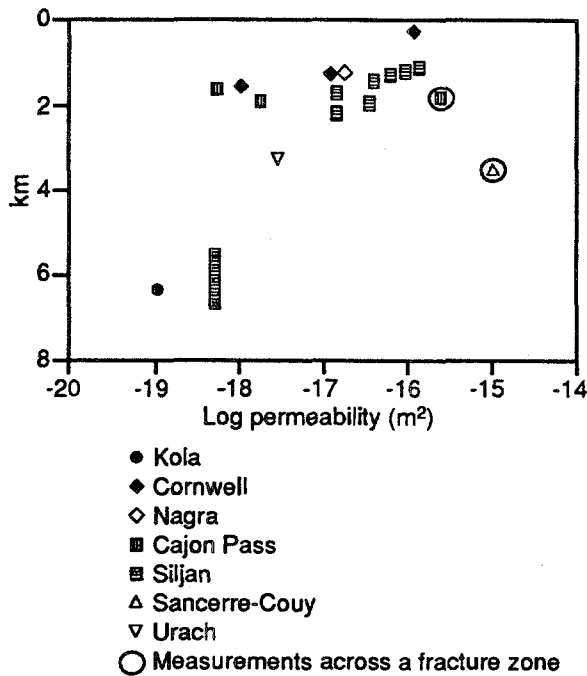
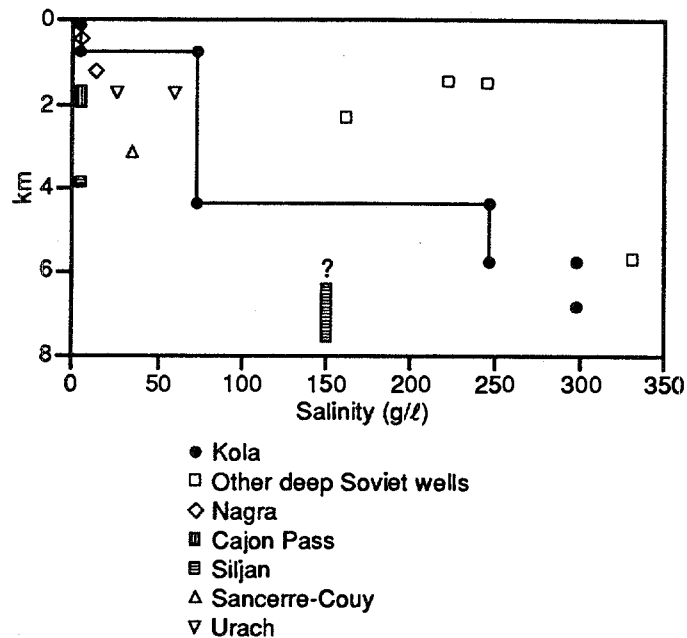


Fig. 8. Permeability estimates in deep drillholes (from SKB, 1989). Most permeabilities below a depth of 4 km are less than 10⁻¹⁸ m².

Fig. 9. Salinities of formation waters from deep drillholes in crystalline rocks (from SKB, 1989).



Fritz *et al.* (1991) analyzed the chemistry of fluids from a depth of 4000 m in the KTB pilot hole (Table 2). Isotopic data from the well suggest that the calcite in fractures originates from groundwater percolation in a low-temperature regime. All data suggest the presence of a past deep meteoric circulation system to that depth through a now-sealed fault zone (Bram *et al.*, 1994).

However, fluids recovered from a depth of >5452 m at Gravberg have extremely high helium concentrations and high salinity (40,000 ppm Ca^+ and 12,000 ppm Na^+ with Cl^- being the major anion). Tritium analyses of the deep water showed that there had been no mixing with surface waters. A repository in granitic basement rocks would be isolated from the surface.

- Long-term changes in conditions at depths of 3 to 4 km are most likely minimal and related to the drilling and fracturing process if there has been any artificial hydrofracturing in the well. There are few data from *in-situ* instruments left in deep wells for long periods of time and no data from long-term changes. Changes in stress regime related to regional uplift are documented, but only at the surface. Relatively shallow heatflow is affected by both long-term climate changes and erosion, but that phenomenon is limited to a zone with meteoric water circulation (usually the uppermost 1000 m).

Table 2.
Chemistry of Fluids at 4000 m in the KTB Pilot Hole^a

Conditions		Saturation Indices ^b (100°C)	
Discharge Temperature	10.3°C	Calcite	-0.03
Formation Temperature	119°C	Aragonite	-0.10
Conductivity (25°C)	82.2 mS/cm	Dolomite	-1.25
Redox (Eh)	-440 mV	Strontianite	1.60
pH	8.38	Anhydrite	-0.06
		Gypsum	-0.39
		Celestite	-0.64
Composition		Quartz	-0.08
Sodium	5500 mg/l	Chalcedony	-0.30
Potassium	200 mg/l	Halite	-2.58
Lithium	5.4 mg/l	Fluorite	0.06
Calcium	14700 mg/l	Fe ³⁺ -Hydroxite	0.32
Magnesium	6.8 mg/l	Albite	-0.10
Strontium	270 mg/l	Microcline	0.41
Aluminum	0.07 mg/l	Chlorite	7.73
Iron	3.74 mg/l	Laumontite	-0.15
Manganese	0.67 mg/l	Epidote	9.29
Zinc	0.17 mg/l	Prehnite	4.76
		Kaolinite	-1.78
Chloride	39500 mg/l		
Bromide	493 mg/l		
Fluoride	1.45 mg/l		
Sulphate	390 mg/l		
Phosphate	0.0 mg/l		
Silica	50.7 mg/l		
Alkalinity ^c	97.6 mg/l		
DOC ^c	50.2 mg/l		
pCO ₂ (calc. 100°C)	0.45•10 ⁻⁶ atm		
pH (calc. 100°C)	8.45		
Brine δ ¹⁸ O	-5.75 ‰ SMOW		
Brine δ ² H	27.3 ‰ SMOW		
Brine Tritium	<0000.7 TU		
Sulphate δ ¹⁸ O	8.7 ‰ SMOW		
Sulphate δ ³⁴ S	6.8 ‰ CDT		
³ He/ ⁴ He	2.9•10 ⁻⁷ (R/R _a = 0.21)		

^a From Fritz et al. (1991).

