UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

GEOLOGIC AND HYDROLOGIC CONSIDERATIONS FOR VARIOUS CONCEPTS OF HIGH-LEVEL RADIOACTIVE WASTE DISPOSAL IN CONTERMINOUS UNITED STATES

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ABSTRACT

The purpose of this investigation is to evaluate and identify which geohydrologic environments in conterminous United States are best suited for various concepts or methods of underground disposal of high-level radioactive wastes and to establish geologic and hydrologic criteria that are pertinent to high-level waste disposal. The unproven methods of disposal include (1) a very deep drill hole (30,000-50,000 ft or 9,140-15,240 m), (2) a matrix of (an array of multiple) drill holes (1,000-20,000 ft or 305-6,100 m), (3) a mined chamber (1,000-10,000 ft or 305-3,050 m), (4) a cavity with separate manmade structures (1,000-10,000 ft or 305-3,050 m), and (5) an exploded cavity (2,000-20,000 ft or 610-6,100 m).

The geohydrologic investigation is made on the presumption that the concepts or methods of disposal are technically feasible. Field and laboratory experiments in the future may demonstrate whether or not any of the methods are practical and safe. All the conclusions drawn are tentative pending experimental confirmation. The investigation focuses principally on the geohydrologic possibilities of several methods of disposal in rocks other than salt. Disposal in mined chambers in salt is currently under field investigation, and this disposal method has been intensely investigated and evaluated by various workers under the sponsorship of the Atomic Energy Commission.

Of the various geohydrologic factors that must be considered in the selection of optimum waste-disposal sites, the most important is hydrologic isolation to assure that the wastes will be safely contained within a small radius of the emplacement zone. To achieve this degree of hydrologic isolation, the host rock for the wastes must have very low permeability and the site must be virtually free of faults. In

addition, the locality should be in (1) an area of low seismic risk where the possibility of large earthquakes rupturing the emplacement zone is very low, (2) where the possibility of flooding by sea-level rise is very low, (3) where a possible return of glacial or pluvial climate will not cause potentially hazardous changes in surface- or ground-water regimens, and (4) where danger of exhumation by erosion is nil. The geographic location for an optimum site is one that is far removed from major drainages, lakes, and oceans, where population density is low, and where the topographic relief is gentle in order to avoid steep surface-water drainage gradients that would allow rapid distribution of contaminants in case of accident.

The most suitable medium for the unproven deep drill-hole, matrix-holes, and exploded-cavity methods appears to be crystalline rocks, either intrusive igneous or metamorphic because of their potentially low permeabilities and high mechanical strengths. Salt (either in thick beds or stable domes), tuff, and possibly shale appear to be suitable for mined chambers and cavities with separate manmade structures. Salt appears to be suitable because of its very low permeability, high thermal conductivity, and natural plasticity. Tuff and shale appear suitable because of their very low permeabilities and high ion-exchange capacities. Sedimentary rocks other than shale and volcanic rocks, exclusive of tuff, are considered to be generally unsuitable for waste emplacement because of their potentially high permeabilities.

Areas that appear to satisfy most geohydrologic requirements for the deep drill hole and the matrix holes include principally (1) the stable continental interior where the sedimentary cover is thin or absent, (2) the shield area of the North-Central States, and (3) the metamorphic belt of Eastern United States--primarily the Piedmont. These areas are possibly suitable also for the exploded cavity and the mined chamber because the possibility of finding rock with very low permeability at depths from 1,000± feet (305± m) to 20,000 feet (6,100 m) appears to be high.

The Basin and Range province of Western United States, particularly the Great Basin exclusive of seismic-risk zone 3, appears to have potential for mined chambers above deep water tables in tuff, shale, or argillite. In addition, some granitic stocks, for example the Climax stock at Nevada Test Site, may be suitable for matrix holes, mined chambers, and exploded cavities.

Other parts of the United States which have rocks and terrains possibly suitable for some of the disposal methods include the sedimentary basins in the continental interior and coastal plain that contain salt--principally for mined chambers or exploded cavities at depths of about 3,000 feet (910 m) or less (the natural plasticity of salt appears to rule out disposal at greater depths). The preferred environments for salt emplacement are those where oil and gas potential is low and where no important aquifers are present above the salt bed or stable dome. Using shale for waste disposal in the sedimentary basins appears to be hazardous because most shale contains thin permeable interbeds of sandstone and limestone that could serve as passageways for contaminated ground water to reach aquifers and oil and gas reservoirs. The possibility exists that saturated shale below depths of about 7,000 feet (2,130 m) has such low permeability that it could safely contain the wastes, but this remains to be demonstrated by exploratory drilling and extensive hydraulic testing. The greatest potential for using shale for waste disposal is in arid and semiarid parts of the United States where chambers can be mined well above existing water tables.

Areas considered to be unsuitable for waste disposal are those where seismic risk is high, where possible sea-level rise would inundate potential sites, where high topographic relief coincides with high frequency of faults, where there are unfavorable ground-water conditions, and where no suitable rocks are known to be present to depths of 20,000 feet (6,100 m) or more, and where these strata either contain large volumes of ground water or have high oil and gas potential.

Geohydrologic environments that are concluded to be potentially suitable for waste disposal in this investigation should be further evaluated at State- and county-wide levels in order to pinpoint the most suitable locations. The localities should then be (1) mapped in detail and seismically monitored to delineate active fault zones and areas of crustal unrest, (2) surveyed by geophysical techniques (where applicable) to locate buried faults and to better define subsurface conditions, and (3) drilled and hydraulically tested to locate the zones having the lowest permeabilities. Finally, the drill core should be analyzed physically and chemically in order to predict the nature of the rock-waste interaction.

INTRODUCTION

Purpose and scope of investigation

In late 1972, the U.S. Geological Survey was requested by the U.S. Atomic Energy Commission, Division of Waste Management and Transportation, to participate in a study of potential alternative means for long-term management of high-level radioactive waste being performed for the AEC by the Pacific Northwest Laboratories of Battelle Memorial Institute (BNW). The purpose of the Survey participation would be to evaluate the geohydrologic possibilities of placing high-level wastes in geologic formations in terrestial locations; principally, to consider placement in formations other than salt. Geologic disposal in mined chambers in bedded salt deposits is, at present, under study by the Oak Ridge National Laboratory for the Atomic Energy Commission.

The contract that was agreed upon between the Atomic Energy Commission and the U.S. Geological Survey specified that the USGS part of the study should consider emplacement of wastes in:

a. A very deep drill hole (30,000-50,000 ft, or 9,140-15,240 m deep) for solid or liquid wastes;

b. A matrix (geometric array) of shallow to moderate-depth drill holes (multiple holes 1,000-20,000 ft, or 305-6,100 m deep) for solid wastes;

c. Shallow depth mined chambers (1,000-10,000 ft, or 305-3,050 m deep) for solid or liquid wastes;

d. Cavities with separate manmade structures (1,000-10,000 ft, or 305-3,050 m deep) for solid wastes; and

e. Exploded cavities (2,000-20,000 ft, or 610-6,100 m deep) for liquid wastes.

The methods of disposal of high-level radioactive waste listed above were conceived by BNW. Field and laboratory experiments and pilot studies in the future may demonstrate whether or not any of the disposal methods are practical and safe. The USGS study is based on the presumption that the modes are technically feasible, but all the conclusions drawn are tentative pending experimental confirmation.

The contract specified that the USGS report should establish for the various modes of disposal:

(1) Geohydrologic criteria.

(2) Preferred geohydrologic environments (report shall include a discussion of why other environments are less preferable).

(3) Specific geologic and hydrologic problems that may be encountered within the preferred environments including:

(a) State-of-the-art in terms of geologic and hydrologic knowledge.

(b) Research and development, including field exploration needed to solve specific geohydrologic problems.

(4) General distribution and number of preferred environments. Specific sites shall not be evaluated in this initial phase of the study, although some examples of the types of preferred environments shall be identified.

(5) Summary and conclusions.

In addition to the above major items, the contract specified that the final report should include the following:

1. Overall description of Earth systems.

2. Geologic characteristics/descriptions of lithology and geochronology.

3. Hydrologic considerations (including above-versus-below saturated zone).

4. Physiographic considerations.

5. Geotectonic considerations.

6. Geochemical considerations.

7. Continental glaciation.

8. Climate considerations.

9. Résumé of preferred geologic/hydrologic and related characteristics.

10. A list of selected properties of important rocks which are pertinent to waste disposal (for example, thermal conductivity, specific heat, permeability, strength, and so forth).

11. Seismic risk and (or) earthquake map(s) within the U.S.A.

12. Simplified rock distribution map(s) within the U.S.A. for important waste disposal.

13. Favorability maps may be included.

14. A good list of key references.

15. A glossary of geohydrologic terms used in the report.

The contract also specified that parts of the USGS report would be used within the framework of a larger report by BNW. The larger report by BNW contains descriptions of the systems requirements for waste management including drilling modes, cooling techniques for solid and (or) liquid wastes, vapor processing, types of drill hole, types of hole completion, and other management considerations. Other topics discussed by BNW include detailed descriptions of the disposal methods listed above and also others, technical feasibility of the methods, safety methodology, anticipated period of required isolation of wastes, research and development requirements, general environmental impact, heat sources, heat-transfer problems, and geochemical considerations.

The geochemical considerations outlined by BNW include a brief discussion of waste and rock interaction, leaching rates, and transport characteristics of some radionuclides. The USGS report confines itself to ion-exchange characteristics of a few selected chemical species and rock types. The transport characteristics of plutonium and other transuranic isotopes are not discussed because these are not fully understood and must be evaluated by field and laboratory investigations.

Some basic assumptions, in addition to presuming that the modes are technically feasible, had to be made in order to proceed with the study. The assumptions include: (1) that the wastes can be made chemically compatible with the host environment, (2) that injection pressures of liquid wastes will not cause hydrofracturing of the host rock, (3) that the final waste form is a solid, regardless of phase during emplacement, and (4) that a plant on the site can operate for a period of some 25 years in producing, processing, and handling the wastes without releasing hazardous constituents to man's environment.

The disposal of wastes considered in this report requires that the wastes be isolated from man's environment for a period of 1 m.y. (million years). This requirement was set by BNW and is based on the anticipated dangerous life of some of the constituents of the wastes, principally the transuranium isotopes.

The term "disposal" as used in this investigation is defined by Rubin (1972) as "planned emplacement of radioactive materials without any intent to recover them." The term "storage," in contrast, is applied to those concepts of waste management whereby retrieval is intended and is within the realm of available technology (Rubin, 1972). From the standpoint of geology and hydrology, the cavity with separate manmade structures (item d, above) for permanent disposal of waste must be considered as equivalent to a shallow-depth mined chamber. This is because of the impossibility of predicting what the long-term (1 m.y.) effect of the waste products on the structure will be and how long any manmade structure can withstand the ravages of geologic processes through time.

The following geohydrologic environments will be briefly described and evaluated: (1) sedimentary basins, (2) complexly folded mountain belts, (3) areas of intrusive igneous and metamorphic rocks, (4) areas of gently folded volcanic terranes, (5) Colorado Plateau and central interior areas exclusive of basins, and (6) Basin and Range province. Within each environment the principal rocks will be evaluated in terms of apparent ability to satisfy required conditions for each proposed but untested waste-disposal method. The determination of suitability is based mainly on our evaluation of the ability of the rocks in the various environments to effectively "contain" the waste products. The term "contain" as used herein denotes the ability of a rock to limit the movement of radionuclides to an acceptable radius of the disposal site--a radius that precludes contaminating man's environment for a period of about 1 m.y.

The disposal of wastes is a special problem in each environment, and the occurrence of suitable rock types and favorable local geohydrologic conditions will dictate whether a particular area is suitable for waste disposal. However, the general and very basic considerations listed in the contract specifications must be evaluated for all sites and for any disposal method. The most important of these considerations are: (1) hydrology, (2) possible climatic changes, (3) effects of erosion and rates of denudation, (4) long-term tectonic effects, and (5) seismic risk and its bearing on site selection. These considerations and the various rocks that could be used for waste disposal are briefly discussed and evaluated in the Appendixes. Additional information can be obtained from standard geologic, hydrologic, seismic, and climatologic textbooks.

In the discussion that follows, specialized geologic and hydrologic terms are kept to a minimum. Those used are defined in a glossary of geohydrologic terms in Appendix D.

Previous studies

Under the sponsorship of the Atomic Energy Commission, many studies concerning the feasibility of radioactive-waste storage or disposal have been made. Because of the short time (about 7 weeks) allowed for the basic USGS report, a comprehensive review of all existing literature on the subject of terrestial waste disposal could not be made and, undoubtedly, many studies have been overlooked. Most previous work, however, has been oriented toward the feasibility of injecting liquid wastes deep into the ground. Clebsch and Baltz (1967) review the progress in the United States toward deep-well disposal. This technique requires formations that are sufficiently porous and permeable to receive large quantities of waste. These formations are found principally in deep sedimentary basins. The possibility of disposal in such basins has been reviewed by Galley (1968). Repenning (1959, 1961), deWitt (1961), Love and Hoover (1961), Colton (1962), Beikman (1962), LeGrand (1962), Sandberg (1962, 1966), and MacLachlan (1964) describe various basins and their stratigraphy. Additional reviews have been made by the American Association of Petroleum Geologists (1964, 1972).

The possibility of using salt beds or domes for storage and disposal has been reviewed by the National Academy of Sciences, National Research Council (1970), Anderson, Eargle, and Davis (1973), Hite and Lohman (1973), Gera and Jacobs (1972), Gera (1972), and Brokaw, Jones, Cooley, and Hays (1972). These reports contain a host of many additional pertinent references. The potential for using crystalline rocks at the AEC Savannah Plant in South Carolina for disposal of wastes has been described by Proctor and Marine (1965), Parker (1969), and Christl (1964). Birch (1958), Skibitzke (1957), and Nace (1960) consider the thermal factors that bear on the problem of deep waste disposal. Theis (1955, 1956b, and 1959) and Piper (1969) consider various problems concerning waste disposal in a hydrologic environment. Many other pertinent references can be found in an annotated bibliography prepared by Rima, Chase, and Myers (1971).

ANALYSIS OF GEOLOGIC AND HYDROLOGIC FACTORS AFFECTING EACH DISPOSAL CONCEPT

All the concepts for disposal of radioactive wastes considered in this report require that the wastes be completely isolated from man's environment for a period of about 1 m.y. To achieve this, many requirements have to be met, and, although the disposal methods are similar in many ways (all entail emplacement of wastes at some depth within the ground), they nevertheless differ sufficiently that the best location for one mode of disposal may not necessarily be the best location for another. The purpose of this part of the report is to outline geologic and hydrologic environments that appear to provide required conditions for each disposal method and to outline reasons why a certain environment(s) may be more suitable than others.

Deep drill hole (30,000-50,000 ft or 9,140-15,240 m)

Geologic and hydrologic setting

Because of the great depth involved in this method and the great physical separation of wastes from man's environment that it will provide, it seemingly matters little what climatic or other changes might eventually occur that could affect surface conditions. The principal geohydrologic requirement is the necessity for a fairly thick sequence of rock having very low permeability to occur at some depth within the 30,000-50,000-foot (9,140-15,240-m) deep hole, preferably below a depth of about 25,000 feet (7,620 m), to achieve maximum vertical isolation. This requirement can be found in a variety of terranes, but the preferred setting is one where homogeneous, low permeability, metamorphic, and intrusive igneous rocks (Appendixes B and C) persist from on or near the surface to great depths. Deep sedimentary basins of interbedded rocks having varying degrees of permeability are generally not suitable for this method because of the great potential for contaminating regional aquifers and (or) oil-bearing strata by lateral and (or) vertical movements of contaminated ground water.

If actual field experiments demonstrate that after the wastes are emplaced the hole can be effectively and permanently sealed, then the upper several thousand feet (a few thousand metres) of strata above the waste emplacement zone can be safely ignored regardless of its characteristics. This would allow the use of many parts of the United States that are mantled by thin (5,000± ft or 1,520± m) layers of permeable sedimentary rocks but are underlain by metamorphic or igneous rocks having very low permeabilities, provided that other requirements are satisfied (see below).

The conclusion that metamorphic rocks beneath a thin sedimentary cover might be suitable for high-level waste disposal is based on studies at the Savannah River Plant near Aiken, S. C., and the knowledge that some deep mines in crystalline rocks, for example, at Sudbury, Ontario, and in Michigan, are extremely dry in their lower levels (Appendixes B and C). According to Proctor and Marine (1965), Parker (1969), and Christl (1964), disposal of high-level wastes at depths of 1,300-1,700 feet (400-520 m) beneath the surface at the

Savannah Plant is technically feasible because the basement (crystalline) rocks have very low permeability, and a layer of clay between the basement rocks and the sedimentary rock would serve as a barrier that would prevent the upward migration of the radionuclides. Proctor and Marine (1965) feel that the radionuclides would be confined to a radius well within the plant boundaries for a period much greater than the 600-year period required to render the wastes innocuous. It seems possible that at depths greater than 5,000 feet (1,520 m) at Savannah, S. C., and in other areas, especially in the stable continental interior, crystalline rocks would have even less permeability than that encountered at the shallow depths considered at Savannah.

An important consideration if liquid wastes are emplaced in the drill hole is whether or not extensive fractures will develop as a result of the expansion of molten rock owing to radiogenic heat. Such fracturing may not extend far into the medium but could, nevertheless, result in leakage to adjacent, possibly permeable, saturated zones. Field experiments must be performed prior to any attempt to inject liquid high-level wastes into crystalline rocks to determine the extent and nature of possible fracturing, and also to determine precisely the potential for geysering that might result from the buildup of heat after final sealing of the drill hole. Conductivities of the crystalline rocks are comparable to that of salt (Appendix C). Birch (1958), Skibitzke (1961), and Nace (1960) consider the thermal factors that bear on the problem of waste liquid injected into a deep formation.

Areas of high heat flow such as coastal California, the Basin and Range province, and Columbia Plateau (including the Snake River Plain) must be regarded as less suitable for the deep drill hole than areas of normal flow. Volcanic activity has occurred in all these areas in the past few million years, and, locally, molten rock may even exist at levels considerably above 49,200 feet (15,000 m) (Tuttle and Bowen, 1958).

