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USING GEOLOGIC CONDITIONS AND MULTIATTRIBUTE DECISION ANALYSIS TO DETERMINE THE RELATIVE FAVORABILITY OF SELECTED AREAS FOR SITING A HIGH-LEVEL RADIOACTIVE WASTE REPOSITORY

by

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DISCLAIMER

This report presents a method for determining the relative favorability of geologically defined units for high-level radioactive waste isolation. The method was applied to crystalline rock areas and subareas in the northeastern United States for illustrative purposes only. No conclusions should be drawn as to the absolute suitability of any of the subareas for development of a repository for such wastes. Extant geologic information was simply used to demonstrate how seismotectonic screening and multiattribute decision analysis can help identify the areas and subareas within a particular region having the most favorable attributes for repository development relative to other areas and subareas in that region. Final determinations of relative favorability would require consideration of nongeologic information as well as more detailed geologic data.

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P.J. Barosh, Director, New England Seismotectonic Study, Weston Observatory, Boston College;

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ABSTRACT

A method is presented for determining the relative favorability of geologically complex areas for isolating high-level radioactive wastes. In applying the method to the northeastern region of the United States, seismicity and tectonic activity were the screening criteria used to divide the region into three areas of increasing seismotectonic risk. The following criteria, specified by the U.S. Department of Energy's National Waste Terminal Storage Program, were then used to subdivide the area of lowest seismotectonic risk into six geologically distinct subareas: geologic characteristics, surface-water and groundwater hydrology, potential human intrusion, site geometry, surface characteristics, and tectonic environment. Criteria related to land ownership, demographics, environmental protection, and socioeconomic consequences were not considered.

Decision analysis was then used to identify the subareas most favorable from a geologic standpoint for further investigation, with a view to selecting a site for a repository. Three subareas (parts of northeastern Vermont, northern New Hampshire, and western Maine) were found to be the most favorable, using this method and existing data. However, because this study assessed relative geologic favorability, no conclusions should be drawn concerning the absolute suitability of individual subareas for high-level radioactive waste isolation. The role of decision analysis could be expanded to consider relevant nongeologic screening variables.

1 INTRODUCTION

A method is presented for designating and ranking areas and subareas with respect to their geologic favorability for isolating high-level radioactive waste. The reported application of the method to the northeastern region of the United States relies heavily on the geologic information compiled in Harrison et al. (1983a, 1983b), a comprehensive survey of the geologic characteristics of crystalline* rock bodies in that region. The survey volumes cover (1) the size and shape, age, origin, petrography, structure, and geophysics of individual rock units; (2) the region's mineral resources, geohydrology, tectonics, seismicity, and surficial materials and processes; and (3) the estimated effects of future regional geologic events.

The screening factors used were developed from geologic criteria promulgated for the Nuclear Waste Terminal Storage (NWTS) Program (U.S. Department of Energy, 1981). Although this application of the method considers geologic criteria only, the method permits simultaneous consideration of other important siting criteria, such as land ownership, demographics, environmental consequences, socioeconomic effects, and waste transport considerations.

We first assumed that a mined repository for high-level radioactive waste should be constructed in an area where there is high probability of seismotectonic stability during approximately the next 10,000 years. A large seismicity data base was available in the literature to determine areas of seismic stability. We then evaluated those large masses of homogeneous and relatively impermeable crystalline rocks within the areas of seismic stability. This second step required the use of geologic attributes such as host-rock petrology and structure, areal hydrology, nearness and importance of mineral resources or mining activities, and geotechnical considerations.

In this way, the northeastern region was first divided into three areas of relative favorability based on seismotectonic stability. The two more favorable areas were then divided into subareas using the U.S. Department of Energy (1981) geologic screening criteria. Decision analysis was then used to compare and rank the subareas in the most favorable area.

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*Crystalline rocks are defined in this report as medium- to coarse-grained igneous and high-grade metamorphic rocks.

2 DESIGNATION OF AREAS

We used a hierarchical approach to screen areas within the northeastern region as to their relative geologic favorability for further investigation related to siting a repository for high-level radioactive waste. Seismotectonic information was considered first because of the perceived importance of crustal stability to repository integrity and the superiority of the seismicity data base compared with those for the other NWTS criteria.

2.1 SEISMOTECTONIC CRITERIA

The criteria used to designate areas of relative tectonic stability are:

1. Distance from zones of present or past seismic activity.
2. Susceptibility of area to strong ground motions from earthquakes with epicenters located within or adjacent to the northeastern region.
3. Distance from known or suspected vertical crustal movements.
4. Distance from suspected Holocene faults.
5. Distance from coastal Cretaceous and Tertiary deposits.
6. Distance from major northwest- and north- to north-northeast-trending extensional faults and grabens.
7. Distance from zones of known Cretaceous or suspected Quaternary igneous activity.

The rationale for the importance of these criteria is given in Harrison et al. (1983a, Sec. 3.2).

2.2 DESIGNATION OF THE MOST FAVORABLE AREA (AREA 1)

Applying the seismotectonic criteria presented in Sec. 2.1 to the northeastern region resulted in delineation of an elongated area of relatively low seismicity that extends northward from northwestern Connecticut through western Massachusetts and eastern Vermont to northern New Hampshire and western and parts of northern Maine. Setting the boundaries for this most favorable area (area 1) required several steps, the first being elimination of areas of high seismicity using the seismic regionalization analysis discussed in Harrison et al. (1983a).

The main zones of high seismicity are in parts of lowland Maine, most of central and southern New Hampshire, eastern Massachusetts, most of Rhode Island and Connecticut, part of the Adirondack Mountains, and the lowland areas of southeastern New York and northern New Jersey (see Fig. 1). The area of peak regional seismicity is in or near La Malbaie, Quebec, in Canada. The initial boundary drawn to exclude areas of high seismicity was conservative in that it did not cross the contour line representing 5% of peak regional seismic activity. In other words, all portions of the region with 5% or more of peak regional seismic activity were excluded from area 1.

The spatial filtering process used to construct Fig. 1 divides the region into 0.3° by 0.3° squares and determines the seismicity in each square relative to that in the highest seismicity square at La Malbaie, Quebec. This process "smears out" local areas

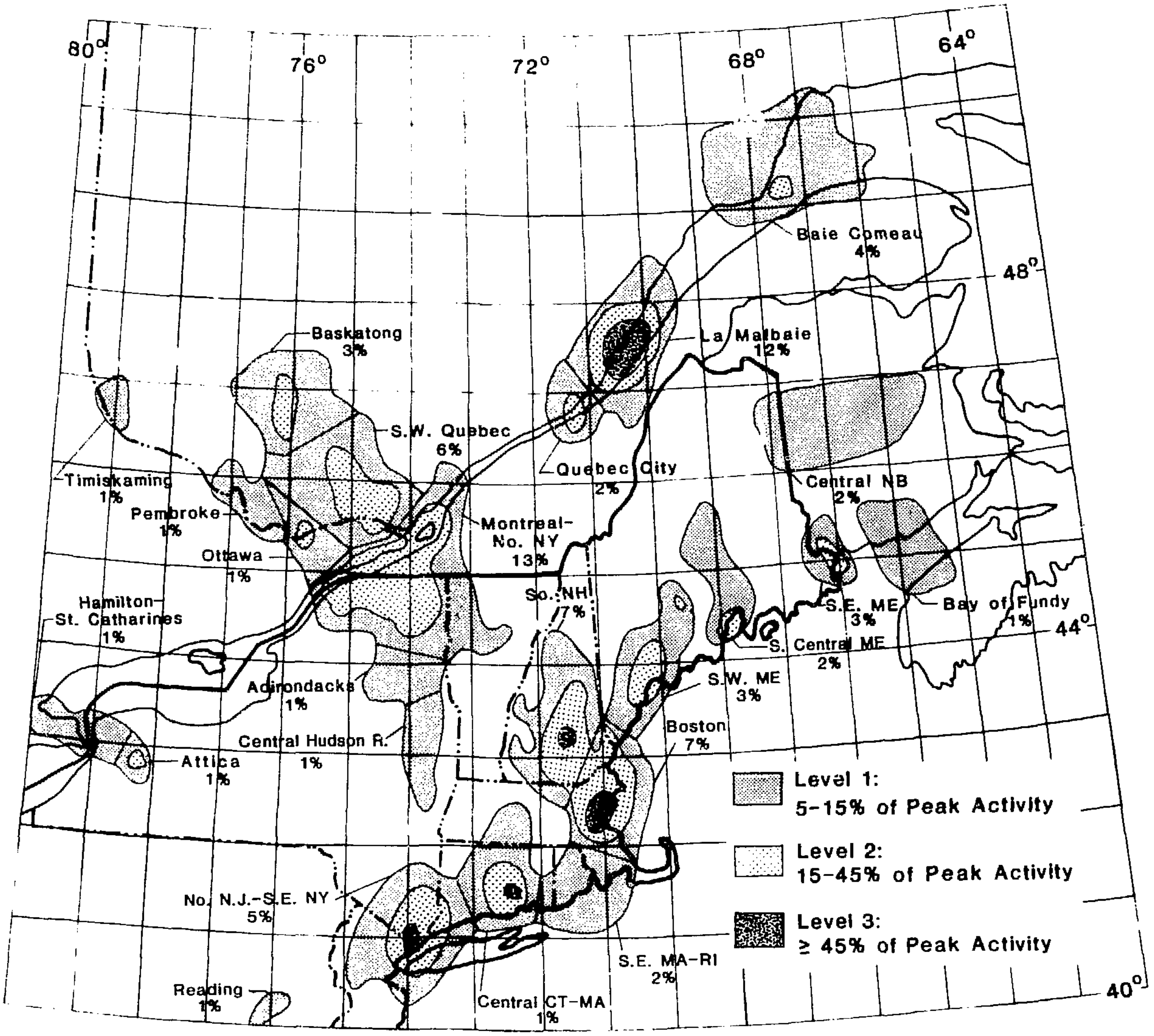

FIGURE 1 Relative Seismic Activity in the Northeastern Region, 1534-1977 (Source: Adapted from Chiburis, 1981)

of seismicity by up to 0.3°, or up to about 30 km (19 mi). In other words, lines delineating areas of greater than 5% of peak activity could be removed from a center of high seismicity or a high-intensity epicenter by about 30 km (19 mi) or more. Given epicentral intensity decay with distance (Harrison et al., 1983a), peak epicentral intensity is reduced by two to three intensity units at a distance of 30 km (19 mi). High-intensity epicenters (Modified Mercalli intensity [I_{MM}] ≥ VIII) in the northeastern region are usually located more than 30 km (19 mi) inside the 5% contour of peak seismic activity (Chiburis, 1981, Fig. 6). Therefore, an I_{MM} = VIII earthquake outside the most favorable area will probably cause no more than I_{MM} = V to VI shaking within the most favorable area.

The second criterion -- that no part of area 1 should be susceptible to ground motions of intensity I_{MM} = VI or greater from earthquakes whose epicenters are within or adjacent to the area (see Fig. 2) -- was used to refine the initial area 1 boundary based on Fig. 1. (An I_{MM} = VI earthquake is felt by everyone. Although heavy furniture may be moved, plaster may be loosened and fall, and chimneys may be damaged, overall damage is slight.)

The intensity contours of I_{MM} = VI (see Fig. 2) were used to adjust the limits of area 1 in northern Maine. Here, the effects of I_{MM} ≥ VI earthquakes at La Malbaie can be felt. Also, isolated I_{MM} = VI earthquakes occurred near the New Hampshire-Vermont-Quebec border and in central Maine just west of Millinocket. The boundary of area 1 was further refined in northeastern Maine as a result of the earthquake of January 9, 1982, whose epicenter was at 47.0° N, 66.5° W and whose intensity was 5.5 (M_L).* No earthquake data beyond this last date were considered.

The value I_{MM} = VI was chosen rather arbitrarily because no method exists for specifying an acceptable level of seismic risk for a repository for high-level radioactive wastes. In his preliminary assessment of this problem, Dawson (1980) concludes:

> . . .although seismic design procedures for surface structures are highly developed, dynamic analysis and tools specifically related to the dynamic design of cavities in rock have not been developed to a stage where they can be used in day-to-day design.

Table 1 summarizes hypothetical failure modes and hazards resulting from earthquake activity for various phases of development and operation of a mined repository. The operational phases in the table are based on Canada's program to develop repositories for high-level radioactive waste.

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*M_L is defined as a magnitude determined from short-period surface waves using Wood-Anderson instruments. M_L is appropriate for southern California earthquakes. A scale that calibrates northeastern U.S. magnitudes with those from southern California is introduced in Ebel (1982) and resulted in the 5.5 value given here.

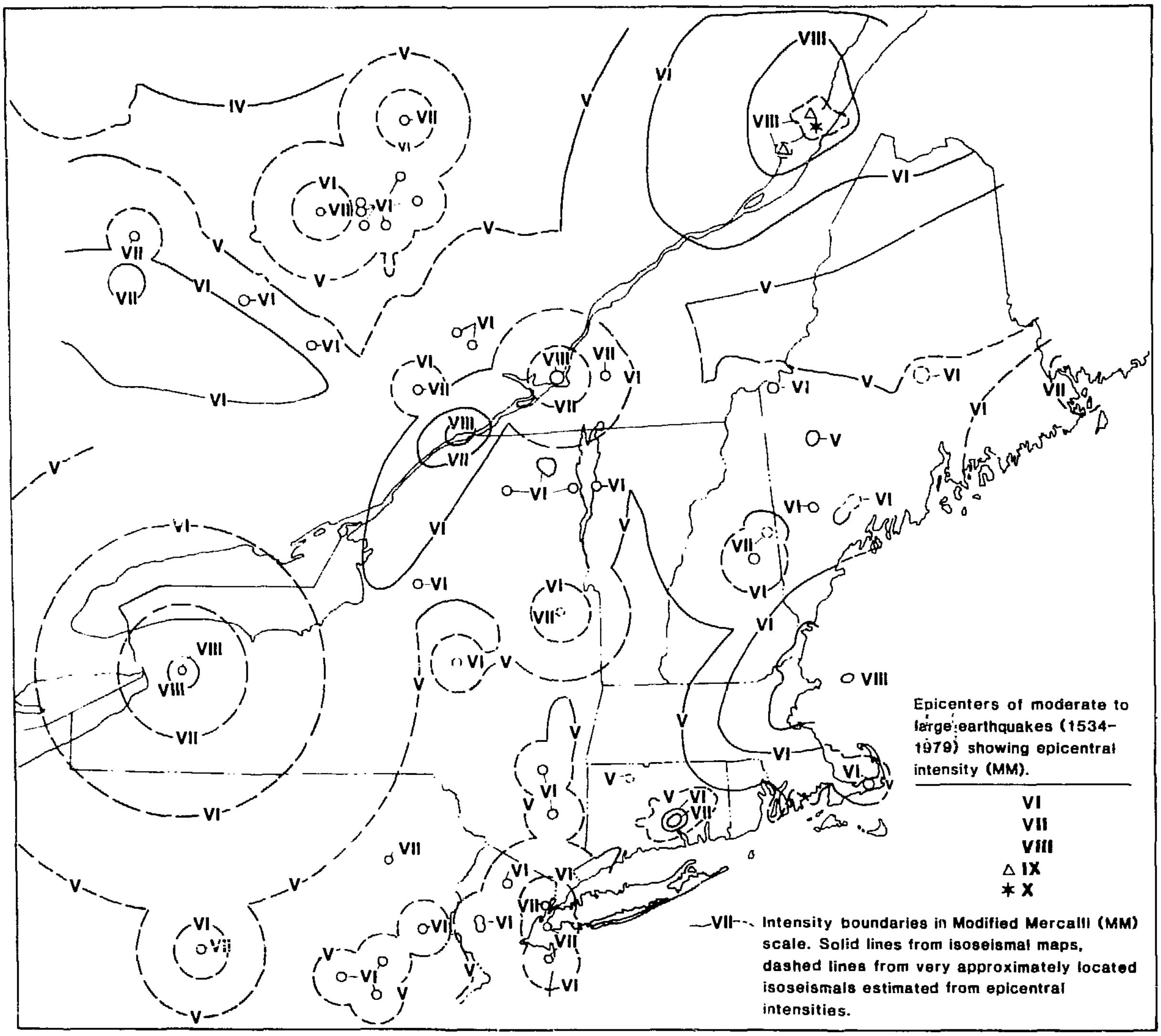

FIGURE 2 Maximum Recorded Earthquake Intensities in the Northeastern Region and Adjacent Areas in Canada (Source: Harrison et al., 1983a, Fig. 3.17)

During the operational period of a repository (0–50 years), surface structures, such as hoisting equipment (see Table 1), would be the most vulnerable to an I_{MM} = VI earthquake. However, such equipment should survive I_{MM} = VI shaking rather well. With respect to the mined repository and waste packages, Dawson (1980) concludes that:

> . . .the observed performance of underground structures such as tunnels and mines during earthquakes indicates that, providing they are not intersected by an active fault, such structures have high seismic resistance.

TABLE 1 Effects of Earthquake Activity on Repository Design and Performance

Period	Repository Status	Earthquake-Related Damage or Effects	Consequences for Repository[a]	Seismic Design Considerations
Operational period (0-50 years)	Construction	Failure of surface structures, facilities, etc.	Shutdown of operation	
	Emplacement	Increased instability of vault	Decreased personal safety, loss of access, and damage to containers	Return period for a site-design[b] earthquake for noncritical components is 100 years
	Monitoring	Overstressing of monitoring equipment, etc.	Loss of monitoring capabilities	Return period for a design-basis[b] earthquake for critical components is greater than 100 years and less than 1000 years
		Changes in rock joint system (formation of new joints and changes in existing joints)	Increased groundwater flow	
		Fracture of waste containers	Increased radioactive contamination	
Isolation phase 1 (50-400 years)[c]	Decommissioned and sealed	Changes in rock joint system (formation of new joints and changes in existing joints)	Increased groundwater flow	Return period for an isolation-basis earthquake depends on risk
		Fracture of waste containers	Increased radioactive contamination	
Isolation phase 2 (400-10,000 years)	Sealed	Effects and consequences are the same as in isolation phase 1	Effects and consequences are the same as in isolation phase 1	Maximum credible earthquake should be based on tectonic considerations

[a] The hazard diminishes as the radioactive wastes decay.

[b] These criteria are included for illustrative purposes only and do not represent criteria proposed by Argonne National Laboratory or the U.S. Department of Energy.

[c] The length of isolation phase 1 is determined by the availability of historical seismicity data. For this study, data are available from 1534 to the present, or approximately 450 years.

Source: Adapted from Dawson (1980, Table 3).

Finally, participants in a workshop on the seismic performance of underground facilities concluded that (Marine, 1982):

> . . .the basic observation still stands that subsurface damage from earthquakes is far less than surface damage from the same earthquake. Thus, the same seismic criteria that are applied to site a surface nuclear facility would appear to be conservative in siting a subsurface repository.

Thus, designation of the most favorable area as one where instances of I_{MM} = VI or higher ground motions are unknown over 400 years seems sufficiently conservative for the operational period.

The maximum acceptable earthquake intensity for isolation phase 1 (50-400 years) is more difficult to specify (see Table 1). During this phase, an increase in return period is required because the potential hazard from the radioactive waste is still relatively high (Dawson, 1980). Isolation phase 2 (400-10,000 years) lasts far longer than the life spans of engineering structures. Dawson (1980) recommends that repository design for isolation phase 2 be based on the maximum credible earthquake as determined from tectonic considerations. Such an earthquake would be of larger magnitude than any historically recorded event in the northeastern region.

The geologically most favorable area should have the lowest likelihood of any area in the northeastern region of having the epicenter of the maximum credible earthquake within its boundaries. Such an event might subject areas of the Northeast that had not experienced an I_{MM} = VI earthquake to intensities of this value or higher. Therefore, the seemingly ultraconservative limit of I_{MM} = VI used for designating the most favorable area is probably only moderately conservative over a time scale of 10,000 years. That ultraconservatism is warranted for such a time scale is supported by Allen (1975):

> . . .In view of the difficulties of interpreting the historic record, and in view of the large variation of geological environments in which major earthquakes have occurred, I feel that geologists and geophysicists must continue to be exceedingly conservative in their estimates of the likelihoods of major damaging earthquakes in specific areas. We have been surprised too often in the past, and we cannot afford to be surprised too many times in the future.

Because no evidence exists of significant current uplift or subsidence within area 1, the vertical-movements criterion did not alter its boundaries. Also, area 1 does not contain suspected Holocene faults, and no part of it occurs along the edges of coastal Cretaceous and Tertiary deposits. It does not contain major northwest- and north- to north-northeast-trending extensional faults and grabens. Finally, no Cretaceous or Quaternary igneous activity has been recorded within the area. The closest warm springs (24°C [75°F]) are at Sandy Springs, which is located in the northwestern corner of Massachusetts, about 10 km (6 mi) west of area 1's western boundary.

2.3 DESIGNATION OF THE LEAST FAVORABLE AREA (AREA 3)

The two main geologic criteria used to designate the area least favorable for further investigation were (1) location in zones of greater than 5% of peak regional seismic activity (see Fig. 1) and (2) location in zones of relatively high intensity earthquakes (i.e., those zones in which events of $I_{MM} \geq$ VI have been recorded) (see Fig. 2). Of lesser importance were distance from (1) known or suspected vertical crustal movements; (2) deep-seated faults, faults with large displacements, or zones of diverse fault trends; (3) suspected Holocene fault movement; and (4) zones of known Cretaceous or suspected Quaternary igneous activity.

Application of these seismotectonic criteria yielded several areas considered unsuitable for further investigation. These were lumped together and designated area 3 (see Fig. 3). Because designation of area 3 was based on one or more of the above criteria being characteristic, its boundaries are also quite conservative.

Although only the northern portions of the Adirondack Mountains would have been eliminated based on seismicity considerations alone (see Figs. 1 and 2), the entire Adirondacks subregion was included in area 3 because of evidence of active uplift. The regional releveling data of Barnett and Isachsen (1980) can be interpreted to indicate that the Adirondacks are rising at the rate of about 3.5 mm/year (0.14 in./year). This interpretation has been questioned by Brown and Reilinger (1980). Isachsen (1982) believes that the youthful drainage system on the Adirondack dome is further evidence of

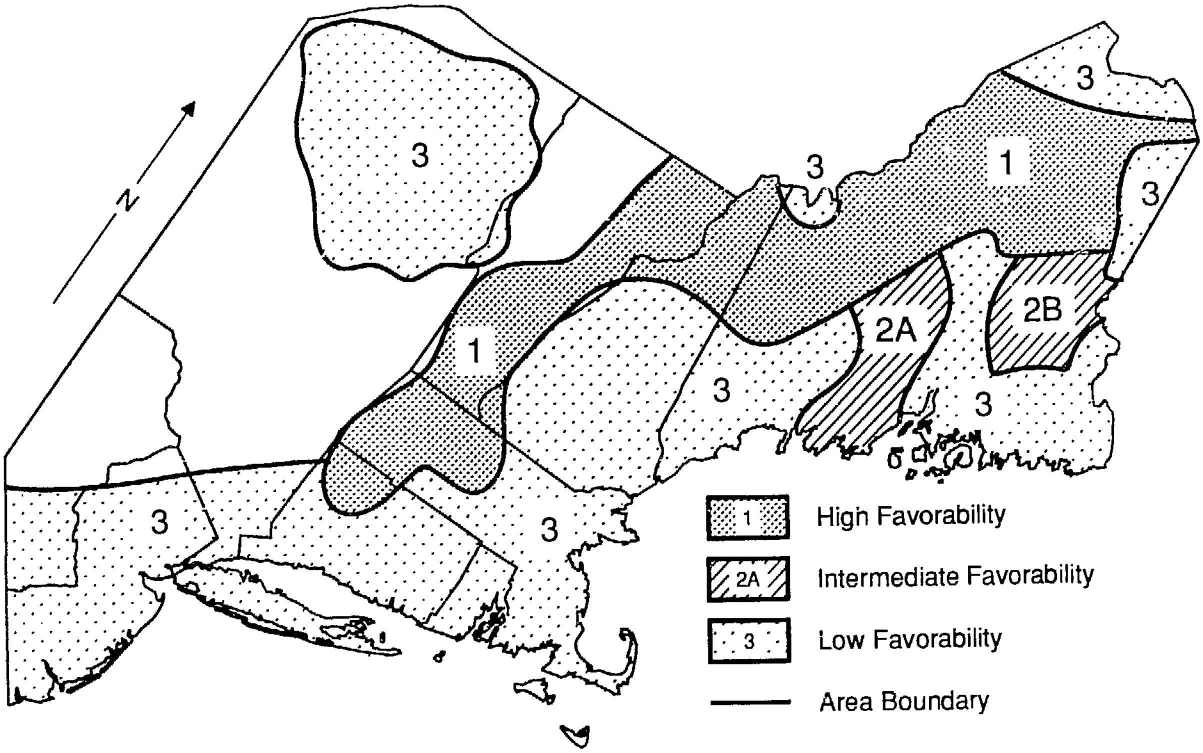

FIGURE 3 Designated Areas of Relative Seismotectonic Favorability

uplift, although not necessarily of present-day uplift. Finally, the presence of springs bearing carbon dioxide (>2000 ppm) along the eastern margin of the Adirondacks tends to support the concept of a zone with potential for rising mantle material and crustal uplift (Isachsen, 1982). Because of this evidence of instability, the Adirondack dome was not considered further.

2.4 DESIGNATION OF THE AREA OF INTERMEDIATE FAVORABILITY (AREA 2)

Application of the seismotectonic criteria (see Sec. 2.1) yields values between those used to define the clearly unfavorable area and those used to define the most favorable area (see Fig. 3), thereby defining an area of intermediate favorability. Portions of area 2 are more favorable than others, depending on proximity to the boundaries of areas 1 or 3. For example, the extreme southeastern boundary of subarea 2A is close to the Sears Island fault, which may have experienced movement within the last 15,000 years (Gerber and Rand, 1978), and the southern boundary of subarea 2B is close to the Norumbega fault zone (Thompson, 1981). The northern boundaries of subareas 2A and 2B, however, are in contact with the seismotectonically quiet part of area 1 in central Maine. The boundaries of the three areas are also shown on Plate I, a microfiche copy of which is attached to the inside back cover of this report.

3 DESIGNATION OF SUBAREAS

3.1 CRITERIA USED FOR SUBAREA DESIGNATION

The geologic criteria developed in U.S. Department of Energy (1981) provided the framework for designating the areas and subareas. The criterion "tectonic environment" was used more in area designation than in subarea designation. Descriptions follow of the six geologic criteria and how they were evaluated in this study.