^b Solmineq.88

^c Contamination through mud additives is possible.

A. Fluid Movement Within Crystalline Rocks of Stable Cratons

What we know about fluid movement within deep crustal rocks comes from research boreholes. Downhole measurement and sampling experiences are summarized here.

1. Permeability; fractures connected to the biosphere. Crystalline basement (plutonic/metamorphic) rock units below depths of 1 km have very low permeabilities except along faults. If not fractured, these rocks, at a depth of 4 km, have permeabilities in the range of 10^{-18} to 10^{-19} m² (SKB, 1989). For comparison, the permeability of clean gravels in a stream deposit ranges from 10^{-7} to 10^{-10} m². (Permeability is the rate of flow through a porous medium; for example, 10^{-19} m² = 0.000000001 ℓ of water per second per square meter of cross-sectional area under a pressure gradient of one atmosphere per cm). Even across fracture zones, these rocks have permeabilities in the range of 10^{-15} to 10^{-16} m² (KTB-Urach, Germany, and Cajon Pass, California drillholes). Similar fractured rocks near the surface can have permeabilities of 10^{-11} to 10^{-5} m². Even though there may be open, brine-filled cavities at depths of greater than 1 km, there are rarely any documented cases with evidence for connections with near-surface meteoric waters.

Open, fluid-filled fractures have been encountered by deep drillholes into tectonically stable, crystalline rock (SKB, 1989); these wells did not encounter the type of fluid "overpressures" that would be required to naturally fracture the rock. If an active fault were penetrated, brittle deformation is certainly possible at a depth of 4 km; however, site characterization will be used to avoid any active faults at a disposal site.

2. Driving force for fluid circulation. Although it is unlikely that there will be much permeability at the disposal depth, if there is any circulation, flow may be driven by externally applied pressure gradients (*forced convection*, sometimes called *advection*) or by buoyancy effects of density gradients, caused by temperature gradients (*free convection*).

Fluids in deep wells appear to be compartmentalized, with little connection between compartments. If the disposal site were to become hot, it is likely that any thermally driven convection would stay within the deep reservoir. Further site-specific observation and modeling is needed to verify this hypothesis.

3. Creation of transport pathways by earthquakes and other natural phenomena. Fluid overpressures of 5 to 10 MPa (50 to 100 bars) can fracture crystalline rocks. Natural fracturing occurs within magmatic and geothermal systems, both of which will be carefully avoided for this project. In addition to the fracturing along active faults during earthquakes, there can be sympathetic movement along faults tens or hundreds of km from an earthquake epicenter. This phenomenon was

observed recently in southern California during the Northridge and Landers earthquakes. Deep (>1-km) fluid circulation along normal faults occurs within tectonically active areas, as is verified by existence of basin-and-range hydrothermal systems; meteoric water is sometimes heated to >200°C, then rises buoyantly along the permeable fault zone, where it reaches the surface as boiling springs. Nearly all of the permeability within these systems is fracture-controlled.

4. Undetected transport pathways. If fluids sampled downhole indicate that there has been some connection with the surface (revealed by water composition and age), and none of the known transport pathways can be verified, the site and corehole will offer a challenge to hydrologists, geologists, and geochemists; the site might even be abandoned.

III. Present Thermal State, Including Radiogenic Heat Generation

Throughout the region of interest (mid-Continent US), temperature gradients range from <15°C/km depth to 35°C/km (Hinze *et al.*, 1986; Kron and Stix, 1982; Guffanti and Nathenson, 1980); the region has mostly low temperature gradients (Fig. 10). Locally, some granitic bodies with high K, U, and Th can have higher thermal gradients because of radioactive heat generation (Roy *et al.*, 1968). This observation was used by Costain (1977) to look for buried plutons with radiogenic heat production as geothermal heat sources. For this project, it is necessary to avoid these plutons (although even with the higher gradients, the sites are probably acceptable).

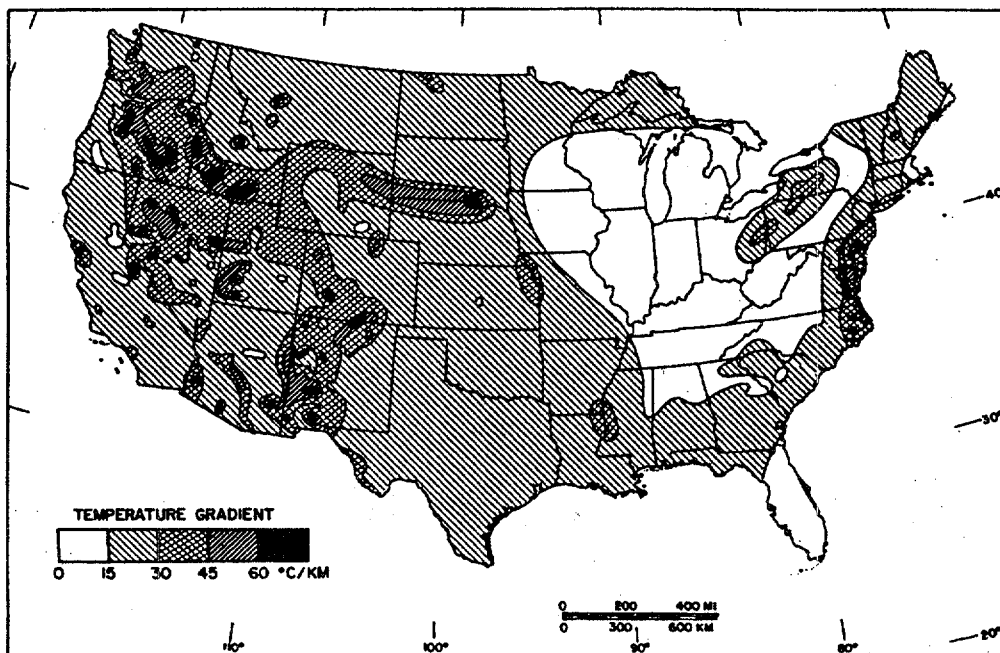
With much of the region having thermal gradients of <15° to 20°C/km depth, bottomhole temperatures at a depth of 4 km are 60° to 80°C. For this project, we must determine the highest acceptable temperature for safe disposal.