Seismicity and faults

Crustal stability is of extreme importance when evaluating terranes for any waste-disposal method. For deep drill hole disposal the greatest threat to safety, assuming that the wastes are emplaced in suitable media, is the possibility of fault movements rupturing the contaminated zone in or near the waste column and creating passageways for ground water to carry contaminants to the surface. In addition to this obvious hazard there is a dire need for crustal stability in order to even drill such a hole. Even moderate earthquakes, if in close proximity to the drill hole, could cause the loss of the hole. Therefore, all areas of seismic risk zone 3 (for definitions of seismic risk, see Appendix B) must be precluded from deep drill hole consideration, and the selection of sites in other seismic zones must await seismic monitoring and detailed geologic and geophysical mapping to establish the existence of fault systems and the locations of seismically active zones.

The emplacement zone of the hole must be free of faults, whether currently active or not, because most faults provide potential avenues for fluid movement. Apparently, great depth does not necessarily guarantee that faults and fractures will be closed and healed despite the knowledge that porosity and permeability generally diminish with depth (McCulloh, 1967) (fig. 1). Hydrologic testing at Nevada Test Site reveals that fractures have low to moderate permeability (see Appendix B) at least to 13,686 feet (4,170 m) (Blankennagel and Weir, 1973), and fractures below 20,000 feet (6,100 m) in the Ralph Lowe Estate drill hole in the Delaware basin of Pecos County in Texas were found to be permeable (H. N. Frenzel, written commun., 1973). Potential sites must also be carefully evaluated to ascertain the possible presence of buried faults adjacent to the drill hole site.

Geographic setting

A site for deep drill hole disposal should be (1) as far removed from oceans and major lakes and streams as is practicable to keep the transit time of contaminants into man's environment as long as possible in case of accident during transport, loading, or emplacement of wastes; (2) the site locality should be as far removed from human population centers as is practicable; and (3) the site should be in as gentle terrain as possible in order to avoid steep drainage gradients that would allow rapid distribution of contaminants in case of accident.

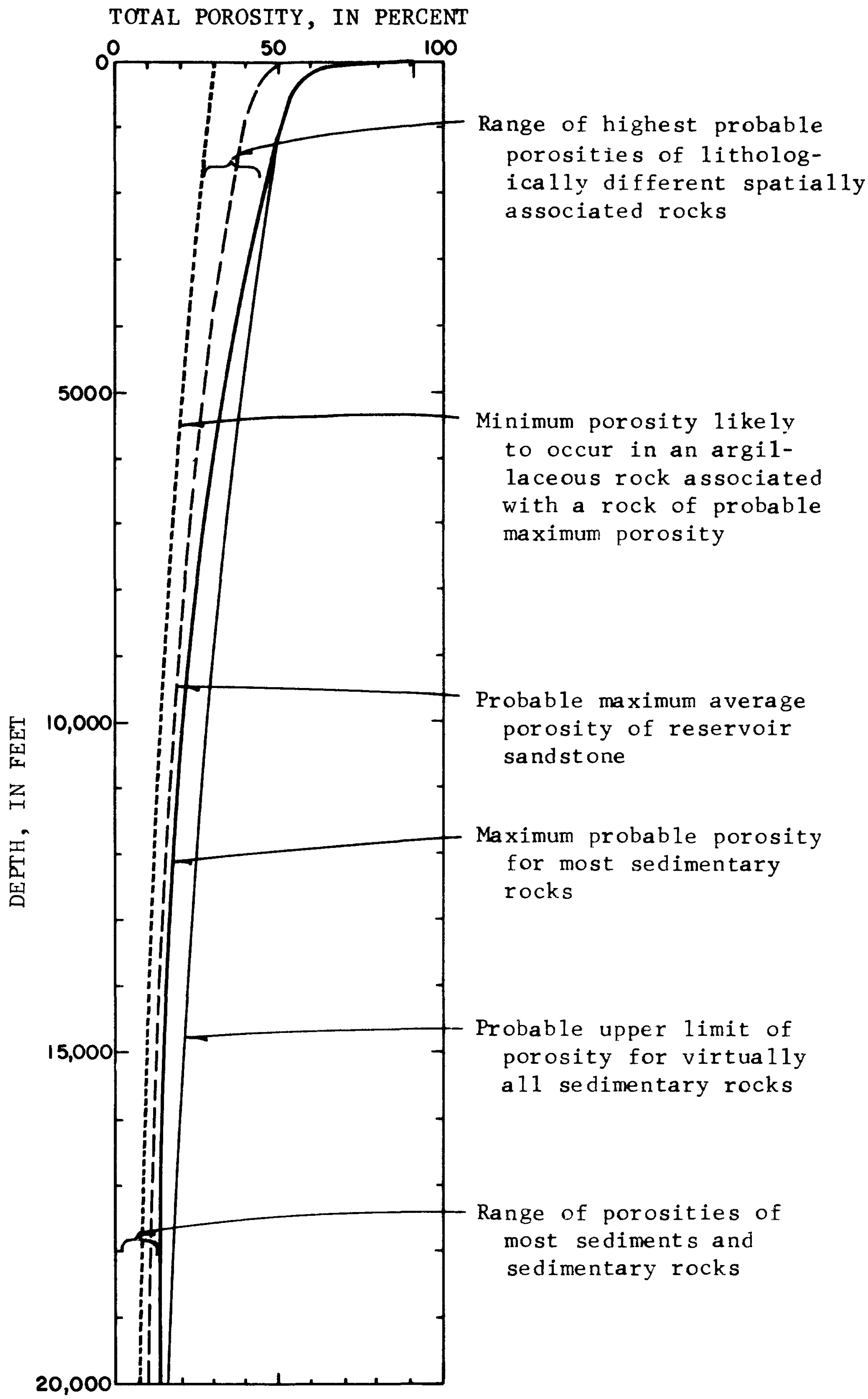


Figure 1.--Total porosities of sedimentary rocks versus depth. Modified from McCulloh (1967).

Advantages and disadvantages of deep drill hole methods versus other disposal methods

The principal advantages of the deep drill hole method when compared to all others include (1) great versatility--the possibility of providing safe emplacement of high-level radioactive wastes at desirable geographic locations where suitable rocks do not exist at shallow or moderate depths, and (2) the ability to place the wastes as far from man's environment as possible--the longer the flow path, the longer the time required for contaminants to reach man's environment.

Other attractive features of the deep drill hole (assuming that the top of the wastes is at least several thousand feet, a few thousand metres, deep) are (1) elimination of danger of exhumation of wastes by any erosional process, including glaciation, and (2) elimination of dangers from flooding, including rising sea levels (assuming complete sealing of unused portion of drill hole).

The principal disadvantages of the deep drill hole include tremendous drilling expense and long drilling times, especially in hard metamorphic and igneous rocks. In addition, exploratory or pilot holes to assure suitable rocks at depths of 30,000-50,000 feet (9,140-15,240 m) seemingly are ruled out by factors of time and expense.

Matrix holes (1,000-20,000 ft or 305-6,100 m)

Geologic and hydrologic setting

A geometric array of multiple holes drilled on 200-foot± (61-m±) centers to depths of as much as 20,000 feet (6,100 m) with as large diameters as practical, provides a possible means of disposing of wastes without the complexities of mining or exploding a cavity. This method requires a thick sequence of rock media having very low permeability in order that the necessary waste-holding capacity be obtained without drilling an impractical number of holes, each of which must be considered a potential avenue for the escape of contaminants. The principal geohydrologic requirement, then, is similar to the deep drill hole. The main difference is a need for rock having very low permeability to be present at shallower depths than is necessary for the very deep drill hole (30,000-50,000 ft or 9,140-15,240 m), and a need for a larger surface area to accommodate several holes on about 200-foot (61-m) centers. This last requirement is not a critical factor because, in an environment where a vertical column of thick very impermeable rock is present, areas can certainly be found where such rock is contiguous over lateral distances of many miles (many kilometres), or, at the very least, several thousand feet (a few thousand metres). The spacing of holes would be controlled by fault and fracture trends, local terrain and drilling conditions, hole deviations, the temperature and chemical properties of wastes, potential fracturing owing to the expansion of the waste and rock mass, rock conductivity, and other physical characteristics of the host media (for descriptions and properties of various rocks, see Appendix C).

The requirement for a thick sequence of homogeneous rock having very low permeability is most likely to be found in terranes where metamorphic or igneous rocks are exposed at the surface or where such rocks are at shallow depth. The possibility of using beds of salt or sequences of shale only a few hundred feet (a few hundred metres) thick for multiple-hole emplacement appears hazardous and difficult. As stated above, drilling a large number of holes into a thin bed to achieve the necessary waste-holding capacity would greatly increase the possibility of creating manmade avenues for contaminant escape. The possibility exists that stable salt domes may be used, but this possibility must be considered tentative because, although the salt there would be many thousands of feet (a few thousands of metres) thick, it could prove to be unstable in large-diameter holes drilled to depths of more than about 3,000 feet (900 m).

Very thick sequences of shale occur in sedimentary basins, but these sequences are rarely pure. They commonly contain many interbeds of permeable sandstone and limestone. Because of the interbeds and the common occurrence of faults and other fractures in the basins it seems extremely unlikely that wastes emplaced in a large vertical column could be effectively contained in shale, especially at shallow depths where porosities and permeabilities of interbeds and fractures would be very high. Because of the general decrease of porosity and permeability with depth, exploratory drilling may define shale sequences at some interval within 20,000 feet (6,100 m) that are thick enough to be suitable hosts for matrix-hole waste emplacement. The fact that the thick deeply buried shale sequences occur only in sedimentary basins that are the principal producers of oil and gas indicates that extensive exploratory drilling and hydraulic testing will be necessary to definitely prove hydrologic isolation of the potential waste emplacement zone. In most environments depth to suitable shale, if it exists at all, probably will be in excess of 7,000 feet (2,130 m) (fig. 1).

Seismicity and faults

Crustal stability is essential for safe disposal of wastes in matrix holes for the same reasons as outlined for the deep drill hole. The danger of losing the hole(s) if earthquakes should occur is less because of shorter total hole length. Faults within the waste-emplacement zones, unless hydraulic testing demonstrates conclusively that they are completely healed and "water tight," cannot be tolerated because of the great potential for ground-water contamination and the threat of earthquake activity causing movements to occur along these planes of weakness. A potential site area must be mapped in detail and seismically monitored. Because of shallow to moderate drilling depths, exploratory holes are economically feasible and should be drilled and hydrologically tested to delineate rocks having the lowest permeability and to locate areas free of buried faults.

Climatic setting

Unlike the setting for a very deep drill hole where the wastes will be far removed from the surface and possible climatic changes are of little concern, the setting for multiple holes should be carefully evaluated if the top of the waste column is within 1,000 feet (305 m) or so of the surface. If the disposal site is in an area of gentle relief there is little danger that erosion will actually exhume the wastes even in areas that may be covered by glaciers, but if a climatic change should cause a radical change in precipitation, there is a potential danger that surface and ground-water regimens will be dramatically changed. The site, therefore, must be so selected that the most hazardous conceivable hydrologic change will not create foreseeable avenues for escape of contaminants. For long-term safety, because climatic changes cannot be predicted with any degree of accuracy, it seems advisable to place the top of the wastes at least several thousand feet (a few thousand metres) below the Earth's surface in any potential site locality having integrated surface drainage, despite the fact that hydrologic studies in a given locality indicate the existence of rock having very low permeability to within a few hundred feet (a few hundred metres) of the surface.

In general, it seems advisable to select a site locality that can be continuously monitored by man because of the impossibility of selecting any site that can be guaranteed to be "leakproof" for a period of about 1 m.y. Therefore, all areas that conceivably could be inundated by rising sea levels, or covered by glaciers or pluvial lakes, must be considered less suitable for multiple-hole disposal or any other disposal technique than areas that are free from those potential dangers.

Geographic setting

The optimum geographic setting for a matrix-hole disposal site is nearly the same as with the deep drill hole. The principal difference is a need for a slightly larger area of gentle relief in the immediate area of the disposal site in order to accommodate several drill sites. If the general area is one of gentle relief this should pose no problem. If it is necessary to locate a site in terrane having locally high or moderate relief, the topography may become the principal factor in choosing a suitable site.

Advantages and disadvantages of matrix hole method versus other disposal methods

In most environments, a sequence of holes drilled to depths of as much as 20,000 feet (6,100 m) will prove to be a much more practical means of disposing of high-level radioactive wastes than a single very deep drill hole. The reasons for this include: (1) the shallower holes can be drilled to larger average diameters and will have larger ratios of waste capacity per total footage drilled, (2) preemplacement pilot or exploratory holes are economically feasible for this mode and are essential for safety evaluation, (3) shallower holes are less likely to be lost by drilling problems or earthquake activity, and (4) drilling times will be much less and several rigs could be employed simultaneously.

Whether a sequence of holes or a mined or exploded cavity would be preferred in any given locality would depend on the geologic and hydrologic information obtained from detailed investigations. In addition, laboratory or actual field tests must be made to determine whether a concentration of solidified wastes in a chamber at 4,000-5,000 feet (1,220-1,520 m) would pose problems from the standpoint of heat transfer for the particular rock at the potential site locality that would not exist in a drilled hole and vice versa.

If exploration reveals that rock having acceptable very low permeability and other acceptable physical and chemical properties is present only between 3,000 and 5,000 feet (910 and 1,520 m), then it would appear that a mined or exploded cavity would be a more practical mode. Any final decision, however, would depend upon several factors that would be specific for a given area.

Mined chamber (1,000-10,000 ft or 305-3,050 m)

Geologic and hydrologic setting

This disposal method requires a zone of strata having very low permeability at some interval within 10,000 feet (3,050 m) of the surface. The interval must be sufficiently thick to include zones of very low permeability at least several hundred feet (a few hundred metres) thick, both above and below a potential chamber or cavity (containing the high-level waste products) in order to assure that the chamber can be effectively sealed from man's environment.

The mined chamber enables the use of bedded salt and other strata that are not sufficiently thick to be practical repositories for drilled hole disposal sites. Of the various rock media that are potentially favorable for this concept, the most suitable appears to be rock salt either in relatively thick beds or in stable domes. Salt has nearly zero porosity and zero permeability, which should allow virtually complete hydrologic isolation. In addition, salt has high thermal conductivity, which should allow rapid dissipation of heat from the chamber (Appendix C). Mined chambers in salt may be limited to depths of about 3,000 feet (910 m) owing to the natural plasticity of salt and the potential for serious flowage problems at greater depth.

Other rocks that might be suitable for this method include tuff, some metamorphic rocks, and intrusive igneous rocks. Favorable properties of these rocks include low permeabilities and high mechanical strengths. They can be mined with a minimum of problems. Chambers have been mined successfully in tuff at Nevada Test Site to depths of as much as 5,000 feet (1,520 m). That mined chambers in metamorphic and igneous rocks are feasible is clearly indicated at Sudbury, Ontario, and in deep copper mines in Michigan. In both of these areas the rocks have such low permeabilities that the mines are dry, even in the lowest levels. Thermal conductivities of metamorphic and igneous rocks vary considerably from values much less than that of salt to levels slightly higher (Appendix C).

The possibility of using shale for mined chambers is attractive from the standpoint of placing wastes in rock having both high ion-exchange capacity and very low permeability. As pointed out in the analysis of matrix holes, however, shale sequences are rarely without thin permeable interbeds of sandstone and (or) limestone, and the possibility of finding zones that are sufficiently thick to assure complete hydrologic isolation of a mined chamber appears very remote. In addition, shale is one of the most difficult rocks to mine because of its plasticity. Perhaps the only areas where shale can be safely used for waste disposal are areas where the chamber can be mined well above an existing water table, and where evaporation exceeds precipitation. Such areas exist in the arid and semiarid parts of Western United States (see discussion of geohydrologic environments, p. 35). The possibility of eventual water-table rise owing to climatic changes must be considered in these areas, but it is reasonable to presume that any such changes, if they did occur, would be slow, and the possibility exists that the repository could remain above the water table for the entire disposal period. In the event that ground water would reach the emplacement zone before the radioactivity had diminished to safe levels the high ion-exchange capacity and very low permeability of the shale would drastically impede the outward movement of radionuclide contaminants.

The possibility of using tuff for an above-the-water-table repository is also appealing for the same reasons as outlined for shale. Tuff has the highest ion-exchange capacity of the igneous rocks (Appendixes B and C). This property and its very low permeability would assure very slow outward movement of radionuclides in the event that climatic change would cause ground water to reach the emplacement zone.

The use of metamorphic, intrusive igneous, or volcanic rocks other than tuff is much less attractive for above-the-water-table repositories because these rocks have much lower ion-exchange capacities than either tuff or shale and, in general, greater potentials for high permeabilities at shallow depths. Lavas of all kinds would be generally unsuitable for this method because of high permeabilities (Appendixes B and C).

Seismicity and faults

Areas of seismic risk zone 3 must be precluded from consideration for mined chamber disposal, and areas in seismic zones 2 or less must be carefully mapped and seismically monitored to assure that fault systems are avoided. The principal danger is the same as with drilled hole emplacement, namely that fault movements could rupture either the emplacement zone or the contaminated rocks surrounding the chamber and create passageways for ground water to carry contaminants to man's environment. Because any fault, whether active or not, could be an avenue for fluid escape, horizontal drilling and tunneling should be employed to check for faults or other permeable zones in the vicinity of the site prior to final chamber construction. For sites above the water table, in areas where evaporation exceeds precipitation, earthquake rupturing of the chamber or vicinity would not necessarily create an immediate hazard, but the possibility of eventual ground-water encroachment during a period of 1 m.y. must be considered.

Climatic setting

Climatic setting is a critical factor in selecting a suitable location for a site for a mined chamber. To insure the safe long-term containment of radioactive wastes in salt, for example, it is necessary to establish the nature and rates of present-day salt removal by surface waters near the site and the underground dissolution rates by circulating ground waters. Careful studies must then be made (1) To determine how the salt-removal rates would be affected by increased (or decreased) rainfall, and how changes in regimens of nearby streams might affect ground-water flow systems, and (2) to accurately predict the denudation and erosion rates that will prevail during the lifetime of the disposal facility--see Stewart (1973).