3.1.1 Geologic Characteristics

The geologic characteristics criterion required consideration of the geologic setting of the crystalline rock bodies. Information was compiled concerning their lithology, structure, and geologic history. To facilitate comparison of subareas, each subarea in area 1 was established so that its plutons exhibit similar geologic characteristics. In other words, each subarea in area 1 contains plutons having the greatest possible similarity in properties considered important to repository performance, namely, hydrologic, geochemical, rheological, and thermal properties. The processes assumed to be of greatest importance in controlling these properties are related to ease and mode of magma emplacement, fractional crystallization, intensity and duration of rock deformation, and type and extent of rock alteration.

The primary geologic criterion used in designating subareas in area 1 is orogenic association. Plutons were classified as being associated with the Grenville, Avalonian, Taconic, Acadian, or Alleghenian orogenic episodes, or as having been intruded soon after one of these episodes. Characteristics used to refine the initial subarea boundaries based on orogenic association are lithology, isotropy, and homogeneity.

Anisotropy in crystalline rock bodies results from preferred orientation of fractures, primary and secondary mineral grains, and secondary intrusives. Foliation, the planar arrangement of textural or structural features, results mainly from magma flow or syntectonic deformation and metamorphism. Foliation also results from long-term activity along faults. Anisotropy can be expressed on the scale of individual mineral grains or on the scale of secondary intrusives, faults, and large fractures. Estimates of relative anisotropy in crystalline rocks of the northeastern region were based on available geologic information.

Heterogeneity within individual plutons exists on all scales and can usually be estimated from available geologic information. Many plutons contain several different lithologies of both igneous and metamorphic origin. Their complexity can be attributed to early fractionation followed by multiple intrusion of magmas of differing composition or to in situ fractionation during or after emplacement of a homogeneous magma. A commonly occurring small-scale heterogeneity is porphyritic texture, in which much larger grains called phenocrysts are embedded in an essentially equigranular groundmass of much smaller grains. Plutonic textures are very diverse and depend on original magma composition, emplacement mode, and fractionation history during crystallization. All such features are greatly affected by the overall tectonic environment, but most particularly by major orogenic episodes. Other heterogeneities can be attributed to fracturing (faults and joints) and alteration of primary minerals.

Although stresses within a pluton might increase costs by presenting problems during repository construction and reducing repository stability, this parameter could not be used for subarea designation because of lack of data. Lee et al. (1979) determined that horizontal paleostresses in plutons along the Maine coast exceed lithostatic pressure. These paleostresses may be the cause of sheeting fractures and rockbursts in local quarries. Because similar sheeting fractures and rockbursts are encountered in quarries throughout the most favorable area, lateral in situ stresses in excess of lithostatic pressure may be present in all of the subareas.

Finally, designing a repository will require an understanding of the thermal and thermal-mechanical properties of the rock body and of the in situ temperature regime. Because data pertaining to thermal diffusivity, thermal expansion, temperature, and heat flow were not available for most of the plutons, these properties could not be used in subarea designation. However, thermal properties are briefly discussed here for the sake of completeness.

The thermal diffusivity and thermal expansion of nine crystalline rock types were tested by Mirkovich (1979), who found their thermal diffusivities to decrease with increasing temperatures. For syenite, diffusivity ranged from 0.0104 cm^2/s at 25°C (0.0016 $in.^2/s$ at 77°F) to 0.0068 cm^2/s at 500°C (0.0010 $in.^2/s$ at 932°F); for granite, it ranged from 0.0160 cm^2/s at 25°C (0.0025 $in.^2/s$ at 77°F) to 0.0075 cm^2/s at 500°C (0.0012 $in.^2/s$ at 932°F). The path of least resistance for heat transmission is described by Mirkovich as along foliation planes. He also reports that chloritized amphibolite samples exhibited a lower thermal expansion (0.40%) than that of the granite samples (1.00%) at 500°C (932°F). In the tests conducted, the orientation of the long axis of the test sample with respect to foliation was found to exert little influence over thermal expansion.

Heat flow values measured in core holes 100-300 m (330-980 ft) deep at 22 sites in New England are reported in Birch et al. (1968); five of these sites are located in the most favorable area. Heat flows at these five sites (uncorrected for topographic and geologic factors) ranged from 1.67×10^{-6} $cal/cm^2/s$ at Millers Falls, Mass., to 1.20×10^{-6} $cal/cm^2/s$ at North Springfield, Vt. Birch et al. (1968) also report an apparent correlation between heat flow and the age and radioactivity of the rocks investigated. Younger, more radioactive rocks tend to exhibit the highest heat flows. For example, the Conway granite, which was investigated at Kancamagus, North Conway, and Waterville, N.H., exhibited heat flows of 2.13×10^{-6} $cal/cm^2/s$, 1.95×10^{-6} $cal/cm^2/s$, and 2.21×10^{-6} $cal/cm^2/s$, respectively. The Conway granite exhibits high uranium and thorium contents compared with those found in the rest of the northeastern region.

3.1.2 Geohydrology and Geochemistry

The original U.S. Department of Energy (1981) geologic criteria for repository siting include both geohydrology and geochemistry as being important for regional and smaller-scale studies of potential repository rocks. Because of the overlap in information required for each of these factors as originally defined, the two were combined in this study into a single geohydrology factor.

Within the category of geohydrology, information was developed for both the surface and subsurface components of the hydrologic system. Surface-water considerations require (1) description of freshwater resources (i.e., ponds, lakes, reservoirs, and streams); (2) investigation of pertinent streamflow characteristics, including low-flow and flood conditions; (3) discussion of water availability and use; and (4) explanation of the interrelationships between surface waters and groundwaters. Groundwater information should include definitions of aquifers and descriptions of water quantity and mobility characteristics.

As originally defined, the geochemistry criterion covered factors that might affect waste stability and waste transport. Among the factors mentioned were porosity, permeability, formation pressure, water chemistry, and groundwater circulation. Although the close association with geohydrologic characteristics is apparent, there are two geochemical considerations that could be important influences on potential waste migration from a repository -- chemical properties of the groundwater and the mineralogy of the host rock, including that of fracture-filling materials, if present. In this report, the chemical properties of groundwater were included as part of the geohydrologic criterion, while the geochemical aspects of the host rock were made part of the geologic characteristics criterion (see Sec. 3.1.1).

Of the various geohydrologic conditions included within this broad criterion, deep groundwater conditions are undoubtedly the most important for waste isolation. However, only very limited information was available on groundwater quantity and chemistry within the crystalline rock bodies of the region at the probable depth of a repository. Because massive, unweathered crystalline rocks have essentially no primary porosity, conditions are considerably less favorable for developing groundwater supplies with large, sustained yields in rocks of this type than they are in alluvial and other nonindurated deposits, as well as in certain types of sedimentary rocks. Krynine and Judd (1957) report porosities of up to 3% for unweathered metamorphic and plutonic igneous rocks, with the most common value being less than 1%. As a consequence, permeabilities tend to be very low. However, the hydraulic conductivity of unweathered crystalline rocks is greatly enhanced by fracturing. Significant fracture zones can occur at depth in plutons that might otherwise be classified on the basis of homogeneity as relatively tight (Mair and Green, 1981).

Two general categories of fractures exist in plutons -- fractures resulting from tectonic stresses and rock-expansion fractures resulting from the release of confining pressures at or near the surface as overlying materials are removed by erosion. These latter fractures are concentrated near the land surface and diminish rapidly in both size and frequency with depth. Although expansion fractures provide small water yields to shallow wells for domestic use, it is unlikely that this type of fracture would penetrate to the anticipated depths of a waste repository. On the other hand, fractures of tectonic origin, which include large faults and shear zones, may extend to great depths and, depending on their openness, may transmit large quantities of water. Therefore, information on fracture-facilitated groundwater flow was important in designating subareas.

Geohydrologic conditions within plutons also depend on some of the other geologic characteristics discussed in Sec. 3.1.1. Therefore, information on the degree of fracturing was used in conjunction with other geologic characteristics affecting the petrologic and structural integrity of crystalline rock bodies to infer probable groundwater conditions. For purposes of subarea designation, we assumed that plutons exhibiting similar geologic characteristics, particularly as regards the degree of tectonic fracturing, possessed analogous geohydrologic environments.

3.1.3 Potential for Human Intrusion

The human intrusion criterion required consideration of past exploration for and exploitation of mineral deposits, as well as currently exploited or potentially exploitable mineral resources, because these conditions could influence possible minerals exploitation by unsuspecting human beings after repository closure. The locations of active and abandoned mines are given on Plates II-IX.* We considered the presence of active mines in a pluton or within 3.2 km (2 mi) of a pluton boundary to be relatively undesirable. Abandoned mines were treated similarly if the potential for reopening them or for finding additional economic prospects close by was considered significant. Plutons located in zones showing promise for mineral exploitation were grouped together. Although such groupings could have been important determinants in subarea designation, geologic characteristics were generally found to be of overriding importance.

3.1.4 Site Geometry

The site geometry criterion required development of information on the depth, thickness, and lateral extent of crystalline rock bodies in the northeastern region. Few data other than those gleaned from surface exposures were available. Because pluton shapes are suggestive of emplacement mode or deformational history, we grouped plutons having similar shapes in map view. Elongate plutons were assumed to be well foliated parallel to their long axes and to contain shear or fracture zones as a result of deformation. Similarly, roughly circular or irregularly shaped plutons were assumed to have experienced relatively little deformation following emplacement. Plutons of this type generally have less well developed foliation and more random fracture patterns compared with deformed plutons.

3.1.5 Surface Characteristics

The surface characteristics criterion required identification of surface features (e.g., landslides) or conditions (e.g., unusually steep grades) that might result in hazardous access to a waste repository site or present other difficulties. In particular, rugged terrains or those judged to be particularly susceptible to landslides were noted. Such factors could affect the design, construction, and eventual safety of transportation corridors used to move waste to the repository. However, existing engineering and

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*Microfiche copies of Plates II-IX are attached to the inside back cover of this report.

geotechnical capabilities should be able to deal successfully with most conditions of this nature. Therefore, under normal circumstances, this particular criterion would be expected to have less significance for subarea designation than those discussed in Secs. 3.1.1-3.1.4.

Surface characteristics are determined principally by bedrock and surficial geology, as modified by geomorphic processes. Differences in bedrock petrography and structure produce different susceptibilities to weathering, erosion, mass wasting, and other processes that dictate landscape development; therefore, surface characteristics are influenced in large part by the geologic characteristics described in Sec. 3.1.1. For the purposes of subarea designation, the surface characteristics of subareas delineated on the basis of similar geologic characteristics were assumed to be broadly similar. Any undesirable surface conditions were noted.

3.1.6 Tectonic Environment

As mentioned at the beginning of Sec. 3, this criterion played a minor role in subarea designation, its major contribution having been to area designation. Using this criterion at the regional scale required careful definition, identification, and cataloging of all known earthquakes and evaluation of Quaternary faults and igneous activity; therefore, such information was available to be applied on a local scale as well and did assist in subarea designation. For example, we used the distribution of earthquake epicenters within an area, along with other criteria, to help draw the boundaries of subareas.

3.2 BOUNDARY RELATIONSHIPS BETWEEN GEOLOGIC SUBAREAS AND HYDROLOGIC UNITS

As discussed in Sec. 3.1.1, subareas were designated primarily on the basis of selected geologic characteristics. Although such characteristics determine to a large extent the geohydrologic conditions of an area, especially several groundwater parameters and circulation patterns, other geologic and nongeologic factors also play a role. For these reasons, the designated subareas do not coincide with the region's natural water resources areas, which tend to coincide with major drainage basins. The larger subareas incorporate portions of several drainage basins, and those portions may exhibit different hydrologic attributes. Also, large basins may drain portions of more than one subarea.

Because water resources investigations are usually designed around natural hydrologic units, the correspondence between geologic subareas and principal drainage basins must be established. Figure 4 shows the principal hydrologic units within the states of Connecticut, Massachusetts, and Rhode Island, as well as the boundaries of the areas and subareas defined in this report. Similarly, the major hydrologic units and area and subarea boundaries for the states of Vermont and New Hampshire are shown in Fig. 5; Fig. 6 gives the same information for Maine. Although most of the hydrologic units shown correspond to the major drainage basins of the area, some represent a composite of smaller basins where no integrated master drainage has developed. The hydrologic unit boundaries in Figs. 4-6 were obtained in most cases from the corresponding hydrologic unit maps published by the U.S. Geological Survey (1974a,

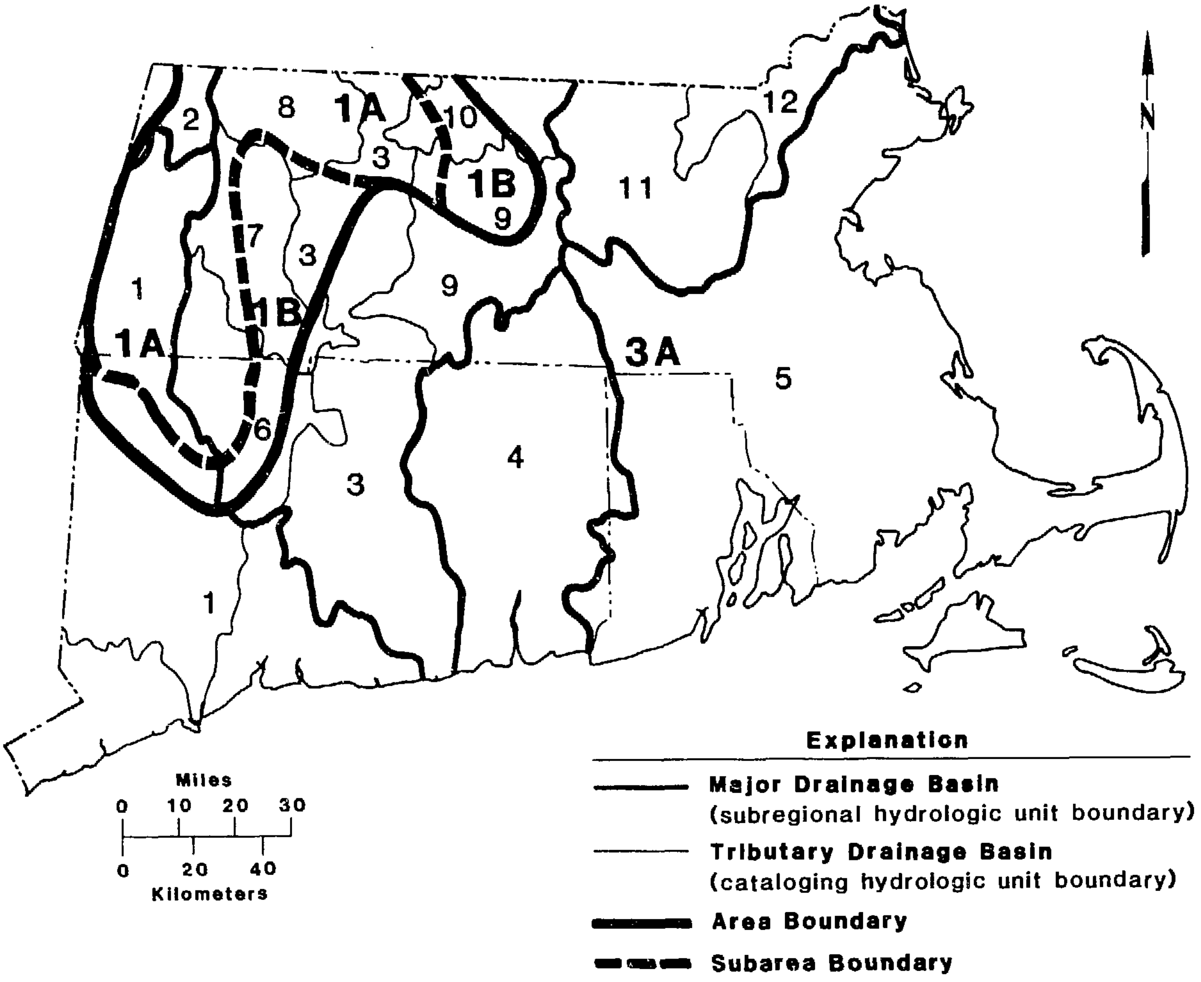

FIGURE 4 Map of Connecticut, Massachusetts, and Rhode Island Showing the Principal Drainage Basins and Subareas (see Table 2 for the names of the major drainage basins and hydrologic data)

1974b, and 1974c). For ease of illustration, however, standard mapped units were grouped in some cases with adjacent areas to form a larger unit. This type of simplification is restricted primarily to area 3 (see Fig. 3). Because area 3 is the least favorable for repository siting, it received little consideration.

Tables 2-4 contain additional information on the hydrologic units illustrated in Figs. 4-6, respectively. Each table lists the major drainage basin(s) within each hydrologic unit and the subareas associated with each. Data summarizing surface-water and groundwater quantity and quality are cataloged in the computerized NAWDEX (National Water Data Exchange) system by the hydrologic unit code number given in these tables. Also included in the tables is the number of active and inactive sites within the hydrologic unit for which data of the indicated category are available. These tables clearly show the paucity of groundwater data for the northeastern region. However, limited additional data for a particular subarea may be available from sources other than NAWDEX.

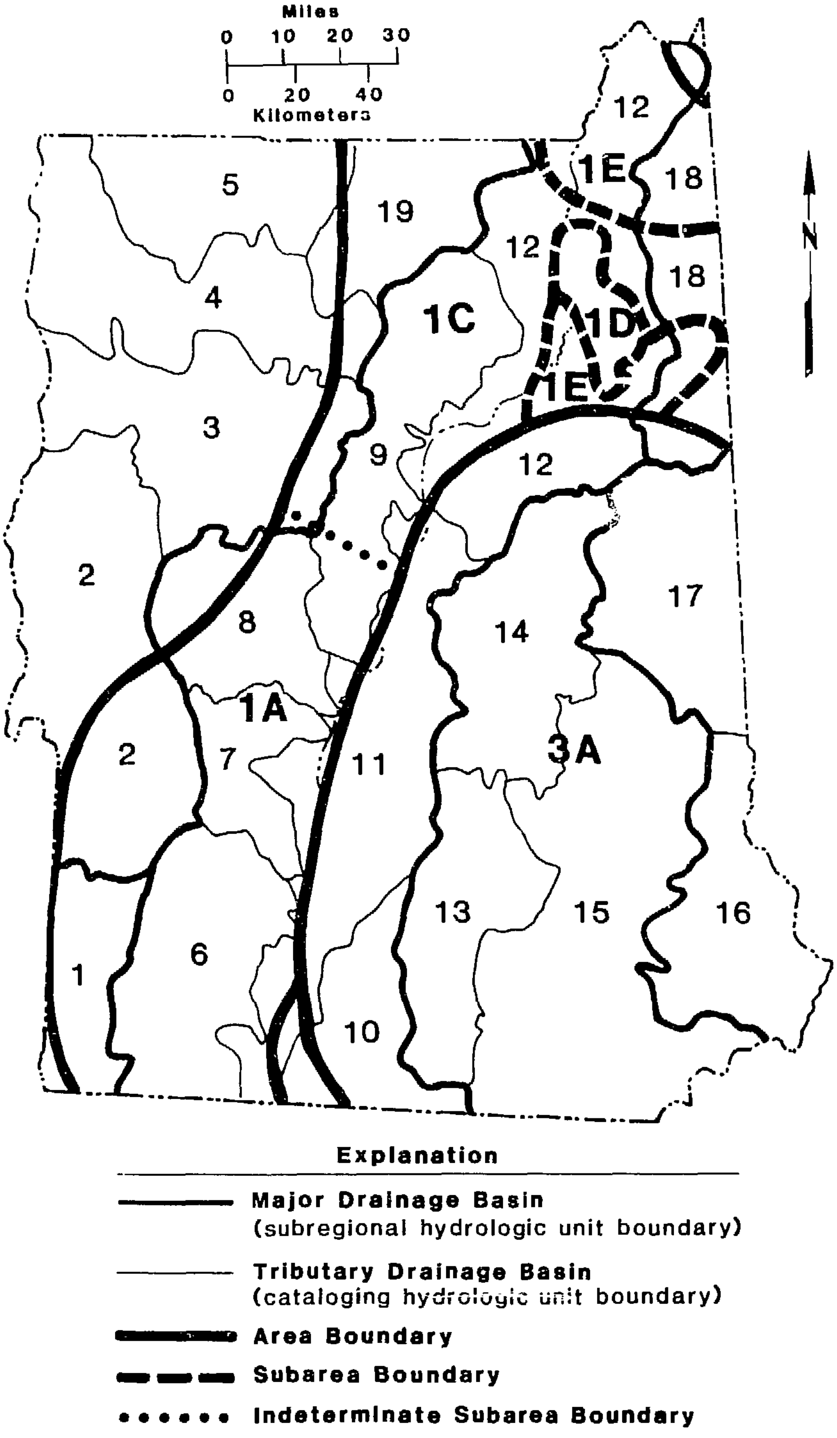

FIGURE 5 Map of New Hampshire and Vermont Showing the Principal Drainage Basins and Subareas (see Table 3 for the names of the major drainage basins and hydrologic data)

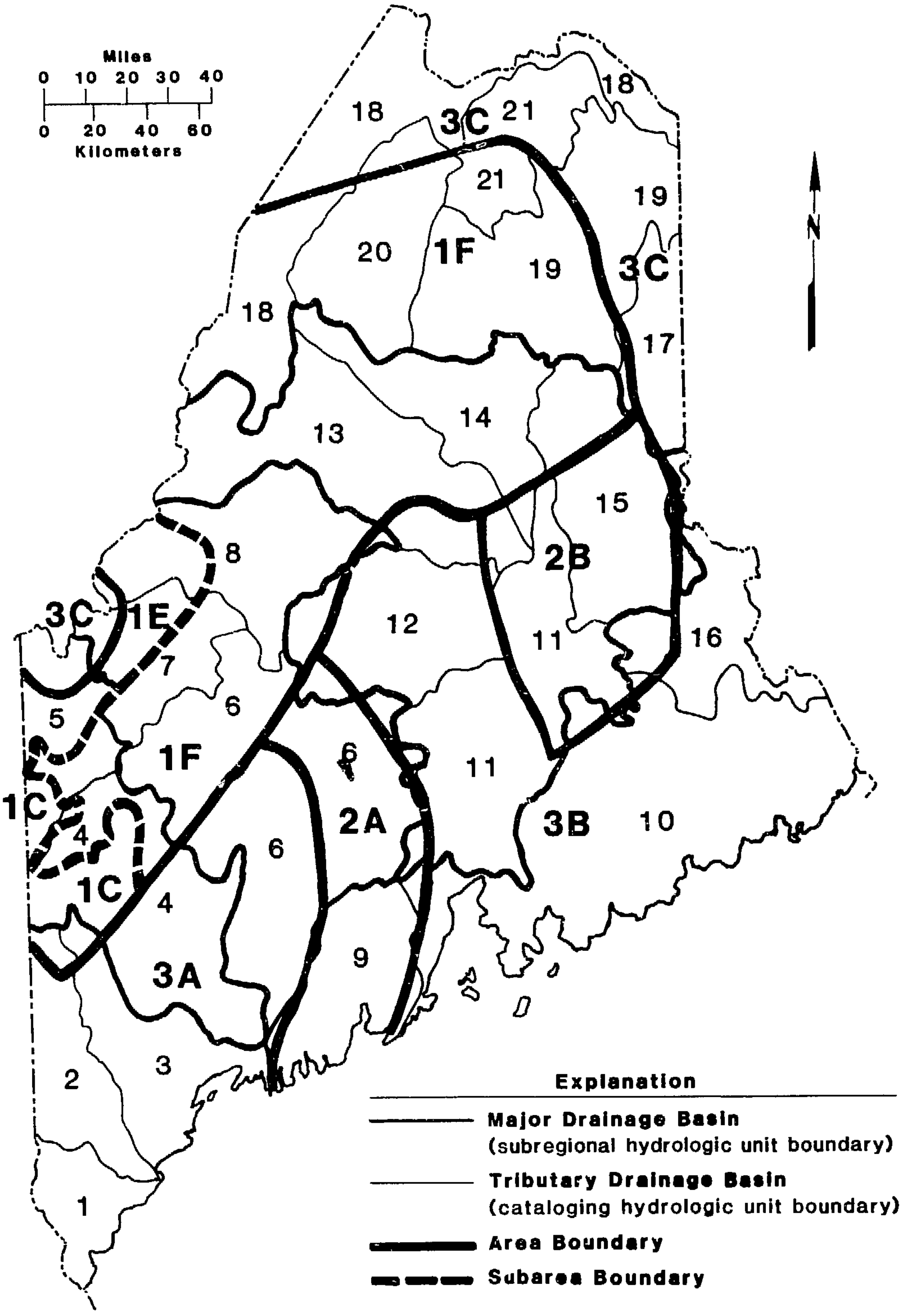

FIGURE 6 Map of Maine Showing the Principal Drainage Basins and Subareas (see Table 4 for the names of the major drainage basins and hydrologic data)

TABLE 2 Summary of Hydrologic Data Indexed by the National Water Data Exchange (NAWDEX) and Subarea Designations for the Major Drainage Basins of Connecticut, Massachusetts, and Rhode Island

Number in Fig. 4	Drainage Basins	Subarea Designation	Hydrologic Unit[a]	Surface-Water Data Sites[b]		Surface-Water Quality Sites[c]		Groundwater Data Sites[d]		Groundwater Quality Sites[c]	
				Active	Inactive	Active	Inactive	Active	Inactive	Active	Inactive
1	Housatonic[e]	1A,1B,3A	01100005	50	162	118	358	0	0	21	227
2	Hoosic	1A	02020003	29	96	28	190	3	0	0	50
3	Lower Connecticut[e]	1A,1B,3A	01080205 01080201	39	124	50	337	0	0	0	322
4	Thames-Quinebaug-Shetucket[e,f]	3A	01100003 01100002 01100001	37	158	56	482	0	0	0	197
5	Blackstone, Taunton, Charles, and numerous smaller basins[e]	3A	01090005 01090004 01090003 01090002 01090001	72	505	43	696	0	0	197	303
6	Farmington[g]	1A,1B,3A	01080207	25	28	18	81	0	0	0	120
7	Westfield[g]	1A,1B,3A	01080206	16	51	22	29	0	0	0	10
8	Deerfield[g]	1A,1B	01080203	10	48	13	30	0	0	0	32
9	Chicopee-Quaboag-Swift-Ware[g]	1A,1B,3A	01080204	21	50	17	61	0	0	0	7
10	Millers[g]	1A,1B,3A	01080202	16	17	21	40	0	0	0	11
11	Nashua, Concord[h,i]	3A	01070004 01070005	43	100	54	121	0	0	81	83
12	Lower Merrimack[e]	3A	01070002	38	142	64	145	0	0	29	82

[a] Identification number for access to NAWDEX system; designates river basins of drainage area greater than 1810 km^2 (700 mi^2).