IV. Qualifying Conditions (from the National Academy of Sciences Report of 1994)

The qualifying conditions for a potentially acceptable site are specified by emplacement design and regulatory guidelines. *Emplacement design* refers to the engineering parameters of the repository environment that, if left unchallenged, isolate the fissile materials from the biosphere and retain a measure of material safeguards and security. *Regulatory guidelines* are the institutional criteria that enhance confidence in the technical suitability of sites to isolate radioactive materials from the environment.

Engineering parameters for the deep borehole repository environment applicable to siting within the continental US landmass are found in the text of the National Academy of Sciences report "Management and Disposition of Excess Weapons Plutonium" (NAS, 1994) and to a lesser

Fig. 10. Geothermal gradient map of the conterminous United States. Data are from 900 conductive temperature measurements in wells deeper than 50 m (from Kron and Stix, 1982).



degree from "Excess Plutonium Disposition: The Deep Borehole Option" (Ferguson, 1994). The deep borehole conceptual design proposed for disposal of fissile materials is an adaptation of the very deep borehole concept proposed by a number of prominent European countries for the disposal of spent fuel or high-level radioactive wastes. Favorable attributes of the rock mass environment for the purpose of retaining criteria for isolation of fissile materials is therefore driven by the research initiatives and engineering activities funded by or in collaboration with those countries. Qualifying conditions for the rock mass surrounding proposed repositories of this nature may change with time as a consequence of continued research activities in this area; however, those referenced in the NAS (1994) report are of particular relevance at this time. Qualifying conditions may be segregated into three categories: rock characteristics; tectonics; and geochemistry. These conditions are given in Table 3.

A Westinghouse Savannah River report by Ferguson (1994), which also discusses the deep borehole option for the disposal of fissile materials, is based largely on the information contained in the NAS (1994) report. Ferguson proceeds, however, by establishing a list of 14 geological and hydrological parameters that he describes as being important to the performance assessment of the deep borehole option. Although those parameters may in fact be important for some characterization activities, the regional geologic reconnaissance conducted by the following methods does not take into account the Ferguson geological and hydrological

Table 3.
**Qualifying Conditions for Deep Borehole Disposal
of Fissile Materials, as cited in the NAS (1994) Report**

Rock Characteristics

- 2- to 4-km-deep host-rock horizon
- free of vertical faults
- very low permeability
- very low hydraulic conductivity
- crystalline rock (granite)
- absence of faults
- absence of major faulting for many millennia to come

Tectonics

- free of geologic activity

Geochemistry

- very saline water at repository levels, preferably with fresh water above
- homogeneity of rock properties

parameters for three reasons. (1) The parameter set exceeds the qualifying conditions of the NAS report. (2) The justification for expanding the parameter base is not provided; nor are the technical attributes of the qualifying conditions described. (3) Unlike the NAS report, which was requested by the National Security Advisor to the President, the Ferguson report does not appear to have been similarly commissioned; nor does the report incorporate the views and critiques of a scientific board addressing the difficult issues facing the emplacement option.

The regulatory framework for licensing a deep borehole repository is the source for a second set of qualifying conditions for regional geologic reconnaissance. Unfortunately, deep borehole disposal has not been addressed by the Nuclear Regulatory Commission and would require new regulations (NAS, 1994). In the absence of a regulatory framework, Halsey (1995) suggested that site-suitability guidelines such as those of 10 CFR Part 960 might be useful for deep borehole siting.

Because many provisions of 10 CFR Part 960, which were developed for high-level radioactive waste, are not appropriate to siting or characterizing deep borehole disposal sites, it is the intent of the guidance that it should be used to formulate specific guidelines and not the guidelines verbatim.

Most applicable to this activity are Section 960.3-1-4-1 and Appendix IV of Part 960, which address site identification as potentially acceptable. The types of information that provide a reasonable basis for assessing merits or shortcomings of a site against these guidelines are provided in

the Appendix IV categories of geohydrology (six criteria), geochemistry (five criteria), rock characteristics (four criteria), erosion (three criteria), dissolution (two criteria), and tectonics (six criteria).

V. Methodology

The procedure for conducting this reconnaissance evolved from the three components of the activity: collecting evidence, linking evidence to geographic domains, and qualifying the geographic domains to siting criteria. The evidence to be collected refers to the geological and hydrological information as described above. The majority of this information will be obtained from the literature in the public domain or private sector. This is an effort to collect massive amounts of data for a large geographic area. The information that will most benefit reconnaissance activities must display a number of attributes: (a) the information must be available at the scale of the reconnaissance activity; (b) the information must be of similar density and level of confidence; and (c) the information must be of such density as to represent the geographic domain to which it will be linked. It is likely that of all the qualifying conditions defined in the previous section, only a fraction of the criteria will have sufficient literature-available evidence to satisfy these three attributes. Therefore, an additional attribute is that the combined evidence must form a subset of geological and hydrological information meaningful to the site selection process.

Cursory review of the available literature suggests that the geological and hydrological evidence listed in Table 4 would form the basic informational subset for an evaluation of geographic domains to siting criteria. The qualifying condition(s) being addressed by the geological and hydrological evidence is presented in the right-hand column of Table 4. The symbol 'NAS' refers to a qualifying condition from the National Academy of Sciences report; the other listed conditions refer to the corresponding section in Appendix IV of 10 CFR Part 960. The qualifying conditions represented will provide a meaningful combination of evidence for regional selection criteria.