For disposal in tuff or shale (or other media) above present-day water tables, rock-erosion rates including both denudation and escarpment-retreat rates (Appendix B) must be established. Estimates of how these rates will be affected by possible changes in rainfall also must be made. Calculations must be made to estimate how rapidly a ground-water table could rise with increasing rainfall and how large an increase in rainfall would be necessary to cause precipitation rates to exceed evaporation rates.

Geographic setting

A site for mined chamber disposal should be (1) as far removed from oceans and major lakes and streams as is practicable to keep the transit time of contaminants to man's environment as long as possible in case of accident, (2) the site locality should be as far removed from human population centers as is practicable, and (3) the site should be in as gentle terrain as possible in order to avoid steep drainage gradients that would allow rapid distribution of contaminants in case of accident.

A site for a chamber above the water table will, of necessity, be located in the arid or semiarid southwest. Although many terranes in that area are potentially suitable for this concept the Great Basin with its internal drainage appears to best meet the required conditions.

Advantages and disadvantages of mined chamber method versus other disposal methods

The principal advantage of the mined chamber method is the ability to provide safe emplacement of high-level radioactive wastes in highly suitable rocks, such as salt beds that are too thin for drilled hole emplacement to be practicable, and to provide safe emplacement in other favorable rocks, such as tuff and shale above existing water tables in areas where evaporation exceeds precipitation. The mined chamber possibly is also a practical method in metamorphic and intrusive igneous terranes, but drill holes or deep exploded cavities probably are better suited for waste disposal in those environments because of their greater potential to place wastes farther from man's environment.

Disadvantages of the mined chamber include (1) possible short flow paths of contaminants to man's environment, (2) possible danger of exhumation of wastes by erosional processes, (3) possible danger from flooding, including rising sea levels, and (4) possible danger resulting from an unpredictable change in ground-water regimen.

Cavity with separate manmade structures

From the standpoint of geology and hydrology, this method is a slight modification of a mined chamber. The "manmade structures" will be designed to greatly restrict or, it is hoped, to completely inhibit movement of radionuclides beyond the chamber for a limited time after all the wastes are emplaced and to allow a greater degree of retrievability. Terranes and rocks that are best suited for this method are the same as those outlined for mined chambers.

Exploded cavities (2,000-20,000 ft or 610-6,100 m)

Geologic and hydrologic setting

Developing an underground cavity by means of conventional explosives or nuclear devices provides a means of creating a sizeable waste-holding facility without the depth limitations of conventional mining techniques. The wastes being considered for this method will be initially liquid. This requires that the site be located at or adjacent to the fuel-processing plant, because liquid wastes cannot be safely transported (Gera and Jacobs, 1972, p. 14).

Cavities have been created by nuclear devices in a variety of rocks at the Nevada Test Site and other parts of the United States, and a concept for using a deep nuclear cavity (chimney) for the in situ incorporation of nuclear fuel-reprocessing waste in molten silicate rock has been described by Cohen, Lewis, and Braun (1971). This concept involves in situ melting of rubble and wallrock by the high-level radioactive liquid wastes. Strata of very low permeability, at least 600 feet (180 m) thick, is required for their particular model to contain the molten rock at its maximum dimension. We consider that, in addition, at least several hundred feet of rock having very low permeability would be essential, both above and below the potential molten zone, for safe confinement of contaminants. The chances of finding such a sequence in sedimentary environments is remote except possibly in shale at depths of 7,000 feet (2,130 m) or more in deep sedimentary basins where the potential of contaminating oil, gas, and water reservoirs is great. The need for drill-hole connections to the cavity for the introduction of waste and the release of volatiles for a period of about 25 years (Cohen and others, 1971) further adds to the potential of introducing contaminants to the overlying strata.

A satisfactory environment, therefore, must satisfy the need for (1) a thick sequence of rock having very low permeability to effectively contain the exploded cavity and the molten mass of waste and rock, and (2) rock having very low permeability above the emplacement zone in order to avoid introducing contaminants into water or oil and gas reservoirs during the period of waste injection and steam release. These requirements are most easily met in metamorphic and intrusive igneous terranes. The optimum locality from this standpoint appears to be one where metamorphic and (or) intrusive igneous rocks having very low permeabilities extend from the surface to great depths. A potential problem, however, is posed by the knowledge that a volume increase due to rock melting and the possible accompanying production of gaseous constituents could result in significant fracturing in these low-porosity rocks which might be hazardous. Field experimentation appears vital to determine the extent and nature of such fracturing.

Terranes that might also be suitable for this concept are those where thick sequences of tuff form the surface rocks and extend to great depth. Such terranes exist in several localities in the Great Basin, principally in old volcanic centers. Chambers have been mined in tuff in one of the volcanic centers at the Nevada Test Site to depths of about 5,000 feet (1,520 m). At this depth the tuff had low permeability. At deeper levels the potential for finding rock having even less permeability appears high. The possibility of creating hazardous fractures in tuff is predictably less than in granitic rocks because of its much greater porosity (20 percent or more in tuff versus 5 percent or less in granitic rocks).

Nuclear devices have been detonated in salt in Mississippi and New Mexico. These experiments have shown the feasibility of creating stable cavities in salt by small nuclear devices. The explosion near Carlsbad, New Mexico, for example (project Gnome), formed a cavity about 70 feet (21.3 m) high and more than 150 feet (45.7 m) across by means of a 3-kiloton device (Gard, 1968). Postshot studies at project Gnome indicate that blast-induced fractures and faults were mainly confined to a radial distance of about 140 feet (42.7 m) from the shotpoint (Gard, 1968), and indicate that nuclear explosions in salt will not necessarily create hazardous fractures around the shotpoint. Whether or not the cavity will remain open for the required period of time and whether or not high-level radioactive liquid wastes can be safely injected into a cavity in salt without causing extensive and prohibitive salt flowage and solution can only be determined by field experimentation.

Seismicity and faults

Areas of seismic risk zone 3 must be precluded from consideration for emplacement of wastes in explosion-induced cavities for essentially the same reasons as outlined for the other disposal methods. The principal danger is that fault movements could create passageways for ground water to reach the contaminated zone and carry contaminants to man's environment. An additional danger (and this pertains to any disposal technique requiring open holes for liquid-waste injection and for the release of volatiles) is the possibility of earthquake activity rupturing the holes and creating immediate passageways for contaminants to reach aquifers above the emplacement zone. Negligible amounts of water approaching the emplacement zone itself may not pose an immediate hazard because the water would tend to be driven away by the intense heat before it becomes contaminated (Cohen and others, 1971). Any considerable amounts of water, however, flowing into the emplacement vicinity probably would create explosive conditions that could cause complete loss of the connecting holes and possible loss of the chimney itself. If the rocks above the chimney are unsaturated or have such low permeability that little or no ground water would enter the system in the event of fault movements, there is, nevertheless, a potential danger that the cooling system could rupture and the chimney would be lost (Cohen and others, 1971), and contaminated volatiles could escape to the surface.

These potential dangers from fault movements indicate that a site must be selected where surface exposures indicate a virtual absence of faults both within and adjacent to the potential cavity.

Climatic setting

Except for the need for continuous monitoring of the site there is little danger from potential climatic changes if the cavity is 2,000 feet (610 m) or more beneath the surface. Because it seems advisable that sites for any disposal mode be selected where they can be continuously accessible to man, areas of potential glaciation, sea-level rise, or areas occupied by former pluvial lakes should be avoided.

Geographic setting

A site for an exploded cavity must be in the same location as the reprocessing plant. Therefore, selections of geographic locations for reprocessing plants should await geologic and hydrologic analyses to determine the most suitable locations for underground nuclear cavities or other disposal modes. As pointed out in the discussion of the deep drill hole, the great depth involved with that method may allow disposal of wastes at existing reprocessing plants. Whether an exploded cavity at depths of as much as 20,000 feet (6,100 m) also might be suitable depends on local geologic and hydrologic conditions and the nearness to damage-prone manmade structures.

Because of the potential for release of contaminated steam from the underground facility prior to final sealing, either because of earthquake activity or human miscalculations, it seems necessary to locate the site as far from population centers, oceans, major lakes, and streams as is practicable.

Advantages and disadvantages of exploded cavities versus other disposal methods

The principal advantage of the exploded cavity over the mined chamber is the ability to create voids at much greater depths than is possible with mining techniques and also to create cavities at relatively shallow depths (5,000-10,000 ft or 1,520-3,050 m) where high underground temperatures or, perhaps, dangerous mining conditions preclude manpower techniques. The main advantage over the deep drill hole and matrix holes is the ability to obtain much larger disposal volumes.

The development of radial and other fractures around the expanding molten mass compounds the problem of potential hazards from fracture porosity and permeability. In general, however, terranes and rocks that are suitable for a mined chamber appear to be suitable also for a shallow-depth exploded cavity (excluding above-the-water-table emplacement), and terranes and rocks suitable for deep matrix holes probably are suitable for a deep nuclear cavity.

GEOHYDROLOGIC ENVIRONMENTS

Sedimentary basins

The U.S. Geological Survey, on behalf of the Division of Reactor Development, U.S. Atomic Energy Commission, began a study of sedimentary basins in the conterminous United States as early as 1957. The purpose of that study was to summarize the gross geologic features and natural resources of the major basins as an aid in selection of basins for deep-well injection of liquid radioactive waste. The study was primarily descriptive and was not intended as an evaluation or appraisal of the various basins for waste disposal. The present study is in contrast with the earlier one in that the basins as a single type of environment are evaluated for suitability for various disposal methods. No attempt is made to evaluate which basins are best suited for a particular method.

The sedimentary basins throughout the United States (fig. 2) all owe their existence to downwarping and (or) downfaulting of the Earth's crust. They differ individually in areal extent, depth to basement rocks, structure, and geologic age. They are similar in that they are filled with relatively gently dipping sedimentary rocks and, locally, volcanic rocks. They range in area from 1,000 mi^2 (2,590 km^2) to more than 100,000 mi^2 (259,000 km^2), and they range in depth from about 4,000 feet (1,220 m) to more than 50,000 feet (15,240 m) (table 1). Many of the younger basins in the western area of the United States and in the coastal plains contain unconsolidated sediments or slightly consolidated rocks. The older basins in the central and

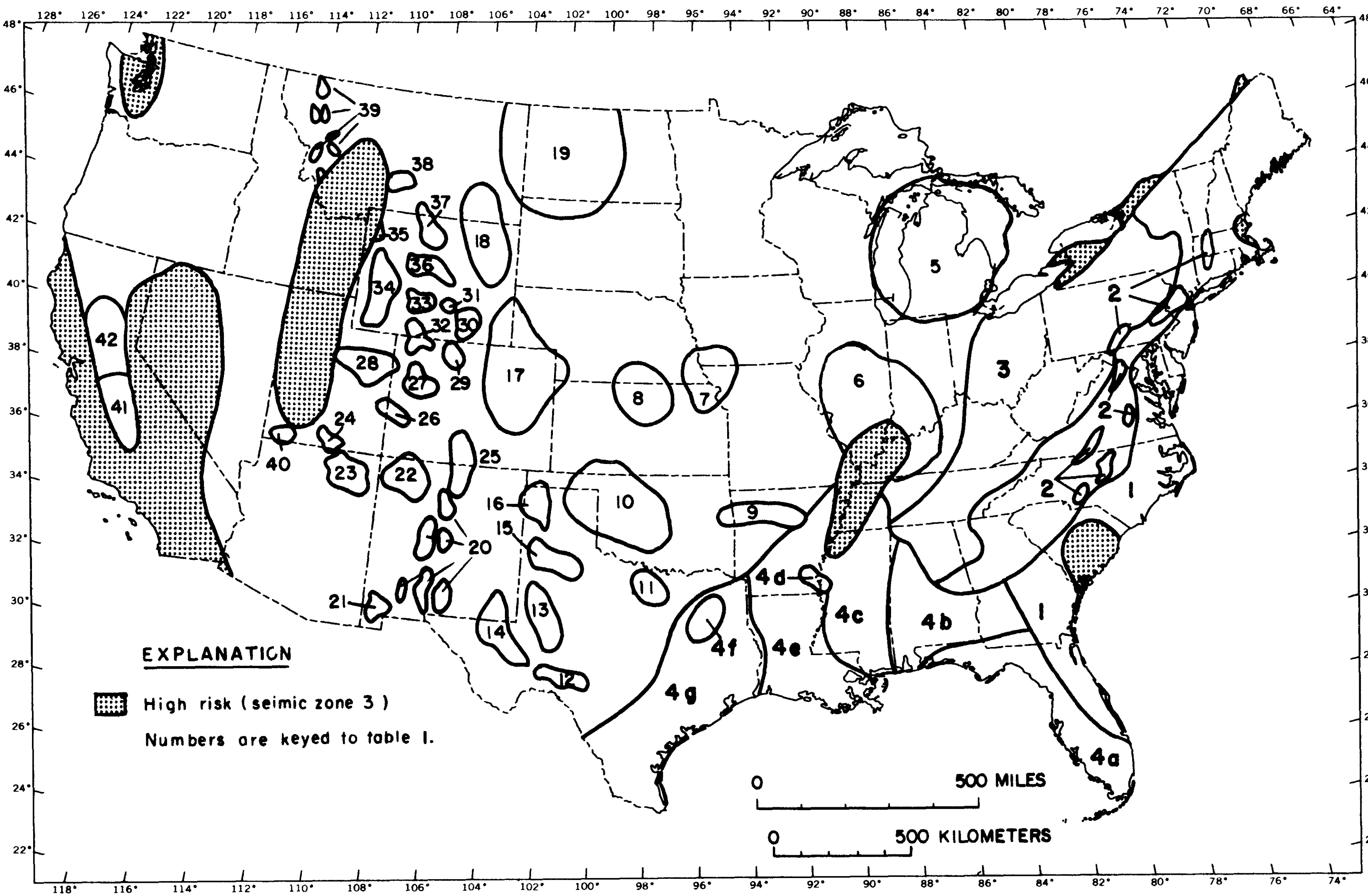


Figure 2.--Locations of sedimentary basins. Basins from Love and Hoover (1961) and and seismic risk from Algermissen (1969)

eastern areas of the United States contain mostly well consolidated rocks. Unconsolidated and slightly consolidated sand and gravel deposits are the predominant aquifers, especially in the western basins (Meinzer, 1923, p. 271; Walton, 1970, p. 37), but consolidated rocks such as sandstone, limestone, and dolomite are also important aquifers in many areas.

Ground water in the basins is under both water-table and artesian conditions. At places where the aquifers are unconfined, ground water occurs under water-table conditions, and water levels in wells do not rise above the top of the aquifer. At places where the aquifers are confined by strata that have very low permeability, such as shale, ground water can occur under artesian conditions, and the water is under pressure so that the water levels in wells rise above the top of the aquifer. If the pressure is great enough, the well will flow at the surface. In general, the shallower aquifers are more likely to be under water-table conditions and the deeper aquifers are more likely to be under artesian conditions.

The water levels found in wells are generally shallower in areas of high precipitation or in areas of low topographic relief, such as basins in the eastern half of the United States. There, water levels commonly range from above land surface (artesian) to shallow depths of less than 100-200 feet (30.5-61 m). Water levels are generally deeper in areas of high topographic relief, such as basins in the western half of the United States. In those basins, water levels commonly range from above land surface to great depths of 500 to at least 1,000 feet (150 to 305 m).

The movement of ground water generally consists of recharge of water to an aquifer either from precipitation or from seepage from streams. This recharge moves downward and laterally under the forces of gravity and hydrostatic pressure through the aquifer toward points or areas of discharge. Discharge generally occurs in springs, in areas of evaporation and transpiration by plants, or by subsurface flow out of a basin either into surrounding rock, into streams, or into a body of water such as a lake or an ocean. Examples of ground-water flow under artesian conditions from areas of recharge at the land surface toward areas of discharge at the center or the margins of the basins are shown in appendix B.

Most basins contain faults and folds, and all contain many lateral and vertical variations in rock types and permeability resulting in a complex pattern of ground-water flow. Geologic structures exert considerable influence on the movement of ground water, and aquifers that are generally separated by rocks having very low permeability may be hydraulically connected along faults and fractures. A decrease in porosity and permeability at great depths may occur due to the compaction of rocks under the great weight of overlying rocks (Meinzer, 1923, p. 40). If pressures differ between aquifers, flow may occur through either interstices or fractures across the rocks of very low permeabilities that separate the aquifers. In many sedimentary basins the determination of the exact flow path of ground-water movement from recharge area to discharge area may not always be possible.

Several other factors of significance in sedimentary basins are abnormal subsurface pressures, the presence of salt water or highly mineralized water, and the occurrence of thermal springs. Abnormal subsurface pressures may influence the movement of ground water. For instance, some basins in California and Wyoming and in the Gulf Coastal Plain have subsurface pressures that are higher than normal, probably owing to the compaction of unconsolidated sand and clay deposits (Denton, 1972, p. 15-16). Salt water or highly mineralized water may affect the movement of ground water. The aquifers in the Atlantic and Gulf Coastal Plains were filled with salt water when the sands were deposited under the sea, but now the aquifers have been flushed by fresh water to great depths of from 1,000 to 5,900 feet (305 to 1,800 m) (McGuinness, 1963, p. 69). In other basins some deep water is highly mineralized although shallow water is fresh.

Hot or warm thermal springs that originate at great depths and rise along deep faults or fissures indicate an upward movement of water aided by artesian pressure, hydrothermal activity, or both. Nearly all thermal springs are associated with volcanic rocks (Waring, 1965, p. 4), and this may indicate that unpredictable upward movement of ground water may occur in basins that contain hot springs.

Most of the basins are important producers of oil, gas, or coal. Some produce salt, potash, ceramic clays, and various other nonmetallic and metallic minerals.

A generalized cross section through two typical sedimentary basins is shown on figure 3, and the evaluation of suitability of the rock media (in the sedimentary basins) for the various disposal methods is shown in table 2.