[b] Includes stream-gage, streamflow, and lake- or reservoir-volume data.

[c] Includes data on biological, physical, sediment, and chemical analyses for both surface waters and groundwaters.

[d] Includes water-level data and well- or spring-discharge data.

[e] Tributary to Atlantic Ocean.

[f] Basin names separated by hyphens indicate a tributary situation within a master drainage system.

[g] Tributary to Connecticut River.

[h] Tributary to Merrimack River.

[i] Basin names separated by commas indicate discrete, nontributary basins draining a hydrologic area.

Source: U.S. Geological Survey (1981).

TABLE 3 Summary of Hydrologic Data Indexed by the National Water Data Exchange (NAWDEX) and Subarea Designations for the Major Drainage Basins of New Hampshire and Vermont

Number in Fig. 5	Drainage Basins	Subarea Designation	Hydrologic Unit[a]	Surface-Water Data Sites[b]		Surface-Water Quality Sites[c]		Groundwater Data Sites[d]		Groundwater Quality Sites[c]	
				Active	Inactive	Active	Inactive	Active	Inactive	Active	Inactive
1	Hoosic-Batten Kill[e]	1A	02020003	29	96	28	190	3	0	0	50
2	Poultney, Otter Creek[f,g]	1A	02020001 02020002	8	32	6	100	0	0	0	10
3	Winooski[f]	1C	02010003	16	26	50	158	0	0	1	3
4	Lamoille[f]	1C	02010005	3	7	41	181	0	0	0	1
5	Missisquoi[f]		02010007	4	2	16	107	0	0	0	1
6	Deerfield, West Branch Deerfield[h]	1A	01080203 01080107	19	57	35	129	0	0	0	32
7	Ottauquechee[h]	1A,1C	01080106	8	13	37	20	0	0	0	2
8	White[h]	1A,1C	01080105	3	5	2	5	0	0	0	2
9	Ompompanoosuc, Waits, Wells, Passumpsic[h]	1C	01080103 01080102	8	17	36	49	0	0	0	3
10	Ashuelot[h]	1B,3A	01080201	17	77	34	85	0	0	0	90
11	Middle Connecticut	1A,1B,1C,3A	01080104	11	11	16	44	0	0	0	12
12	Upper Connecticut	1C,1D,1E,3A	01080101	16	15	17	75	0	0	9	7
13	Contoocook-Warner[i]	3A	01070003	13	9	23	15	0	0	0	5
14	Upper Merrimack-Baker, Pemigewasset	3A	01070001	11	9	22	13	0	0	0	8
15	Middle Merimack	3A	01070002	38	142	64	145	0	0	29	82
16	Salmon Falls-Lamprey-Cocheco[j]	3A	01060003	16	55	17	145	0	0	2	7
17	Bear Camp-Saco	3A	01060002	8	9	32	30	0	0	1	17
18	Upper Androscoggin	1C,1E,3A	01040001	8	2	8	20	0	0	0	4
19	Lake Memphremagog	1C	0111000	5	2	67	137	0	0	0	2

[a] Identification number for access to NAWDEX system; designates river basins of drainage area greater than 1810 km^2 (700 mi^2).

[b] Includes stream-gage, streamflow, and lake- or reservoir-volume data.

[c] Includes data on biological, physical, sediment, and chemical analyses for both surface waters and groundwaters.

[d] Includes water-level data and well- or spring-discharge data.

[e] Basin names separated by hyphens indicate a tributary situation within a master drainage system.

[f] Tributary to Lake Champlain.

[g] Basin names separated by commas indicate discrete, nontributary basins draining a hydrologic area.

[h] Tributary to Connecticut River.

[i] Tributary to Merrimack River.

[j] Tributary to Atlantic Ocean.

Source: U.S. Geological Survey (1981).

TABLE 4 Summary of Hydrologic Data Indexed by the National Water Data Exchange (NAWDEX) and Subarea Designations for the Major Drainage Basins of Maine

Number in Fig. 6	Drainage Basins	Subarea Designation	Hydrologic Unit[a]	Surface-Water Data Sites[b]		Surface-Water Quality Sites[c]		Groundwater Data Sites[d]		Groundwater Quality Sites[c]	
				Active	Inactive	Active	Inactive	Active	Inactive	Active	Inactive
1	Salmon Falls[e,f]	3A	01060003	16	55	17	145	0	0	2	7
2	Saco[e,f]	1C,3A	01060002	8	9	32	30	0	0	1	17
3	Presumpscot[f]	1C,3A	01060001	9	8	22	78	0	0	0	23
4	Androscoggin[e,f]	1C,1F,3A	01040002	14	5	38	43	0	0	9	14
5	Magalloway, Cupsuptic, Kennebago[e,f,g]	1C,1E,1F	01040001	8	2	8	20	0	0	0	4
6	Kennebec-Sebasticook-Carrabassett[f,h]	1F,2A,3A	01030003	15	11	38	41	2	0	0	12
7	Dead[i]	1E,1F	01030002	3	1	8	0	0	0	0	0
8	Moose, Upper Kennebec	1E,1F	01030001	7	4	1	18	0	0	0	0
9	St. George and several smaller basins[f]	2A	01050003	1	1	3	1	0	0	0	0
10	Union, Narraguagus, Machias, and numerous small basins[f]	2B,3B	01050002	10	12	23	97	1	0	1	4
11	Penobscot[f]	2A,2B,3B	01020005	5	6	11	19	1	0	2	0
12	Piscataquis-Pleasant[j]	1F,2A,3B	01020004	5	2	22	8	0	0	0	0
13	West Branch Penobscot	1F,2B,3B	01020001	0	1	0	2	0	0	0	0
14	East Branch Penobscot	1F,2B	01020002	3	1	2	13	0	0	0	0
15	Mattawamkeag[j]	2B	01020003	1	3	2	12	0	0	0	0
16	St. Croix[f]	2B,3B	01050001	4	2	14	34	0	0	0	0
17	Meduxnekeag[g]	1F,3C	01010005	2	0	3	4	0	0	0	0
18	St. John[f]	1F,3C	01010001	6	4	35	9	0	0	0	4
19	Aroostook[k]	1F,3C	01010004	5	3	8	10	0	0	2	6
20	Allagash[k]	1F,3C	01010002	1	0	2	0	1	0	0	0
21	Fish[k]	1F,3C	01010003	1	1	19	17	1	0	0	0

[a] Identification number for access to NAWDEX system; designates river basins of drainage area greater than 1810 km^2 (700 mi^2).

[b] Includes stream-gage, streamflow, and lake- or reservoir-volume data.

[c] Includes data on biological, physical, sediment, and chemical analyses for both surface waters and groundwaters.

[d] Includes water-level data and well- or spring-discharge data.

[e] Drainage basin extends into New Hampshire.

[f] Tributary to Atlantic Ocean.

[g] Basin names separated by commas indicate discrete, nontributary basins draining a hydrologic area.

[h] Basin names separated by hyphens indicate a tributary situation within a master drainage system.

[i] Tributary to Kennebec River.

[j] Tributary to Penobscot River.

[k] Tributary to St. John River.

Source: U.S. Geological Survey (1981).

4 RANKING OF THE AREA 1 SUBAREAS

The six subareas of area 1 were ranked using geologic criteria (U.S. Department of Energy, 1981) and formal decision analysis. The area 2 subareas were not ranked because of reservations about their seismotectonic stability over the next 10,000 years.

Five of the authors of this report familiar with the technical aspects of the geologic problems provided the probability distribution estimates and the value judgments reported in this section. More specifically, the judgments for a particular attribute were provided by the appropriate technical expert. The value judgments used in constructing the multiattribute utility function were the result of group discussion.

Although the authors providing the probability distribution estimates and value judgments are very knowledgeable with respect to the technical issues raised in this report, the main objective was to explore the usefulness of a formal analytical technique such as decision analysis in helping to evaluate the relative geologic favorability of designated subareas for a repository for high-level radioactive waste. Therefore, the resultant ranking is relatively unimportant compared with the successful demonstration of the method.

4.1 DECISION-ANALYSIS PARADIGM FOR SUBAREA RANKING

Six subareas within area 1 were designated (see Sec. 3), primarily on the basis of their geologic characteristics. However, in ranking the subareas as to their favorability for possible detailed geologic investigation leading to repository siting, all six U.S. Department of Energy (1981) geologic criteria were used. Even though these criteria cover geologic aspects only (e.g., economic costs and social considerations were not estimated), evaluating and ranking of the subareas remained a complex problem. Four conditions requiring consideration were:

1. *Multiple objectives.* For each of the general geologic criteria, one or more objectives can be specified to evaluate the desirability of a subarea. The overall evaluation and comparison of subareas depends on the level of achievement for each subarea with respect to each objective. Tradeoffs between various levels of achievement must be made.

2. *Uncertainties.* In many instances, characterization of the subareas with respect to the criteria involves considerable uncertainty, especially for criteria involving lengthy periods or requiring evaluation with limited data. The uncertainty is present not only because additional technical information is needed but also because the quantification required for precise characterization is often very difficult if not impossible to achieve. Variability within a subarea is another source of uncertainty.

3. *Diverse units of measure.* The evaluation criteria cannot be measured in terms of easily comparable scales. The presence or absence of certain geologic features may provide the basis for constructing evaluation scales for one criterion, while the percentage of the surface area covered, the frequency of a feature, or the intensity of a characteristic may determine evaluation scales for other criteria.

4. *Value judgments.* The ranking of subareas requires explicit treatment of preferences for consequences. In addition, the preferences should account for risk attitudes, that is, for preferences for outcomes under uncertain conditions.

Because of these complexities and a desire to present a method that takes full advantage of professional value judgments, we used formal decision analysis to rank the subareas. The goal is to improve the likelihood that the best subarea(s) will be selected for further study and to provide a documented framework for evaluating and comparing subareas. An overview of the procedure and the actual protocol are presented in Secs. 4.1.1 and 4.1.2.

4.1.1 Characteristics of the Decision-Analysis Paradigm

Decision analysis is a systematic and logical set of procedures for analyzing complex, multiple-objective problems. The basic strategy is to divide the overall problem into small, understandable parts; to analyze each part; and to meaningfully integrate the parts to form an overall solution. The methodology is well founded on theoretical grounds (Keeney and Raiffa, 1976) and has been applied extensively over the past 20 years. Among the energy-related applications in recent years are analyses of U.S. synthetic fuel policy (Synfuels Interagency Task Force, 1975); the breeder reactor program (Manne and Richels, 1978); expansion of electrical capacity (Judd, 1978; Woodward-Clyde Consultants, 1982); and commercialization of solar photovoltaic systems (Boyd et al., 1982). Closely related to the problem being addressed here is the siting of energy facilities (Keeney, 1980; Sarin, 1980); the evaluation of nuclear waste disposal sites (Otway and Edwards, 1977); and management of nuclear waste (Lathrop and Watson, 1982). Although different tools of decision analysis were applied in the cited references, it is evident that the general techniques have something to offer in the analysis of complex problems, especially those in which an overall evaluation or ranking is required.

The decision-analysis paradigm applied in this analysis of relative geologic favorability of subareas involved the following general stages (Keeney and Raiffa, 1976):

1. *Preanalysis.* The problem is defined, and viable alternatives are identified.

2. *Structural analysis.* The important qualitative aspects of the problem are structured. A set of objectives is formulated, and

attributes (scales that measure levels of achievement of those objectives) are specified.

3. *Uncertainty analysis.* Where performance of alternatives with respect to some attributes is not known exactly, uncertainties are specified.

4. *Utility or value analysis.* Preferences for consequences are assessed by dividing the overall problem into small parts. An overall utility function is developed, which assigns a number u(x) to each possible outcome x. The utility function has two important properties (Keeney, 1980): (1) $u(x) > u(x')$ if and only if (x) is preferred to (x') and (2) in situations involving uncertainty, the expected value of u is the appropriate index with which to evaluate alternatives.

5. *Optimization analysis.* After carrying out the previous steps, the optimal strategy is the alternative with maximum expected utility. Sensitivity analysis is used to explore the implications of different assumptions, probabilities, and preferences.

The methods described here are widely accepted as being helpful in complex decision problems, such as ranking the subareas. Although the method appears to stress the end result (ranking of subareas), considerable benefits (e.g., more specific characterization of the subareas and uncertainties) result from carrying out the process. Informal analysis has little to offer in the way of justification for selection. The professional judgments and value judgments used here are explicit and available for examination, sensitivity analysis, and substitution of differing judgments by others.

4.1.2 Summary of the Protocol Used to Rank Subareas

Actual implementation of the stages listed in the previous section and the results of that implementation are described in the following sections:

1. *Adaptation of the U.S. Department of Energy (1981) criteria* (see Sec. 4.2). Some of the criteria are better described by dividing them into understandable and measurable objectives. A set of objectives and attributes covering the six geologic criteria was defined.

2. *Characterization of the subareas* (see Sec. 4.3). Each subarea's characteristics with respect to each attribute were specified. In many cases, the characteristics were represented by a probability distribution over different levels of desirability.

3. *Preferences for single attributes* (see Sec. 4.4). Preferences for various levels of each attribute were assessed, one attribute at a time.

4. *Construction of the multiattribute utility function* (see Sec. 4.5). The value tradeoffs between attributes were discussed, assessed, and revised in group meetings, and the overall utility function was constructed.

5. *Ranking subareas and sensitivity analysis* (see Sec. 4.6). The collected data and constructed utility function were used to rank the relative favorability of the six subareas. Limited sensitivity analyses of key parameters also were performed.

6. *Conclusions* (see Sec. 4.7). The overall conclusions were based on the results of the ranking process and the insights developed as a result of the total effort.

4.2 ADAPTATION OF U.S. DEPARTMENT OF ENERGY (1981) CRITERIA

For the application of decision analysis described here, we found it useful to subdivide or define more narrowly the six geologic site performance criteria used throughout this study. The geologic characteristics criterion, for example, was divided into distinct components. The resulting units were more understandable, more amenable to quantification, and more manageable. Also, the overall relevance of a criterion to specific subareas may be enhanced by subdividing it into well-defined parts.

Table 5 presents the 11 attributes used in the analysis for subarea ranking. They are listed in the order of their relative importance with respect to subarea ranking. Their relationships to the six primary criteria and the kinds of information covered by each attribute are shown. The information covered is mostly determined by data available in the literature (Harrison et al., 1983a, 1983b) and does not necessarily equate precisely with that desired by the authors of the U.S. Department of Energy (1981) criteria. The 11 attributes are more fully described in Secs. 4.2.1-4.2.11. One or more objectives are given for each attribute, as appropriate, as are scales of desirability (from least to most) for the six subareas under consideration. The decisions involved in constructing the relative desirability scales are explained to provide accountability for the judgments involved, which were to be as objective as possible.

The geological experts had already gathered most of the data when the decision analysis effort began. The appropriate set of objectives and attributes to cover the desired criteria were determined in group sessions involving lengthy discussions about important issues. After the objectives had been identified, the attribute scales were developed by the appropriate geological experts, with assistance from the decision analysts.

The attribute scales described in the following sections are discrete; that is, they are defined only for specific points in the range of possible consequences. The alternate type of scale is a continuous scale (e.g., degrees Celsius on a Celsius temperature scale), which is usually preferred because it describes the consequences more precisely. In this study, however, only one or two of the 11 attributes were suited for continuous scales (e.g., surface-water bodies). Because discrete scales were compatible with the available

TABLE 5 Relationship between Site-Performance Criteria and Decision-Analysis Attributes Used in This Study

Criteria and Factors to Be Covered[a]	Attribute Name and Information Covered in This Report	Attribute Designation
Geologic characteristics	Lithologic homogeneity and isotropy	X_1
Stratigraphy Host-rock characteristics Virgin rock strength	Uniformity in composition and texture; structural characteristics (banding, layering, foliation, and lineation); migmatization and secondary veining; and injections and intrusions	
	Faulting, fracturing, and shearing	X_2
	Spacing and orientation of fractures and faults, and shearing/granulation that could affect groundwater movement at depth	
	Folding and deformation	X_3
	Degree and nature of rock deformation	
	Metamorphism and alteration	X_4
	Degree of recrystallization and nature and extent of rock alteration	
Geohydrology	Surface-water bodies	X_5
Hydrology regime, path length, and travel time Water bodies and climatic cycles Aquifer flow and repository construction Rock dissolution	Percentage of crystalline rock body surfaces covered by bogs, marshes, ponds, and lakes	
	Surface-water drainage	X_6
	Relationship of crystalline rock bodies to drainage networks and susceptibility of subarea to flooding	

TABLE 5 (Cont'd)

Criteria and Factors to Be Covered	Attribute Name and Information Covered in This Report	Attribute Designation
	Groundwater	X_7
	Association of crystalline rock bodies with aquifers and yields of wells in crystalline units	
Human intrusion	Mineral resources	X_8
Resources Exploration history Ownership and control[b]	Potential for human intrusion related to past, present, or projected future resource exploitation	
Site geometry	Site geometry	X_9
Minimum depth Thickness Lateral extent	Inferred three-dimensional shapes of crystalline rock bodies	
Surface characteristics	Surface characteristics	X_{10}
Hydrological system[c] Topographic features Meteorological phenomena[b] Industrial, transportation, and military installations[b]	Nature of topography and surficial materials throughout subarea	
Tectonic environment[d]	Local seismicity	X_{11}
Tectonic elements Quaternary faults Quaternary igneous activity Uplift or subsidence rates Regional seismicity	Distribution of epicenters and earthquake recurrences and intensities within subareas	

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[a] These criteria and the factors to be covered are from U.S. Department of Energy (1981), Table A-1. Some of the factors do not apply to crystalline regions.

[b] Not covered in the present study.

[c] Covered under attributes X_5 and X_6.

[d] Information on tectonic environment was used primarily in the regional seismotectonic assessment that resulted in designation of areas 1-3. It was not used again, under this criterion heading, for subarea ranking.

decision analysis software, discrete scales were encoded directly. The alternative would have been to begin with continuous scales and convert them to discrete scales. From three to five intervals were constructed for each attribute.

4.2.1 Lithologic Homogeneity and Isotropy (X_1)

The objective addressed by attribute X_1 is selection of subareas containing the most homogeneous and isotropic crystalline rock bodies. The relative desirability scale was constructed to include the ranges of lithologic associations, foliations, and lineations that are present in an area as geologically complex as the northeastern region. Rock properties important to repository performance would tend to have more uniform and predictable values in homogeneous, isotropic rock. Therefore, homogeneous, isotropic lithologies are considered much more desirable than inhomogeneous, anisotropic ones. These considerations were included in the four-level desirability scale of Table 6.

4.2.2 Faulting, Fracturing, and Shearing (X_2)

The objective addressed by attribute X_2 is selection of subareas containing crystalline rock bodies whose structural discontinuities are few, small, and widely spaced. The main concern here is that through-going fractures, especially those that intersect each other, may provide for groundwater movement at depth, which could jeopardize the ability of some host rocks to isolate high-level radioactive waste. Other undesirable features commonly present in faulted bodies are greater probability of

TABLE 6 Relative Desirability Scale for the Lithologic Homogeneity and Isotropy Attribute (X_1) (arrow is in the direction of increasing desirability)

Numerical Index	Scale Descriptions
↑ 4	Crystalline rock bodies with uniform, random texture and uniform lithologic composition.
3	Crystalline rock body or rock series with lithologically mixed or foliated margins but containing substantial interior portions of uniform composition and random texture.
2	Crystalline rock series with one member being the dominant lithological type but with multiple injections. Foliation and/or lineation poorly developed but present throughout the rock body.
1	Thinly banded, interlayered, or mixed crystalline rock lithologies of various types; intense foliation; and/or lineation. Examples would be rock bodies exhibiting migmatized zones, intense veining, or multiple injections or intrusions.

seismic response, increased alteration, and decreased rock mass strength, but these features are considered to be less important to repository integrity than groundwater circulation at depth.

Because all faults in the subareas are assumed to have been inactive since at least Quaternary time, fault reactivation is not considered here. The rating scale in Table 7 uses the terms "local" and "regional" to describe fault systems. Local faults are defined as being less than 1 km (0.6 mi) in length and affecting bedrock structures in their immediate vicinity only. Regional fault systems are defined as a series of faults that individually or collectively extend for tens of kilometers or more. These systems control bedrock structural features on a regional scale. Shearing refers to rock disturbance related to faulting. Intensely sheared rock has been crushed and brecciated.

As regards groundwater movement, regional fault systems are considered more influential at repository depth because they are probably related to deeper-seated tectonic forces than are local faults. Local faults are assumed to extend only to a fraction of the depths reached by regional faults.

4.2.3 Folding and Deformation (X_3)

The objective addressed by attribute X_3 is selection of subareas whose crystalline rock bodies exhibit minimum folding and deformation. Unfolded rock is most desirable because it tends not to contain highly oriented and pervasive foliation. Such foliation creates directional variations in rock properties. Least desirable are highly deformed crystalline rock bodies that have been subjected to multiple phases of folding.

TABLE 7 Relative Desirability Scale for the Faulting, Fracturing, and Shearing Attribute (X_2) (arrow is in the direction of increasing desirability)

Numerical Index	Scale Descriptions
↑ 4	No regional or local fault systems whose interconnections would facilitate groundwater movement at depth. Minimal shearing, granulation, etc.
3	Regional fault system with one orientation. Minimal or nonexistent local faulting and granulation. Faults are so widely spaced that there are unfaulted bodies or unfaulted areas large enough to contain a mined repository.
2	Local and/or regional, widely spaced fault systems with one orientation. Moderate shearing, granulation, etc.
1	Local and/or regional, closely spaced fault systems with two or more orientations. Intense shearing, granulation, etc.

Their well-developed and complexly oriented foliations could create planes of weakness or zones of increased permeability. Next in desirability are crystalline rock bodies that are tightly folded as a result of a single phase of deformation. Because such tight, complex, or closely spaced folds may be structures nearly as complicated as those in the polyphase case, little difference exists between these two cases in terms of desirability. Much more desirable are broadly folded rock bodies that have been deformed by a single phase of folding. Single-phase, broadly folded rock bodies are nearly as desirable as unfolded bodies in terms of predicting rock properties. These relationships underlie the desirability scale given in Table 8.

4.2.4 Metamorphism and Alteration (X_4)

The objective addressed by attribute X_4 is selection of subareas whose crystalline rock bodies have not been substantially changed through metamorphism and/or mineral alteration. Recrystallized igneous bodies exhibit somewhat decreased rock strength and substantially greater directional variability in rock properties than bodies possessing primary fabrics. No consideration was given to changes in geochemical properties caused by the presence of alteration products.

Least desirable are crystalline rocks featuring decreased or variable strength and very weak zones at vein intersections. A situation in which chemical alteration and low-grade metamorphism may have slightly weakened the rock mass, but in which few very weak veins are present, is more desirable. Minor recrystallization or deuteric alteration of crystalline rock bodies is not likely to result in significant decreases in the strength of rock masses, but mostly unaltered bodies are most desirable because the properties afforded by the original rock fabric are preserved. These relationships are shown in the relative desirability scale in Table 9.

TABLE 8 Relative Desirability Scale for the Folding and Deformation Attribute (X_3) (arrow is in the direction of increasing desirability)

Numerical Index	Scale Descriptions
↑ 4	Crystalline rock bodies exhibiting primary flow or foliation features only.
3	Crystalline rock bodies exhibiting single-phase folding, with broad folds only.
2	Crystalline rock bodies exhibiting single-phase folding that is complex and tight.
1	Crystalline rock bodies exhibiting polyphase folding as a result of which primary features have been largely obscured.

TABLE 9 Relative Desirability Scale for the Metamorphism and Alteration Attribute (X_4) (arrow is in the direction of increasing desirability)

Numerical Index	Scale Descriptions
4	Original mineralogy and texture largely unchanged. No recrystallization or pervasive alteration. Intrusives may have narrow contact aureoles. Weathered rind may be present.
3	Evidence of low-grade metamorphism, but primary textures largely preserved. Presence of minor secondary alteration.
2	Low-grade metamorphism and alteration, accompanied by development of secondary fabric. No significant veining.
1	Medium- to high-grade regional metamorphic imprint, with extensive alteration and multidirectional veining.

4.2.5 Surface-Water Bodies (X_5)

The objective addressed by attribute X_5 is selection of subareas with minimal areas of marshes, bogs, ponds, lakes, and reservoirs within mapped crystalline rock body boundaries. Bogs and marshy areas, particularly in upland areas some distance from stream channels, suggest nonintegration of the existing surface-drainage network, poor internal drainage, and occurrence of shallow or perhaps perched water-table conditions. Because of the possibility of interconnection with the deeper groundwater system, subareas with abundant wetlands were considered less desirable than those with few or no such areas.

Similarly, subareas with ponds, lakes, and reservoirs located within pluton boundaries were considered less favorable than those lacking these surface-water features. Such lakes could serve as sources for groundwater recharge or discharge via rock fractures. Under these conditions, exchange could occur between the surface-water and groundwater systems, thereby providing a potential pathway for contaminant transport.

Typically, lakes receive water from the subsurface (Caswell, 1979); however, depending on the topographic position of the lake with respect to other areas of groundwater recharge and discharge, as well as other local geologic conditions, lakes could serve as recharge points. Furthermore, the presence or absence of a thick intervening layer of glacial drift or other surficial geologic material between the lake bottom and the upper pluton surface, along with the physical properties of that material, will affect the degree and rate of exchange of water between the lake and bedrock. In general, the detailed information required to evaluate this condition for individual subareas is unavailable.

Table 10 details the relative desirabilities for the attribute concerning surface-water bodies. The relative desirability of subareas was made a function of the percentage of the mapped surface areas of crystalline rock bodies covered by surface-water features. Although these percentages were assigned somewhat subjectively, they are intended to reflect the varying likelihood of significant interaction between surface waters and groundwaters within the crystalline rock units.

4.2.6 Surface-Water Drainage (X_6)

Attribute X_6 addresses the proximity of crystalline rock bodies within a subarea to established stream and river channels, and the possibility of crystalline rock areas being affected by major flooding. The objective is to select subareas containing plutons that have been minimally dissected by major stream channels and that are least likely to be affected by major floods.

The location of crystalline rock bodies relative to drainage basin boundaries and to the established drainage channel network is considered to reflect overall streamflow conditions in a qualitative way. Although it is unlikely that the magnitude, frequency, and duration of streamflows will significantly affect the long-term integrity and isolation capabilities of a repository, low-flow characteristics reflect the contribution of groundwater to streamflow, and flooding could disrupt surface transportation or otherwise limit access to the aboveground facilities of a repository during construction and active operation.