The choice of geographic domain follows from the NAS (1994) qualifying conditions for a crystalline host rock at horizons from 2 to 4 km depth and from Section 960.3-2-1, which requires that the process consider large land masses with potentially favorable geologic features. The first condition generally implies that the repository should be located in basement rock. It is suggested that the geographic domain thus reflect tectonic blocks and structural entities of the basement geology, which is also considered to be the primary structure of the continent. Tectonic blocks and structural entities typically reflect a volume of basement rock with similar gross geologic characteristics as well as a distinctive history and structure. The basement geology is believed to be

formed by one or both of two processes: accretion and reworking of cratonized crust. For either process, tectonic blocks and structural entities have responded to tectonic stresses through a segment of geologic time and have since retained their identity. In detail, however, there is an overprint of secondary and tertiary structures, which will also contribute distinctively to regional geologic reconnaissance. A technical advantage to defining tectonic blocks and structural entities of the basement geology as geographic domains is that they may be detected and delineated by remote sensing methods when blocks lie beneath a surface veneer of other rock.

Geographic outlines must be tentatively established early in the reconnaissance in order to survey the geologic and hydrologic data attributes as the collection process is initiated. Sources of information for interpretation of tectonic blocks and structural entities are found among geologic surface maps, satellite imagery, and aerial photographs — especially for locations with exposed basement rock — aeromagnetic- and Bouguer gravity-anomaly maps, and from radiogenic ages of sampled basement rock. Much of this interpretation may be readily accessible in the literature. Interpretation of block boundaries may involve the use of one or more combinations of data types.

Technical guidelines identify the degree of qualification of geological and hydrological evidence to the qualifying conditions of either the NAS (1994) report or 10 CFR Part 960. The process of determining compliance

Table 4.
Regional Geological and Hydrological Evidence

Geological/Hydrological Evidence	Qualifying Condition
Basement Parameters	
Depth to basement	NAS
Rock type in basement	NAS; geochemistry
Radiogenic age of basement rock	Tectonics; rock characteristics; geochemistry
Block Tectonics Parameters	
Historic seismicity	Tectonics
Crustal stress data	Tectonics
Heatflow	Tectonics
Fault traces	Tectonics
Overlying Rock-Unit Parameters	
Stratigraphy	Rock characteristics; erosion
Dissolution features	Dissolution; alteration
Regional hydrogeology	Geohydrology

is the third component of the reconnaissance methodology. Categories of evidence are collected and linked to the geographic domain. The evidence for each domain is then evaluated for compliance to qualifying conditions. The measure of compliance corresponds to the ability of the evidence to meet characteristics of the technical guidelines. Compliance is categorized by the abilities to display favorable conditions, potentially adverse conditions, or disqualifying conditions. The technical guidelines for geological and hydrological evidence in Table 4 are presented in Table 5.

VI. Screening Geographic Domains

A screening process is performed to identify geographic domains, recognized as tectonic blocks and structural entities and the rock volume between the basement and surface, that exhibit overall favorable conditions for further site selection consideration. The screening process requires evaluation of the geological evidence of a geographic domain against technical guidelines and elimination of domains from further consideration through a ranking process. The evaluation is recorded in matrix form, similar to Table 5, with the geologic evidence listed in a column adjacent to the degree of qualification. Each land unit will be provided with a record of the evaluation matrix.

Elimination of land units from further consideration will be performed by ranking land units according to their aggregate evaluation matrices. Land units are eliminated first by association with any disqualifying condition. The remaining land units are each associated with a matrix of favorable and potentially adverse conditions. A system of ranking will be devised to elevate qualification of a domain for the presence of favorable conditions while penalizing a land unit for its potentially adverse conditions. Geographic domains that, in the aggregate, exhibit the strongest favorable qualifications will be considered for site selection characterization over domains exhibiting potentially adverse conditions. The result from this screening process is the identification of a select group of domains that are potentially acceptable for repository emplacement but warrant detailed analysis of site characterization.

**TABLE 5
TECHNICAL GUIDELINES**

	FAVORABLE CONDITION	POTENTIALLY ADVERSE CONDITION	DISQUALIFYING CONDITION
DEPTH TO BASEMENT	Surface of crystalline basement rocks generally no deeper than 2 km over a wide region of the tectonic rock	Basement structure known to contain mappable thrust faults that have displaced rock over younger or contemporaneous rock units Extensive portions of tectonic block with sedimentary and volcanic rock veneer thicker than 2 km that would significantly reduce the flexibility of selecting a repository horizon in basement rock at 2- to 4-km depth	Surface of crystalline basement rocks generally deeper than 2 km
ROCK TYPE IN BASEMENT	Reasonable projection of the geology and structure of basement rock to the 2- to 4-km interval suggests rock type is, in the broadest definition, granitic or dominantly granitic plutonic rocks	Projection of the geology or structure suggests that either the lateral extent is not sufficient to allow significant flexibility in selecting the location of a deep borehole facility or granitic rocks form structures that significantly reduce flexibility for selecting a location with granite at the 2- to 4-km-depth interval	Little or no evidence of granitic rock in the basement. Granitic rock known to be strongly foliated or fractured
RADIOGENIC AGE OF BASEMENT ROCK	Radiometric ages from basement rock generally cluster around a single age, and isotopic ages obtained from different nuclide decay schemes for the same rock samples are concordant	Radiometric ages provide evidence that granitic rock represents intrusive granites younger than generally unique radiometric age pattern for other basement rocks of the tectonic block	Pattern of radiometric ages for basement rock strongly suggests nonuniformity among characteristics of rock deformation, recrystallization, and cooling
HISTORIC SEISMICITY	Nature and rates of ground motion associated with historic seismic events occurring within the tectonic block would not likely lead to releases of radionuclides to accessible environment	Historic earthquakes within tectonic block of such magnitude that, if they recurred, could affect repository engineering structures and operations Historic seismic events suggest potential for landslides or subsidence that could create large-scale surface water impoundments that may change the regional groundwater flow system	Historic nature and rates of fault movement or other ground motion can reasonably be expected to jeopardize natural barrier capability of repository
CRUSTAL STRESS DATA	Stress profiles with depth compare to known crustal averages of similar tectonic setting	Maximum to minimum horizontal stresses of such relative magnitudes as to potentially cause borehole breakouts at repository interval of 2- to 4-km depth	