Discussion of factors that influence suitability

Sedimentary basins represent a significant part of the conterminous United States; however, most sedimentary rocks, excluding shale, commonly have significant porosities and permeabilities at depths as great as 20,000 feet (6,100 m). This fact and the common occurrence of important aquifers and (or) oil- and gas-producing strata above, below, and within shale sequences make the basins generally unsuitable for the waste-disposal methods considered in this investigation, <u>except for disposal in salt</u>.

Because shale has very low permeability and high ion-exchange capacity it has been used as a repository for low-level wastes at the Oak Ridge National Laboratory in Tennessee (Boegly and others, 1966). Partly as a result of this usage, consideration has been given to using shale as repositories for high-level wastes. Shale sequences throughout the United States recently have been evaluated for radioactive waste disposal by Merewether, Sharps, Gill, and Cooley (1973). They conclude that, in general, the shale sequences are not suitable for waste disposal but that detailed investigations may disclose some strata that are acceptable. Because the study by Merewether, Sharps, Gill, and Cooley (1973) did not evaluate the concepts considered in this investigation, it is necessary to outline the factors that influenced our classification of suitability (table 2).

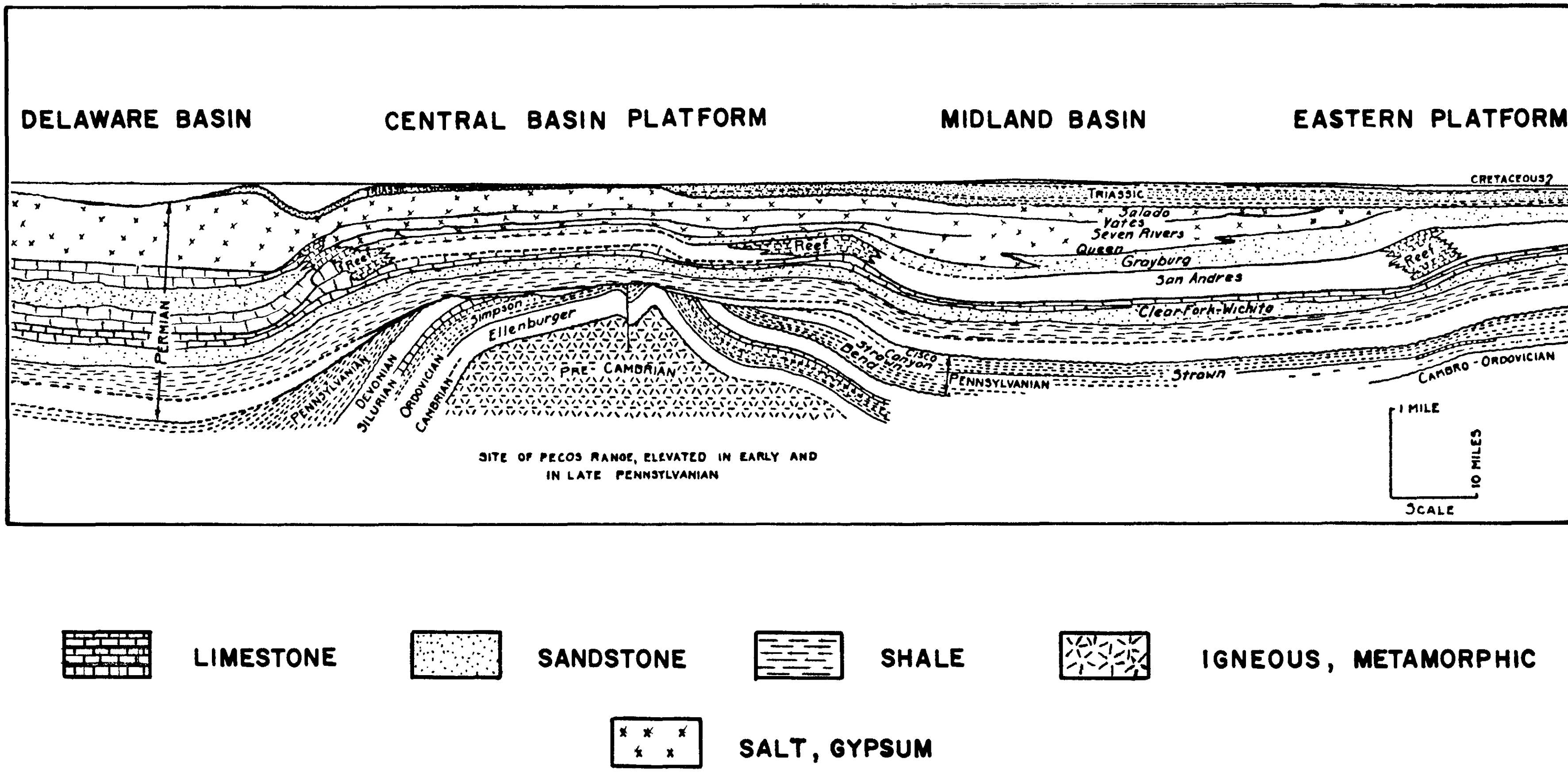


Figure 3.--Geologic section through Delaware and Midland basins, New Mexico and Texas. Modified from King and others (1942)

Table 2.--Suitability of rocks to disposal methods--sedimentary basins

[MS, most suitable; S, suitable; PS, possibly suitable. Ratings are based on the premise that sites can be demonstrated to be isolated, and predictably will remain isolated from hydrologic system; or, for salt, that plastic flowage proves to be insignificant. NS, not suitable (principally because rock not isolated from hydrologic system)]

Rock type	Very deep drill hole (30,000-50,000 ft or 9,140-15,240 m)	Matrix holes (1,000-20,000 ft or 305-6,100 m)	Mined chamber (1,000-10,000 ft or 305-3,050 m)	Exploded cavity (2,000-20,000 ft or 610-6,100 m)	Cavity with separate man-made structures (1,000-10,000 ft or 305-3,050 m)
Sandstone----	1/	NS	NS	NS	NS
Carbonate----	1/	NS	NS	NS	NS
Shale--------	1/	PS (below about 7,000 ft or 2,130 m)	S (above the water table)	PS (below about 7,000 ft or 2,130 m)	S (above the water table)
Bedded salt--	1/	PS	MS	S	MS
Salt in domes 2/	NS	PS	MS	MS	MS

1/ Probably granite or equivalent at 50,000 feet (15,240 m) except in Gulf Coast. All rocks except salt possibly suitable below 30,000 feet (9,140 m).

2/ Salt domes of proved stability. Domes that are tectonically active are considered unfavorable for all concepts.

In most basins where thick shale sequences occur, drill-hole data indicate that few zones exist without thin interbeds of sandstone and (or) limestone that drastically increase the overall permeability of the sequence. In some basins, water moves slowly through shale because of pressure gradients established during compaction of the sediments. The velocity of such movement and other water movements related to basin flow systems can be greatly increased by the occurrence of permeable interbeds that are cut and displaced by faults and fractures. Because at shallow depths both water-bearing fractures and faults and permeable interbeds probably occur in the vicinity of any potential waste-disposal site, it is extremely unlikely that wastes can be effectively contained for a period of about 1 m.y. if they are initially emplaced in shale below existing water tables. The possibility seems good, however, that shale can be effectively used for shallow-depth mined chambers for "above-the-water-table" emplacement in parts of Western United States where the water tables are fairly deep and sites can be selected that are far removed from rivers and lakes.

At depths below about 7,000 feet (2,130 m), detailed investigations in some basins may define thick shale sequences in which fluid flow, with concurrent transport of radionuclides, can be predicted to be extremely slow, and, therefore, the matrix (multiple) hole and exploded cavity methods are classified as "possibly suitable." The basic premise being that at depths below about 7,000 feet (2,130 m) fractures in shale will probably be tight, and porosities and permeabilities of thin interbeds will be diminished. At these depths, however, the structural instability of some shale may still prove to be a difficult problem. For instance, according to H. N. Franzel (written commun., 1973) shale in the Woodford Chert caved into the Ralph Lowe drill hole in the Delaware basin at depths below 20,000 feet (6,100 m).

Geologically and hydrologically, salt seems to be the most suitable medium for waste disposal in the sedimentary basins (fig. 4). Extensive studies indicate that salt (bedded or in stable domes) is potentially suitable for shallow-depth mined chambers and for shallow- or moderate-depth explosive cavities. A series of drill holes in salt also appears to be potentially suitable, but it remains to be proved whether or not large-diameter drill holes will be stable and remain open in salt at depths below 3,000-4,000 feet (920-1,220 m).

Deep-well disposal of liquid waste into deep permeable reservoirs containing salt brine (Galley, 1966, p. 45) is not suitable according to the total containment concepts of this investigation. In addition, saline ground water is increasingly being recognized as a natural resource of great economic importance because it can be used without treatment for many industrial purposes; it can be desalinized for public supplies, and it can be a source of valuable chemical byproducts (Winslow and others, 1968, sheet 1).

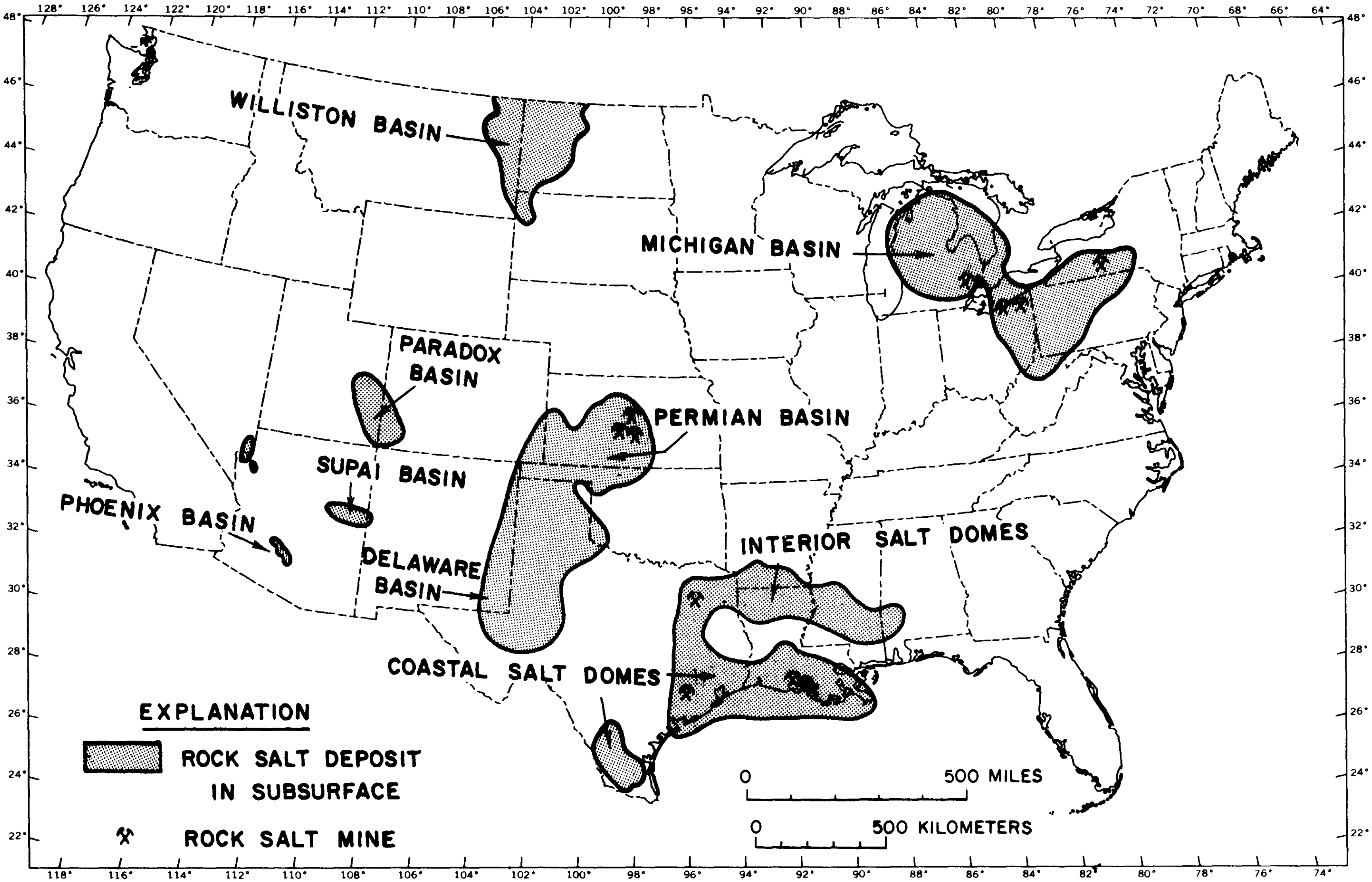


Figure 4.--Rock salt deposits in the United States, parts of which are potentially suitable for waste disposal. Modified from Pierce and Rich (1962)

Complexly folded terranes

Two large areas containing complexly folded rocks, exclusive of the broad metamorphic belts (described and evaluated separately), are present in the United States. One area is in eastern United States (the Valley and Ridge physiographic province) (fig. 5) and the other is in the western United States (the Rocky Mountains). The present state of knowledge of the geology, hydrology, and topography of the two areas, suggests that neither area is particularly attractive for waste disposal.

Valley and Ridge province

The Valley and Ridge province (Appalachian Mountain province, fig. 6) is a long narrow belt, within which 30,000-40,000 feet (9,140-12,200 m) of sedimentary rocks has been tightly compressed to form a series of northeast-trending anticlines and synclines. The weaker rocks in the sequence, from the standpoint of physical strength (shale) and resistance to weathering (limestone), form the valleys, and the well-cemented sandstones and conglomerates form the ridges. Because of the tight folding, which causes a single resistant stratum to surface repeatedly, a small number of strong formations suffice to make a great number of ridges (Fenneman, 1931). Elevations range from less than 400 feet (120 m) along the large rivers in the northern states to over 3,000 feet (910 m) on the highest ridges.

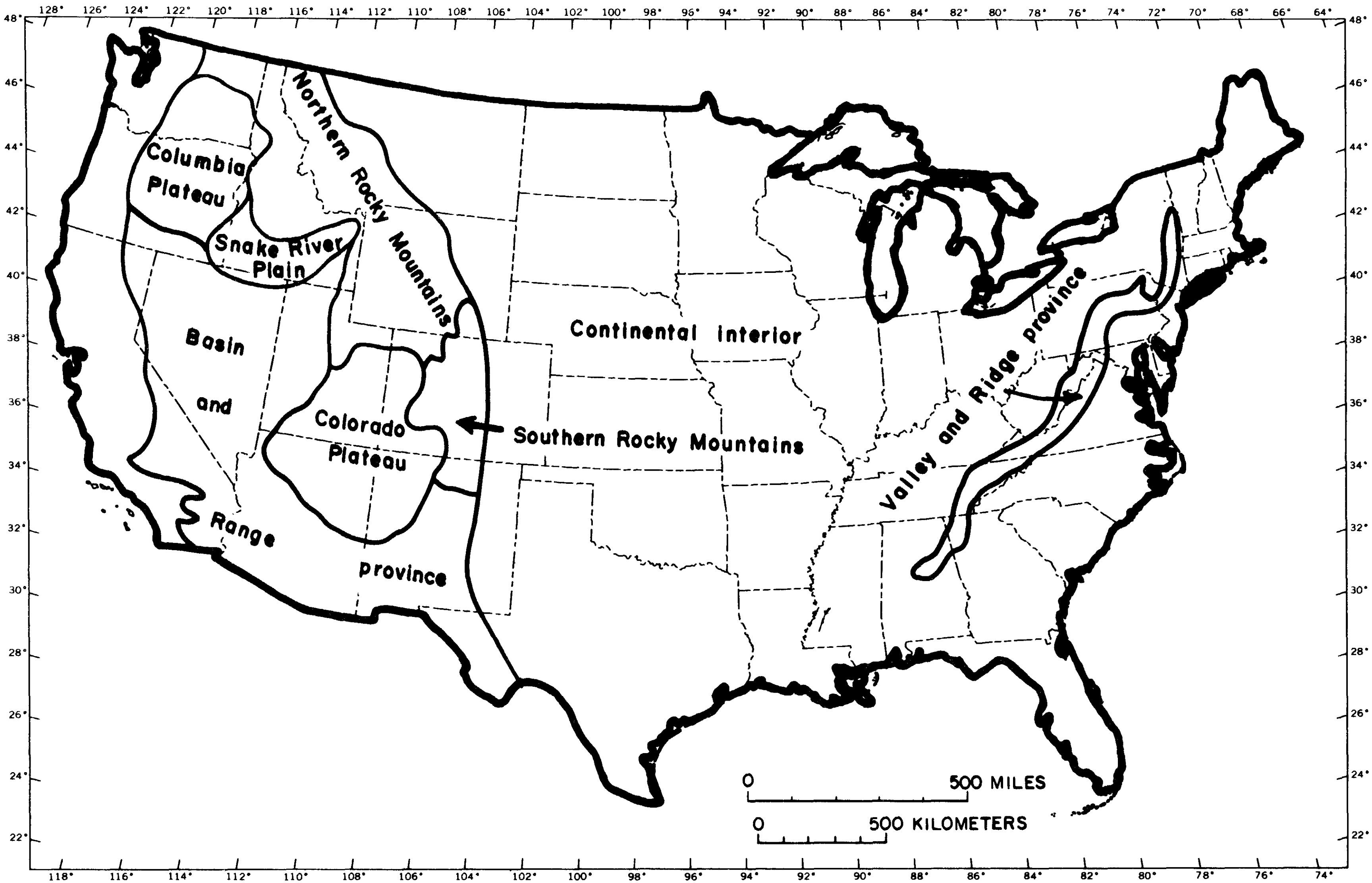


Figure 5.--Provinces evaluated in this investigation (exclusive of sedimentary basins and principal areas of intrusive igneous and metamorphic terranes). From Fenneman (1931)