Subareas having crystalline rock bodies located near the headwaters of major rivers or within smaller watersheds tributary to major drainage stems are considered to

TABLE 10 Relative Desirability Scale for the Surface-Water-Bodies Attribute (X_5) (arrow is in the direction of increasing desirability)

Numerical Index	Scale Descriptions
4	Less than 10% of the mapped surface areas of crystalline rock bodies contains marshes, bogs, ponds, lakes, and reservoirs.
3	Standing-surface-water features cover 10-30% of the land within mapped pluton boundaries.
2	Standing-surface-water features cover 30-50% of the land within mapped pluton boundaries.
1	More than 50% of the mapped pluton surface areas contains standing-surface-water features.

be more desirable than those having major rivers flowing across or near mapped plutons. A major consideration in this regard is that larger river channels receive sizable quantities of groundwater discharge from the nonindurated alluvial or glaciofluvial deposits commonly found within their valleys. These sediments could also be hydraulically connected to underlying and adjacent rocks, thereby providing a mechanism for interchange between groundwater in bedrock and surface water.

Streams erode vertically in zones of weakness within otherwise resistant rock units; therefore, the presence of a major river valley in a crystalline rock area could indicate the presence of a subsurface fault or shear zone. Such features increase the likelihood of water moving through the pluton. Furthermore, areas adjacent to major waterways are more susceptible to larger flood flows that are sustained for longer periods of time than are areas within smaller watersheds. Although overbank flows are relatively more frequent in smaller drainage channels, peak discharges are much less and flood conditions do not last as long. These two main considerations are expressed in the relative desirability scale for the surface-water-drainage attribute (see Table 11).

4.2.7 Groundwater (X_7)

Attribute X_7 incorporates several types of groundwater information from each of the subareas: (1) geologic and geohydrologic characteristics of known unconsolidated and bedrock aquifers and any data helpful in estimating hydraulic interconnection with any proximal plutons, (2) known or estimated yields to wells completed in crystalline rock units, and (3) presence or possible presence of groundwater circulation at depth through fractures within the plutons. Because this last condition relates to the extent of faulting, fracturing, and shearing, this aspect was incorporated into the definition and application of attribute X_2 (see Sec. 4.2.2).

TABLE 11 Relative Desirability Scale for the Surface-Water-Drainage Attribute (X_6) (arrow is in the direction of increasing desirability)

Numerical Index	Scale Descriptions
↑ 3	Plutons located in upland areas and drained by small, low-order streams that are unlikely to experience major flooding.
2	Plutons drained or crossed by moderately sized streams, but the probability of severe flooding is minimized by the streams' topographic position.
1	Major river channels cross the mapped plutons, and the plutons generally occur in low-lying areas of low relief and flat slopes.

The objective addressed by the groundwater attribute is selection of subareas with crystalline rock bodies that yield minimal amounts of water to wells and that have the lowest probability of hydraulic interconnection with known aquifers. This attribute could have been subdivided into two attributes, each one covering one of the two issues. This subdivision was not done for the sake of simplicity in this initial evaluation of the applicability of decision analysis to this problem.

Although some bedrock units in area 1 are known and exploited aquifers, the coarse-grained glacial, glaciofluvial, and alluvial sediments found along the major river valleys usually provide larger volumes of groundwater. The less extensive sand and gravel deposits found in association with glacial drift at various other locations throughout the area are also a much-used source of groundwater. If plutons within a given subarea are close to known and exploited water-bearing units, the subarea was considered to be less desirable than one whose incorporated plutons are not close to water-bearing units. Significant groundwater circulation between the plutons and aquifers is less likely in this latter case.

If shallow, unconsolidated aquifers are present, they are more often used as a source of water than are deeper bedrock aquifers. The unconsolidated aquifers usually provide larger quantities of good-quality water and are much easier and less expensive to explore and develop. Consequently, the spatial relationship between plutons and unconsolidated aquifers was given more weight in constructing the desirability scale shown in Table 12 than was the relationship between plutons and bedrock aquifers.

TABLE 12 Relative Desirability Scale for the Groundwater Attribute (X_7) (arrow is in the direction of increasing desirability)

Numerical Index	Scale Descriptions
↑ 4	Plutons not located beneath unconsolidated aquifers or geologically associated with bedrock aquifers; well yields in plutons are consistently less than 10 gallons per minute (gpm).
3	Plutons not located beneath major unconsolidated aquifers but may be geologically associated with bedrock aquifers; well yields in plutons are generally 11-25 gpm.
2	Plutons located beneath unconsolidated aquifers but probably not geologically associated with bedrock aquifers; well yields in plutons are generally 26-50 gpm.
1	Most plutons overlain by unconsolidated aquifers or geologically associated with known bedrock aquifers; well yields are generally more than 50 gpm.

Furthermore, the relationship with shallow, unconsolidated units can be more readily and reliably ascertained than can conditions at depth.

Available information on measured or estimated yields to wells completed in crystalline rocks was also incorporated into the desirability scale. Although the amount of information and its accuracy vary from one subarea to another, as well as among wells within individual subareas, data on well yields indicate not only the variation in shallow-water availability but fracture porosity and permeability as well. The likelihood of deep fractures and groundwater circulation at depth is greater in crystalline units providing substantially greater water yields to shallow wells than in those providing small yields. In summary, subareas having crystalline rock units that yield small quantities of water to wells are considered more desirable than those with wells having larger yields.

4.2.8 Mineral Resources (X_8)

The U.S. Department of Energy (1981) human intrusion criterion requires consideration of the potential for mineral or rock exploitation after repository closure, especially within crystalline rock bodies or up to 3.2 km (2 mi) from their boundaries. To accomplish this objective, four subobjectives were defined and incorporated into the relative desirability scale in Table 13: (1) minimize the number of active or reserve mining properties, (2) minimize the number of inactive mining properties, (3) minimize the number of known deposits, and (4) minimize the number of properties actively quarrying granitic dimension stone. Thus, active and inactive mining and quarrying and

TABLE 13 Relative Desirability Scale for the Mineral Resources Attribute (X_8) (arrow is in the direction of increasing desirability)

Numerical Index	Scale Descriptions
↑ 5	No active, inactive, or reserve mines or active stone quarries; no known deposits.
4	One or two inactive mines or active stone quarries; no known deposits.
3	Known deposits and/or three or more inactive mines or active stone quarries; and/or as many as two active talc mines.
2	One active and/or reserve mine or inactive strategic metals mine; and/or multiple active talc mines.
1	Multiple active and/or reserve mines; and/or inactive strategic metals mining properties.

the presence of potentially exploitable mineral deposits were considered to generally indicate the likelihood of future human intrusion in a given subarea.

Generally, the presence of active mines or quarries, inactive mines, or reserve properties in the vicinity of a crystalline rock body (distances greater than 3.2 km [2 mi]) is indicative of a higher potential for exploitation within the 3.2-km (2-mi) exclusion distance. Therefore, the constructed scale does not specify the distance per se but allows estimates of the probability of exploitation in or near plutons.

The scale descriptions and their order are based on the following premises: (1) active and reserve mining properties are more likely to continue to be or to become active; (2) changing economic conditions may increase the likelihood of known but presently uneconomic deposits becoming economic and subject to exploitation; (3) inactive as opposed to exhausted mines usually have uneconomic reserves that are as likely to be exploited in the future as are new deposits; (4) because of the limited areal extent of active granite dimension stone quarries, their presence within or near a crystalline rock body is roughly equal to the presence of a known deposit or an inactive mine; (5) strategic metals are of greater importance than nonstrategic metals; and (6) talc is a resource of greater importance than dimension stone. The effect of these last two premises is to lower the numerical index by one value when strategic metals or talc are involved as compared with nonstrategic metals or granitic rock quarries.

4.2.9 Site Geometry (X_9)

The objective addressed by attribute X_9 is identifying subareas containing crystalline rock bodies of sufficiently large volumes to provide a natural barrier to migration of high-level radioactive waste to the accessible environment. All crystalline rock bodies considered in this report meet the minimum criterion of being at least 80 km^2 (30 mi^2) in mapped surface area (U.S. Department of Energy, 1981). The relative desirability scale shown in Table 14 considers differences in the subsurface dimensions of these rock bodies.

Batholiths by definition have mapped surface areas greater than 100 km^2 (40 mi^2) and no known floors. Subareas containing large batholiths (>260 km^2 [>100 mi^2]), which extend many kilometers in depth, are the most desirable for further investigation. Subareas with batholithlike bodies of lesser surface area (80-260 km^2 [30-100 mi^2]) are next in desirability. These latter bodies tend to possess well-defined margins and narrower subsurface shapes and could be several kilometers deep. Sheetlike bodies of the same mapped areal extent as the moderately large ones might attain 1-3 km (0.6-1.9 mi) in depth, but their ability to adequately isolate radioactive material is less certain than that of the batholithlike bodies. Subareas with such tabular bodies are the least desirable. Although crystalline rock bodies of any of these three geometries might provide adequate rock volume for waste isolation, the larger rock masses would provide more certainty.

TABLE 14 Relative Desirability Scale for the Site Geometry Attribute (X_9) (arrow is in the direction of increasing desirability)

Numerical Index	Scale Descriptions
↑ 3	Most bodies are batholiths with large mapped surface areas (>260 km^2 [>100 mi^2]).
2	Most bodies are small batholiths or large stocks with moderately large mapped surface areas (80-260 km^2 [30-100 mi^2]).
1	Most bodies are sheetlike with moderately large mapped surface areas (80-260 km^2 [30-100 mi^2]).

4.2.10 Surface Characteristics (X_{10})

In adapting the surface characteristics criterion (U.S. Department of Energy, 1981), the objective was to minimize the percentage of each subarea that could present special engineering problems related to constructing and maintaining safe and reliable access roads and site facilities. Potentially undesirable surficial features included high relief, slope instability, excessively clayey or rocky surficial materials, and wetlands. If a subarea was judged as particularly unlikely to present significant surficial problems, the existence of a road network was taken as additional evidence of a low potential for a surficial materials hazard.

A relative desirability scale was constructed whereby subareas could be evaluated as to their likelihood of presenting problems related to surficial materials or surficial processes (see Table 15). In constructing the scale, relief was considered to be the dominant factor. Other factors were considered to be somewhat comparable in undesirability, and their hazard potentials were keyed to how much of the subarea was affected by the problem. Roads became a factor only when a decision had to be made on a numerical index of from two to five and when differentiation using the preceding factors was difficult or ambiguous.

4.2.11 Local Seismicity (X_{11})

The objective addressed by attribute X_{11} is to minimize seismic activity. The term "local seismicity" covers that very restricted part of the U.S. Department of Energy (1981) tectonic environment criterion that relates to earthquakes whose epicenters fall within the subareas. Table 16 gives the relative desirability scale constructed for the local seismicity attribute. Of importance in evaluating the subareas was whether epicenters were located within the boundaries of a pluton or within 24 km (15 mi) of a pluton boundary.

TABLE 15 Relative Desirability Scale for the Surface Characteristics Attribute (X_{10}) (arrow is in the direction of increasing desirability)

Numerical Index	Scale Descriptions
5	Subarea has low relief, stable slopes, minimal development of wetlands and excessively clayey or rocky surficial materials, and a road network compatible with general land use and demography as indicated on topographic maps.
4	Sections have moderate relief, stable slopes, excessively clayey or rocky surficial materials, or wetlands that dominate no more than approximately 20% of the subarea. Some roads are present.
3	Sections have moderate relief, unstable slopes, excessively clayey or rocky surficial materials, or wetlands that cover no more than approximately 20% of the subarea. Some roads are present.
2	Sections have moderate relief, unstable slopes, excessively clayey or rocky surficial materials, or wetlands that cover 20-50% of subarea.
1	Subarea is dominated by high relief or wetlands.

4.3 CHARACTERIZATION OF THE DESIGNATED SUBAREAS IN TERMS OF THE DECISION-ANALYSIS ATTRIBUTES

The next step in the analysis was to specify each subarea's characteristics with respect to each of the 11 attributes by estimating probability distributions over the corresponding relative desirability scales. Uncertainty was involved in this process because the available information for the several subareas was more or less complete, because each attribute varied to some degree within the individual subareas, and because the scale descriptions did not always precisely match the characteristics of a given subarea.

The probability distributions for each attribute by subarea were prepared by appropriate geological experts, who incorporated the three aspects of uncertainty discussed above. Appendix B summarizes the characterizations of each subarea by attribute and briefly explains the technical judgments needed. These discussions illustrate how the qualitative information often used in making decisions complements the quantitative information used in decision analysis.

TABLE 16 Relative Desirability Scale for the Local Seismicity Attribute (X_{11}) (arrow is in the direction of increasing desirability)

Numerical Index	Scale Descriptions
↑ 4	No more than three epicenters of Modified Mercalli intensity (I_{MM}) IV or less, either within pluton boundaries or within 24 km (15 mi) of pluton boundaries; no more than three total events for these epicenters.
3	No more than three epicenters of I_{MM} V or less, either within pluton boundaries or within 24 km (15 mi) of pluton boundaries; no more than four total events for these epicenters.
2	Four to six epicenters of I_{MM} V or less, either within pluton boundaries or within 24 km (15 mi) of pluton boundaries; no more than eight total events for these epicenters.
1	Six to eight epicenters of I_{MM} V or less, either within pluton boundaries or within 24 km (15 mi) of pluton boundaries; more than eight total events for these epicenters.

4.4 PREFERENCES FOR OUTCOME LEVELS ON SINGLE ATTRIBUTES

A multiattribute utility function (MUF) is quantified in terms of single-attribute utility functions, which are quantified first. If the requisite independence conditions* (Keeney and Raiffa, 1976) hold, then either an additive MUF

$$u(x) = \sum_{i=1}^{11} k_i u_i(x_i) \qquad (1)$$

or a multiplicative MUF

$$u(x) = \frac{1}{k}\left(\prod_{i=1}^{11} [1 + k\, k_i u_i(x_i)] - 1\right) \qquad (2)$$

is appropriate. (The symbols for these and subsequent equations are defined in Table 17.) In the course of assessing the single-attribute utility functions and the scaling

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*The independence conditions are called utility independence and preferential independence.

TABLE 17 Definitions of Symbols Used in Formal Decision Analysis

Symbol	Definition
X_i	denotes attribute i
X_{ij}	denotes the space containing attributes i and j
$X_{ij'}$	denotes the space containing all attributes but i and j
x_i^o	denotes the least preferred outcome level for X_i
x_i^*	denotes the most preferred outcome level for X_i
x_i	denotes an outcome amount or level for attribute X_i such that $x_i^o \le x_i' \le x_i^*$
$(x_1, x_2, \ldots, x_{11})$	denotes outcome levels for each of the 11 attributes
(x^o)	denotes the least preferred outcome for all attributes
(x^*)	denotes the most preferred outcome for all attributes
$u(x)$	denote an MUF over outcomes for attributes X_1 through X_{11}
$u(x_1, \ldots, x_{11})$	
$u_i(x_i)$	denote the single-attribute utility function for X_i, given that the other 10 attributes are at their least preferred levels; true for any x_i if the utility independence condition holds
$u_i(x_i \mid x_{i'}^o)$	
k_i	denotes the scaling constant in a MUF associated with $u_i(x_i)$ for attribute X_i
k	denotes a scaling constant in the multiplicative form of the MUF
$u_i(x_i^o) = 0$	boundary conditions used to scale the single-attribute utility functions and the MUF
$u_i(x_i^*) = 1$	
$u(x^o) = 0$	
$u(x^*) = 1$	

constants, we verified that the requisite independence conditions for either the additive or multiplicative forms held. Finally, we determined that the multiplicative form was the appropriate one for this evaluation.

Single-attribute utility functions were each defined independently. Because each of the attributes was defined on a discrete scale, the utility of each level was assessed separately using probabilistic propositions. For example, the utility function for X_1 (lithological homogeneity and isotropy) was assessed as follows. Four levels were defined for attribute X_1. Given that the other attributes (X_2 through X_{11}) were fixed at their worst levels, the single-attribute utility function $u_1(x_1) = u(x_1/x_{1'}^{o})$ was first scaled on a zero-to-one basis.* This means that $u_1(x_1^{o}) = u_1(x_1 = 1) = 0$ and $u_1(x_1^{*}) = u_1(x_1 = 4) = 1$. A choice (hereafter called an outcome) was made between a subarea having X_1 at level 2 with a probability of 1.0 (the certain outcome) and all others at their worst levels, and a lottery involving two other outcomes. One of these outcomes had X_1 at level 4 (the most desirable) and the other attributes at their worst levels, denoted $(x_1^{*}, x_{1'}^{o})$; the other outcome had all attributes at their worst levels, denoted $(x_1^{o}, x_{1'}^{o})$. The lottery would yield the former outcome with probability p and the latter one with probability 1 - p. A probability wheel (Spetzler and von Holstein, 1975) was used to help determine the probability p at which there was indifference between the outcome having X_1 at level 2 and the lottery. For the p corresponding to indifference, the utility of the sure outcome must be equal to the expected utility of the lottery and so, it follows that

$$u(x_1 = 2, x_{1'}^{o}) = pu(x_1^{*}, x_{1'}^{o}) + (1 - p)\, u(x_1^{o}, x_{1'}^{o}) \tag{3}$$

from either Eq. 1 or 2. This expression in turn simplifies to

$$u_1(x_1 = 2) = p \tag{4}$$

The value of p was determined by alternatively considering high values (like 0.9), which favor choosing the lottery, and low values (like 0.1), which favor not choosing the lottery, to narrow the range of the value of p at which indifference was approached.

These steps were repeated to determine $u_1(x_1 = 3)$. The value of the probability q at which a lottery yielding $(x_1 = 4, x_{1'}^{o})$ with probability q or $(x_1 = 1, x_{1'}^{o})$ with probability 1 - q was indifferent to $(x_1 = 3, x_{1'}^{o})$ was also determined. Checks were used to verify the consistency of these responses. For example, the value of r at which a lottery yielding $(x_1 = 3, x_{1'}^{o})$ with probability r or $(x_1^{o}, x_{1'}^{o})$ with probability 1 - r was indifferent to $(x_1 = 2, x_{1'}^{o})$ was assessed. Equating expected utilities and simplifying the expressions results in $r = p/q$. Any inconsistencies found were explained, and causative ambiguities were resolved by redefinition or restatement of the problem so as to bring r, q, and p into agreement with this relationship.

The results for the single-attribute utility function for X_1 are $p = u_1(x_1 = 2) = 0.85$, $q = u_1\ (x_1 = 3) = 0.98$, and $r = 0.88$. Because $p/q = 0.87$, this consistency check increased confidence in the assessed values for p and q.

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*The shorthand symbol $u_i(x_i)$ can be used for any x_i, when the appropriate independence condition holds, as explained and verified later.

At this point, consistency was further checked by referring back to the proposition used to assess $u_1(x_1 = 2)$. Levels on attributes X_2 through X_{11} were changed to levels designated by $(x'_2, \ldots, x'_{11}) = (x'_{1'})$, and, again, the probability p was assessed for the lottery involving $(x_1^*, x'_{1'})$ and $(x_1^0, x'_{1'})$. Indifference was still encountered at $p = 0.85$ between the lottery and the outcome designated by $(x_1 = 2, x'_{1'})$. This result established that X_1 is utility independent of the other 10 attributes (i.e., that the utility independence condition held).

These steps were repeated to assess the other 10 single-attribute utility functions; care was taken to test for consistency. The results for each of the $u_i(x_i)$ are shown in Fig. 7.

4.5 CONSTRUCTION OF THE MULTIATTRIBUTE UTILITY FUNCTION

4.5.1 Procedure

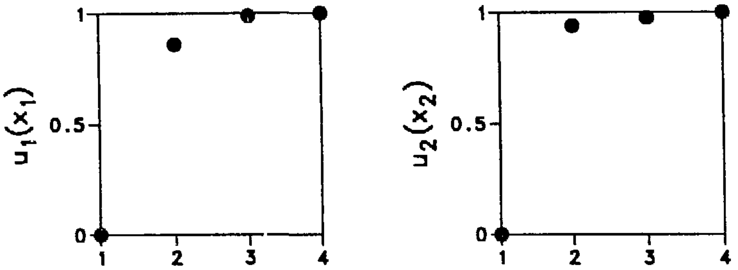
Section 4.5.1 summarizes the procedure, and Sec. 4.5.2 provides a few of the details of the actual assessment process. Given the single-attribute utility functions described in Sec. 4.4, construction of the MUF proceeded as follows:

1. *Ordering the attributes* was accomplished by first assuming that all attributes were at their least desirable levels and then deciding which attribute should first be raised from its least desirable level, x_i^0, to its most desirable level, x_i^*, and then repeating this process for all the attributes. The first attribute to be raised was, in a sense, the most important (i.e., the one to be associated with the largest scaling constant, k_i).

2. *Determining the relative values of the scaling constants* was accomplished by finding two outcome levels that were equally desirable and using Eq. 2 to solve for relationships between the k_i. The procedure is simplified if only two attributes change levels in the two outcomes used. Since the utility scales were discrete, such simplification was not always possible; in those cases, a probabilistic proposition was required.

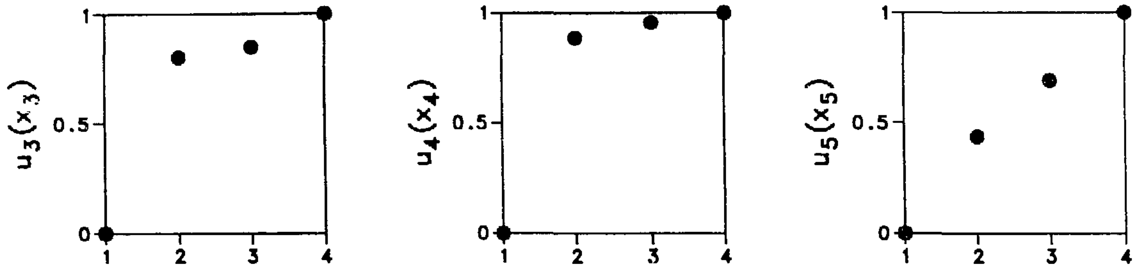
3. *Testing for utility independence (UI) and preferential independence (PI)* had already been accomplished. The UI condition was tested for while assessing the $u_i(x_i)$; the PI condition was tested for while assessing the scaling constants.

4. *Constructing the MUF* was accomplished using the appropriate independence conditions, $u_i(x_i)$, and the scaling constants. If UI and PI can be established, then either the additive (Eq. 1) or multiplicative (Eq. 2) form of the MUF is appropriate. If the additive form is appropriate, then the k_i sum to one and their



x_1: Lithologic Homogeneity and Isotropy Index

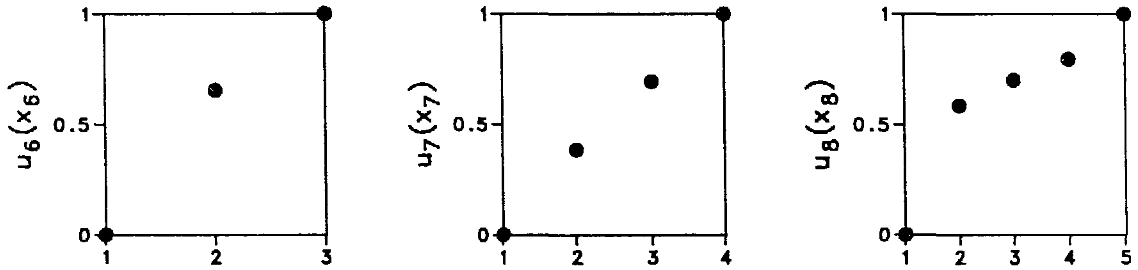
x_2: Faulting, Fracturing, and Shearing Index



x_3: Folding and Deformation Index

x_4: Metamorphism and Alteration Index

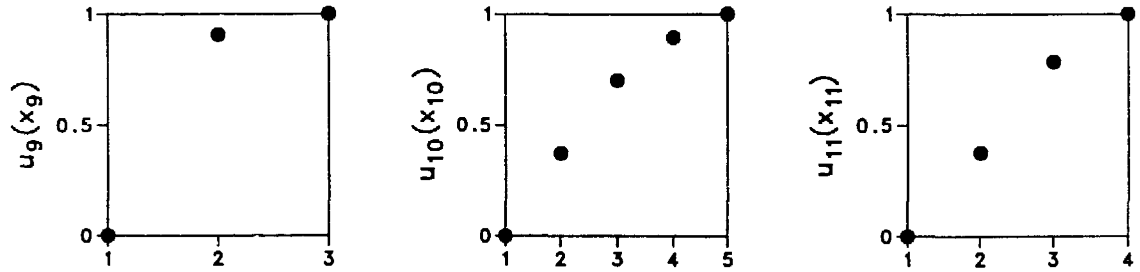
x_5: Surface-Water-Bodies Index



x_6: Surface-Water-Drainage Index

x_7: Groundwater Index

x_8: Mineral Resources Index



x_9: Site Geometry Index

x_{10}: Surface Characteristics Index

x_{11}: Local Seismicity Index

FIGURE 7 Level of Preferences for Single-Attribute Utility Function Outcome numerical values can be determined. If the multiplicative form is appropriate, the numerical value of one of the k_i must first be determined. The values of the other k_i follow (because they are proportional to each other), and the value of k can be determined from Eq. 2.

4.5.2 Details of the Assessment Process

Given the outcome levels described in Sec. 4.2, a subarea was postulated as having each attribute at its worst level, denoted by $(x_1^o, x_2^o, ..., x_{11}^o)$ or x^o. Then, given that any single attribute could be changed from its worst level (x_i^o) to its best level (x_i^*), that one attribute was selected. Considerations involved in this selection were the importance and meaning of the least desirable and most desirable levels of each attribute.

We decided that it was most important to raise attribute X_2 (faulting, fracturing, and shearing) from its worst level ($x_2^o = 1$) to its best level ($x_2^* = 4$) before raising any of the others. Next, given that X_2 could not be changed, we decided that it was most important to raise X_1 (lithological homogeneity and isotropy). This process was continued until all of the attributes were ordered for the first time.* In the course of establishing the relative desirabilities of various levels, some changes in the initial ordering resulted. Such adjustments are to be expected as tradeoffs become known in more detail.