**TABLE 5 (cont.)
TECHNICAL GUIDELINES**

	FAVORABLE CONDITION	POTENTIALLY ADVERSE CONDITION	DISQUALIFYING CONDITION
HEAT FLOW	Low regional heat flow, although variable, relatively uniform and comparable in magnitude to similar geologic provinces	High geothermal gradients require use of special engineering skills, tools, techniques, and hardware for repository construction, material emplacement, and closure—challenging technologic feasibility of repository construction and adding undue costs Regions of high heat flow may significantly contribute to difficulty of characterizing or modeling geohydrologic system	Projected <i>in-situ</i> thermal conditions combined with heat loading from materials' radioactive decay and published parameter-model hydrologic scenarios for deep borehole repositories suggest transport times of <1,000 years to accessible environment for circulating water
FAULT/ FRACTURE/ JOINTS TRACES	Tectonic block lacks evidence for active faults, fractures, or joints during Quaternary Period	Evidence of active faulting during Quaternary Period Historic seismic events located along trace of mapped fault planes Near-vertical fault planes may provide groundwater circulation from deep repository to accessible environment	Nature and rates of fault movement during Quaternary Period are significant enough to jeopardize waste isolation of conceptual repository design
STRATIGRAPHY	Stratigraphy overlying basement rock not intensely deformed, maintains a mechanical advantage feasible for construction, operation, and closure of facility	Rock conditions could require engineering measures beyond reasonably available technology for construction, operation, and closure of repository, if necessary to ensure waste containment or isolation Potential for hydration or dehydration of mineral components, brine migration, other physical- or chemical-related phenomena that could affect waste containment or isolation Geologic setting shows evidence of extreme erosion during Quaternary Period Rocks overlying basement rock have geomechanical properties that could necessitate extensive maintenance of borehole during repository operation and closure Deformed stratigraphic section could diminish certainty for modeling post-closure hydrologic condition surrounding repository.	

**TABLE 5 (cont.)
TECHNICAL GUIDELINES**

	FAVORABLE CONDITION	POTENTIALLY ADVERSE CONDITION	DISQUALIFYING CONDITION
DISSOLUTION FEATURES, PRECIPITATION, DIAGENESIS	No evidence of significant alteration within tectonic block during Quaternary Period	Evidence for breccia pipes, dissolution cavities, significant volume reductions in sedimentary stratigraphy, or structural collapse that could indicate hydraulic interconnectivity	
REGIONAL HYDRO- GEOLOGY	Absence of aquifers between repository host rock and land surface Availability of water required for repository construction, operation, and closure	Groundwater conditions could require complex engineering measures for repository construction, operation, and closure	Expected groundwater conditions likely to require engineering measures beyond reasonably available technology required for repository construction, operation, or closure

VII. Site Characterization Techniques

A. Regional Geologic Reconnaissance

Identification of potentially acceptable sites for the long-term storage of excess weapons plutonium in very deep boreholes within the continental US landmass will be conducted with a systematic process of regional geologic reconnaissance. Reconnaissance entails the three activities of collecting evidence, linking evidence to geographic domains, and qualifying the geographic domain to siting criteria.

The *first* activity, collection of evidence, refers to gathering of geologic and hydrological information explicit to the parameter matrix of the proposed repository. At the level of a reconnaissance, this information may be generally broad but must be available over the extent of the continental US landmass. Informational sources may include literature in the public domain and private sector and may be supplemented with field investigations.

The *second* activity of the reconnaissance will be to link the collected information to a geographic domain. A geographic domain is an area which retains similar gross geologic characteristics. These areas may be tectonic blocks or structural entities which have behaved uniformly to tectonic stresses throughout a segment of geologic time and have retained their identity to the present.

The *third* activity, classifying specific geographic domains as acceptable for continued site selection evaluation, is performed by algorithm. The algorithm is a step-by-step recursive procedure that evaluates the geologic and hydrologic characteristics of each land unit against qualifying conditions proposed for the repository. The algorithm may remove land units from further consideration because of disqualifying attributes and will rank the remaining land units based on their ability to match favorable qualifying repository attributes. The result is the identification of a select group of geographic domains that have potentially acceptable geological and hydrological attributes for repository emplacement but warrant the detailed analysis of site characterization.

B. Volcanology

Eruption frequency, magnitude, and degree of subsurface disturbance by intrusions will be evaluated. Obviously, areas with Holocene activity will be avoided, but if there is minor volcanism in the area, it should be evaluated. Particular attention should be paid not just to surface areas covered by lava flows or pyroclastic deposits, but also to the width and length of subsurface dikes that fed the eruptions.

C. Regional Geophysical Surveys

Many regional geophysical surveys have been made of the US by government-university consortia to produce maps and databases at many different scales. All of these data (most with interpretation) will be invaluable for the site-selection process.

1. **Gravity.** There are existing databases of gravity readings across the mid-continent of the US; many of these data are now available on CD-ROM. These data are especially useful for identifying gravity lows associated with granitic rocks.
2. **Seismic lines.** Crustal studies in the mid-continent US have employed a variety of seismic techniques. The most commonly used are refraction profiling and measurements of surface-wave dispersion. These techniques provide information on crustal thickness and structure.
3. **Magnetic anomaly data.** There are many publications, databases, and maps of magnetic anomaly data collected during the last 30 years across the US. Magnetic anomaly data are an effective means of evaluating the geometry, depth, and physical properties of crystalline rocks of the upper crust. Magnetic surveys are especially effective in regions where crystalline rocks are covered by sedimentary rocks. There are excellent 1:250,000-scale magnetic anomaly maps of the US.