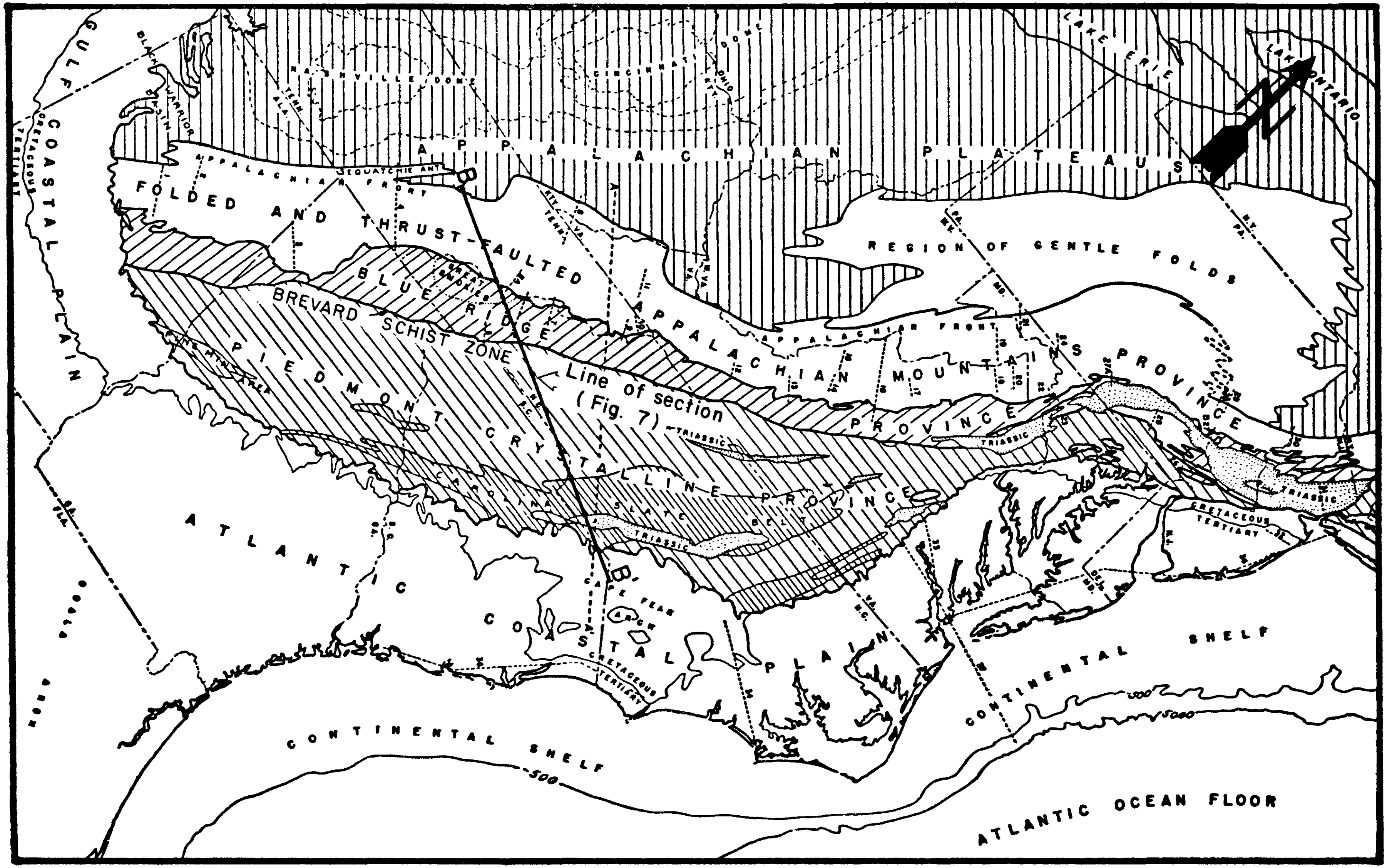


Figure 6.--Index map of the structural systems of the eastern margin of the United States. Modified from Eardley (1962).

Rocks are all of Paleozoic age and consist of a large variety of shales, sandstones, limestones, and coal. These rocks are locally overlain by thin veneers of recently deposited alluvium and, in the northern part, by glacial deposits. Of principal interest to this investigation are the shales. These range in age from Cambrian to Carboniferous. The shale sequences are overall as much as several thousand feet (a few thousand metres) thick, but few sequences consist of pure shale. Most contain thin beds of sandstone, sandy shale, and limestone (Merewether and others, 1973; Colton, 1962). The sequences are commonly thrust faulted (fig. 7). Thrusts are present in Pennsylvania and increase in abundance toward the south. Some of the thrusts and some high-angle faults are major structures having several miles of displacement. These structures pose serious problems for all concepts of waste disposal. Most drill holes would probably encounter faults at depth, and the difficulty of predicting stratigraphic sequences at great depths is obvious. As pointed out in the discussion of sedimentary basins, some shale at shallow depth has been used for disposal of low-level wastes at Oak Ridge, Tenn. The procedure followed there has been injection of fluid and grout into the shale under high pressure (Boegly and others, 1966).

The predominant aquifers in the Valley and Ridge province are sandstone and limestone, particularly limestone because of solution cavities, sink holes, and caves. Numerous thermal springs flow from limestones in West Virginia and Virginia. Some shales are dependable sources of water to depths of about 300 feet (91 m) Bieber, 1961, p. 21-22). Depth to water ranges from about ground level to about 150 feet (46 m).

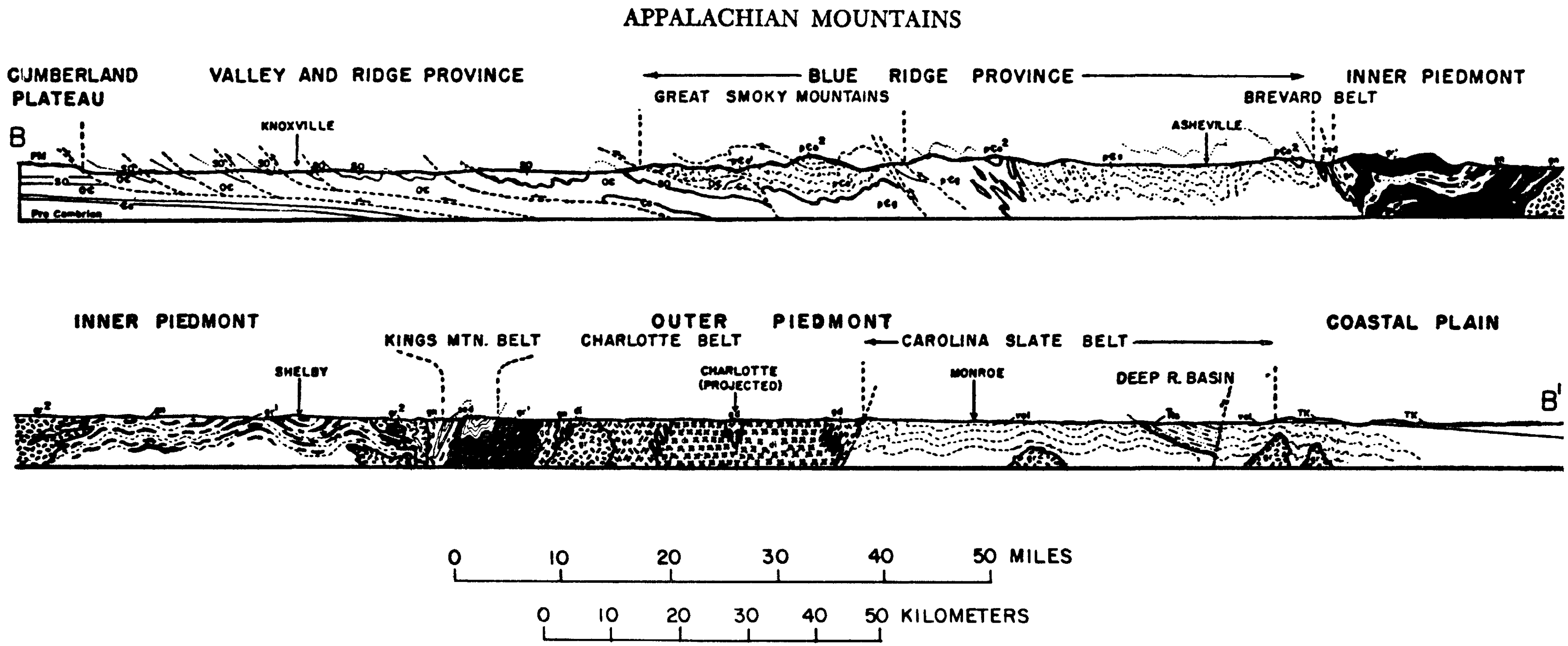


Figure 7.--Cross section of Appalachian system from Cumberland Plateau to Atlantic Coastal Plain. Modified from Eardley (1962).

Rocky Mountain system

The Rocky Mountain system (fig. 5) extends from northern New Mexico through Colorado, Wyoming, Montana, and Idaho into Canada. The system composes the most rugged terrane in conterminous United States and contains some of the most scenic mountainous areas in the world. The system is not a continuous mountain belt but is broken by the broad Wyoming basin and by an east-trending depression that extends through Yellowstone National Park. The mountains display a wide variety of geologic structures and contain, at one locality or another all the principal rock types known in the Earth's crust.

The southern Rocky Mountains in Colorado and northern New Mexico are principally north-trending anticlines that have been uplifted several times and deeply eroded to expose broad belts of granite and (or) metamorphic rocks of Precambrian age. The southern Rocky Mountains also encompass, in southwestern Colorado, the majestic San Juan Mountains that include extensive areas of volcanic tuff, lava, and intrusive masses of Tertiary age. Extending northward from the Basin and Range province in New Mexico through the southern Rocky Mountains in Colorado is a broad discontinuous depression or system of grabens that are similar in many ways to the larger basins in the Basin and Range province. This system forms the famous treeless parks of Colorado termed North, Middle and South Parks, and the broad San Luis Valley. The middle and northern Rocky Mountains include broad anticlinal uplifted areas with cores of Precambrian rocks, the volcanic terrane of the Yellowstone Plateau, the block-faulted Grand Tetons, the broad Uinta uplift, and the dissected uplifts of Montana and Idaho.

Elevations in the Rocky Mountain system range from less than 5,000 feet (1,520 m) to over 14,000 feet (4,270 m), and the higher ranges have been extensively glaciated. In the northern parts, particularly in Glacier National Park, glaciers still exist. Alpine glaciers have covered parts of the region several times, and vigorous glacial erosion is largely responsible for the rugged character of the higher ranges.

Precipitation ranges from less than 10 inches (25 cm) at lower elevations to more than 35 inches (89 cm) in the higher ranges. Sources of ground water include wells of small yield from shallow fractures in metamorphic and igneous rocks in the mountain ranges and wells of larger yield in unconsolidated sand and gravel in the valleys. Depth to water is generally shallow in both mountains and valleys. Thermal springs are common throughout the entire region (fig. 8) and indicate deep circulation, high subsurface pressures, and upward movement of water controlled in large part by deep-seated faults.

The mountains in many areas are cut by numerous thrust and vertical faults. Vertical or high-angle (greater than 45°) faults are especially abundant along the margins of the uplifts. Although large areas of crystalline rocks that are potentially suitable for waste disposal occur throughout the mountains, the abundance of faults in these rocks, both high and low angle, and the fact that the crystalline rocks are exposed principally in the ruggedest parts of the region where precipitation is greatest make the mountainous areas generally unattractive for all concepts of waste disposal. From the standpoint of potential accidents

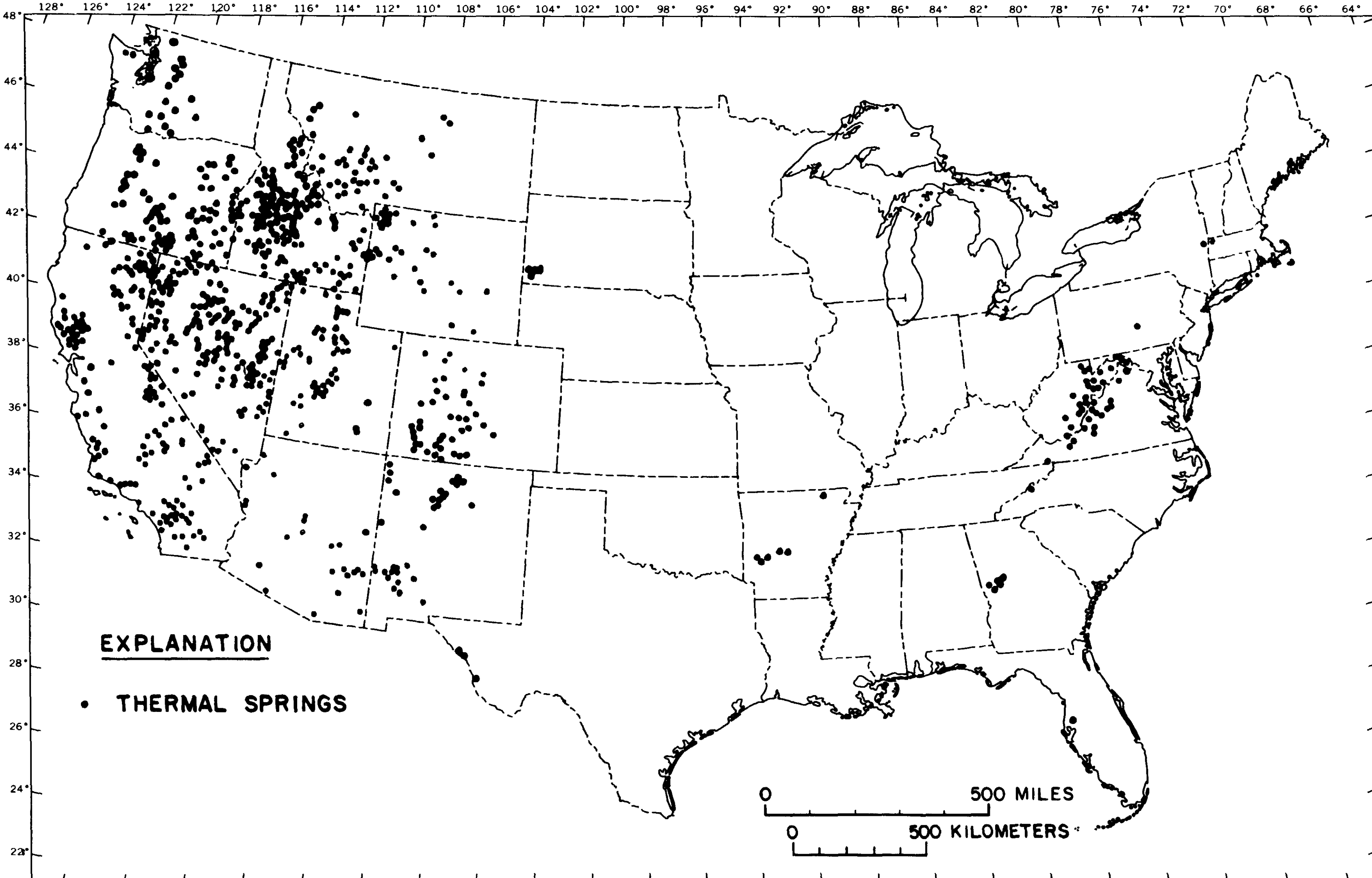


Figure 8.--Thermal springs in the United States. Modified from Waring (1965)

it must be pointed out that eight of the largest rivers in the United States head in the Rocky Mountains. Moreover, the ultimate source of recharge for more than 20 major regional aquifers is the Rocky Mountains.

Lower parts of the Rocky Mountain system, however, may be potentially suitable for shallow depth mined chanbers above existing water tables. These parts would include the structural basins, principally in Wyoming, where shale crops out or is near the surface in many areas. Precipitation is low, and ground-water tables locally are several hundred feet (a few hundred metres) below the surface.

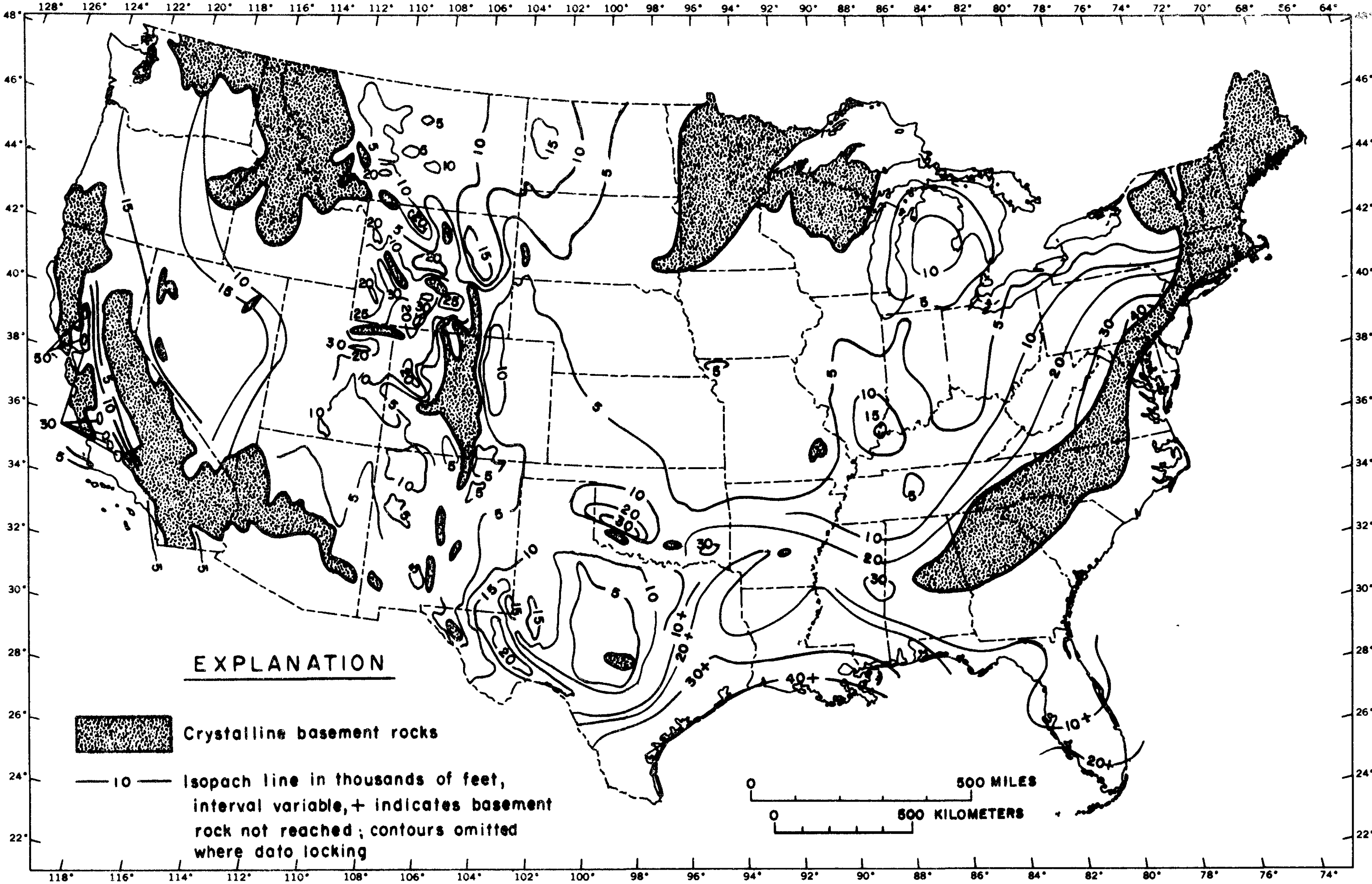
Sites for shallow depth mined chambers in Wyoming and all other areas in conterminous United States must be in areas of seismic risk zone 2 or less. Sites must be as far removed as possible from lakes and streams to make transit time to populated areas, water supplies, or aquifers as long as possible, and sites must be vertically isolated from aquifers or other permeable strata. Shale appears to provide the very low permeability that is essential for "vertical isolation" and, in addition, provides high ion-exchange capacity that is essential to slow the transport of radionuclides if leaks develop in the storage cell.