The final ordering is $X_2, X_1, X_9, X_8, X_7, X_4, X_3, X_6, X_5, X_{10}, X_{11}$, where X_2 is most preferred and X_{11} is least preferred. To say that X_2 is preferred to X_1 means that a change from x_2^o to x_2^* is preferred to a change from x_1^o to x_1^*, all other things being equal. Given this preference ordering, it follows from either the additive or multiplicative forms of the multiattribute utility function that

$$k_2 > k_1 > k_9 > k_8 > k_7 > k_4 > k_3 > k_6 > k_5 > k_{10} > k_{11} \tag{6}$$

The relative values of the scaling constants were determined using two methods. The first finds two points in utility space that are equally desirable, such as $(x'_i, x'_j, x^o_{\overline{ij}})$ and $(x''_i, x''_j, x^o_{\overline{ij}})$. Fixing all attributes except X_i and X_j at their worst levels greatly simplifies the mathematics involved; it is also perfectly valid if UI holds, which was verified in this case. When precise indifference points could not be determined using this method, a second choice was postulated between a sure outcome and a lottery, and an indifference probability was established for the lottery to determine the relative k values.

Each successive pair of attributes was compared to accomplish this step. Thus, X_2 (the most important attribute) and X_1 (the next most important attribute) were first

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*Although ties are possible, no ties were encountered in this assessment.

compared. After much discussion, it was concluded that ($x_2 = 3$, $x_1 = 1$, $x^o_{21'}$) was as desirable as ($x_2 = 1$, $x_1 = 4$, $x^o_{21'}$). Then, from either Eq. 1 or 2, it follows that

$$k_1 = k_2 u_2(x_2 = 3) \tag{7}$$

The assessed value of $u_2(x_2 = 3)$ is 0.97, so the result on k_1 is

$$k_1 = 0.97\ k_2 \tag{8}$$

At this point, a test for PI of combinations of attributes from the remaining attributes was performed by rephrasing the previous question. The levels on attributes X_3 through X_{11} were changed from ($x^o_3, \ldots, x^o_{11}$) to ($x'_3, \ldots, x'_{11}$), to see if this affected the previously established indifference level with respect to X_1 and X_2. We decided that the level of the other nine attributes did not affect tradeoffs between X_1 and X_2, which verified that X_1 and X_2 were preferentially independent of the other attributes. Further questioning established that this was true in general, so PI was established for the MUF.

Next, X_1 was compared to X_9. Because there was no convenient pair of points in utility space involving X_1 and X_9, we established that ($x_9 = 3$, $x_1 = 1$, $x^o_{91'}$) was as desirable as a lottery yielding ($x_9 = 1$, $x_1 = 2$, $x^o_{91'}$) with probability 0.75 or ($x_9 = 1$, $x_1 = 1$, $x^o_{91'}$) with probability 0.25. It then follows that

$$\begin{aligned} k_9 &= 0.75\ k_1 u_1(x_1 = 2) \\ &= 0.75\ k_1(0.85) \end{aligned} \tag{9}$$

This process was continued with each succeeding pair of attributes until 10 equations were developed (see Table 18). By determining the value of k_2, the largest scaling constant, all other k_i would be known.

To determine the absolute value of k_2, a choice was presented between the outcome (x^*_2, $x^o_{2'}$), or a lottery in which (x^*) obtains with probability p and (x^o) obtains with probability 1 - p. The probability p had to be set so that the sure outcome and the lottery were indifferent (equally desirable). We decided that the value of p should be approximately 0.55.

This was the final piece of information needed to completely scale the MUF. The last column in Table 18 shows the values of the k_i; their sum is 2.27. Because the sum is not equal to 1, the multiplicative form is the appropriate form of the MUF (Keeney and Raiffa, 1976). The value of k in Eq. 2 is determined by noting that $u(x^*) = 1$ and $u_i(x^*_i) = 1$; it therefore follows that

$$1 + k = \prod_{i=1}^{11} (1 + kk_i), \tag{10}$$

which can be solved iteratively for the nonzero solution for k. The result is $k = -0.927$.

TABLE 18 Evaluating the Scaling Constants in the Utility Function

Attribute	Description	Rank Order	Indifference Relationship[a]	Relative Scaling Constants	Multiplicative Scaling Constants
X_1	Homogeneity	2	$(x_1^*, x_2^o) \sim (x_1^o, x_2 = 3)$	$k_1 = 0.97\ k_2$	0.53
X_2	Faulting	1	--	$k_2 = k_2$	0.55
X_3	Folding	7	$(x_3^*, x_4^o) \sim (x_3^o, x_4^*)$	$k_3 = k_4$	0.12
X_4	Metamorphism	6	$(x_4^*, x_7^o) \sim (x_4^o, x_7 = 3)$	$k_4 = 0.7\ k_7$	0.12
X_5	Surface-water bodies	9	$(x_5^*, x_6^o) \sim \left\langle \begin{array}{l} 0.7\ (x_5^o, x_6 = 2) \\ 0.3\ (x_5^o, x_6^o) \end{array} \right.$	$k_5 = 0.46\ k_6$	0.05
X_6	Surface-water drainage	8	$(x_6^*, x_3^o) \sim \left\langle \begin{array}{l} 0.7\ (x_6^o, x_3 = 3) \\ 0.3\ (x_6^o, x_3 = 2) \end{array} \right.$	$k_6 = 0.84\ k_3$	0.10
X_7	Groundwater	5	$(x_7^*, x_8^o) \sim \left\langle \begin{array}{l} 0.5\ (x_7^o, x_8 = 4) \\ 0.5\ (x_7^o, x_8 = 3) \end{array} \right.$	$k_7 = 0.75\ k_8$	0.17
X_8	Mineral resources	4	$(x_8^*, x_9^o) \sim \left\langle \begin{array}{l} 0.75\ (x_8^o, x_9 = 2) \\ 0.25\ (x_8^o, x_9^o) \end{array} \right.$	$k_8 = 0.68\ k_9$	0.23
X_9	Site geometry	3	$(x_9^*, x_1^o) \sim \left\langle \begin{array}{l} 0.75\ (x_9^o, x_1 = 2) \\ 0.25\ (x_9^o, x_1^o) \end{array} \right.$	$k_9 = 0.64\ k_1$	0.34
X_{10}	Surface characteristics	10	$(x_{10}^*, x_5^o) \sim \left\langle \begin{array}{l} 0.5\ (x_{10}^o, x_5 = 3) \\ 0.5\ (x_{10}^o, x_5 = 2) \end{array} \right.$	$k_{10} = 0.57\ k_5$	0.03
X_{11}	Local seismicity	11	$(x_{11}^*, x_{10}^o) \sim (x_{11}^o, x_{10}^*)$	$k_{11} = k_{10}$	0.03
					$\sum k_i = 2.27$

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[a] The notation $(x_1^*, x_2^o) \sim (x_1^o, x_2 = 3)$ means that the outcome (x_1^*, x_2^o) is indifferent to the outcome $(x_1^o, x_2 = 3)$, with all other attribute levels being equal; the notation $\left\langle \begin{array}{l} p\ \ x \\ 1-p\ \ y \end{array} \right.$ denotes a lottery in which outcome x obtains with probability p and y obtains with probability 1 − p.

4.6 RANKING OF SUBAREAS

Section 4.3 and App. B discuss the development of probability functions for the characteristics of the subareas, and Sec. 4.5 discusses construction of a MUF, which quantitatively represents preferences for tradeoffs between the various levels of achievement of the objectives (see Sec. 4.2) by each subarea. In Sec. 4.6, the subareas are ranked as to their desirability. The results of sensitivity analyses (see Sec. 4.6.2) indicate that the recommended ranking is stable over a wide range of consequences and values centered around the base-case estimates.

4.6.1 Baseline Results

The most desirable subarea is identified by computing the expected utility for each subarea and then selecting the one with the largest expected utility. Mathematically, this process is written as

$$\max_{s} EU(SA_s) = \sum_{x} P_{SA_s}(x_1, \ldots, x_{11})\, u(x_1, \ldots, x_{11}) \tag{11}$$

where:

$EU(SA_s)$ = expected utility of subarea s (s = 1A, ..., 1F),

$P_{SA_s}(x)$ = probability function describing all possible outcomes for SA_s,

$u(x)$ = MUF over the 11 attributes, and

$\sum_{x}$ = summation over all possible outcomes for SA_s.

The baseline utility function is multiplicative in form, with the scaling constants listed in Table 18 (i.e., $k_1 = 0.53$, $k_2 = 0.55$, ... $k_{11} = 0.03$), the single-attribute utility functions shown in Fig. 7, and $k = -0.927$. The results are shown in Table 19, where case 1 is the baseline case.

The resulting subarea ranking based on maximizing expected utility is 1D, 1C, 1F, 1E, 1B, and 1A, where 1D is most desirable and 1A is least desirable. As discussed in Sec. 4.6.2, this result is not very sensitive to changes in probabilities, scaling factors, or the form of the MUF.

4.6.2 Sensitivity Analysis

In assessing the scaling constants, k_2 was fixed at approximately 0.55, which resulted in a multiplicative utility function. Other consistency checks showed that an additive utility function could also be used to represent the indicated preferences. An additive utility function results when $k_2 = 0.24$ and the k_i are related to k_2 as indicated in Table 18. Expected utility results for this additive utility function are shown as case 2 in Table 19. There are no reversals in the order of desirability, although the relative

TABLE 19 Expected Utilities of the Six Subareas for the Various Utility Functions

	Case[a]		
Subarea	1 ($k_2 = 0.55$)	2 ($k_2 = 0.24$)	3 ($k_i = \frac{1}{11}$)
1A	0.51	0.27	0.30
1B	0.62	0.38	0.48
1C	0.92	0.77	0.72
1D	0.98[b]	0.92[b]	0.83[b]
1E	0.77	0.53	0.54
1F	0.84	0.62	0.51

[a] Case 1 corresponds to a multiplicative MUF; cases 2 and 3, which correspond to additive MUFs, are included to test the sensitivity of the results to the form of the MUF.

[b] Denotes the largest expected utility for each case.

values of expected utility are different. This result was the first indication that the baseline results were stable. A more detailed analysis of the sensitivity of the results to the value of k_2 showed that this rank order remained unchanged over k_2 values from 0.15 to 0.55.

A completely different utility function also was investigated wherein all of the k_i were made equal, which resulted in an additive MUF. Thus, $k_i = 1/11$ for all i. The results are also given in Table 19 as case 3. This change was a major departure from the case 1 and case 2 utility functions, and the resultant rank order of the subareas (1D, 1C, 1E, 1F, 1B, 1A) closely resembled the baseline ranking (only the order of 1E and 1F changed).

To determine how much more desirable subarea 1D was than 1C, the second-best subarea, the technical ratings of subarea 1C were improved on the most important attribute, X_2 (faulting, fracturing and shearing), by setting the probability of achieving the best level ($s_2 = 4$) on X_2 at 1.0. This change, which was significant because the baseline information in Table B.2 shows a probability of 0.25 that $x_2 = 1$, 0.5 that $x_2 = 2$, and 0.25 that $x_2 = 3$. This change increased the expected utility of SA_{1C}, but it still did not equal or exceed $EU(SA_{1D})$. The expected utility of SA_{1D} was made less than that for subarea 1C by assigning a high probability to the outcome x_2^o (i.e., the least desirable level on X_2) for subarea 1D. These results can be interpreted to mean that the technical rating for attribute X_2 must be grossly in error to reverse the desirabilities of subareas 1D and 1C.

The sensitivity analyses reported here are just a few of the many that could have been done. Their purpose was to show that a wide variety of different assumptions, and their effects on the rankings, can be investigated. Although only one MUF was assessed, the sensitivity analyses represent a number of different value structures. The insensitivity of the rankings to major changes indicates that a reasonably stable solution has been found.

5 CONCLUDING REMARKS

A multiattribute decision analysis method that incorporates geologic attributes was used to rank the area 1 subareas as to the ability of a repository constructed in a subarea pluton to isolate high-level radioactive waste from the accessible environment. This method (1) requires inventorying and documenting all objective and subjective judgments, (2) allows readers to evaluate and track those judgments, (3) allows uncertainty to be quantified and incorporated into the judgment process, and (4) gives an acceptable and accountable basis for making decisions based on multiple conflicting objectives. Formal decision analysis is a systematic and logical way to account for the information and value judgments used to appraise alternatives. One advantage of having the value judgments made explicit is that sensitivity analysis can establish how stable the evaluation is, even if different value judgments are used.

Table 20 summarizes the conclusions reached through application of seismotectonic screening and multiattribute decision analysis using geologic attributes based on the NWTS criteria in U.S. Department of Energy (1981). The study demonstrates that formal decision analysis has much to offer in helping to analyze the problem of siting a repository for high-level radioactive waste, one of the most complex tasks in the field of radioactive waste management. The overall method of this study could be expanded to include additional screening criteria, such as land ownership, demographics, environmental consequences, socioeconomic effects, and waste transport considerations.

TABLE 20 Summary of Conclusions

Subareas[a]	Conclusions
1D and 1C	Most desirable subareas for detailed study.
1F and 1E	Subareas of intermediate desirability for further study. (Several attributes would have to increase in value for 1E and 1F to equal the decision-analysis ratings of 1C and 1D.)
1B and 1A	Least desirable subareas for further study.

[a] The more favorable of each pair of subareas is listed first.

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APPENDIX A

DESCRIPTIONS OF SUBAREAS WITH RESPECT TO THE GEOLOGIC CRITERIA USED FOR SUBAREA DESIGNATION

APPENDIX A

DESCRIPTIONS OF SUBAREAS WITH RESPECT TO THE GEOLOGIC CRITERIA USED FOR SUBAREA DESIGNATION*

MOST FAVORABLE AREA (AREA 1)

Subarea 1A

Geologic Characteristics

Subarea 1A (see Plate I) extends from east-central Vermont southwest to northwestern Connecticut and contains extensive exposures of Precambrian basement rocks and a linear Cambrian-Silurian unit. The plutons in subarea 1A are listed below by state. Also given are the numbers of the plutons as assigned in Plates II-IX and the tectonic associations (ga = Grenville and Avalonian and ta = Taconic).

Vermont (Plate IV)

1 Sadawga and Ray Pond domes (ga)

2 Mt. Holly complex, southern exposure (ga)

3 Chester dome (ga)

4 Barnard gneiss (ta)

Massachusetts (Plate VI)

1 Berkshire massif (ga)

2 Mt. Holly complex, southern exposure (ga)

3 Barnard gneiss (ta)

7 Pelham dome (ga)

Connecticut (Plate VIII)

8 Berkshire massif (ga)

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*Appendix A is based on the information compiled in Harrison et al. (1983a, 1983b). The references that support the subarea descriptions are found in those reports.

All domal rocks in Vermont are lithologically similar to those of the Mt. Holly complex. The layered, highly crystalline gneiss (75%), schist and quartzite (20%), and greenstone (4%) Precambrian units are overlain unconformably by Cambrian metasediments. High-grade metamorphic rocks occur in the core zones, and evidence points to complex cascade folding within the Green Mountain anticlinorium. Mt.-Holly-type rocks are compositionally and texturally heterogeneous and anisotropic as a result of variations in folding and metamorphic grade. Fracture cleavage and local overthrusting of overturned folds are also reported.

The Barnard gneiss represents metamorphosed interbedded felsic and mafic volcanics. The included minor schist and phyllite represent metamorphosed sediments. The linearity and heterogeneity of this unit make it undesirable for a repository; consequently, it is not described further. No adjustment of the subarea 1A boundary was made to accommodate the Barnard gneiss.

The Berkshire massif of Connecticut and Massachusetts is lithologically similar to the Mt. Holly complex but may have a higher percentage of primary igneous rocks. It is also strongly heterogeneous and anisotropic in both lithology and texture. Its three recognized stratigraphic units have been overprinted by at least two periods of intense metamorphism during the Taconic and Acadian orogenies. Several north-south, low-angle thrust faults cross the massif. Imbricate thrust slices of recumbent Precambrian folds occur in the west and southwest. Secondary discordant intrusions are confined to peripheral pegmatite veins. High-angle faults similar to those cutting the Hudson Highlands to the southwest are probably present along the western side of the massif.

Because the Mt. Holly complex and Berkshire massif represent the root zones of major anticlinoria, they probably extend to great depths. They are composed of preexisting intrusive and extrusive rocks, with subordinate material of sedimentary origin. Their surface exposures are extensive.

The Pelham dome, which crops out in west-central Massachusetts, is a layered complex of quartzites, gneisses, and amphibolites derived from sedimentary and volcanogenic protoliths. The dome incorporates metamorphosed remnants of minor secondary intrusions. Its rock fabric is typical of Precambrian complexes and may reflect overprinting from faulting and metamorphism during the Taconic and Acadian orogenies. Contacts with country rock are diffuse. No gravity data are available, but stratigraphic thicknesses of approximately 2130 m (7000 ft) have been estimated. However, estimating the depth of a gneiss using thickness data alone is suspect because of possible stratigraphic repetition as a result of faulting or secondary intrusion.

Geohydrology

The northern, upland portion of subarea 1A forms the drainage divide between the Connecticut River basin to the east and the watersheds of Lake Champlain and the Hudson River to the west. Thus, the subarea includes the upper reaches of Otter Creek and the Poultney-Mettawee rivers, which are tributary to Lake Champlain, and the headwater portions of the Hoosic-Batten-Kill-Green drainage basin, whose streams are tributary to the Hudson River. To the south, the area west of the topographic divide is drained by the Housatonic River and its major tributary, the Naugatuck River. The headwaters of both of these rivers also drain portions of subarea 1B (see Figs. 4 and 5 and Tables 2 and 3 of this report).

With the exception of a small area in north-central Massachusetts, this subarea incorporates only those tributaries draining the western portion of the Connecticut River basin. Also included within subarea 1A are the headwaters of the Ottauquechee River; all of the Black, Williams, Saxtons, and West Branch Deerfield drainage basins in Vermont; all of the Deerfield River drainage and upper portions of the Westfield and Farmington rivers, and the lower portion of the Millers River basin in Massachusetts; and the middle reaches of the Farmington River in Connecticut.

The areal distribution of average annual precipitation over subarea 1A is fairly uniform, with most of the subarea receiving 100-130 cm (40-50 in.), depending mostly on altitude. Precipitation is also distributed relatively evenly throughout the year, with average snow accumulations at higher elevations of 130-200 cm (50-80 in.). Mean annual runoff exhibits greater variation than precipitation, with values ranging from about 50 cm (20 in.) in certain western and southern portions of the subarea to 100 cm (40 in.) or more in the Green Mountains. These values indicate that average annual runoff accounts for about 50% of average annual precipitation in the central and southern portions of the subarea. More than 85% of the precipitation is consumed by runoff in the Green Mountains. However, this large percentage diminishes rapidly in adjacent areas of lower elevation and less relief. Most of the runoff from the subarea is discharged to Long Island Sound via the Connecticut and Housatonic rivers.

More than 10 reservoirs or controlled natural lakes and a number of uncontrolled natural lakes are found in subarea 1A. Most of the lakes and reservoirs of the subarea are located within mapped pluton boundaries (see Plates IV, VI, and VIII). Several marshy or swampy areas found in the subarea are located in the Naugatuck River valley in subareas 1A and 1B. Also, an extensive swampy area in the Housatonic valley in the vicinity of Canaan, Conn., extends several miles on either side of the Connecticut-Massachusetts border. Although this poorly drained area falls within subareas 1A and 1B, it is beyond the mapped boundary of the Berkshire massif. Therefore, it is not of great importance in determining the relative favorability of subarea 1A.

Although general information on shallow well yields from crystalline rocks of subarea 1A is available on a regional scale, no data on groundwater conditions in specific plutons were obtained. Because subarea 1A rocks are strongly metamorphosed, exhibit several geologic characteristics indicating deformation and folding, and are cut by several north-south, low-angle thrust faults, groundwater may be present and actively circulating through fractures and fissures at depth.

Although several different hydrologic units are partially included in subarea 1A, they do not differ sufficiently in hydrologic character to have affected basing the designation of this subarea on geologic characteristics.

Potential for Human Intrusion

The level of past and present mining activity in subarea 1A can be gauged by referring to Plates IV, VI, and VIII. The four active mines in Vermont are talc mines (see Plate IV: S, T, U, and V), which lie within about 1.6 km (1 mi) of the boundaries of the Chester dome (S and U) or within 5 km (3 mi) of the eastern boundary of the Mt. Holly complex (T and V). Seven abandoned mines occur within the boundaries of the Vermont plutons or complexes of subarea 1A.

In Massachusetts and Connecticut, no active mines occur in either the Pelham dome (see Plate V) or the Berkshire massif (see Plates V and VI). The closest active mine to the boundaries of either of these plutons is a marble mine that occurs 3.2 km (2 mi) from the western margin of the Berkshire massif in Connecticut. Twelve abandoned mines occur in the Berkshire massif and two in the Pelham dome.

The potential for human intrusion was not a limiting factor for repository siting in subarea 1A, except for restricted zones in the vicinity of the active talc mines in Vermont. The prognosis of minerals exploitation in this subarea is poor. The relatively even distribution of past and present mineral extraction activities within the subarea supports its designation on other grounds.

Site Geometry

Most of the Precambrian plutons within subarea 1A are very large in surficial outcrop area. Because they form the root zones of major anticlinoria, they probably extend to great depths.

Surface Characteristics

The Green Mountains of Vermont and the Berkshire Hills of Massachusetts form the backbone of subarea 1A. In Vermont, these mountainous areas exhibit relief of less than 760 m (2500 ft). In certain small areas of the Green Mountains, slopes are very steep, suggesting the need for steep grades or switchbacks for roads constructed through these areas. Subarea 1A is generally an area of large, forested hills.

Till covers almost the entire subarea and is generally of gneissose, schistose, or granitic rock origin. Soils weathered in place tend to be sandy to loamy rather than clayey. Stony and bouldery soils are common in this subarea.

Large bedrock outcrops occur on mountaintops, especially on the west-facing slopes of the northern Green Mountains. Drainageways tend to have exposed glaciofluvial deposits. Many of the drainageways, especially in the lower-relief areas of Connecticut and Massachusetts, contain large bogs and marshes. The uplands, however, tend to be well drained and not unusually unstable or prone to erosion.

The greater part of subarea 1A is suitable for surface development because of the sandy to loamy nature of the till covering. However, some areas of high relief occur in the Vermont portion of the subarea. With the exception of the Vermont portion, where more isolated areas occur, heavy- and medium-duty roads are plentiful. Even in Vermont, however, a specific site would only rarely be farther than 8 km (5 mi) from an existing medium-duty road or farther than 16 km (10 mi) from a heavy-duty road. Because surface characteristics are broadly similar throughout subarea 1A, subarea designation was supported on other grounds.

Tectonic Environment

The seven earthquake epicenters located within this subarea represent eight events ranging in intensity from I_{MM} = II to I_{MM} = V. Of these events, only two are located within pluton boundaries. The distribution of epicenters throughout the subarea shows no particular trend. There was no problem, therefore, in basing subarea designation on geologic characteristics.

Subarea 1B

Geologic Characteristics

Subarea 1B (see Plate I) includes a north-south strip in west-central Massachusetts that loops into the northwestern corner of Connecticut and a second, separate portion in central Massachusetts and the contiguous southernmost tips of New Hampshire and Vermont. Plutons in this subarea were emplaced during the Taconic (ta) and Acadian (ac) orogenies.

New Hampshire (Plate III)

2 Ashuelot pluton (ac)

3 Westmoreland-Swanzey and Related Domes (ta)

Connecticut (Plate VIII)

1 Mine Hill, Tyler Lake, and other granitic rocks of probable Ordovician age (ta)

3 Granitic gneisses (includes Mine Hill, Tyler Lake, Ansonia, and Siscowit gneisses (ta)

4 Brookfield gneiss (ta)

7 Housatonic massif (ga)

9 Nonewaug granite (ac)

Massachusetts (Plate VI)

3 Barnard gneiss (ta)

4 Williamsburg granodiorite (ac)

8 Monson gneiss (ta)

9 Hardwick-Coys Hill granite (ac)

In southwestern New Hampshire, the Westmoreland-Swanzey and related domes are probably syntectonic and belong to the Oliverian magma series. The Ashuelot pluton is a sheet of Kinsman quartz monzonite overlying Oliverian rocks. The New Hampshire bodies are relatively small and consist of metadiorite and metagranodiorite gneiss. They appear to have been forcefully intruded as sheetlike bodies that were later intensely folded. Secondary dikes, sills, and veins traverse the main bodies. Detailed data on fracturing are not available.

In Massachusetts, the Williamsburg granodiorite is exposed as several small bodies and two larger irregular masses 52 km^2 (20 mi^2) and 62 km^2 (24 mi^2) in area. These latter bodies are texturally variable, with fine- to medium-grained center portions and very coarse grained, localized masses and sheets. Secondary intrusions of pegmatite and aplite are profuse and form a halo around the main bodies. Sericitization of feldspars is present, and pegmatitic phases exhibit moderate hydrothermal alteration.

The Monson gneiss consists of four bodies of variable lithology in west-central Massachusetts. One of these, the Warwick dome, extends northward into New Hampshire. The ages and emplacement mechanisms of the various lithologies are controversial. The rock types forming the Warwick dome exhibit igneous flow foliation and have been deformed by faulting. Sericitization of feldspars and replacement of primary hornblende by chlorite are common. Faults are present in the main pluton bodies as well as in the Warwick dome.

The Hardwick-Coys Hill granite is an elongate, north-trending batholith in central Massachusetts. Stratigraphic correlations indicate that it is probably of Devonian or younger age. The granite is very coarse grained and contains local inclusions of schistose country rock. Little information is available on fracturing, deformation, secondary intrusions, or alteration.

Nonewaug granite crops out in subarea 1B in three bodies and is one of the more isotropic of the plutons in the subarea. It consists of a gradational association of fine- to coarse-grained granites exhibiting igneous flow textures. No folding, faulting, or other structural deformation is evident. Little information is available on pluton geometry. If it is a laccolith, it would probably not be deeply rooted (<300 m [<1000 ft]).

Only two small bodies of Brookfield gneiss are exposed in subarea 1B. Because the bodies located within the most favorable area are too small to be considered as potential repository sites, the Brookfield gneiss is not discussed further. A single pluton related to the Mine Hill and Tyler Lake bodies is located within subarea 1B. The hourglass shape and small outcrop area of this body make it relatively less suitable as a potential repository site. An irregularly shaped mass of rock identified as part of the Housatonic massif is situated in the northwestern corner of subarea 1B. The rocks of the Housatonic massif are similar to those forming the cores of the Hudson and Berkshire highlands. Rock types include quartz-mica schist, granitic gneiss, hornblende gneiss, and small amounts of marble and quartzite.

The Barnard gneiss, located in the west-central Massachusetts portion of subarea 1B, is too narrow to be suitable for a repository site.

Geohydrology

Because of the proximity of subareas 1A and 1B, many of the drainage basins are common to both. In Connecticut, subarea 1B incorporates portions of both the Housatonic-Naugatuck and Farmington basins. The northward extension of the subarea into Massachusetts includes more than half of the Westfield River watershed and a number of smaller streams, such as the Mill and Manhan rivers, which are tributary to the Connecticut River to the east. The eastern portion of the subarea encompasses approximately one-third of the Chicopee-Ware drainage basin, including about one-half of the surface area of Quabbin reservoir. To the northwest, this eastern portion includes the middle portion of the Millers River drainage area in north-central Massachusetts and the lower portion of the Ashuelot River drainage area in extreme southwestern New Hampshire.