VIII. Summary: Generic Site Description

We are looking for an *ideal* site with the geological properties discussed below and depicted in Fig. 11.

The best site for a deep borehole facility is in the midcontinent US, surrounded by farmland and characterized by low, rolling terrain; the area is so flat that there are only five 20-m contours across an entire 7.5' topographic quadrangle. The elevation is 200 m and there is maximum relief of about 25 m. Most of the base is above the floodplain and has never been flooded during its 50 year history. It is, however, a windy location, with winter blizzards and spring and summer tornadoes. The nearest town is 30 km distant and has a declining population, presently at 40,000. The nearest city with a population of greater than 500,000 is 450 km from the site. There are no major commercial air corridors within 100 km of the site.

Precambrian crystalline rocks of the craton, with isotopic ages ranging from 1.7 to 3.6 billion years, are either exposed or overlain by <1 km of Phanerozoic sedimentary rocks (Fig. 12). Much of the midcontinent US

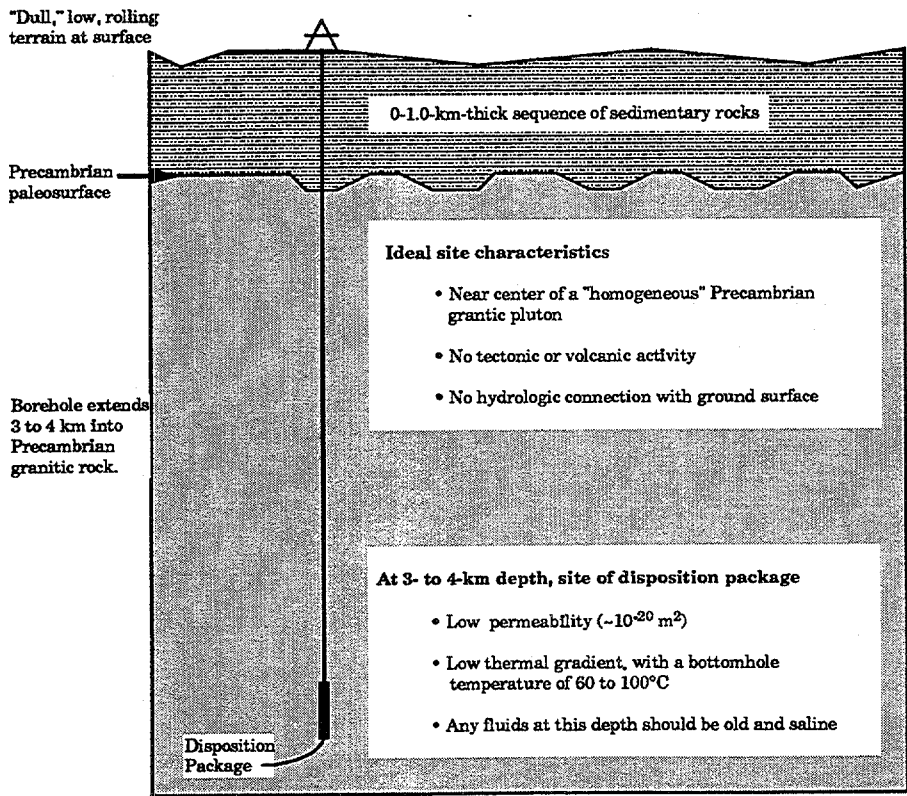


Fig. 11. The ideal "generic" site.

is extremely stable tectonically; there are few recorded earthquakes with a Mercalli intensity of over V. Thermal gradients within the "basement" rocks are also low; 15°C/km of depth to as high as 30°C/km of depth. Heatflow patterns indicate little or no movement of fluids within the crystalline basement rocks. Long-term changes in conditions at depths of 3 to 4 km are most likely minimal and would be related to the drilling process. Changes in stress regime related to regional uplift (post-glacial) are documented, but only at the surface.

The stable cratonic environment here is a promising candidate for deep-borehole disposal of excess Pu. The limited information that we have indicates that the rock types consist of a complicated mixture of granites, ortho- and para-gneisses, mafic granulites, and anorthosites. Such environments have not been subject to volcanic, tectonic, or seismic activity for billions of years. In addition, they are most likely anhydrous with little potential for internal generation of crustal fluids. However, fluid infiltration of a deep borehole is of concern because the borehole itself represents a potential pathway for surface fluids.

To minimize heterogeneities within the target rocks, we will be looking for a plutonic body with a map area of >100 km² that is relatively homogeneous texturally and structurally.