Areas of intrusive igneous and metamorphic rocks exclusive of the Basin and Range province

Crystalline igneous and metamorphic rocks occur at or near the surface in several large areas in the eastern,western, and northern United States and also in several small areas in the continental interior. Because these rocks (where they are not faulted) have very low porosities and permeabilities, especially in the subsurface below depths of a few thousand feet (a few thousand metres) they might be potentially suitable for waste disposal. The principal areas are shown by the stippled pattern on figure 9. The areas include the Idaho batholith, which, although physiographically a part of the Rocky Mountain system, represents such a large expanse of igneous and metamorphic rocks that it is logically included in this section.

Eastern metamorphic belt

The eastern metamorphic belt extending from Maine to Alabama is bounded on the east by the Atlantic Coastal Plain and Atlantic Ocean and on the west by the Appalachian Valley and Ridge province and Appalachian Plateaus. The southern part of the belt (fig. 6) includes two distinctly different terrains that are separated in part by a major northeast-trending, strike-slip fault zone (the Brevard schist zone). The western terrain, the Blue Ridge province (including the Great Smoky Mountains) is a mountainous region consisting of linear belts of metamorphosed alternating hard and soft rocks. The eastern part, the Piedmont province, is a region of relatively gentle terrain composed of strongly metamorphosed rocks that differ only slightly in their resistance to weathering and erosion despite great individual differences in rock composition.



Compiled by William Thordarson, 1972; Data taken from American Association of Petroleum Geologists and U.S. Geological Survey, 1967; Rocky Mountain Association of Geologists (1972)

Figure 9.--Principal areas of intrusive igneous and metamorphic rocks and thickness of sedimentary rocks in the United States

The Blue Ridge province is tightly folded and intensely faulted. Faults include several major thrust faults (fig. 7) especially in the southern part of the province. These geologic features in company with the rugged character of the terrain make the southern Blue Ridge province from northern Georgia to southern Virginia a most unattractive area for any concept of waste disposal. The northern part of the Blue Ridge, notably in northern Virginia, consists of an older Precambrian core of granite, granodiorite, and gneiss that is overlain and flanked by later Precambrian and Lower Cambrian metamorphosed sedimentary rocks and volcanic rocks, which are principally of basaltic composition. The possibility exists that the granitic core rocks may be potentially favorable for waste disposal.

The rocks of the Piedmont are upper Precambrian and lower Paleozoic gneisses, schists, and slates with minor amounts of marble and quartzite. Domes of gneiss occur locally within the schist. Large granitic intrusive masses, ranging in age from early to late Paleozoic, and small masses of ultramafic rocks such as peridotite, dunite, and pyroxenite, which may be early Paleozoic in age, are scattered throughout the province. Few faults have been recognized. The most important of these are the faults that bound the Triassic grabens, which are shown as sedimentary basins (fig. 2). The granitic and ultramafic bodies and the gneissic rocks seem to compose the most suitable media for waste disposal. At the Atomic Energy Commission's Savannah River Plant, near the boundary of the Piedmont and the Atlantic Coastal Plain, hydraulic tests were run in several holes completed in crystalline rock at shallow depths (to 1,900 ft or 580 m) (Marine, 1967). The rock contained fractured zones, but permeabilities generally were low.

Transmissivity, determined from the tests, ranges from $2x10^{-3}$ to $2x10^{-1}$ gallons per day per foot ($2x10^{-5}$ to $2x10^{-3}$ cubic metres per day per metre). At deeper levels the rocks may have even lower transmissivity.

The northern part of the eastern belt comprises the igneous and metamorphic rocks of the New England States (fig. 10). These rocks are tightly folded and include thick marbles in the western part and slates and schists in the eastern part. These rocks are locally intruded by granitic plutons of two ages. The older intrusive masses (early Paleozoic in age) have been metamorphosed and deformed. The later masses (middle and late Paleozoic in age) are fresh and undeformed and thus seem to offer the greatest potential for disposal.

In general, igneous and metamorphic rocks of the eastern metamorphic belt yield abundant water to wells that average less than 450 feet (140 m) in depth (Cederstrom, 1972, p. 35). Fractures in the rock carry the water, and these logically may be tight and possibly healed in the deeper subsurface. Sheet mica is mined successfully in the Piedmont at shallow depths, and the mines are virtually dry (W. R. Griffitts, oral commun., 1973).

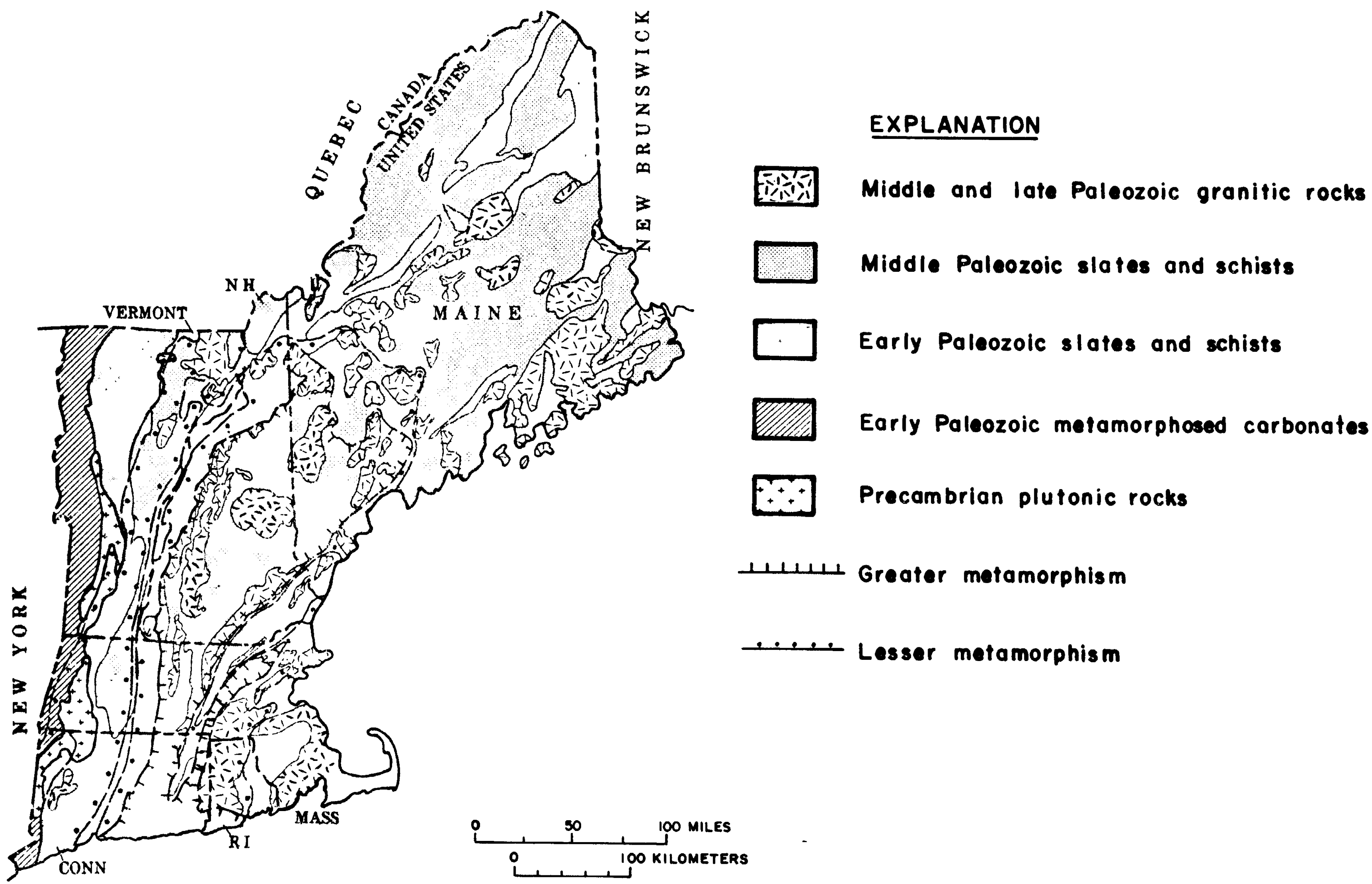


Figure 10.--Geologic map of New England. Modified from Hamilton and Meyers (1967)

Shield area

The only shield area in the United States, with the exclusion of the Adirondacks, is an extension of the Canadian Shield into Minnesota, Michigan, and Wisconsin. Adirondacks, which have igneous and metamorphic rocks younger than those of the shield area of the north-central part of the country, are discussed as an isolated area under the heading of "Small areas in the continental interior" (p. 63). The shield in Minnesota, Michigan, and Wisconsin is a broad area of gentle terrain mantled with glacial drift and underlain by Precambrian igneous and metamorphic rocks. The shield comprises some of the oldest rocks of the continent in a region that is tectonically stable. Most of these rocks have moderate to low permeabilities at the surface and, at depths below a few thousand feet (a few thousand metres) where they are not faulted, probably have very low permeabilities.

The Precambrian rocks making up the shield in Minnesota, Michigan, and Wisconsin (fig. 11) consist of an old series of highly contorted and metamorphosed clastic sediments and volcanics, which are largely of basaltic composition and gneissic granite. This series is, in turn, overlain by younger metamorphosed rocks consisting of quartzites, dolomites, and slates and clastic rocks interbedded with lava. The younger rocks, which include the iron formations of the Lake Superior region, occupy a smaller part of the shield. Superposed on these rocks are thick sequences of basaltic lava and sandstone which are gently tilted and which are locally copper bearing. A body of gabbro 140 miles (225 km) long and nearly 50,000 feet (15,240 m) thick, whose edge emerges along the southwestern shore of Lake Superior, separates

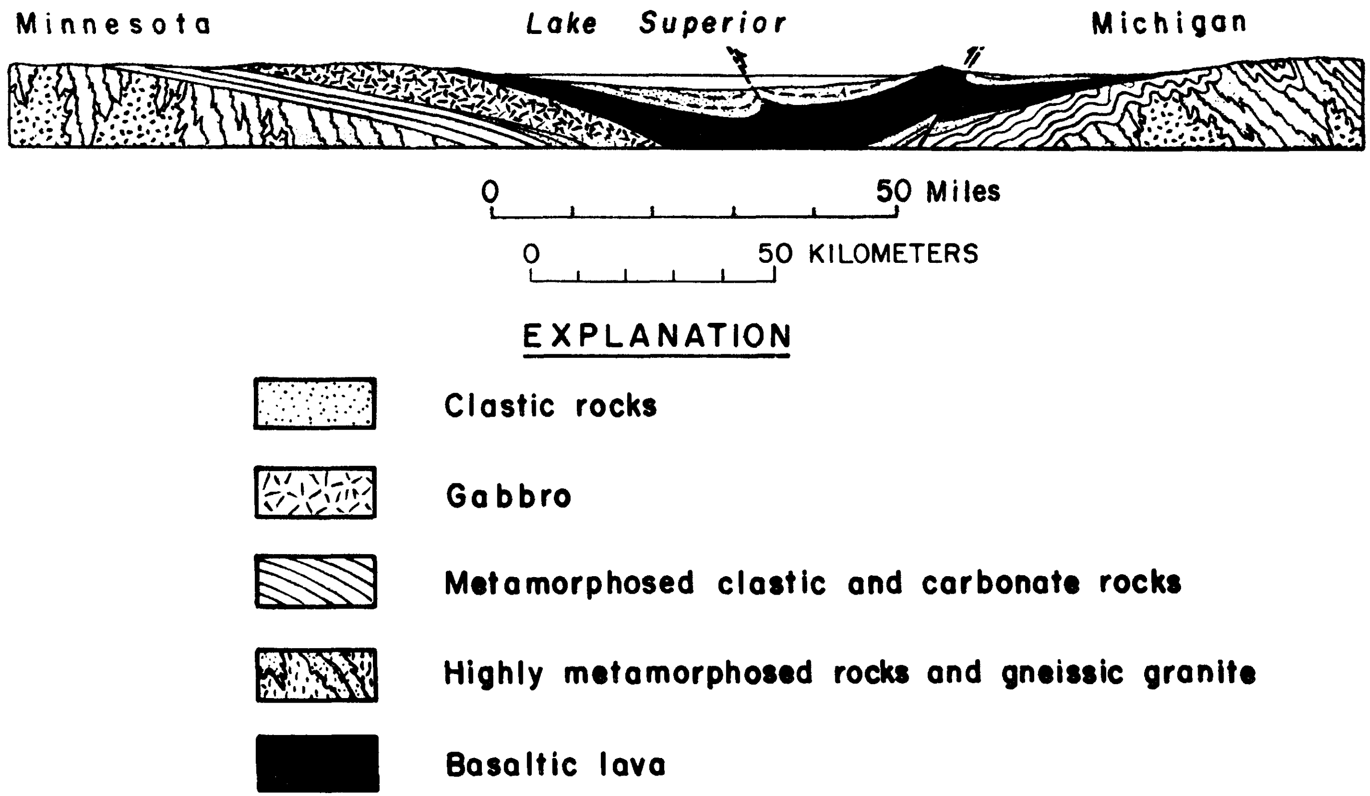


Figure 11.--Generalized geologic section across Lake Superior region. Modified from P. B. King (1959).

the youngest sequence of rocks from the older groups. The gabbro represents a mafic body that probably has roots extending to great depths in the crust. Because of its great thickness and extent, homogeneity, and probable very low permeability below the zone of open fractures and strong weathering, the gabbro probably is suitable for waste disposal provided a major fracture zone is not encountered at depth.

The ancient crystalline rocks, though heterogenous, are highly metamorphosed and stabilized and, therefore, could probably be considered as a single, more or less homogeneous body for concepts of waste disposal. Because of proximity to the Great Lakes, special care must be taken to ensure absolute confinement of waste to the disposal site. Fault and fracture patterns must be analyzed in great detail to evaluate possible migration paths of radionuclides vertically and laterally. Even slight contamination of the Great Lakes or other bodies of water in the area cannot be tolerated.

Precambrian shield rocks yield little water and usually are explored only for small domestic supplies. Near the surface, fractures and clayey weathered zones in the igneous and metamorphic rocks yield small supplies of water (McGuinness, 1963, p. 434). Mines in the shield rocks at Sudbury, Ontario, are extremely dry in levels below a few hundred feet (a few tens of metres) of the surface (A. L. Brokaw, oral commun., 1973) and mines of the Michigan Copper Company, which have hundreds of miles (hundreds of kilometres) of workings to depths of 5,000 feet (1,520 m) encounter such small amounts of water that no pumps are required (W. R. Griffitts, oral commun., 1973). These facts suggest that rocks in other parts of the shield area are probably equally dry, but this possibility would, of course, have to be proved by extensive borehole investigation.

Small areas in the continental interior

Small isolated areas of Precambrian intrusive igneous and metamorphic rocks in the continental interior may be potentially suitable for waste disposal. These include the Adirondack Mountains of New York, the St. Francois Mountains of Missouri, the Wichita Mountains of Oklahoma, and the Llano uplift of central Texas. A small area of upper Cretaceous intrusive igneous rocks in central Arkansas also may be suitable for waste disposal.

Adirondacks.--The Adirondacks constitute a nearly circular uplift about 150 miles (240 km) across having a core of granitic and mafic rocks. A large mass of anorthosite 40-50 miles (60-80 km) across and covering 1,200 m^2 (3,110 km^2) is located in the eastern part of the uplift.

St. Francois Mountains.--The St. Francois Mountains occupy an area of less than 100 mi^2 (260 km^2) on the crest of the Ozark dome and are made up mainly of granitic intrusive rocks and metamorphosed volcanic rocks. The granitic rocks are believed to represent the uppermost part of a batholith.

Wichita Mountains.--The Wichita Mountains comprise a group of hills, rising about 1,500 feet (460 m) above the plains and scattered through an area 60 miles (100 km) long and 25 miles (40 km) wide. The hills are chiefly granite with some mafic rocks, and may represent the silicic caprocks of a larger body of mafic rocks at depth.

Llano uplift.--The Llano uplift is a topographic basin superposed on a structural uplift as the result of erosion of the exposed crystalline rocks that is more rapid than that of the more resistant sedimentary rocks that rim the crystallines. The area of crystalline rocks is about 50 miles (80 km) long and 25 miles (40 km) wide and is made up of schists, gneisses, and intrusive granites and mafic rocks.