Except for relatively minor deviations related to elevation and topography, the distribution of precipitation in subarea 1B is fairly uniform, ranging from a minimum of about 97-102 cm (38-40 in.) per year in northwestern Connecticut to a maximum of approximately 122 cm (48 in.) in west-central Connecticut and west-central Massachusetts. Thus, the total variation in mean annual precipitation is approximately 20-25 cm (8-10 in.), with an average value of about 112-117 cm (44-46 in.). Similarly, mean annual runoff shows very little variation throughout the subarea, with values ranging from about 51 cm (20 in.) in northwestern Connecticut and southwestern New Hampshire to approximately 66 cm (26 in.) in west-central Massachusetts in the upland areas of the Westfield River watershed.

Several reservoirs and controlled natural lakes are located within subarea 1B, including Quabbin reservoir, which has the largest storage capacity of all man-made reservoirs in New England. A few smaller natural lakes and ponds are found throughout the subregion; however, their total surface area and storage capacity are small. Although swampy or marshy areas are found at scattered locations adjacent to several of the streams in the low-relief portions of the subarea, their areal extent is small. Therefore, marsh and bog conditions are not an important aspect of the surface-water characteristics of this subarea. The surface-water characteristics of subarea 1B are not at variance with this subarea being designated on other grounds.

No data were obtained that would indicate the presence of groundwater at depth within the crystalline rocks of subarea 1B. However, in plutons that are faulted, folded, fractured, foliated, and traversed by veins and dikes, pathways for the transport of water are more likely to extend to great depths. Because geologic characteristics determine the groundwater environment, subarea designation was based on geologic characteristics.

Potential for Human Intrusion

The only active mines within subarea 1B are three marble mines located 3.2-8 km (2-5 mi) north of the Housatonic massif in northwestern Connecticut (see Plate VIII). These mines are just beyond the 3.2-km (2-mi) exclusionary radius. Ten abandoned mines are located within pluton boundaries in this subarea. The distribution of past and present mining activities is compatible with basing designation of the subarea primarily on geologic characteristics. Prospects for opening new mines or reactivating abandoned mines in this subarea are poor; therefore, the potential for human intrusion should not be a limiting factor for repository siting.

Site Geometry

The plutons of subarea 1B are relatively small to moderate in areal extent. Although geometries are available for only a few of the plutons, many appear to be fairly shallow, sheetlike bodies.

Surface Characteristics

The eastern portion of subarea 1B lies east of the Connecticut River and is an upland area with hills and a few low mountains. The western portion of subarea 1B is located in the hills and low mountains west of the Connecticut River valley. In subarea 1B, there is generally less than 460 m (1500 ft) of relief.

The entire subarea is covered by till; bedrock exposures are common in the uplands and in a few marshes and bogs in some of the more poorly drained valleys. The Connecticut River valley lowlands are characteristically covered with stratified deposits derived from sandstone, shale, conglomerate, and basalt. The uplands are mostly covered with till derived from gneiss, schist, and granite, although stratified deposits of these same materials occur throughout the subarea. Some limestone- and schist-derived tills are found in the far northwestern reaches of subarea 1B. Soils in subarea 1B are generally well drained and not unusually unstable or prone to erosion.

The low mountains and hills of subarea 1B are covered with loamy to sandy till. Stony till is also present. Although these surficial materials tend to be well drained, there are some wet areas in poorly drained basins. The river valley portions of subarea 1B are also sandy and well drained, and major traffic arteries parallel these valleys. The low-relief mountains and hills, with their stable surficial materials, also support a number of heavy- and medium-duty roads. The lack of high relief makes steep grades and switchbacks largely unnecessary. The surface characteristics of subarea 1B are, therefore, broadly uniform and did not prevent this subarea from being designated based on geologic characteristics.

Tectonic Environment

The three earthquake epicenters recorded within subarea 1B were of I_{MM} = IV, I_{MM} = V, and unknown intensities. Only one of the epicenters is located within pluton boundaries. This subarea's seismotectonic environment is consistent with its designation based on geologic characteristics.

Subarea 1C

Geologic Characteristics

Subarea 1C is located in northeastern Vermont, northern New Hampshire, and west-central Maine (see Plate I). It includes a cluster of moderately sized plutons emplaced during or following the Acadian orogeny.

Vermont (Plate IV)

6 Knox Mountain pluton (ac)

7 Victory pluton (ac)

9 Maidstone pluton (ac)

10 Willoughby pluton (ac)

11 Nulhegan pluton (ac)

12 Echo Pond pluton (ac)

13 Averill pluton (ac)

New Hampshire (Plate III)

12 Long Mountain granite (ac)

13 Umbagog granodiorite (ac)

Maine (Plate II)

6 Sebago Lake batholith (ac)

14 Umbagog granodiorite (ac)

Compared with the Precambrian gneisses of subarea 1A, plutons in subarea 1C are lithologically more homogeneous and structurally more isotropic. They have no fold structures.

The Knox Mountain pluton is large and consists of coarse-grained granite that was probably intruded forcefully into high-grade quartz-muscovite schists. Within the Knox Mountain body, two principal fracture sets with very steep to vertical dips trend N. 20°-40° E. and east-west. Other fractures strike N. 5°-25° E. and dip either to the northwest or southeast. Cross joints with steep dips strike west-northwest. Local pegmatite and quartz veins occur along joint trends. Minor foliation may reflect original igneous flow structures.

The remaining plutons in Vermont form a cluster in the northeastern corner of the state. The Echo Pond pluton is the least homogeneous and includes monzonite, diorite, and gabbro. Although some igneous layering is present, metamorphic foliation is absent. The other plutons (Willoughby, Averill, Nulhegan, Maidstone, and Victory) consist of relatively homogeneous lithologies, including monzonite, granite, and granodiorite. These bodies generally have isotropic textures except near contact zones, where flow textures commonly are present. Two major fracture directions are well developed in each body -- N. 20°-60° E. and N. 25°-60° W. The fracture planes are usually steeply dipping. Significant faulting is reported from Averill Mountain, where a downfaulted metasedimentary block is preserved within the pluton.

The Long Mountain granite pluton is an ovoid body in north-central New Hampshire that is composed of fine- to medium-grained Concord granite. It was forcefully injected following the Acadian orogeny, as evidenced by brittle deformation of the country rock. No data are available on internal structure, fracturing, alteration, or secondary intrusions.

In western Maine, the northernmost portion of the Sebago Lake batholith is included in subarea 1C and consists of a large (362-km^2 [140-mi^2]) exposure of Songo granodiorite, which is part of the larger composite body. Inclusions of metasedimentary country rock and gently dipping primary foliation suggest forceful intrusion. Four vertical joint sets, some parallel to regional fold structures and the east-trending Moll Ockett fault, are included within the granodiorite body. Pegmatite dikes, sills, and lenses up to kilometers in thickness are also reported. Gravity data suggest that the Sebago Lake batholith is a relatively thin and shallow subhorizontal sheet.

Located in western Maine and easternmost New Hampshire, the Umbagog granodiorite is a cylindrical plug of medium-grained granodiorite exhibiting smooth, sharp, and steep contacts with metamorphosed country rock and a brecciated contact zone with the adjacent Mooselookmeguntic pluton. The body is massive or it exhibits weak primary foliation; metamorphic mineral assemblages occur, particularly near the contact zones. No pegmatites are associated with the Umbagog granodiorite, and no data on fracturing are available.

Almost all of the plutons in this subarea are forcefully emplaced, posttectonic intrusions that exhibit isotropic fabrics and essentially igneous textures. Some may be composite bodies, but heterogeneities appear to be largely gradational, reflecting subtle changes in grain size and mineral assemblages. Small pegmatite dikes are present in the marginal areas of all plutons within subarea 1C. Alteration is mostly incipient, with the development of chlorite and sericite being very common.

Geohydrology

Within the states of Vermont and New Hampshire, subarea 1C is drained by the Connecticut River and its tributaries, except for a small area located in the headwaters of the Winooski and Lamoille rivers, which are tributary to Lake Champlain; an area that includes most of the Barton-Black-Clyde (Lake Memphremagog) system, which eventually flows into the St. Lawrence River via the St. Francis River in Quebec; and a small portion in northeastern New Hampshire that is drained by the Androscoggin River. The Maine portion of the subarea is within the Androscoggin drainage basin, except for a small area in the upland portions of the Presumpscot and Saco drainage basins.

Mean annual precipitation varies from a low of 86 cm (34 in.) in central Vermont to a maximum of 112 cm (44 in.) in northern New Hampshire and western Maine. Average annual runoff ranges from a low of about 50 cm (20 in.) in much of Vermont to about 100 cm (40 in.) in northern New Hampshire. The Connecticut and Androscoggin rivers have the largest discharges from the subarea.

At least five controlled natural lakes and reservoirs occur within subarea 1C. Several other lakes of various sizes are found scattered throughout the subarea. In northeastern Vermont and western Maine, many of these are located over plutons. However, a layer of till of unknown thickness may separate the lake bottoms from the upper surfaces of the plutons. Most of the major stream valleys in the area are floored with discontinuous stratified drift of variable thickness. The drift consists of clay to silt, silt to sand, and gravel. A number of poorly drained swampy areas are found within the upper Connecticut valley, but most of these have small surface areas. A large swampy area exists within the lowlands of the Nulhegan and Clyde drainage basins in northeastern Vermont. This area overlies portions of the Echo Pond, Nulhegan, and Maidstone plutons. Surface-water considerations suggest that geologic characteristics are of overriding importance in subarea 1C.

Groundwater conditions in subarea 1C are similar to those described for subareas 1A and 1B. The descriptions of the geologic characteristics of the plutons within subarea 1C indicate considerable variation in terms of jointing, fracturing, foliation, and other features affecting groundwater movement. Because groundwater hydrology is a function of these geologic features, geologic criteria were used to designate the boundaries of this subarea.

Potential for Human Intrusion

In Vermont, four active mines occur within 1.6 km (1 mi) of the southwestern edge of the Knox Mountain pluton (see Plate IV). These mines are in the Barre granite or in metamorphic country rock just to the south. They produce granite monument stone, marble, or crushed metadiabase. A fifth active granite mine occurs 10-14 km (6-9 mi) west of the Echo Pond and Averill plutons. Two other active mines in Vermont occur several kilometers from pluton boundaries. The only abandoned mine that lies within a pluton in this subarea is located at the west end of the Willoughby pluton. The distribution of past and present mineral extraction activity in subarea 1C (see Plates II-IV) did not preclude its designation as a subarea on other grounds.

Site Geometry

With the exception of the Sebago Lake batholith, the plutons within subarea 1C are moderate in areal extent, with a mean exposure area of approximately 130 km^2 (50 mi^2). Their vertical extent remains uncertain because their subsurface geometries have not been described. Some may be shallow.

Surface Characteristics

The part of subarea 1C in Vermont consists of low mountains and hilly terrain. The New Hampshire and Maine portions of subarea 1C include foothill areas of the White Mountains but exclude areas of higher elevation. Bedrock outcrops occur throughout subarea 1C, and till and till-derived soils cover most of the subarea. Particularly in Maine and Vermont, there are areas of well-defined cirques, moraines, and drumlins. Bogs and marshes occur throughout the subarea, and alluvial materials floor the major drainageways. Because soils derived from till tend to be well drained, they are not unusually erodable or unstable. Heavy- and medium-duty highways are plentiful in this subarea, with the possible exception of parts of northeastern Vermont. However, the Vermont portion of this subarea is near an interstate highway (I-91). Because subarea 1C is sufficiently homogeneous as far as its surficial characteristics, designation of this subarea on other grounds is acceptable.

Tectonic Environment

The five earthquake epicenters located within the boundaries of subarea 1C are evenly distributed. The earthquake of greatest intensity (I_{MM} = V) occurred in 1957 just north of the New Hampshire border on the 72nd meridian. None of the epicenters in this subarea fall within pluton boundaries. The seismotectonic characteristics of this subarea are compatible with its designation as a discrete unit based on geologic characteristics.

Subarea 1D

Geologic Characteristics

Subarea 1D includes a group of mildly alkaline stocks of moderate surface exposure in northwestern New Hampshire. These Mesozoic intrusions postdate the Alleghenian orogeny (a) and are characterized by ring complexes, stocks, and large plutons of homogeneous granite, syenite, and monzonite.

New Hampshire (Plate III)

11 Pilot-Pliny complex (includes Percy Peaks and Gore Mountain stocks (a)

The Pilot-Pliny complex includes several distinct bodies intruded from separate centers into high-grade gneiss and schist of Devonian age. The Pilot and Pliny ring-dike complexes are concentric about centers approximately 3.2 km (2 mi) apart and are cored by coarse-grained stocks of granite, syenite, and quartz monzonite. The Conway granite is the main component of the Pilot complex. The Percy Peaks and Gore Mountain intrusives are similar and consist of homogeneous bodies composed mainly of Conway granite. They were probably emplaced by cauldron subsidence in a strongly discordant mode, which is characteristic of these Mesozoic intrusions. Homogeneous and isotropic plutonic lithologies that extend to considerable depths are also characteristic. Secondary intrusions are sparse, and contacts with country rock are clear-cut.

Logs of a 900-m (3000-ft) core hole drilled into Conway granite at Redstone, N.H.,* in subarea 3A were examined because of the similarity of the granite to that of the plutons of subarea 1D. Analysis of the logs disclosed that the corehole penetrated two phases of Conway granite -- an altered, medium-grained green phase approximately 335 m (1100 ft) thick and an underlying, less-altered, coarse-grained red phase approximately 396 m (1300 ft) thick. These two phases have a contact zone 8-10 cm (3-4 in.) thick that apparently dips 40°. Albany quartz syenite, which is interlayered with the lower portion of the red phase of the Conway granite, has a total thickness of approximately 12 m (40 ft). A hastingsite-biotite granite occurs in the bottom 61 m (200 ft) of the core hole. Contacts between the lower lithologies apparently dip 30°-40°. Minor borehole lithologies include mottled syenite; foliated, fine-grained granite; and lamprophyres.

The granite rocks contain eight major zones of hydrothermal alteration that range in thickness from 1 m (3 ft) to 46 m (150 ft). Albitization of potassium feldspar and replacement of other minerals by clay minerals and hematite are the main types of alteration. Minor sulfides and calcite are also present. Most fractures in the core are steep to nearly vertical. Subhorizontal sheeting fractures are more prevalent in the upper 61 m (200 ft) of core, but some are found as deep as 183 m (600 ft).

The radioactivity of the Conway granite has been known to be anomalously high in the White Mountain batholith. Studies of the Redstone cores indicate that radioactivity in the green phase of Conway granite is associated with zones of fracturing, shearing, or alteration, or with fine-grained dikes. The red phase generally exhibits higher radioactivity than the green phase; peak radioactivity is usually associated with miarolitic cavities in the red phase. Vein deposits of uranium are likely present because of the mineralogical alteration and radiometric conditions in the core hole. Heat-flow potential is highest in the red phase of the granite. Temperature logging revealed that the temperature at the base of the core hole was 33.6°C (92.5°F).

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*Hoag, R.B., Jr., and G.W. Stewart, 1977, *Preliminary Petrographic and Geophysical Interpretations of the Exploratory Geothermal Drill Hole and Core, Redstone, New Hampshire*, prepared for Division of Geothermal Energy, Energy Research and Development Administration.

Geohydrology

Subarea 1D is drained mainly by the Upper Ammonoosuc River and its largest tributary, Nash Stream. Part of the southwestern portion of the subarea is drained by tributaries of the Israel River, and the Gore Mountain area is drained by smaller streams directly tributary to the Connecticut River. Mean annual precipitation for this area of New Hampshire is approximately 101 cm (40 in.), with average annual runoff accounting for almost 75% of that amount.

No reservoirs or controlled natural lakes occur within subarea 1D, although numerous small lakes and ponds exist at scattered locations. Some are located within or adjacent to mapped pluton boundaries. Although many swamps and bogs are located in low-lying portions of the subarea, none of these appear to be located directly above the main pluton bodies.

Groundwater circulation within the plutons of subarea 1D is in all likelihood controlled mainly by fracturing. The influence of miarolitic cavities on permeability would be slight, because they would tend not to be interconnected, except by fractures. No data were found for specific water wells within subarea 1D.

There are no unusual geohydrologic conditions that would warrant modification of the subarea boundaries defined on the basis of geologic characteristics.

Potential for Human Intrusion

No active mines and only one inactive granite mine occur in subarea 1D (see Plate III). Thus, the potential for human intrusion should not be an impediment to siting a repository in a pluton in subarea 1D.

Site Geometry

The intrusives of subarea 1D are stocks and ring complexes that generally have clear-cut contacts with country rocks. Their geometries remain unconfirmed. Any similarity to the Conway granite of the White Mountain batholith is problematical. The stocks may extend to considerable depths.

Surface Characteristics

Subarea 1D includes much of the Pilot Range of the White Mountains, which rises more than 915 m (3000 ft) from the Connecticut River valley to the west. The surficial materials of the Pilot Range are largely till, but other materials are also present. Steep slopes, bedrock outcrops, and many stones and boulders characterize the Pilot Range region. The remainder of subarea 1D to the north and northwest of the Pilot Range is mountainous, with many bedrock exposures, and covered with thin layers of till that are usually less than 3 m (10 ft) thick. Some marshes and bogs are present, but valleys are usually well drained, and surficial materials are not unduly susceptible to erosion.

Heavy-duty roads in and near subarea 1D are generally located in the alluvial materials of the major drainageways. No part of this subarea is farther than 8 km (5 mi) from a heavy-duty road, and a railroad line bisects the subarea. No special topographic hazards were found in subarea 1D, except at the higher elevations of the Pilot Range and in the mountains in the northwestern part of the subarea. This hazard consists of the usual rockslide risks at road cuts in the bedrock. The surficial characteristics of subarea 1D are sufficiently homogeneous to warrant designation of this subarea as a distinct unit on other grounds.

Tectonic Environment

Only three epicenters are known in subarea 1D, one for an I_{MM} = II event and two for I_{MM} = IV events. Because the subarea is seismically quiescent, seismotectonic considerations did not alter the boundaries based on geologic characteristics.

Subarea 1E

Geologic Characteristics

Subarea 1E includes two separate sections in the northern part of the Maine-New Hampshire and New Hampshire-Vermont border regions. The plutons were emplaced during the Grenville-Avalonian and Taconic orogenies.

New Hampshire (Plate III)

9 Lost Nation group (ta)

10 Jefferson dome (ta)

Maine (Plate II)

21 Chain Lakes massif (ga)

22 Attean quartz monzonite (ta)

Vermont (Plate IV)

8 Lost Nation group (ta)

A member of the Highlandcroft series, the Lost Nation group consists of irregularly shaped intrusions of massive, subporphyritic to porphyritic diorite or quartz monzonite. Aplitic dikes, quartz veins, and epidote druses are commonly found within its well-developed joint sets. Mafic dikes are also present. The Jefferson dome is possibly coeval and is composed of foliated and intensely fractured granite, monzonite, and syenite intruded into medium- to fine-grained amphibolite and gneiss. The southeastern flank of the Jefferson dome is downthrown by the Pine Mountain fault. Both plutons appear to be anisotropic and to consist of heterogeneous lithologies and textures. Alteration is moderate and pervasive. Marginal zones are cut by dikes and sills.

In Maine, subarea 1E includes two intrusives of significant outcrop area -- the Attean quartz monzonite and the Chain Lakes massif. The Attean pluton is irregularly shaped and is located on the crest and southeastern limb of the Boundary Mountains anticlinorium, which extends southwestward into New Hampshire. The pluton is massive in texture, being composed of medium- to coarse-grained quartz monzonite with little alignment of mineral grains. It is highly altered in the northern and western portions of the outcrop area and traversed by basic dikes up to about a meter in thickness, all of which contributes to its substantial heterogeneity. Fractures are abundant, but few exhibit slickensides or other evidence of movement. However, schistose shear zones appear to parallel joint systems. A north- to northwest-striking vertical fault traverses the southern half of the outcrop area.

The Chain Lakes massif is a thick complex of metasedimentary and metavolcanic granofels, gneiss, schist, amphibolite, and quartzite. It is intruded by the smaller Attean quartz monzonite body. Metamorphism of the Chain Lakes massif rocks to at least sillimanite grade and subsequent hydrothermal alteration have been reported. The variable and complex lithologies of the Chain Lakes massif make it relatively unsuitable for a repository.

The plutons of subarea 1E are generally heterogeneous, as evidenced by lithologic diversity, secondary intrusive activity, and significant alteration in some bodies. Structural and textural anisotropies vary but are generally marked.

Geohydrology

Subarea 1E comprises two geographically separate but geologically similar areas. With the exception of the eastern portion of the southern area, which lies within the Androscoggin basin, all of the subarea in Vermont and New Hampshire is drained by the Connecticut River and its tributaries. The tributaries include those flowing into First and Second Connecticut and Francis lakes in extreme northern New Hampshire. The Mohawk River, Simms River, headwater portions of the Upper Ammonoosuc watershed, and lower reaches of the Israel River are also included. The portion of subarea 1E in Maine encompasses a portion of the uppermost drainage basins of the Androscoggin and Kennebec rivers.

Mean annual precipitation within subarea 1E is about 91-97 cm (36-38 in.) in Maine and within the Connecticut valley and more than 112 cm (44 in.) in New Hampshire. Most of the relatively minor variations in precipitation that exist throughout the subarea can be attributed to differences in elevation. Average annual runoff ranges from less than 51 cm (20 in.) adjacent to the Connecticut River and in western Maine to more than 102 cm (40 in.) at higher elevations in New Hampshire. Variations in snowfall accumulation are also related to differences in elevation. Precipitation is distributed relatively uniformly throughout the year, particularly in areas receiving significant snowfall.

Reservoirs and controlled natural lakes occur within subarea 1E. Also present are a significant number of large lakes and smaller ponds, particularly in the Maine portion. All or portions of Upper Richardson, Cupsuptic, and Spencer lakes; Attean, Wood, and Holeb ponds; and several small, unnamed ponds are located within mapped pluton boundaries.

Marsh and bog areas are present throughout the subarea but are particularly abundant in Maine. Extensive, poorly drained areas are found in the vicinity of Kennebago Lake and within the Moose River watershed. This latter area overlies much of the Attean quartz monzonite body. Also, several drainage channels and valleys are superimposed over plutons in this subarea. The Androscoggin River and some of its tributaries are within the mapped boundaries of the Lost Nation group in New Hampshire, and the Connecticut River flows across this same mapped unit at the New Hampshire-Vermont border.

Very little information is available for evaluating groundwater conditions within subarea 1E. However, the geologic characteristics of the crystalline rocks in the subarea enhance the probability of groundwater occurrence at depth. There is no known geohydrologic evidence to support rejecting the subarea boundaries as defined by geologic characteristics.

Potential for Human Intrusion

No active mines and only three inactive mines occur in subarea 1E. An abandoned granite mine is within the boundaries of the Lost Nation group (see Plate III). Thus, the potential for human intrusion was not an important factor in designating this subarea.

Site Geometry

The plutons of subarea 1E are relatively large in terms of surface exposure. All but one of these bodies are associated with the Taconic orogeny. As mountain root zones, they may extend to considerable depth, but their depths have not been determined.

Surface Characteristics

Subarea 1E, which has large bedrock outcrops, is located in the Mt. Blue area and in the foothills, uplands, and lowlands of the White and Longfellow mountain ranges. The low mountains of this subarea generally rise less than 610 m (2000 ft) above the surrounding lowlands. A few peaks reach 915 m (3000 ft) above valley floors.

The surficial materials of subarea 1E consist primarily of till and till-derived soils. In the northern, larger part of subarea 1E, the surficial materials are derived from compact, silty till. In the two smaller parts of subarea 1E, the till is generally sandy in the lowlands and loamy in the uplands. Landforms commonly found in glaciated terrains are present, such as glaciofluvial deposits and eskers. Marshy areas abound, especially in the northern part of subarea 1E. Alluvial materials are found in the floodplains of the Connecticut and Androscoggin rivers.

Heavy-duty highways and railroads flank the southern portions of subarea 1E. The northern, larger part of subarea 1E is accessible only from medium-duty highways, which roughly follow the subarea's boundaries. The differences between the northern part of subarea 1E and the southern part in terms of topography and surficial materials are mainly related to elevation and till characteristics. However, the differences are of little account when compared with the importance of the geologic characteristics used to designate this subarea.

Tectonic Environment

No earthquake epicenters have been plotted in the southwestern part of subarea 1E, but a single event (I_{MM} = II) was recorded near its border. In the eastern part, only one event (I_{MM} = V) was recorded. Within the northern portion of subarea 1E, there was a single, low-intensity event (I_{MM} = II). The seismicity of subarea 1E is compatible with its designation as a subarea based on geologic characteristics.

Subarea 1F

Geologic Characteristics

Subarea 1F embraces several large crystalline intrusives that postdate the Acadian orogeny. These plutons crop out across central Maine and probably are a related suite of bodies.

Maine (Plate II)

12 Phillips pluton (ac)

13 Mooselookmeguntic pluton (ac)

15 Redington pluton (ac)

16 Sugarloaf pluton (ac)

17 Lexington batholith (ac)

18 Pierce Pond pluton (ac)

19 Flagstaff Lake complex (ac)

23 Moxie pluton (ac)

24 Katahdin batholith (ac)

The Phillips, Redington, and Lexington plutons are probably cogenetic and represent separate exposed cupolas of a single underlying body. Contact relations indicate that these bodies were forcefully intruded following the Acadian orogeny. Lithologies are fine-grained to very coarse grained granodiorite, diorite, quartz monzonite, and syenite, and range from aphyric (e.g., Phillips) to coarsely porphyritic (e.g., Redington). The Lexington pluton exhibits all of the above mineralogies and textures. Pluton interiors are mostly coarse grained, with equigranular groundmasses; extensive alteration, probably deuteric, has been reported for each body. Flow textures are observed near contacts with country rock. Neither postintrusive folding nor faulting is evident. Models based on gravity data suggest an average depth of about 1520 m (5000 ft), but the plutons may extend to 3050 m (10,000 ft).

Because the Flagstaff Lake, Pierce Pond, Sugarloaf, and Moxie plutons are sheetlike bodies with mafic lithologies, they are presumably related and could be interconnected at depth. They occupy areas of moderate to low relief in west-central Maine.