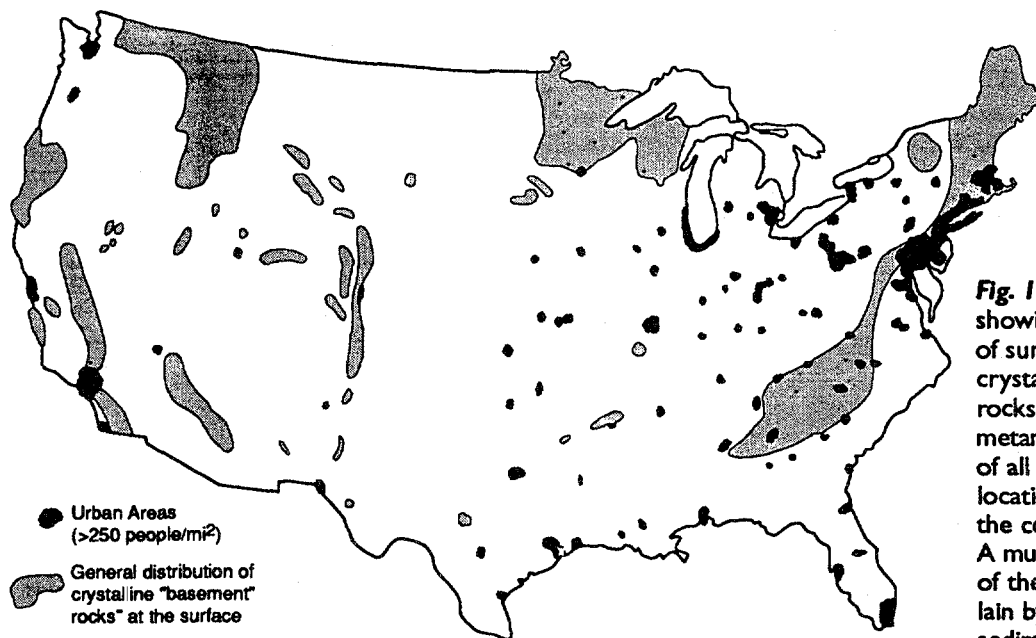


Fig. 12. General map showing the distribution of surface exposures of crystalline basement rocks (predominantly metamorphic and plutonic) of all ages as well as the location of urban areas in the conterminous US. A much larger distribution of these rock types is overlain by less than 1 km of sedimentary rocks. (Adapted from Flawn, 1967.)

A. Estimated Conditions at a Depth of 4 km

- In most deep boreholes in crystalline rocks, there is great petrologic and structural variability in crystalline rock types — granites, ortho- and para-gneisses, mafic granulites, and anorthosites. For this project, we will focus our efforts in locating the boreholes over the center of a homogeneous plutonic body.
- There is a rapid increase in seismic velocity in crystalline rocks with depth within the upper 1000 m and a stable average velocity below 1000 m, implying that there are few open fractures. Permeabilities may be low as 10^{-20} m².
- Rock composition is the controlling factor in determining the average velocity, and a few shallow fracture zones are responsible for low-velocity zones along short intervals.
- If there are distinct, compartmentalized fluid systems at all depths, then salinities of fluids (as known in other deep drill-holes) will generally increase with depth, once the 1000-m depth has been passed. This is particularly evident in the 12-km-deep Kola Peninsula hole in Russia. The expected trend of decreasing permeability and increasing salinity with depth is, however, based on a sparse data set.
- The thermal gradient is in the range of $<15^{\circ}$ to $30^{\circ}\text{C}/\text{km}$. Bottomhole temperature is predicted to range from $<60^{\circ}$ to 100°C .

B. Matching a "Generic Site" with Known Precambrian Plutonic Terraces within the Central United States

Using the parameters established for the generic site, the site-specific search will be conducted by the process outlined below.

1. Compile all known information about Precambrian plutons within the central US, including size, shape, depth to pluton surface, composition, and structure. This body of information includes data from regional geophysical and geological surveys and drillholes.
2. Select those plutons within regions that fit the geographic and demographic parameters (Section I.A.).
3. Examine closely the plutons that fit the general criteria established for the generic site, using geophysical surveys and pilot drillholes to determine:

- compositional and structural homogeneity,
- permeabilities and other hydrologic characteristics,
- fluid compositions,
- ages of fracture-filling material,
- tectonic stability,
- thermal gradient and heatflow, and
- the absence of any disruptive geologic processes such as shearing along a fault or penetration by a volcanic system.

(Each of these criteria should be weighted according to performance; sites should be graded numerically.)

PART 3 DEEP/HARDROCK DRILLING

The KTB core hole project to 4 km was a remarkable success. It is also an excellent example of how the *pilot* corehole served as a guide to the drilling plan of the near top of the ultra-deep hole. The KTB pilot corehole is an excellent example of a coring project design that provided a 150-mm diameter to a depth of, and core recovery of >98 %. Such a diameter was possible only by careful design of the core-drilling rig and downhole tools and drill string.

The 150-mm diameter corehole has all sorts of advantages for logging, testing, and monitoring. In fact, the monitoring plan may require that a corehole be located adjacent to each shaft location and that one or more coreholes be located at distance(s) from the shaft arrays.

I. Pilot Hole

The pilot hole(s) should:

- (1) be core-drilled continuously, with a wire line rig/equipment designed like that of the KTB system;
- (2) have a hole diameter of 150 mm;
- (3) have a depth of perhaps 200 m greater than that of adjacent boreholes so that vertical seismic profiling can be run to determine deeper geological structures and to provide access to deeper zones for fluid sampling and monitoring;
- (4) provide a core recovery of greater than 98%; and
- (5) provide an on-site core-analyses laboratory.

If monitoring plans are to be developed, the casing and long-term instruments and periodic measurement programs should be determined early so that they can be designed into the pilot corehole programs.

In some recent crystalline rock projects, borehole instability was a major problem and a surprise. That means that the stress state and rock properties were not understood relative to stability. This means also that the important role of selection of the proper drilling fluid/additives was not correctly considered. In the borehole project this is a central, critical issue. Both short- and long-term borehole stability are most important issues. This situation is similar to the careful selection of a "drill-in" fluid for petroleum reservoirs.

The pilot hole program must focus considerable attention and expertise on the borehole stability question. In fact, it seems that the incorrect use of drilling fluids could make a truly *in-situ* stable rock type *appear to be unstable/unsuitable for long-term disposal*. The issue of core-drilling the pilot hole(s) to somewhat deeper depths than anticipated for the borehole is also an important issue because the situation beneath the borehole site

is as important as the situation at radial distances from the site/shafts. This is a tougher issue to address because we have few methods of observing, measuring, and monitoring this part of the subsurface.

The corehole offers some good opportunities for drilling performance enhancement (improving on the KTB results). The use of advanced, thermally stable diamond (TSD)-enhanced impregnated core bits is one example of improved technology. The other is offered by the Chinese and Russian experience on percussion augmented core drilling. This can considerably improve both rate of penetration and recovery. The use of a special rig for coring with a top drive and derrick modified to run deep wire-line-coring operations is essential.