Central Arkansas.--Scattered hills of low relief, located in the vicinity of Little Rock, Arkansas, are made up of nepheline syenite, a quartz-poor, competent granitoid rock that is remarkably homogeneous in its lithology and engineering properties. Bauxite, derived from highly altered syenite, occurs on the slopes and is mined for aluminum, but less altered syenite underlies the crests and should be relatively fresh below the zone of weathering.

The granitic and mafic rocks of these isolated areas in the continental interior seem to offer characteristics that meet requirements for waste disposal. Fracturing and faulting, however, will predictably preclude parts of the areas, and drilling is necessary to ascertain to what depths water-bearing fractures and faults will extend.

Sierra Nevada

The mountains of the Sierra Nevada trend northwestward for 400 miles (640 km) through the east-central part of California. The chain is contiguous with, but geologically distinct from, the Cascade Ranges that extend through Oregon and Washington. The Sierra Nevada is bounded on the east by the Basin and Range province and on the west by the Great (or Central) Valley of California.

Physiographically, the Sierra Nevada may be described as a huge block of resistant rocks, locally of unequal strength and complex structure, that has been uplifted by faulting and tilted to the west. The block is dissected by deep valleys and, in its higher parts, strong glaciated (Fenneman, 1931, p. 398).

Three-fourths of the rocks underlying the Sierra Nevada are granitic. The granitic rocks are part of a batholith that extends no deeper than about 33,000 feet (10,100 m) below the central mountains (Hamilton and Myers, 1967, p. C2). Beneath these granitic rocks are gneissic metamorphic rocks, as inferred mainly from geophysical data.

The granitic and gneissic rocks in the deeper subsurface of the area probably constitute favorable media for waste disposal, on the basis of their physical properties and the presumed absence at depth of open, water-bearing fractures. However, a general unsuitability of the Sierra Nevada for waste emplacement is indicated by (1) a high degree of seismic risk (most of the mountain range is in seismic risk zone 3), (2) potential hazards from renewed glaciation, (3) the fact that the mountain mass serves the the ultimate recharge source for very important aquifers in the Great Valley of California and Owens Valley, (4) several large rivers that head in these mountains, and (5) the steep drainage gradients probably make the Sierra Nevada generally unsuitable for waste-disposal sites.

Idaho batholith and related plutons

The Idaho batholith and related plutons are in the Northern Rocky Mountains, mainly in central and northern Idaho but extending into western Montana. The batholithic terrain is a broad area of crystalline rocks and is characterized by deeply dissected mountain uplands and intervening intermountain basins. The rocks are almost uniformly resistant to erosion and give rise to a topography of almost no linearity.

Crest levels of the central mountains vary from 7,000 to 12,000 feet (2,130 to 3,660 m); valleys are mostly narrow and are at elevations of 3,000-5,000 feet (910-1,520 m).

The batholith consists of virtually structureless granodiorite and quartz monzonite. These rocks underlie two main regions, one in the southwestern part of the area and the other in the northeastern; elsewhere, much schist and gneiss are interspersed with the intrusive rocks (Hamilton and Myers, 1967, p. C5). The plutonic intrusives are dated as Cretaceous, but additional igneous activity has occurred during Tertiary time. Some volcanic rocks forming a crust over the batholith are of Eocene age.

The widespread occurrence of thermal springs (fig. 8) (Waring, 1965, p. 14) indicates circulation of water at moderate or great depths. The igneous and metamorphic rocks also yield water from the shallow subsurface, where joints and other fractures are open and the rocks are weathered, and mines in or adjacent to the batholith at Butte, Mont., and in the Coeur d'Alene district of Idaho produce abundant water and require pumping even in levels as deep as 7,000 feet (2,130 m) (J. W. Hasler, G. B. Gott, and E. T. Ruppel, oral commun., 1973). Runoff from the mountain ranges contribute to the recharge of several highly productive aquifers on the south, east, and west sides of the batholith. Of particular note are the basaltic aquifers of the Snake River Plain to the south.

The igneous and metamorphic rocks of the batholith probably locally constitute suitable media for the deeper methods of waste disposal; however, the indication of moderate or deep circulation of water given by thermal springs and deep mines, the large runoff of surface water, relatively high seismic risk, possibility of renewed glaciation in the higher parts, and rugged terrain make the Idaho batholith and related plutons generally unsuitable for all methods of waste disposal.

The suitability of rocks to the various disposal methods in the shield area, eastern metamorphic belt, and small areas of the continental interior are given in table 3.

Discussion of factors that influence suitability

The conclusion that the metamorphic and intrusive igneous rocks are suitable or possibly suitable for waste disposal in the shield area, eastern metamorphic belt, and small areas in the continental interior is based entirely on the inference that these rocks will have low to very low permeabilities (if faults are avoided) a few thousand or a few hundred feet (a few thousand or a few hundred metres) below the surface. The inference stems from field observations,

Table 3.--Suitability of rocks to disposal methods in the shield area, eastern metamorphic belt, and small areas of the continental interior

[S, suitable; PS, possibly suitable. Ratings are based on the premise that sites can be demonstrated to be isolated, and predictably will remain isolated from the hydrologic system. Most crystalline rocks are particularly susceptible to weathering and fracturing; the depth and areal distribution of fracture systems must be determined at any selected disposal site. Pilot studies must also demonstrate that any fractures that might develop as a result of host-rock expansion will be insignificant. Only alkaline wastes can be considered for disposal in marble.]

Rock type	Very deep drill hole (30,000-50,000 ft or 9,140-15,240 m) 1/	Matrix holes (1,000-20,000 ft or 305-6,100 m)	Mined chamber (1,000-10,000 ft or 305-3,050 m)	Exploded cavity (2,000-20,000 ft or 610-6,100 m)	Cavities with separate man-made structure (1,000-10,000 ft or 305-3,050 m)
Slates and schists.	PS	PS	PS	PS	PS
Quartzites	PS	PS	PS	PS	PS
Marbles	PS	PS	PS	PS	PS
Gneisses	S	S	S	S	S
Amphibolites	S	S	S	S	S
Granitic rocks	S	S	S	S	S
Mafic rocks	S	S	S	S	S

1/ Rock types at these depths are very uncertain. Except in large granitic plutons, several rock types will probably be penetrated by deep drill holes in most terrains.

shallow-well data, and the knowledge that some mines in metamorphic and igneous rocks are dry at shallow depths. Data are scanty, however, and until the areas are drilled and hydraulically tested the suitability ratings must be regarded as highly tentative. It also must be pointed out that it might be extremely difficult to locate areas entirely free of faults.

The rating of "possibly suitable" rather than "suitable" for quartzite, marble, slates, and schists is based on the greater potential for permeability in these rocks than in the more massive gneisses, granites and amphibolites.

<u>Areas of gently folded volcanic terrane</u>

Columbia Plateau

The Columbia Plateau (exclusive of the Snake River Plain) is an area of generally gently dipping (but locally tightly folded, at least on the surface) lava flows embracing about 100,000 mi^2 (259,000 km^2) in Washington, Oregon, and Idaho (Fenneman, 1931). The area is bounded on the west by the Cascade Mountains, on the north and east by the Rocky Mountains on the south by the Great Basin. Topographic relief is generally low; however, elevations range from a few hundred feet (few hundred meters) along the Columbia River to over 7,000 feet (2,130 m) in the Blue Mountains in eastern Oregon.

The rocks are principally basalt lava flows that individually are 10 feet (3.05 m) to as much as 200 feet (61 m) thick. The cumulative thickness of the flows, one of the greatest lava piles in the world, ranges from a few hundred feet (several tens of metres) around the margins of the plateau to considerably more than 10,000 feet (3,050 m) in the Pasco Basin, a topographic and structural depression that lies near the center of the plateau. The lavas are overlain locally by thin glacial outwash gravels, lake sediments as much as 1,000 feet (305 m) thick, and windblown loess that provides an unusually porous soil. The soil absorbs moisture so rapidly that there is no direct runoff from most of the area, and, consequently there are few alluvial fans or other features that characterize semiarid and arid terranes. Around the margins of the plateau the rocks beneath the basalt sequence consist of deformed Mesozoic and Paleozoic strata. In the interior, these may be absent and the basalt may overlie oceanic crust (Hamilton and Myers, 1966).

The structure of the Columbia Plateau is, to date, poorly understood. Despite the overall aspect of gentle folds and broad areas of Early horizontal strata, tight folds are locally conspicuous. These are most abundant west of the Pasco Basin and trend west, northwest, and west-northwest. Many folds are asymmetric, some are overturned, some are thrust faulted. The cause of this type of tectonism is not clear, but the folds possibly have developed subaerially in response to convergent plate movements. Continued microseismic activity (R. M. Hamilton, written commun., 1972) in the Hanford area of the Pasco Basin, together with the historic occurrence of major earthquakes on the plateau, indicates that the area is still tectonically active.

The suitability of rocks to the various disposal methods on the Columbia Plateau is given in table 4.

Discussion of factors that influence suitability.--The principal factors that dictate the overall unsuitability of the basalts on the Columbia Plateau for any of the methods of waste disposal are the generally high porosity and permeability of the contact (interflow) zones between individual lava flows. These interflow zones contain weathered rock, rock breccia, and, commonly, porous bedded tuff and sandstone. Any column of strata over a few hundred feet thick can be expected to include several of the highly permeable zones. For this reason it seems unlikely that sufficiently thick zones of very low permeability rock exist in the basalt terrane to accommodate either a shallow depth mined chamber or a shallow nuclear cavity (10,000 ft or 3,050 m, or less). Deep exploration may define zones of very low permeability beneath the basalt or within the basalt at great depths that are sufficiently thick to accommodate matrix holes, a deep nuclear cavity, or a very deep drill hole, but hydrologic isolation from the basalt aquifers must be demonstrated. In spite of the semiarid climate that prevails over most of the region, the reserves of fresh water in the basalt and in the overlying sediments are enormous (McGuinness, 1963). Highly permeable, fresh-water aquifers have been drilled and tested, but most hydrologic data are from shallow holes because water is at shallow depth, less than 100 feet (30.5 m) at some places. Some tests were made in a deep stratigraphic test hole

Table 4.--Suitability of rocks to disposal methods--Columbia Plateau

[PS, possibly suitable, based on the premise that the rocks beneath the basalt can be demonstrated to be hydrologically isolated from the overlying basalt aquifers. NS, not suitable]

Rock type	Very deep drill hole (30,000-50,000 ft or 9,140-15,240 m)[1/]	Matrix holes (1,000-20,000 ft or 305-6,100 m)	Mined chamber (1,000-10,000 ft or 305-3,050 m)	Exploded cavity (2,000-20,000 ft or 610-6,100 m)	Cavities with separate man-made structure (1,000-10,000 ft or 305-3,050 m)
Basalt-----	NS	NS	NS	NS	NS
Underlying rocks.	PS	PS	PS	PS	PS

1/ Oceanic crust, granite, or metamorphic rocks at 50,000 feet (15,240 m).

in the Rattlesnake Hills near the Pasco Basin. Raymond and Tillson (1968) reported that results of these tests show a decreasing head with depth. Ground water thus has the potential to move downward in the vicinity of this hole. They further reported that results of geophysical logging and of chemical analysis of formation-fluid samples show increased dissolved solids content with depth, but, significantly, no evidence of saline or highly brackish water as deep as 5,997 feet (1,830 m) in the test hole. This means that fresh water could occur quite deep in parts of the Columbia Plateau and that even shallow disposal or storage of waste could contaminate a valuable source of water at great depth if the potential for ground water to move downward is substantiated.

Snake River Plain

The Snake River Palin (a physiographic subdivision of the Columbia Plateau) is a 50- to 100-mile-wide (80- to 160-km-wide) east-trending arcuate swath that extends across the Rocky Mountains through the State of Idaho from Yellowstone National Park at the eastern or northeastern end to the Columbia Plateau at the western or northwestern end--a distance of over 300 miles (480 km). The surface of the plain slopes toward the Snake River from a maximum height of nearly 6,000 feet (1,830 m) at the northeast to less than 4,000 feet (1,220 m) at the western end. The plain is formed of basalt and rhyolite lavas and interbeds of tuff and sandstone. The variety of rocks is in marked contrast to the Columbia Plateau proper where basalt is almost the sole rock type.

The structure of the plain is poorly known. The abrupt termination of north-trending faults and other structures by the east-trending plain suggests that the plain is a major graben (Schoen, 1972). Alternative hypotheses include a giant downwarp or monocline (Kirkham, 1931) and a progressively spreading tensional rift (Hamilton, 1963; Hamilton and Myers, 1966). Volcanic eruptions occurred in the area as late as about A.D. 400 according to Bullard and Rylander (1970). The possibility exists, therefore, that volcanism is still in progress and eruptions could occur again within the next 1 m.y.

Data are insufficient to determine the thickness of the volcanic rocks or the types of rocks that underlie the volcanics in the Snake River Plain. Hamilton and Myers (1966) infer that only oceanic crust is present beneath the western plain. Schoen (1972), on the basis of ground-water chemistry, concludes that granitic rocks similar to those in the Idaho batholith underlie the volcanic rocks and that carbonate rocks may underlie the volcanic rocks at some places.

According to Morris (1967), long-term rates of ground-water movement in the basalt sequence are very high, averaging from 1.8 to 2.4 m per day, with short-term rates as great as 16.5 m per day. The high rate of ground-water movement within the sequence of volcanic rocks and the implication of significant permeability at depth, based on the presence of hot springs, require that most concepts to place wastes in this geohydrologic environment must be considered unfavorable. Though little is known of the underlying rocks, wastes placed in them cound still be in proximity to the overlying large supply of fresh water. Acceptability of deep-disposal methods (deep drill hole or deep nuclear cavity) must necessarily depend upon results of exploration of the underlying strata.

Available geologic and hydrologic data suggest there is little difference, from the standpoint of waste disposal, between the Snake River Plain and the Columbia Plateau, except that there is much greater possibility of renewed volcanic activity in the Snake River Plain. Such activity could be extremely hazardous to any waste-disposal site. All concepts are generally unsuitable for the same considerations as given for the Columbia Plateau.

Colorado Plateau and central interior areas exclusive of sedimentary basins

Colorado Plateau province

The Colorado Plateau province is an area of approximately 130,000 mi^2 (337,000 km^2) embracing large parts of Colorado, New Mexico, Arizona, and Utah. The province is bounded on the west and south by the Basin and Range province, on the east by the Rocky Mountains, and on the north by the Wyoming basin. The most distinguishing feature of the Colorado Plateau is the approximate horizontality of its rocks (Fenneman, 1931), and a second distinguishing feature is its great elevation--most of the plateau lies between 5,000 feet (1,520 m) and 11,000 feet (3,350 m) above sea level. The province is not a single large plateau but consists of many small plateaus and mesas separated by large canyons; individual mesas are further segmented by smaller canyons. The Colorado Plateau is a very good example of how a relatively low flat area was uplifted and subjected to extremely rapid erosion. Initially, low erosion rates were changed to much higher erosion rates (Gera and Jacobs, 1972, p. 69) when the region was uplifted. An important feature of the plateau is the retreating escarpment. Mesas lose area at a rapid rate (in terms of geologic time) while suffering little or no loss of height (Fenneman, 1931).

The stratigraphy is varied but most mesas and plains are capped by resistant sandstones of Mesozoic age. Locally, especially around the borders of the province, volcanic rocks of Tertiary age--tuffs and lavas--form the mesa caprocks. These areas include the high plateaus of Utah and the San Francisco volcanic fields of Arizona. Both areas border on the Basin and Range province. Igneous intrusive masses that consist of nearly horizontal sills, mushroom-shaped laccoliths, and large stocks break the "topographic plain" in several areas in the central part of the plateau. These intrusive masses form rugged mountainous terrain.

Except for the basins (principally the Paradox, Uinta, and San Juan) within the Colorado Plateau, the sedimentary rocks above the crystalline basement are thin and consist dominantly of carbonates in the lower part and sandstones and sandy shales in the upper part. Because of the general abundance of highly permeable rocks in this stratigraphic section, the sedimentary rocks on the plateau exclusive of basins are generally unfavorable for all concepts of waste disposal, although depths to water generally are rather large--ranging from a few hundred to more than 1,000 feet (several tens to more than 305 m). Areas having the greatest potential for waste disposal exclusive of the basins appear to be those where the crystalline basement rocks crop out or are present at shallow depth. These areas are zones of major upwarping or uplift. They and the principal basins on the Colorado Plateau are shown on figure 12.