The Flagstaff Lake complex is a composite body made up of medium- to coarse-grained gabbro, troctolite, norite, mafic diorite, monzonite, quartz diorite, quartz monzonite, and granite. Despite the lithologic variety in this pluton, primary layering is poorly developed. Some local shear zones are present, as are faults with northeasterly and northwesterly trends. The Rangely Lake fault is present in the southeastern portion of the pluton, and a smaller, northeasterly trending fault is present at the western margin. The northeastern portion of the Flagstaff Lake complex is in fault contact with the adjacent Pierce Pond pluton.

The Pierce Pond pluton is a subhorizontal, sheetlike body of coarse-grained augite gabbro and gabbroic anorthosite. Although the rocks are not generally foliated, stratiform layering is present in the pluton's northern portion. Inactive faults with northeastern and northwestern trends occur nearby.

The Sugarloaf pluton is a layered gabbroic massif composed of medium- to coarse-grained gabbro, troctolite, and anorthositic gabbro. Geophysical interpretations suggest that it is a thin, sheetlike body with a shallow to moderate northwestward dip. Shear zones and foliation with northeasterly trends are reported in some locations. Weak deuteric alteration is evident throughout the body, but extensive alteration is not reported.

The Moxie and Katahdin plutons also appear to postdate the main Acadian orogeny and were probably forcefully intruded by stoping. They exhibit strongly discordant contacts and vary considerably in lithology and structure. The Moxie pluton is a long and narrow complex comprising several related massive rock types: troctolite, norite, and subsidiary amounts of diorite, gabbro, and dunite. Gravity data indicate a large, sheetlike body that is probably layered and dips 60° SE; aeromagnetic data suggest additional gabbroic bodies at depth. The main body is anisotropic because of igneous layering and flow textures. The rocks are generally fresh, perhaps due to removal of weathered material by glacial scouring.

The Katahdin batholith has the largest surface area of the plutons in subarea 1F. It is probably posttectonic, having been emplaced diapirically with considerable digestion of wall rock. The rocks are largely equigranular, coarse-grained quartz monzonite. Sericitization of feldspars occurs in outcrops at higher elevations. A contact breccia zone up to 1.6 km (1 mi) wide occurs on the eastern flank. Assimilated material in this region ranges from fine-grained aplite to coarse-grained pegmatite. Diorite intrusions crosscut the extreme southwestern tip of the main batholith. Country rocks are diverse, consisting of metavolcanics in the east and rhyolite flows and ash flows to the north and northwest. The main body is devoid of foliation and traversed by closely spaced vertical joints. A small fault traverses the west-central part of the batholith.

The Mooselookmeguntic pluton is a large and irregular intrusion consisting of a heterogeneous mixture of granite, quartz monzonite, granodiorite, and quartz diorite. Gravity surveys suggest that it is a sheetlike body approximately 1.6-2.0 km (1.0-1.2 mi) thick. Syntectonic emplacement is suggested by primary foliation in the granite phase located in the south-central portion of the pluton. Inactive faults trending in a northwesterly direction are abundant at the pluton's eastern margin, and many of these are truncated by the pluton. Pegmatite dikes are common and locally abundant. Saussuritization of calcium plagioclase and chlorite replacement of biotite are common.

In summary, the plutons of subarea 1F are mainly granitic, granodioritic, and gabbroic bodies. Most are massive, relatively homogeneous, and slightly to moderately anisotropic. An exception is the Moxie pluton, which may be less homogeneous because of in situ differentiation. However, the Moxie pluton is less susceptible to deuteric or meteoric alteration.

Geohydrology

Subarea 1F encompasses a portion of each of the four major drainage areas of Maine -- the Androscoggin, Kennebec, Penobscot, and St. John river systems. Mean annual precipitation averages about 102-104 cm (40-41 in.). The average value increases to 127 cm (50 in.) or more in some of the mountainous areas. Certain northern areas sometimes receive in excess of 254 cm (100 in.) of snow, while elsewhere accumulations of 152-178 cm (60-70 in.) are common. Eliminating the local effects of high relief and elevation, average precipitation varies by only 15 cm (6 in.) throughout the subarea. Precipitation is also distributed fairly uniformly throughout the year.

Average annual runoff ranges from less than 51 cm (20 in.) to more than 76 cm (30 in.) in the central part of Maine. The average value for the subarea is about 58 cm (23 in.). Maximum monthly streamflows usually occur in March, April, and May, with flow values 5-10 times the average. Minimum flows occur in late winter in the St. John basin, during the fall in the Penobscot and Kennebec watersheds, and in late summer and early fall in the Androscoggin basin. Typical low flows are about 5-10% of the average value.

Flooding occurs almost annually as a result of heavy spring rains combined with snowmelt runoff and river-ice breakup. Spring flooding is a problem on the Penobscot, Kennebec, and Androscoggin rivers, with annual damage being greatest in the Kennebec basin.

There are 20 controlled natural lakes and reservoirs in subarea 1F. The largest of these, Moosehead Lake, is the second largest natural lake in the northeastern region; only Lake Champlain has greater surface area. A large number of uncontrolled natural lakes and ponds are scattered throughout the subarea. Every pluton within subarea 1F has lakes or ponds within its mapped boundaries.

The groundwater characteristics of subarea 1F are broadly similar to those throughout the state of Maine and those of the other northeastern states. Because of variations in geologic characteristics, differing groundwater conditions within the plutons throughout the subarea can be anticipated. However, insufficient data are available on the geohydrologic conditions within specific plutons. There is no geohydrological evidence to cause the subarea boundaries as fixed by geologic considerations to be modified.

Potential for Human Intrusion

The Rangely garnet mine (see Plate II) near the Flagstaff Lake complex and the Redington pluton is the only active mine of concern in subarea 1F. The 3.2-km (2-mi) exclusionary radius would put parts of these plutons off limits for potential repository development. Three abandoned mines occur within or near the Phillips pluton and the Katahdin batholith. Two of these are cobalt-nickel mines. Because cobalt is a strategic metal, it is possible that the inactive cobalt mines in the southwestern part of the Katahdin batholith could someday be reactivated. Exploration for massive sulfides is under way in this subarea. This activity could militate against siting a repository in this subarea. With these exceptions, the potential for human intrusion was not a significant factor in designating subarea 1F.

Site Geometry

The plutons of subarea 1F are typically of moderate size; however, the Katahdin batholith and the Mooselookmeguntic pluton are much larger. Most of the plutons are thought to be thick, sheetlike bodies. The Moxie pluton differs from the others in that it is a steeply dipping rather than a more horizontal sheet.

Surface Characteristics

Subarea 1F includes the Mt. Blue area and, in its western reaches, a portion of the Mahoosuc Range of the White Mountains. Mt. Katahdin, the highest point in Maine at 1605 m (5267 ft), is also located in subarea 1F. The mountains of subarea 1F trend northeast and are underlain by major plutons. The mountainous southwestern portion of subarea 1F is characterized by large areas of bedrock outcrop and thin surficial materials. In this region, fewer large areas of bogs and marshes occur than in the central and northern portions of subarea 1F, which have lower relief. Surficial materials in this mountainous southwestern area tend to be stony and erodable when disturbed.

The mountainous area around Mt. Katahdin is very different from the mountainous area to the southwest. There are very few large bedrock outcrops, and the surrounding land is gently rolling, with only slight variations in relief. Bogs and marshes occur throughout the area. The topography westward from Mt. Katahdin to the Quebec border is gently rolling. In the western half of this region, there are generally stonier surficial materials, steeper slopes, greater relief, and fewer large marshes.

Eastward from Mt. Katahdin toward New Brunswick, the topography is a mixture of flatlands, smoothly rounded hills, and limited areas of sharper relief. The surficial features range from large bogs and marshes through excessively bouldery and stony areas. Major portions of this area tend to be stony and easily eroded on slopes, while other large segments are covered by deep loamy soils derived from till. The soils are not very stony but tend to be wet and easily eroded when disturbed. Some areas of limestone, shale, and shale-derived materials also exist toward New Brunswick. These materials tend to be wet and shallow, and unstable for construction purposes.

The northern portion of subarea 1F, from Quebec to New Brunswick, is a rolling lowland, with some northeast-trending hills of low relief in the central portion. The northeastern portion of subarea 1F, toward New Brunswick, is poorly drained, with extensive bog and marsh areas. Even upland areas tend to be wet and easily eroded on slopes when disturbed. The northwestern portion of subarea 1F has slightly more relief and tends to be slightly better drained. Marsh and bog areas are not as extensive as in the northeastern portion. The major surficial material in this portion is a deep loamy till, and the resulting soil tends to be wet and erodable on slopes.

Subarea 1F contains a very heterogeneous mixture of terrains, from peat bogs to alpine highlands. In areas of high relief, rockslides are common, particularly at cliffs and road cuts. To reach locations on the higher mountains, rock cuts, steep grades, or switchbacks may be necessary. Heavy- and medium-duty roads wind through the mountains in the southwestern portion of subarea 1F. The area from Mt. Katahdin northward and westward is served by all-weather roads constructed for the paper industry.

Much of subarea 1F is relatively less favorable for development of a repository because of its inaccessibility by road and its wet, erosion-prone surficial materials. The interior portions of the granitic mountains of the southwestern portion of subarea 1F are, for the most part, within 16 km (10 mi) of medium- or heavy-duty highways, and they are generally less than 900 m (3000 ft) above the surrounding lowlands. The heterogeneity of surface characteristics suggests that any future studies in subarea 1F will have to address surface materials and surface processes on a site-specific basis. However, because almost all of the plutons of interest in subarea 1F are in or near mountainous regions, further subdivision of subarea 1F into mountainous and lowlands subareas based on surface characteristics is not necessary.

Tectonic Environment

Although subarea 1F is quite stable, it exhibits relatively high seismicity in its southwestern portion (see Plate I). Six epicenters occur within the boundaries of subarea 1F. In the southern portion of the subarea, three of these are for I_{MM} = V earthquakes. None of these epicenters occurs within pluton boundaries. The seismicity of subarea 1F is compatible with its designation as a subarea based on geologic characteristics.

AREA OF INTERMEDIATE FAVORABILITY (AREA 2)

Subarea 2A

Geologic Characteristics

Subarea 2A encompasses two plutons intruded during the late stages of or subsequent to the Acadian orogeny.

Maine (Plate II)

8 Waldoboro pluton (ac)

10 Hartland pluton (ac)

The southern portion of the Waldoboro pluton extends beneath the Atlantic Ocean at Muscongas Bay. The pluton consists of unevenly textured two-mica granite that is fine to medium grained. Fractures are present, but their orientations have not been described. Pegmatites have been reported, but without descriptive information.

The Hartland pluton is a northeast-striking, elongate body in south-central Maine. Deflection of metasedimentary country rocks suggests forceful emplacement. The rocks consist of an equigranular and holocrystalline hornblende-biotite granite. In view of the pluton's probable posttectonic origin, it could be structurally isotropic.

Geohydrology

The coastal portion of subarea 2A lies within a hydrologic area drained by the St. George, Medemak, and Sheepscot rivers, and other smaller streams. To the north, the subarea encompasses most of the watershed of the Sebasticook River, which is a major tributary of the Kennebec River. The northernmost portion of the subarea is within the basin of the Penobscot River and is drained by the Piscataquis River and some of its tributaries.

Eight reservoirs or controlled natural lakes and numerous uncontrolled lakes and small ponds are located throughout the subarea. Great Moose Lake, other smaller ponds, and portions of the Sebasticook drainage channel network overlie the Hartland pluton. Damariscotta Lake lies adjacent to the southwestern boundary of the Waldoboro pluton. Several other lakes and ponds, and many streams draining the coastal area, are found within the boundary of this pluton. Extensive swampy and poorly drained areas exist throughout subarea 2A. Each pluton has areas of this type associated with it.

The groundwater conditions of subarea 2A are broadly similar to those previously described for other subareas in Maine. Water yields of wells in bedrock are highly variable and generally low, and depend on the fracture characteristics of the rock. Fractures are reported within some subarea 2A plutons, but information is lacking on their extent and structural relationships. Therefore, no reliable estimate of probable groundwater conditions within these crystalline bodies can be made. The coastal position of the Waldoboro intrusive, however, greatly enhances the possibility of water invasion through existing fissures.

There do not appear to be any special geohydrologic conditions to warrant adjusting the subarea boundary, which was based on geologic characteristics.

Potential for Human Intrusion

No active mines are located in or near the Waldoboro or Hartland plutons; abandoned mines in or near these plutons are not likely to be reopened in the near future. Therefore, the potential for human intrusion did not affect the boundary of subarea 2A.

Site Geometry

The two plutons of this subarea are fairly large, elongate bodies. Their subsurface geometries are unknown.

Surface Characteristics

The northeast-trending central lowlands region (Bangor lowland) separates the more northern portion of subarea 2A from the more southern portion. The northern portion consists of rolling, forested hills, with a few mountains or large hills having 300-460 m (1000-1500 ft) of relief. Large bedrock outcrops are numerous in this portion. The southern portion is a northeast-trending mountainous area with forested ridges that generally do not exceed 240 m (800 ft) in relief.

The uplands of the southern portion of subarea 2A are covered with thin, well-drained loamy till on ridges and steeper slopes and with poorly drained, deeper loamy till on more gentle slopes and flatlands. The slopes of upper ridges are prone to severe erosion when disturbed. Some large sandy and gravelly areas of glaciofluvial origin also exist in this area. A line drawn eastward from Camden and then southward along the Kennebec River divides the uplands of the southern portion from the coastal lowlands, where till-derived soils tend to be more clayey and wet, and where soils derived from marine clays predominate in low-lying areas. This coastal area has been intensively developed for recreational uses despite the high water table and thinness of the soils.

The hilly northern upland and central flatland portions of subarea 2A are covered with loamy till derived from lime-seamed slates and shales. In the western half of the northern hill country, from Greenville to Madison, the till is more stony and more prone to erosion on steeper slopes than that in the eastern half.

Marshes and swamps occur throughout subarea 2A. In both the northwestern and southern highlands, there are areas where the till-derived soils are more prone to erosion than in the northeastern and central portions of subarea 2A. In the coastal lowlands, there are large areas of poorly drained or thin surficial materials, or materials derived from marine sediments. Given that the entire subarea is crisscrossed by heavy- and medium-duty roads, potential problems could be handled by proper engineering. The main road and rail transportation arteries of the state lead through the central flatland. The lack of massive mountains and the alignment of long mountainous ridges in the southern portion of subarea 2A make it unlikely that extensive switchbacks or excessively steep grades on access roads would be needed.

Although the existence of the three topographic/surficial provinces within subarea 2A should be taken into account in site-specific studies, no further subdivision is warranted based on surface characteristics alone.

Tectonic Environment

Six earthquake epicenters have been recorded for subarea 2A, and the location having the most intense shocks had four I_{MM} = IV events. There are no groupings of epicenters that would justify modifying subarea boundaries.

Subarea 2B

Geologic Characteristics

Subarea 2B includes two plutons of substantial outcrop area (Center Pond and Bottle Lake quartz monzonites) and two others that extend out of the subarea. All four plutons were emplaced after the Acadian orogeny, as evidenced by discordant contacts, contact aureoles, and lack (in all but one case) of metamorphic flow textures.

Maine (Plate II)

25 Seboeis complex (ac)

26 Center Pond quartz monzonite (ac)

27 Bottle Lake quartz monzonite (ac)

28 Chiputneticook quartz monzonite (ac)

The Bottle Lake complex intrudes low-grade metasediments of the Merrimack synclinorium. The southern lobe is truncated by the Norumbega fault zone. The Bottle Lake complex comprises several intrusions that display two main lithologies: a core facies of coarse-grained phyric quartz monzonite with rapakivi to equigranular texture and a rim facies of hornblende-biotite granite with seriate to equigranular texture. Thin aplite and pegmatite dikes are abundant near contact zones. The intrusive cores are relatively homogeneous, and the limited foliation toward contact zones probably reflects igneous flow. The abundant joints and fractures do not show preferred orientation.

The Center Pond quartz monzonite is an elongate, northwest-trending body. Its coarse-grained core and fine-grained rim facies are very similar to those of the Bottle Lake complex. Marginal zones contain abundant metasedimentary country rock inclusions, whereas mafic inclusions are randomly scattered throughout the intrusion. A major northeast-trending strike-slip fault associated with the Norumbega fault zone cuts diagonally across the outcrop and offsets the northern part of the intrusion by about 2.6 km (1.6 mi). A mylonite zone about 1 km (0.6 mi) wide also trends northeast within the pluton. Alignment of minerals in marginal facies reflects flow during emplacement.

The Chiputneticook quartz monzonite straddles the United States-Canadian border in an arcuate band in the Chiputneticook Lakes area. The outcrops in Maine display lithologies similar to those of other posttectonic Devonian intrusions. There are no distinguishing fracture and fault patterns within the main body, but at least two pre-Devonian faults are truncated by the southwestern edge of the intrusion. A very long (161-km [100-mi]) west-southwest-trending diabase dike about 61 km (200 ft) wide is exposed for 5 km (3 mi) within the body.

Plutons in this subarea are of medium- to coarse-grained granite, quartz monzonite, granodiorite, and diorite. They exhibit igneous rather than metamorphic foliation and are comparatively homogeneous.

Geohydrology

Subarea 2B includes the reach of the Penobscot River between Howland and Medway, and the tributaries entering the main channel between those points. The extreme downstream portions of the east and west branches of the Penobscot River are included where these join in the northwestern part of the subarea. A small portion of the headwaters of the West Branch Union River is included in the southern portion of the subarea, and the headwaters of the Grand Lake drainage area are found in the southeastern section. Most of the subarea is drained by the Mattawamkeag River and its tributaries. This drainage system is a major tributary of the Penobscot River.

Five controlled natural lakes and numerous uncontrolled lakes and ponds are located in the subarea. Extensive marsh and bog areas occur in all sectors. Particularly large, poorly drained areas exist in the northeastern portion of the subarea within the upper reaches of the Mattawamkeag drainage and in the southwestern quadrant drained by the Passadumkeag River. Many lakes and marshy areas lie within the boundaries of the four plutons within the subarea, the most extreme example of this occurring in the Chiputneticook Lakes region.

Although very little information on groundwater conditions is available, it is reasonable to expect that conditions are similar to those described for other subareas in Maine. Groundwater conditions within bedrock units vary considerably from one location to another. A large strike-slip fault is reported within the Center Pond pluton, suggesting that groundwater could be present at depth.

No geohydrologic conditions are known that are incompatible with basing the subarea designation on geologic characteristics.

Potential for Human Intrusion

Because no active or inactive mines are located in subarea 2B, the potential for human intrusion is considered irrelevant to subarea designation.

Site Geometry

The subsurface geometries of the four subarea 2B plutons are unknown.

Surface Characteristics

Subarea 2B is located, for the most part, in an area bounded on the northeast by gently rolling terrain underlain by calcareous till and on the south by uplands and mountains of largely granitic materials. The main part of subarea 2B that falls between these two terrains is covered by glacially deposited materials consisting mainly of till. Significant areas of glacial marine deposits (Presumscot Formation) are present, especially toward the southern portion. Glacial stream deposits of sand and gravel and some end-moraine deposits are scattered throughout the subarea. Nonglacial deposits, such as alluvial stream terraces and floodplains, are found near the Penobscot River and its tributaries. About one-fourth of the northeastern quarter of subarea 2B is covered with swamp and marsh deposits. Subarea 2B ranges from flatlands to mountains. The larger part of it, however, is hilly woodland, with many lakes, streams, and marshes.

Roads through the marine clays of the Presumscot Formation must be engineered to ensure slope stability, but these clays do not liquefy and flow as has occurred in some eastern Canadian locations. Subarea 2B has many roads, including I-95. Because almost all the crystalline outcrops are surrounded by generally cohesionless and well-drained till, no special concern is necessary as far as road or rail access. The problems that would be encountered in building roads are the standard problems of avoiding wetlands and bogs and finding suitable materials for roadbed construction. At higher elevations, freezing and thawing aggravate the rockslide potential of steep rock cuts. However, most of subarea 2B would not require steep grades, extensive switchbacks, or deep rock cuts.

The surficial characteristics of subarea 2B gradually change from wet bottomlands in the north to well-drained uplands in the south. Subarea 2B is relatively homogeneous from a surficial characteristics point of view, except toward its northern and southern boundaries. Therefore, viewing subarea 2B as a unit based on other criteria is not contravened by surface characteristics.

Tectonic Environment

Subarea 2B is seismically quiet; only one weak earthquake epicenter has been recorded. However, the southern boundary of subarea 2B is just north of the Norumbega fault zone, where some evidence of very minor postglacial faulting has been noted. Recent faulting has not been noted within subarea 2B.

LEAST FAVORABLE AREA (AREA 3)

The least favorable area encompasses those parts of the northeastern region that display unacceptable seismotectonic risk. Area 3 (see Plate I) includes crystalline rock bodies of every age and tectonic association encountered in the region and is subdivided on a geographical basis into four subareas.

Subarea 3A

Subarea 3A includes much of the eastern seaboard of the region. It embraces a strip up to 160 km (100 mi) wide that extends from southeastern Pennsylvania to northern New Jersey, southeastern New York, most of Connecticut, Rhode Island, eastern and central Massachusetts, central and southern New Hampshire, and southwestern Maine. Belts of Precambrian gneiss occur in northern New Jersey, southeastern New York, western and southeastern Connecticut, southeastern Massachusetts, parts of Rhode Island, and southern New Hampshire. Extensive exposures of crystalline rocks associated with the Taconic and Acadian orogenies extend from southeastern New York northeastward to southwestern Maine. Many of the post-Alleghenian (Mesozoic) intrusives in the region are found in subarea 3A. These members of the White Mountain plutonic series crop out in New Hampshire and Maine.

Subarea 3B

Subarea 3B is an irregularly shaped area in central and southeastern Maine. It includes half of the Maine coastline and the prominent Norumbega fault zone. Almost all of the plutons in this subarea were emplaced during a post-Acadian intrusive episode.

Subarea 3C

Subarea 3C fringes the northern and northeastern boundaries of Maine and contains no significant plutons.

Subarea 3D

Subarea 3D encompasses the Adirondack massif, which occupies 4000-5000 km^2 (1500-2000 mi^2) in northeastern New York. The massif is made up largely of Precambrian metasedimentary sequences and crystalline rocks. Cropping out in subarea 3D are diverse associations of metamorphosed granite, syenite, diorite, and gabbro. Also present are masses of anorthosite and gneiss and a variety of remobilized sedimentary rocks. Although many of these bodies probably extend to great depth, the rocks are highly foliated and fractured, making them relatively undesirable for waste isolation.

APPENDIX B

PROBABILITY ASSIGNMENTS BY SUBAREA FOR THE SELECTED DECISION-ANALYSIS ATTRIBUTES

APPENDIX B

PROBABILITY ASSIGNMENTS BY SUBAREA FOR THE SELECTED DECISION-ANALYSIS ATTRIBUTES

Appendix B presents the probability distributions for each subarea as prepared by the appropriate geological expert. For each attribute, the technical basis for assigning the probabilities is briefly described. The shapes of the distributions reflect the uncertainties judged by the experts. For example, the probability distribution in Table B.1 for subarea 1D indicates that there is a 50% chance of encountering the conditions described in either numerical index 3 or 4. For subarea 1C, there is a 50% chance of encountering the conditions described in numerical index 3, but only a 25% chance of encountering the conditions described in numerical indexes 2 and 4. A zero probability means that the geological expert felt confident in predicting that the described condition would not be encountered.

Lithologic Homogeneity and Isotropy (X_1)

The probability distributions by subarea for attribute X_1 (see Table B.1) are based on typical pluton ages, orogenic associations, three-dimensional pluton shapes, and other available geologic information.

Subarea 1A

Because of their great age, the Precambrian crystalline rocks of subarea 1A have experienced multiple orogenies and are among the most complexly deformed in the northeastern region. They are also lithologically complex, sometimes including both metasedimentary and igneous facies. They are probably the most heterogeneous and anisotropic rocks in area 1.

Subarea 1B

Although not as complexly deformed as the crystalline rocks of subarea 1A, those of subarea 1B are nonetheless texturally and structurally anisoropic. Folded during the Taconic and Acadian orogenies, the subarea 1B plutons are among the least desirable in area 1 in terms of homogeneity and isotropy, but are not as undesirable as those in subarea 1A.

TABLE B.1 Probability Assignments by Subarea for the Lithologic Homogeneity and Isotropy Attribute (X_1)

	Numerical Index Level[a]			
Subarea	1	2	3	4
1A	1.0	0	0	0
1B	0.75	0.25	0	0
1C	0	0.25	0.50	0.25
1D	0	0	0.50	0.50
1E	0.75	0.25	0	0
1F	0.25	0.50	0.25	0

[a] Levels are defined in Table 6.

Subarea 1C

Plutons within subarea 1C are generally unfolded. Although some are composite bodies, most seem to be dominated by a single rock type. The probability distribution for subarea 1C reflects a higher level of uncertainty for this attribute than those for subareas 1A and 1B.

Subarea 1D

Subarea 1D contains fairly large posttectonic stocks composed mainly of Conway granite. Descriptions of Conway granite based on logs of a deep core hole near Redstone, N.H., suggest that some lithologic and textural variation may occur in the subarea 1D bodies. Also, the presence of miarolitic cavities suggests some potential for variation in fabric. The probability distribution for this subarea is indicative of plutons of a single rock type but with some potential for variation.

Subarea 1E

Multiple injection, composite lithologies, and highly variable textures appear to be characteristic of the crystalline rock bodies in subarea 1E. Although most of them should probably be assigned to the least-desirable index level, their great size suggests that largish homogeneous portions may exist within some of them.

Subarea 1F

Most of the plutons in subarea 1F are relatively homogeneous and have been little affected by postemplacement deformation. However, mixed lithologies and layered bodies are fairly typical.

Faulting, Fracturing, and Shearing (X_2)

Data concerning faults, fractures, or shear zones are sparce for most of the crystalline rock bodies of area 1. The prevalence of surface cover means that few fracture maps are available, except for limited portions of a few plutons. In the absence of detailed information, the ages of the plutons and their orogenic associations were used as surrogate indicators of faults, fractures, and shear zones. The rationale was that the oldest bodies were subjected to multiple deformations with different stress directions and that these events caused intense, multidirectional faulting of the type covered in the least-desirable scale description (see Table 7). The probability distribution for each subarea was estimated based on the age and orogenic associations of its plutons, and whatever field data were available in the literature (see Table B.2).

Subarea 1A

Because all of the plutons in subarea 1A are complexly deformed, the probability of associated faulting and extensive shearing was assumed to be high. Indeed, relatively abundant faults are reported for five of the crystalline rock bodies of subarea 1A. Therefore, subarea 1A was considered the least desirable of the six subareas in terms of the structural discontinuities covered by attribute X_2.