II. Downhole Testing

This is almost always a neglected part of geoscientific projects. It seems that few individuals understand what is needed (and fewer know what can or should be used to develop the tools needed for crystalline rock testing — petroleum tools are largely not suited). However, good packer systems are now available, and most firms will modify or design changes for specific applications. The measurements, however, often leave much to be desired.

The project should identify individuals who can take our evaluation specifications and devise appropriate testing techniques in the pilot coreholes. The testing program and the coring program should be designed together. Tests on wire line with testing tools should be planned to run through the core bit after pulling it off of the bottom of the hole for a short distance.

Present logging techniques in crystalline rocks are unsatisfactory. Some petroleum tools are probably appropriate (for example, fracture evaluation logs — microresistivity), but some other hard-rock geoscientific projects may have developed solutions for this problem.

Both vertical seismic profiling (from the bottom of the pilot coreholes) and cross-hole tomography (between the nearby shaft and the coreholes) are very important. The structure of the crystalline rocks will play an vital role in the evaluation of potential long-term "flowpaths" and the question of any fluid migration — both toward and away from boreholes.

It would be valuable to do a rather detailed literature survey on what the Canadian URL (Underground Research Laboratory) project has learned about similar projects. They have collected and analyzed a great deal of information from shield granites.

III. Applicable New Technologies and Laboratory Experiences

A. Hard-Rock Bits

For coring bits, the use of TSD-impregnated core bits is strongly recommended, and it would be valuable to consider doing some comparison of performance of bits with the TSD enhancement/improvements. Like all coring bits, they are usually "tuned" to the rocks at depth. The use of the TSD core bits will also require training efforts for the drilling crews. The United Kingdom waste disposal project has tested some of these bits and information can be obtained from them.

The other suggested improvement in coring performance is the use of so-called "percussion" core barrels (a small hydraulic hammer that is run on top of the core barrel) and TSD-enhanced impregnated bits. This approach appears to offer the potential for improved rate of penetration, better recovery, and less jamming of barrels. Both Russian versions and Chinese designs/equipment are available for consideration.

B. Hard-Rock Tools

Several geoscientific/waste borehole evaluation projects around the world should soon provide access to these mining types of logging tools. The KTB and URL projects, and perhaps our Russian colleagues as well, have already dealt with this problem. The mining industry in some countries has found tools that provide the valuable information needed from crystalline rocks.

C. Muds

This is an especially critical area because the fluid and additives chosen could make a big difference in how the borehole stability is evaluated. Low invasion is important for ensuring undisturbed conditions and properties for evaluation of cores and boreholes. In addition, the fluid must not cause any sort of instability in the borehole; therefore, the chemistry and infiltration/diffusion properties are important. Of course the drilling fluid must carry cuttings also. These are usually very small in core drilling and are easily removed in the fluid stream. Obviously, early testing of outcrop material and shallow core/boreholes would be necessary. The use of triaxial testing seems to be important.

D. Logging Tools

The decision to core drill the pilot holes at 150 mm can be crucial because this hole size makes all logging operations and tool selection/availability much easier. The use of packers is also much easier at this hole diameter. It is important to recognize that the borehole wall of a diamond-impregnated bit is very good for both logging and packer/testing. A program of radial side-wall coring might be considered important if the rock had large anisotropies related to, for example, intense foliation. Properties determined from cores alone might be

questionable because it might not be clear if the radial properties were determined with sufficient accuracy.

E. Fracture Logging

This is an extremely vital area. It seems that the problems of induced fractures may be of central importance. It is not clear whether both stress/strain relief and mechanical damage around a borehole can alter/add to the natural/existing fractures, and cores may be the key to resolving this issue. Various fracture logging tools might be used for comparison/verification purposes, providing different — but complementary — data at different resolutions and scales. Models of diffusion or flow of fluids will require this information, and a suite of fracture-mapping methods would be most valuable.

PART 4.

LOS ALAMOS PROJECTS, STAFF, AND RESOURCES APPLICABLE TO SITE SELECTION

Of value to the deep borehole disposition project are data acquired by Los Alamos during the drilling of holes for heatflow measurements and hot-dry-rock geothermal exploration. Heatflow drilling requires gradient measurements and thermal conductivities of the crystalline basement rocks. If elevated heatflow is caused by deep hydrothermal circulation, this database also contains information on permeabilities and conductivities of the crystalline basement rocks. Most of these drillholes, however, do not penetrate the crystalline rocks more than a few hundred meters.

For over a decade, LANL drilled multiple holes deep into Precambrian crystalline basement rocks at Fenton Hill, New Mexico. In this project, known as the hot-dry-rock geothermal program, the basic tenets for the SFM-borehole project of low heatflow were not met, but a lot was learned about drilling 4.5-km-deep, slanted holes in crystalline rocks. The drilling was slow and expensive, but was very much a development program in which drilling and logging techniques had to be developed. The Fenton Hill site has been used for fruitful crosshole seismic investigations — seismic velocities decreased as circulation was begun within the man-made geothermal reservoir. The accepted interpretation of the decrease is the opening of new fractures by thermal stresses.

Los Alamos was also involved as a collaborator in the British hot-dry-rock geothermal experiments, conducted in the Carnmenellis granite of Cornwall (Rosmanowes Quarry), where three boreholes were drilled to depths of over 2 km. This project concentrated on state of stress in the rock, physical properties, and fracturing experiments. Data of particular use in the SFM-borehole project include stress testing to a depth of 2.5 km. Hydrofracturing at the Cornwall site shows that fractures migrate downward, following existing joints.

Los Alamos personnel collectively possess over 100 person-years of experience in characterizing regional geology and geophysics, with regard to geothermal exploration and evaluation. The first extensive project was to characterize the hot-dry-rock geothermal resources of the US. The second major project was the Central American Energy and Resources Program, in which geothermal resources were evaluated in numerous Central American and Caribbean countries.

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