TABLE B.2 Probability Assignments by Subarea for the Faulting, Fracturing, and Shearing Attribute (X_2)

	Numerical Index Level[a]			
Subarea	1	2	3	4
1A	1.0	0	0	0
1B	0.50	0.50	0	0
1C	0.25	0.50	0.25	0
1D	0	0.25	0.50	0.25
1E	0.25	0.50	0.25	0
1F	0.25	0.50	0.25	0

[a] Levels are defined in Table 7.

Subarea 1B

Two of the three crystalline rock bodies in subarea 1B that exceed 80 km^2 (30 mi^2) in mapped areal extent exhibit regional and multidirectional faulting, which suggests low desirability in terms of attribute X_2. (No structural information was available for the third rock body.) However, wide spacings between faults could conceivably result in some large blocks of relatively unfractured rock within individual crystalline rock bodies. The probability distribution for subarea 1B reflects this possibility.

Subarea 1C

Although some faults have been mapped in subarea 1C, most of the crystalline rock bodies are not associated with known regional fault systems. Smaller local faults, with and without dikes, and well-developed joint sets are reported in some of the crystalline rock bodies. The probability distribution for subarea 1C reflects the possibility of encountering sizable rock bodies of both greater and lesser desirability.

Subarea 1D

The large stocks of subarea 1D postdate the major deformational events of the northeastern region. Regional fault systems seem to have been truncated by these intrusive bodies, and no local faults within the stocks have been reported. The limited information gathered to date suggests the existence of large volumes of unfaulted rock. The probability distribution for subarea 1D reflects the likelihood of encountering crystalline rock bodies of both greater and lesser desirability than 3.

Subarea 1E

Prominent faults occur within the crystalline rock bodies of subarea 1E; some of them also contain extensive shear zones. The chances of finding a particular location within a pluton that is either more or less desirable than 2 are considered to be about equal.

Subarea 1F

The presence of fault zones in and near some of the crystalline rock bodies in subarea 1F and the absence of detailed data make it difficult to distinguish this subarea from subarea 1E with respect to attribute X_2.

Folding and Deformation (X_3)

Although information concerning folding was not always available for individual crystalline bodies, most subareas were well covered in this regard in the available literature. If field descriptions were lacking or if only a small portion of a larger pluton was discussed, age and orogenic association were considered reliable indicators of deformational history. The oldest rocks were assumed to be the most highly deformed; the younger postorogenic bodies were assumed to be the least deformed. Table B.3 gives the probability distributions by subarea for attribute X_3.

Subarea 1A

The Precambrian crystalline rocks of subarea 1A are highly distorted. On the basis of the intensity and pervasiveness of folding within its boundaries, subarea 1A was assigned a probability of 1 for attribute X_3.

Subarea 1B

The Taconic and Acadian crystalline rock bodies in subarea 1B are generally folded, which suggests assigning a probability of 1 to numerical index 1 for attribute X_3. However, because doubt exists as to the intensity of folding in this subarea, the probabilities assigned needed to reflect the possibility that somewhat more desirable crystalline rock bodies might be present.

Subarea 1C

The crystalline rock bodies in subarea 1C are probably unfolded because they are postorogenic in origin; however, information on deformation is unavailable for most of them.

TABLE B.3 Probability Assignments by Subarea for the Folding and Deformation Attribute (X_3)

	Numerical Index Level[a]			
Subarea	1	2	3	4
1A	1.0	0	0	0
1B	0.75	0.25	0	0
1C	0	0	0.25	0.75
1D	0	0	0	1.0
1E	0.25	0.50	0.25	0
1F	0	0.25	0.50	0.25

[a] Levels are defined in Table 8.

Subarea 1D

Primary foliation features, but no folding, are reported for the crystalline rock bodies in subarea 1D. This subarea is very desirable with respect to attribute X_3.

Subarea 1E

The crystalline rock bodies in subarea 1E are deformed, but available evidence suggests that the folding is intermediate in intensity. However, the descriptions of folding are inadequate for confident prediction of the extent of deformation in these large bodies. The probability distribution reflects this uncertainty.

Subarea 1F

The rock bodies in subarea 1F are probably undeformed because they postdate regional deformation. However, a somewhat conservative probability distribution was assigned for attribute X_3 because information concerning folding is unavailable for most of the subarea's intrusive rocks.

Metamorphism and Alteration (X_4)

Attribute X_4 was difficult to quantify for most of the crystalline rock bodies in area 1 because of limited exposures and lack of data. At least some recrystallization was assumed to have occurred in nearly all of the subareas, unless there were data to the contrary. These uncertainties are reflected in the probability distributions in Table B.4.

Subarea 1A

The Precambrian crystalline rocks of subarea 1A have been repeatedly metamorphosed, are quite extensively altered, and contain many veins.

Subarea 1B

Metamorphism and alteration within subarea 1B are pervasive but of intermediate intensity. Without additional information, no basis exists for distinguishing between the two lower numerical index levels. Nonetheless, it is relatively certain that crystalline rock bodies of greater desirability do not occur within subarea 1B.

TABLE B.4 Probability Assignments by Subarea for the Metamorphism and Alteration Attribute (X_4)

	Numerical Index Level[a]			
Subarea	1	2	3	4
1A	1.0	0	0	0
1B	0.50	0.50	0	0
1C	0	0	0.50	0.50
1D	0	0	0	1.0
1E	0.50	0.50	0	0
1F	0	0.50	0.50	0

[a] Levels are defined in Table 9.

Subarea 1C

The postorogenic crystalline rock bodies in subarea 1C exhibit very little metamorphism and minimal incipient alteration. Because specific information is lacking, no distinction could be made between the two higher numerical index levels. Encountering rocks of lesser desirability is highly unlikely.

Subarea 1D

Alteration or metamorphism of the young intrusive rocks of subarea 1D is probably very slight.

Subarea 1E

Pervasive alteration is characteristic of large portions of the subarea 1E plutons. Metamorphism is generally high grade but of intermediate intensity.

Subarea 1F

Alteration is slight but pervasive in crystalline rock bodies for which alteration data are available. Some recrystallization has occurred in many of them. These characteristics and the uncertainty related to the lack of data make it relatively certain that units at either end of the scale will not be encountered in subarea 1F.

Surface-Water Bodies (X_5)

As defined, the surface-water-body attribute allows relatively high certainty in assigning desirability levels. The adequate map coverage for all subareas meant that areas occupied by surface-water bodies could be readily measured. However, uncertainties arose as to pluton boundaries, even with the aid of stereoscopic aerial photography. Because most plutons are at least partially covered by surficial deposits, inaccuracies in calculating pluton areas are unavoidable. Furthermore, because all subareas contain several crystalline rock bodies, significant variations in the number and size of surface-water features associated with these bodies can occur within a given subarea. These variations make it impossible to assign a specific numerical index level to an entire subarea with absolute certainty (1.0 probability). For these reasons, probabilities assigned for attribute X_5 do not exceed 0.60, even though the constructed scale is concisely defined and can be quantified (see Table B.5).

Subarea 1A

Marsh and bog areas are found adjacent to many of the stream channels in low-relief areas of Connecticut and Massachusetts. Several such areas occur in the Naugatuck River valley in subarea 1A. Also, a wetland area in the Housatonic River valley extends some kilometers on either side of the Connecticut-Massachusetts border. This poorly drained area falls within subareas 1A and 1B, but most of it is beyond the western mapped boundary of the Berkshire massif. Subarea 1A contains at least 10 reservoirs or controlled natural lakes with storage capacities of at least 5000 acre-feet. Several uncontrolled natural lakes and ponds also occur throughout the subarea, with most standing-surface-water bodies being located within mapped pluton boundaries.

TABLE B.5 Probability Assignments by Subarea for the Surface-Water-Bodies Attribute (X_5)

	Numerical Index Level[a]			
Subarea	1	2	3	4
1A	0.25	0.50	0.25	0
1B	0.10	0.20	0.50	0.20
1C	0	0.60	0.40	0
1D	0.10	0.40	0.40	0.10
1E	0.60	0.40	0	0
1F	0.40	0.60	0	0

[a] Levels are defined in Table 10.

Subarea 1B

Marshy areas occur at scattered locations adjacent to streams in the low-relief portions of subarea 1B, but the total extent of these areas is relatively small. The largest wetland area in the subarea is the one near the Connecticut-Massachusetts border that also falls in subarea 1A. At least eight reservoirs or controlled natural lakes with storage capacities greater than 5000 acre-feet are found in the subarea. A portion of Quabbin Reservoir, which has the largest storage capacity of all man-made reservoirs in New England, falls within the subarea boundary. Additionally, several smaller lakes and ponds are found within mapped pluton boundaries, but their total surface area is relatively small.

Subarea 1C

Several poorly drained areas occur in the upper portions of the Connecticut River valley, but many of them appear to be small. The large marsh in the lowlands of the Nulhegan and Clyde drainage basins overlies portions of the Echo Pond, Nulhegan, and Maidstone plutons. At least five reservoirs or controlled natural lakes with storage capacities exceeding 5000 acre-feet are located in subarea 1C. Other lakes of various sizes are located over plutons.

Subarea 1D

Although numerous bogs and marshes occur in low-lying areas throughout subarea 1D, many are relatively small in area. No large controlled natural lakes or reservoirs were constructed in the subarea prior to 1963. Several of the numerous small lakes and ponds found at scattered locations are within mapped pluton boundaries.

Subarea 1E

Bog and marsh areas occur throughout subarea 1E, but they are particularly widespread in Maine. Extensive poorly drained areas are found near Kennebago Lake and within the Moose River drainage basin. At least seven large (greater than 5000 acre-feet of storage capacity) reservoirs or controlled natural lakes are found in the subarea. Many large uncontrolled lakes and smaller ponds occur in the Maine portion of subarea 1E, and most of these are within mapped pluton boundaries.

Subarea 1F

Numerous marshes and bogs occur throughout subarea 1F, and many of these are located within mapped pluton boundaries. The subarea contains at least 20 controlled lakes or reservoirs with storage capacities exceeding 5000 acre-feet. All plutons within the subarea have lakes and ponds within their mapped boundaries. In some cases, only a few smaller ponds are so situated, but some of the largest lakes of the area overlie plutons.

Surface-Water Drainage (X_6)

Attribute X_6 relates to the locations of plutons in a subarea with respect to surface drainage channels, as well as to the risk of major flood effects. The attribute is conceptually sound and an important aspect of the geohydrologic characteristics of subareas; however, significant uncertainty exists in applying the scale descriptions to individual subareas. In terms of the relationships between river channels and plutons, considerable variation may exist within individual subareas. The greater this internal variation, the greater is the level of uncertainty in assigning that subarea to a single desirability level. Additional uncertainty arises from the fact that no quantitative method is available to measure this relationship. Finally, uncertainty is associated with estimating the risk of flooding because of the impossibility of predicting the future magnitudes and frequencies of floods with complete certainty. These limitations are reflected in the conservative probability distributions given in Table B.6.

TABLE B.6 Probability Assignments by Subarea for the Surface-Water-Drainage Attribute (X_6)

	Numerical Index Level[a]		
Subarea	1	2	3
1A	0.60	0.40	0
1B	0.60	0.40	0
1C	0.20	0.50	0.30
1D	0.20	0.30	0.50
1E	0.60	0.40	0
1F	0.20	0.40	0.40

[a] Levels are defined in Table 11.

Subarea 1A

The crystalline rock bodies in subarea 1A are drained by several major tributaries of the Connecticut River, but the main channel and valley of the river lie some kilometers to the east. The main channel and valley of the Housatonic River are along the western margin of the Berkshire massif in Massachusetts and Connecticut. The master drainages of the Batten Kill and Otter Creek systems are located along the western margin of the Mt. Holly complex in Vermont. Although these crystalline areas form portions of several major drainage divides, the presence of several major drainage channels increases the likelihood of extensive local flooding.

Subarea 1B

Although some variation is evident, most of the crystalline rock areas in subarea 1B are traversed by one or more major stream channels -- the Housatonic, Naugatuck, Farmington, and Westfield rivers in the southern portion of the subarea, and the Chicopee, Ware, Millers, and Ashuelot rivers to the north. Flooding could be significant along most of these drainages.

Subarea 1C

Considerable variation with respect to attribute X_6 exists within subarea 1C. Some plutons are traversed by the large valleys and channels of rivers draining the subarea, whereas others are in upland areas some distance from major drainage channels. Most of the subarea is drained by the Connecticut River and its tributaries; the Maine portion is drained primarily by the Androscoggin River. The uncertainty associated with the wide variation is reflected in the probability distribution.

Subarea 1D

No major river channels or stream valleys cross or are adjacent to the crystalline rock bodies in subarea 1D. The Connecticut River flows near the western subarea boundary but is far enough away not to influence the probability distribution. The plutons are generally located in upland areas characterized by greater runoff than adjacent lowlands. Relatively narrow and steep valleys make these areas susceptible to periodic flooding. However, the effects of flooding should be small because of smaller peak flows and the short duration of the floods characteristic of stream channels of this type.

Subarea 1E

The southern portion of subarea 1E is drained by the Connecticut and Androscoggin rivers and their tributaries; the northern portion is drained by headwater tributaries of the Connecticut, Androscoggin, Dead, and Moose rivers. Many plutons are traversed by stream channels, and several crystalline units are found in low-lying areas. Although these conditions enhance the possibility of flooding, they vary considerably throughout the subarea.

Subarea 1F

Subarea 1F is located in the headwater portions of the Androscoggin, Kennebec, Penobscot, and St. John drainages, which are the four main watersheds in Maine. As a consequence, only smaller tributary streams cross the crystalline rock bodies. Many of these rock units form local topographic highs, which lessens the likelihood of severe flooding. The overall characteristics of the subarea with respect to attribute X_6 are generally desirable; however, local conditions vary substantially because of the large size of the subarea. The uncertainty related to this variability is reflected in the probability distribution.

Groundwater (X_7)

As defined, attribute X_7 allows only a moderate degree of certainty in assigning probabilities to the numerical index levels by subarea. Because the pluton boundaries may be in error, small uncertainties are associated with judgments concerning the spatial relationships between crystalline rock bodies and overlying unconsolidated aquifers. Greater uncertainty exists in estimates of the relationships between crystalline units and bedrock aquifers. Also, even though plutons may be spatially associated with known aquifers, the degree of hydraulic interconnection between them can only be established with certainty through detailed field investigation. Nonetheless, the proximity of plutons to known aquifers enhances the likelihood of possible groundwater movement between the two.

Observed or estimated well yields within a given subarea usually vary within individual crystalline rock bodies and between them. These variations reflect, at a minimum, local differences in fracturing, weathering, amount of unconsolidated cover material, topographic conditions, and well characteristics. As a result, uncertainty is associated with assigning probabilities to numerical index levels by subarea based on well yields, although low yields are obviously more desirable than high yields. The probability distributions for attribute X_7 are given in Table B.7.

TABLE B.7 Probability Assignments by Subarea for the Groundwater Attribute (X_7)

	Numerical Index Level[a]			
Subarea	1	2	3	4
1A	0.20	0.40	0.20	0.20
1B	0.25	0.50	0.25	0
1C	0.10	0.40	0.40	0.10
1D	0.15	0.30	0.40	0.15
1E	0.20	0.30	0.30	0.20
1F	0.30	0.30	0.30	0.10

[a] Levels are defined in Table 12.

Subarea 1A

The stratified drift and alluvium found in most major river valleys throughout subarea 1A constitute a good groundwater source. Coarse-grained sediments with estimated yields of 0.0032-0.13 m^3/s (50-2000 gpm) occur beneath the Housatonic River and its major tributaries and in numerous areas adjacent to the Connecticut River. Most tributary valleys in the Connecticut basin are underlain by general information on yields from shallow wells in crystalline rocks is available on a regional various proportions of coarse- and fine-grained stratified drift that yields substantial quantities of water. Although scale, data specific to the subarea were not obtained. Because of the presence of nonindurated aquifers within mapped pluton boundaries and a lack of data specific to the subarea, the low-intermediate desirability index was assigned a probability of 0.40.

Subarea 1B

Within the Connecticut River lowlands of Massachusetts, water yields as high as 0.063 m^3/s (1000 gpm) can be expected from glaciofluvial sands and gravels. An example is the deposits of stratified drift that occupy the valley bottoms of the primary tributaries to the Connecticut River. Substantial yields can also be obtained from the fractured Triassic sedimentary rocks beneath these valley-fill deposits. Yields to wells in crystalline rocks of subarea 1B are estimated to be less than 0.00063 m^3/s (10 gpm), but the data are very limited.

Subarea 1C

Groundwater conditions in subarea 1C are quite similar to those in subareas 1A and 1B. Most of the larger stream valleys are floored with variable thicknesses of stratified drift and alluvium that range from silt and clay to sand and gravel. Well yields of several hundred gallons per minute are common from thick deposits of coarse-grained sediments; lower yields can be expected where accumulations are less extensive and finer grained. Till covers the bedrock over most of the subarea and is locally a source of small quantities of water. The crystalline rocks are generally poor water producers, although yields greater than 0.0025 m^3/s (40 gpm) occur locally. The significant uncertainty associated with the variable conditions in subarea 1C is reflected in the assigned probabilities.

Subarea 1D

The principal valleys of the Ammonoosuc basin are floored with discontinuous but extensive deposits of stratified drift. These deposits are chiefly medium to very coarse sand or sand and gravel with saturated thicknesses sufficient to yield 0.013 m^3/s (200 gpm) to properly located and constructed wells. Much smaller yields can be anticipated from the till and bedrock away from stream valleys. No data were found for wells in upland areas.

Subarea 1E

Limited information is available for evaluating the groundwater conditions in subarea 1E. Because of low population density, groundwater resources have not been extensively developed. The most favorable areas for exploitation are reportedly within the larger valleys in the upper Androscoggin River basin. As in the other subareas, glacial outwash deposits are the most likely units for large well yields. However, some metasedimentary units could provide yields of 0.0063 m^3/s (100 gpm) or more under favorable conditions. Data from a few wells in the Maine portion of the subarea are available; however, most wells are withdrawing water from unconsolidated sediments near streams. Water yields from wells in crystalline rocks are available only on a regional scale.

Subarea 1F

Except for small upland areas, subarea 1F is covered with a mixture of stratified drift and till of variable thickness. The till, which is relatively dense, transmits limited quantities of water to wells. Stratified drift and alluvium are found in most of the larger valleys. These coarser-grained deposits are favorable sources for large groundwater supplies. The crystalline and metasedimentary rocks in the subarea are considered poor candidates for groundwater supplies unless locally highly fractured. Specific data concerning well yields in crystalline rocks are lacking. Because relatively extensive deposits of nonindurated sediments occur within pluton boundaries, the three lower numerical index levels were judged to be equally probable as regards attribute X_7.

Mineral Resources (X_8)

As defined, attribute X_8 allowed assignment of relatively high probabilities to one of the numerical index levels. However, the data did not warrant assigning a probability of 1.0. Table B.8 gives the probability distributions.

TABLE B.8 Probability Assignments by Subarea for the Mineral Resources Attribute (X_8)

	Numerical Index Level[a]				
Subarea	1	2	3	4	5
1A	0	0.8	0.2	0	0
1B	0	0	0.8	0.2	0
1C	0	0	0.8	0.2	0
1D	0	0	0	0.2	0.8
1E	0	0.2	0.8	0	0
1F	0.7	0.3	0	0	0

[a] Levels are defined in Table 13.

Subarea 1A

Four talc mines and one marble quarry, all of which are within 3.2 km (2 mi) of mapped pluton boundaries, are active in subarea 1A. Many inactive or abandoned mines are located in plutons or near mapped pluton boundaries. The assignment of probabilities takes into consideration that the plutons in subarea 1A are large and that prospects for expanded mining in this subarea are poor.

Subarea 1B

Subarea 1B contains three active marble operations, each of which is located a little more than 3.2 km (2 mi) from the boundaries of nearby plutons. Many abandoned mines occur within pluton boundaries, but none of these is likely to be reopened.

Subarea 1C

Of the six active dimension-stone and crushed-rock quarries in subarea 1C, four are within 3.2 km (2 mi) of mapped pluton boundaries.

Subarea 1D

Subarea 1D has no active mining properties and only one inactive granite quarry within its boundaries.

Subarea 1E

Three inactive mines and one inactive granite quarry are located within subarea 1E. The mines were gold-copper, gold, and copper-zinc operations. The likelihood of a future revival of the mining industry in this subarea is low.

Subarea 1F

An active garnet mine and several inactive cobalt and nickel mines are located within mapped pluton boundaries. Because cobalt is a strategic metal, there might be renewed effort to exploit this resource. Exploration for massive sulfides is ongoing in subarea 1F, which increases the likelihood of significant mineral extraction activity.

Site Geometry (X_9)

The assignment of probabilities for each subarea with respect to site geometry is based on the projected sizes of its crystalline rock bodies. Because the absolute sizes of the bodies are unknown, geophysical and geologic interpretations were used to estimate their surface areas and depths. All subareas contain at least some plutons large enough for a mined repository. The probability distributions for attribute X_9 are given in Table B.9.

TABLE B.9 Probability Assignments by Subarea for the Site Geometry Attribute (X_9)

	Numerical Index Level[a]		
Subarea	1	2	3
1A	0	0.25	0.75
1B	0.75	0.25	0
1C	0.25	0.50	0.25
1D	0	0.50	0.50
1E	0.25	0.50	0.25
1F	0.25	0.50	0.25

[a] Levels are defined in Table 14.

Subarea 1A

The crystalline rock bodies in subarea 1A have very large surface exposures and probably extend to great depths. Some uncertainty is reflected in the probability distribution.

Subarea 1B

Subarea 1B contains several sheetlike crystalline rock bodies of moderate surface area, but their subsurface geometries remain unconfirmed.

Subarea 1C

The surface areas of crystalline rock bodies in subarea 1C are generally moderate in size, but their subsurface geometries are not well known.

Subarea 1D

The stocklike plutons in subarea 1D probably extend to considerable depth. However, emplacement may have resulted in the presence of a mass of displaced country rock of unknown characteristics at intermediate depth. The probability assignment for subarea 1D reflects this possibility.

Subarea 1E

Subarea 1E contains large plutons that may extend to considerable depths, but subsurface geometries are unconfirmed.

Subarea 1F

Subarea 1F contains crystalline rock bodies that range from batholiths to thick sheets of moderate to large surface area. The subsurface geometry of most of the bodies has not been determined.

Surface Characteristics (X_{10})

Characterizing the subareas in terms of the potential hazards presented by surficial processes and materials was difficult in that such hazards are generally confined to small portions of a subarea. Even if larger sections of a subarea were undesirable, conditions within the relatively small area required for a repository and its access routes might still be acceptable. The probability distributions for attribute X_{10} are given in Table B.10.

Subarea 1A

Large, forested hills with well-drained and stable slopes characterize most of subarea 1A. Some portions, however, feature steep slopes and extensive bogs and marshes.

Subarea 1B

Subarea 1B is characterized by low to moderate relief and stable slopes, but bogs and marshes occur in some drainageways. Plentiful medium- and heavy-duty roads crisscross the low mountains of this subarea.

TABLE B.10 Probability Assignments by Subarea for the Surface Characteristics Attribute (X_{10})

	Numerical Index Level[a]				
Subarea	1	2	3	4	5
1A	0.3	0.1	0.1	0.5	0
1B	0	0	0.1	0.7	0.2
1C	0	0	0.2	0.7	0.1
1D	0.2	0.3	0.5	0	0
1E	0	0	0.3	0.7	0
1F	0.6	0.4	0	0	0

[a] Levels are defined in Table 15.

Subarea 1C

Subarea 1C is very similar to subarea 1B with respect to surficial materials and features. The areas of poor drainage in subarea 1C are perhaps more plentiful than those in subarea 1B. Also, the relative isolation of the northern portion of subarea 1C makes it less desirable in terms of road access.

Subarea 1D

The existence of heavy-duty roads and a railroad line in subarea 1D suggests that the hills, low mountains, and valleys of this subarea present no special topographic hazards. Marshes and bogs are plentiful but small, and valleys are generally well drained. One upland portion of the subarea, however, has very steep slopes and places where stony and bouldery surficial materials occur near bedrock outcrops. Offsetting these less desirable traits are the stability of bedrock slopes and thinness of the till cover at these higher elevations. Both features allow more direct access to the crystalline rock bodies than in neighboring subareas. The probability distribution reflects the possibility of encountering locations that would be least desirable in terms of surface characteristics.

Subarea 1E

Low mountains, stable slopes, good accessibility, and adequate drainage are typical of large portions of subarea 1E. Some bogs and marshes occur, and some relatively isolated areas have limited road access. Because these roadless areas are characterized by low population density, poor surface conditions are not necessarily implicated.

Subarea 1F

Subarea 1F is both large and varied. The mountainous south-to-southwestern part is generally more desirable with respect to surface characteristics. The north-to-northwestern part is isolated, having few public roads and a hilly to gently rolling topography with many large, poorly drained areas. The mountainous portions of the subarea have some medium- and heavy-duty roads, but instabilities associated with steep grades, switchbacks, and rock cuts would be unavoidable if access roads were to be constructed from existing roads in the valleys to many locations in the surrounding mountains. This subarea is clearly the least favorable of the six in terms of attribute X_{10}.

Local Seismicity (X_{11})

Attribute X_{11} was structured quantitatively such that uncertainty was eliminated from the probability distributions (see Table B.11). The subareas were characterized in terms of the number of epicenters, the number of events, and the maximum intensities of earthquakes, either within pluton boundaries or within 24 km (15 mi) of their boundaries.

Subarea 1A

Subarea 1A has 11 events at 8 epicenters. The maximum-intensity event was I_{MM} = V.

Subarea 1B

Subarea 1B has four events at three epicenters. The maximum-intensity event was I_{MM} = V.

Subarea 1C

Subarea 1C has five events at five epicenters. The maximum-intensity event was I_{MM} = V.

Subarea 1D

Subarea 1D has no historical earthquake events with maximum intensities as high as I_{MM} = V. However, three events at three epicenters are documented at I_{MM} = IV.

TABLE B.11 Probability Assignments by Subarea for the Local Seismicity Attribute (X_{11})

	Numerical Index Level[a]			
Subarea	1	2	3	4
1A	1.0	0	0	0
1B	0	0	1.0	0
1C	0	1.0	0	0
1D	0	0	0	1.0
1E	0	0	1.0	0
1F	1.0	0	0	0

[a] Levels are defined in Table 16.

Subarea 1E

One event at one epicenter (I_{MM} = V) was recorded in subarea 1E.

Subarea 1F

Subarea 1F has nine events at five epicenters. The maximum-intensity event was I_{MM} = V.

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