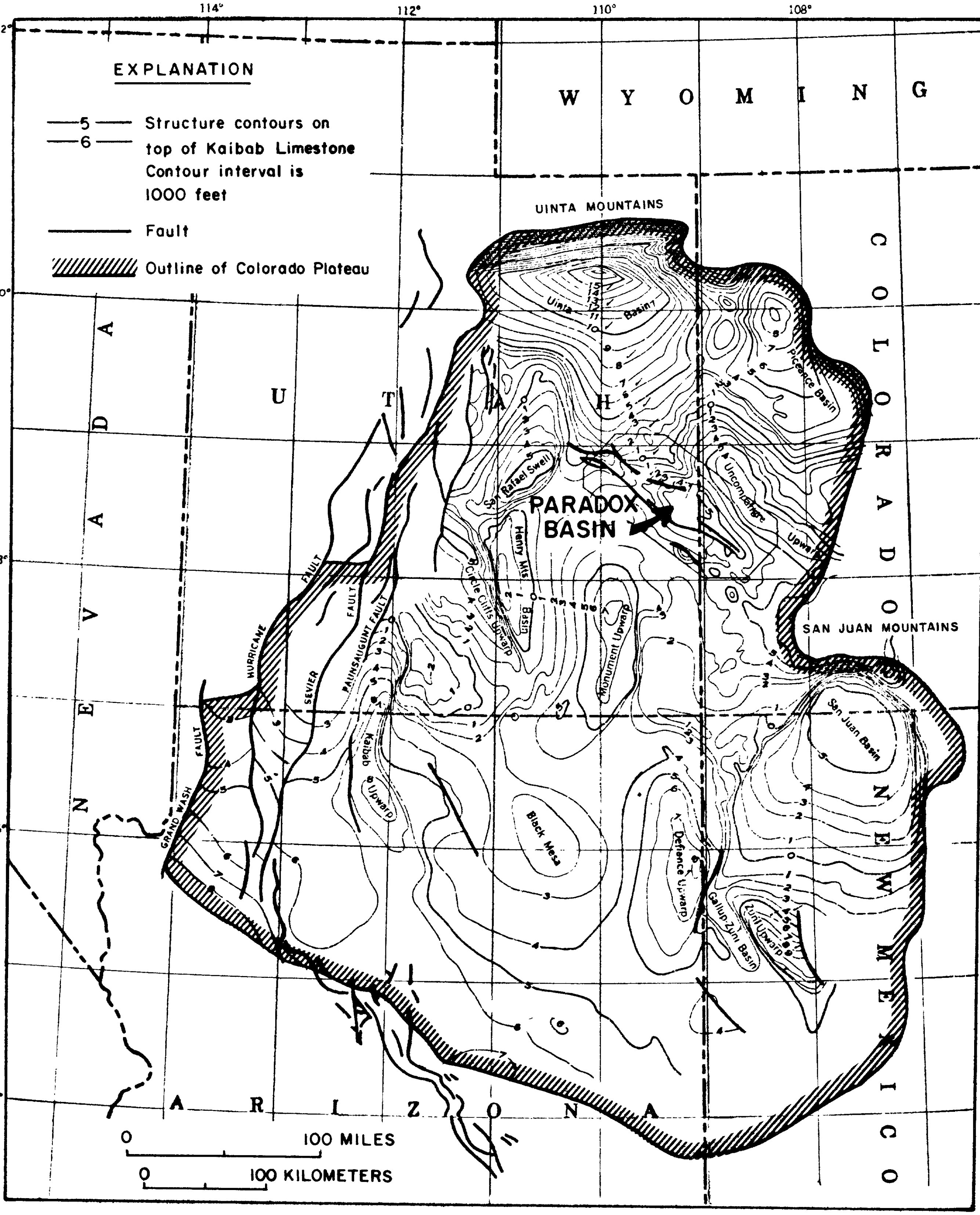


Figure 12.--Structure-contour map of the Colorado Plateau showing areas of major uplift and principal basins. Modified from Hunt (1956).

According to Hunt (1956) the crystalline basement (Precambrian) rocks consist of one or more very thick sequences of metamorphosed sedimentary and volcanic rocks and a series of large and extensive intrusive masses. Principal references to these crystalline rocks are: Defiance upwarp (Gregory, 1917, p. 17), Zuni Mountains (Lindgren and others, 1910), and Uncompahgre Plateau (Dane, 1935; Case and Peterman, 1968). The factors that influence suitability of these areas of crystalline rocks on the Colorado Plateau are nearly the same as those summarized in "Areas of intrusive igneous and metamorphic rocks exclusive of the Basin and Range province" (p. 55).

Central interior areas exclusive of sedimentary basins

The central interior areas referred to herein include the following physiographic subdivisions of Fenneman (1931): the Great Plains, Central Interior Lowlands, and Interior Low Plateau. The central interior areas are bounded on the west by the Rocky Mountains, on the east by the Appalachian Plateau and Appalachian Mountains, on the south by the Atlantic Coastal Plain, and on the north by the Great Lakes shield area and Canada.

This vast area is a region of gentle topography and embraces the principal agricultural belt of the United States. The topography, central location, and generally low seismic risk are very attractive features for waste disposal. The sedimentary sequence is thin, rarely exceeding 5,000 feet (1,520 m) in thickness (fig. 9); the sequence includes much porous sandstone and limestone. In fact, the greatest sandstone and limestone aquifers and the most extensive limestone cave areas of the United States occur in this part of the central interior.

At some places, water in the limestone recharges the sandstone aquifers (Swenson, 1968, p. 163). Shale of late Paleozoic age, which is interbedded with coal and sandstone, is an important rock unit in the eastern part of the area but, except possibly for the sedimentary basins, probably is not of sufficient thickness to ever constitute an acceptable zone for waste disposal. In the northern Great Plains and northern part of the Central Interior Lowlands of Fenneman (1931) the Pierre Shale (Merewether and others, 1973; Tourtelot, 1962; Tourtelot and others, 1960) is an important stratum. It crops out in broad areas in the Great Plains and directly underlies thin glacial drift in many parts of North and South Dakota. This unit, however, directly overlies permeable limestones and sandstones and is in close proximity to the Dakota Sandstone, one of the principal regional artesian aquifers. It is extremely doubtful, therefore, if the Pierre Shale can be used for waste disposal in this region which uses great quantities of ground water from this extremely important artesian reservoir. The Pierre and other shales may be suitable for shallow depth mined chambers in areas far removed from lakes and streams and where exploration defines a thick section without permeable interbeds. Depth to ground water, however, may be a limiting factor.

The crystalline rocks beneath the relatively thin sedimentary cover appear to be the best media for waste disposal in the central area exclusive of sedimentary basins. In most of this region, crystalline rocks are no more than 5,000 feet (1,520 m) below the surface (fig. 9). Public concern over seismic activity resulting from deep-well injection of toxic liquids into the Precambrian basement beneath a thick sedimentary cover at the Rocky Mountain

Arsenal near Denver, Colo., and apprehension over the disposal of high-level liquid or soluble wastes in the Precambrian basement at the Savannah River Plant near Augusta, Ga., should not rule out the potential suitability of crystalline rocks beneath thin sedimentary covers. The disposal of wastes into the Rocky Mountain Arsenal well does show, however, that faults and other unfavorable features may be present at depth in basement rocks and may not be reflected in the overlying sedimentary rocks. The injection of wastes at Denver apparently activated an old fault by overcoming frictional resistance to fracture. The increased pore pressure induced by fluid injection under high pressure decreased the effective normal stress along the fault plane (Healy and others, 1968) and movement occurred. Permeable fractures encountered during drilling at the Savannah plant are most probably related to preerosional tectonics and subsequent weathering during the development of the erosion surfaces. Deeper drilling could show a transition from open to closed fractures with increased depth.

The ability of a metamorphic rock to prevent the escape of liquids within a few thousand feet (several hundred metres) of the surface and the ability of another rock to readily transmit liquids are illustrated by the probable movement of water below the surface at Warm Springs, Ga. (fig. 13). Water percolating downward through permeable basal beds of a quartzite underlain by a gneiss that has very low permeability encounters a marked fault that offsets the quartzite. The fault acts as a barrier to the movement of the water, causing it to return to the surface through permeable beds

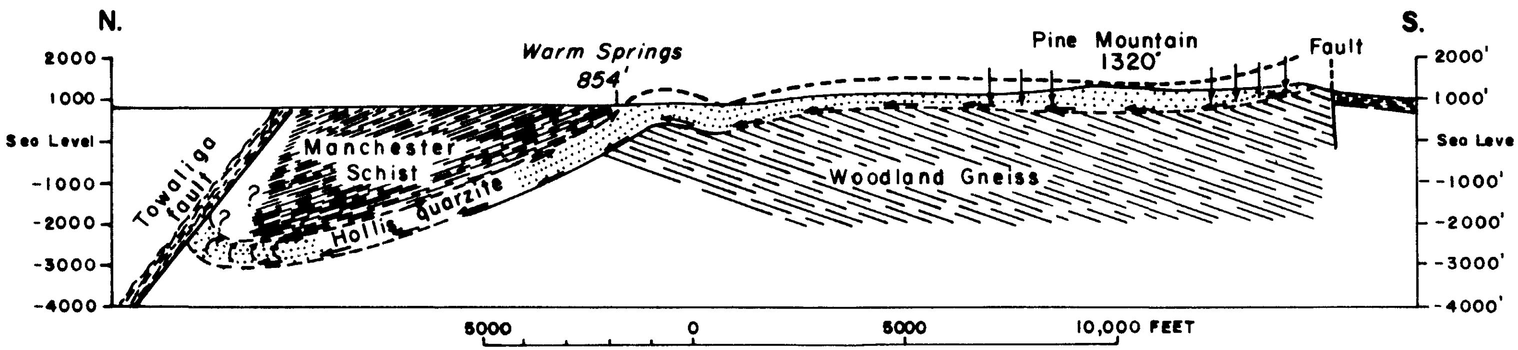


Figure 13.--Cross section through Pine Mountain and Warm Springs, Ga., showing geologic structure and (by arrows) probable course of the water that enters Hollis Quartzite as rain on Pine Mountain and is discharged at Warm Springs. Modified from Hewett and Crickmay (1937).

in the uppermost part of the quartzite. These beds are overlain by a schist having relatively low permeability, which prevents the escape of the water before it reaches the surface at Warm Springs. The fact that the fault acts as a barrier rather than as a conduit indicates that old faults encountered at depth in some areas may be completely healed and are not necessarily detrimental. The suitability of rocks for disposal in the Colorado Plateau and central interior exclusive of sedimentary basins is shown in table 5.

Basin and Range province

A large area in western United States that is characterized by roughly parallel mountain ranges separated by desert basins is termed the Basin and Range province. This province is bounded on the west by the Sierra Nevada, on the east by the Colorado Plateau, and on the north by the Snake River Plain and Columbia Plateau. The province extends southward into Mexico. The northern half, called the Great Basin (fig. 14) is characterized by internal drainage; however, throughout the area most of the runoff from rainfall ends in enclosed basins. The ground-water table is several hundred feet (a few hundred metres) deep in many of the basins and more than 2,000 feet (610 m) deep under some of the ranges and mesas.

The stratigraphy in the province is extremely varied. Some ranges consist dominantly or wholly of pre-Tertiary sedimentary rocks, which are principally carbonates in the eastern part and shales and sandstones in the western part. In other ranges, especially in the central part of the province, volcanic rocks form the principal

Table 5.--Suitability of rocks to disposal methods--Colorado Plateau and central interior areas exclusive of sedimentary basins

[S, suitable. Rating is based on the premise that sites can be demonstrated to be isolated and will predictably remain isolated from hydrologic system. NS, not suitable.]

Rock type	Very deep drill hole (30,000-50,000 ft or 9,140-15,240 m)	Matrix holes (1,000-20,000 ft or 305-6,100 m)	Mined chamber (1,000-10,000 ft or 305-3,050 m)	Exploded cavity (2,000-20,000 ft or 610-6,100 m)	Cavities with separate man-made structure (1,000-10,000 ft or 305-3,050 m)
Basement rocks in upwarps and beneath thin sedimentary rocks.	S	S	S	S	S
Sedimentary rocks other than shale.	Not present at depth.	NS	NS	NS	NS
Shale--------	Not present.	NS	NS	NS	NS

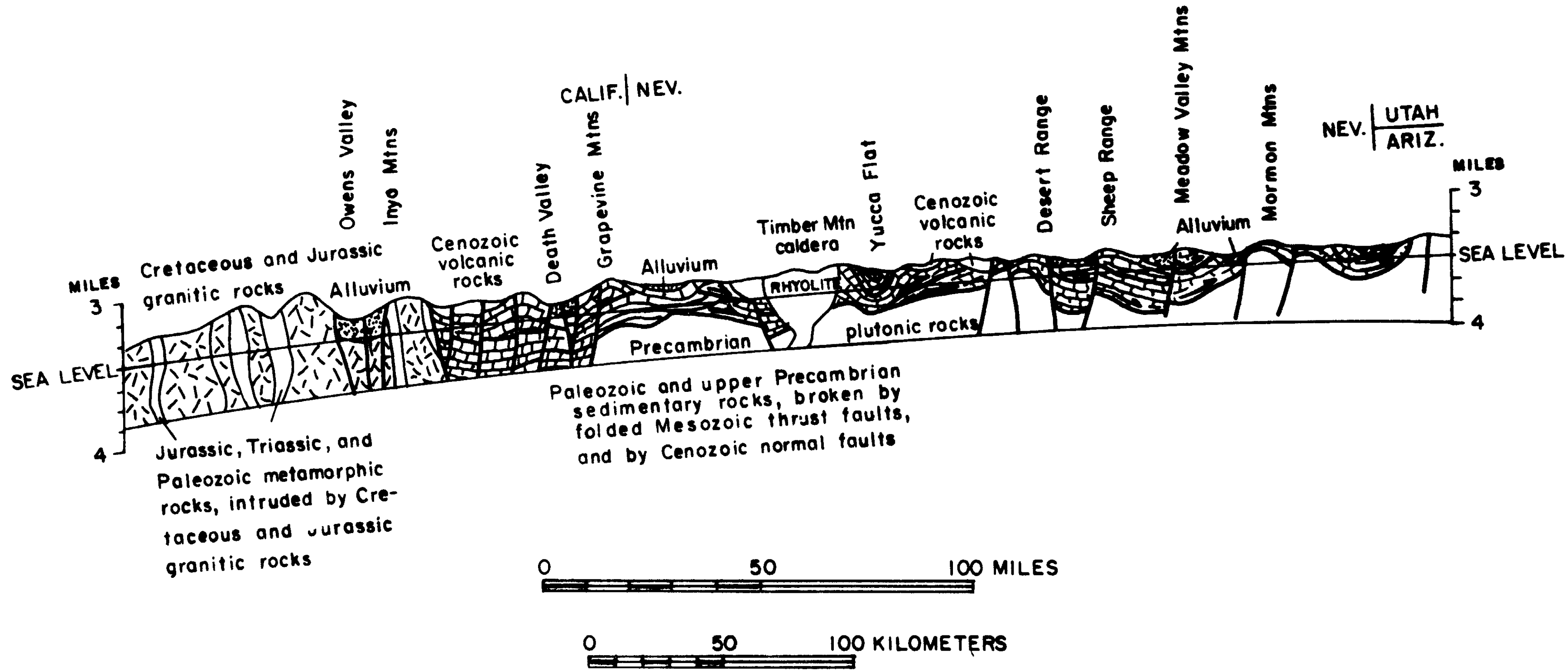


Figure 14.--East-west geologic cross section through the Great Basin. Modified from Hamilton and Pakiser (1965).

outcrops. These are mostly welded ash-flow tuffs but they include a large variety of lavas. Intrusive masses that range in areal extent from a few hundred square feet to several square miles occur in local areas throughout the province but are largest and most numerous in the western part. These masses are composed mostly of granite or closely related rock types such as granodiorite. The valley or basin areas contain the same rocks as found in flanking ranges plus valley-filling alluvium. The alluvial material ranges in thickness from a few feet (few metres) to as much as several thousand feet (a few thousand metres) in the deepest parts of some basins. It is composed of sand, gravel, clay, and (or) shale. In local areas, thick deposits of salt and other evaporite deposits are potential media.

Geologic structures in this province are extremely complex and include faults and folds of various ages. Of principal concern to this study are the abundant steeply dipping faults that control the present-day pattern of basins and ranges. Most basins have faults on both flanks and are, therefore, true grabens (Stewart, 1970). In addition to the flanking faults, faults occur within the basin areas. Most of these are buried and can be located only by drilling and geophysical techniques. There is evidence from aerial photographic studies and general geologic mapping that faulting has occurred in many parts of the Basin and Range province within the last 1 m.y., but currently the most active areas are along the western and eastern flanks.

Despite the complexities of geologic structures, the occurrence of seismically active zones on both flanks of the province, and the occurrence of geothermal areas the combination of thick sections of unsaturated rock, extreme aridity, abundance of strata having low to very low permeability and internal drainage in much of the area make the Basin and Range province (particularly the Great Basin) an attractive area for some waste-disposal methods, such as disposal in chambers above the water table.

Suitability of certain rocks for various disposal methods in the Basin and Range province is shown in table 6.

Discussion of factors that influence suitability

Extensive deep drilling in the Basin and Range province in recent years by the Atomic Energy Commission provides a wealth of geologic and hydrologic information that is unmatched in any part of the United States, exclusive of major oil fields. Because of the need to locate zones in the subsurface that are geologically and hydrologically safe for underground nuclear tests, extensive hydrologic tests were run in most drill holes to determine the nature and extent of permeable zones. Drilling and hydrologic testing have been confined to Nevada Test Site and central Nevada but these tests have been completed in such a variety of strata in so many different environments that the results can be extrapolated to aid trememdously in the evaluation of the Basin and Range province as a waste disposal site.

Table 6.--Suitability of rocks to disposal methods--Basin and Range province

[S, suitable; PS, possibly suitable. Ratings based on the premise that sites can be isolated and predictably will remain isolated from the hydrologic system. NS, not suitable.]

Rock type	Very deep drill hole (30,000-50,000 ft or 9,140-15,240 m)1/	Matrix holes (1,000-20,000 ft or 305-6,100 m)	Mined chamber (1,000-10,000 ft or 305-3,050 m)	Exploded cavity (2,000-20,000 ft or 610-6,100 m)	Cavities with separate man-made structure (1,000-10,000 ft or 305-3,050 m)
Intrusive igneous rocks (principally) granite.	PS	S	S	S	S
Volcanic rocks:					
Lava-------	Not present at these depths	NS	NS	NS	NS
Tuff-------		PS	S	S	S
Sedimentary rocks:					
Alluvium---	----do---------	PS	PS	PS	PS
Carbonate--	----do---------	NS	NS	NS	NS
Shale/ argillite-	----do---------	NS	S (Above the water table)	PS	S (Above the water table)
Salt----------	----do---------	PS	PS	PS	PS

1/ Probably granite or equivalent at depths below about 30,000 feet (9,140 m) regardless of surface or near-surface strata. Area is region of high heat flow--waste disposal in deep drill hole may not be feasible because of potential of encountering prohibitive temperatures.

The drilling and hydrologic testing reveal that areas suitable for either the deep drill-hole or matrix-hole methods are unlikely to be found in the Basin and Range province except possibly in intrusive igneous or metamorphic masses. High underground temperatures in these rocks, however, probably preclude disposal at great depths. No zone of very low permeability greater than a few hundred feet thick has ever been found in tuffs, lavas, or Paleozoic sedimentary rocks in either southern Nevada (Nevada Test Site) or central Nevada. However, most of the testing has been limited to depths of less than 10,000 feet (3,050 m). The possibility exists that at deeper levels thicker sequences of tuff having low permeability can be found that will be suitable for a nuclear cavity. Knowledge of physical properties of in situ granitic rocks is fairly limited but testing in the Climax stock at Nevada Test Site (Walker, 1962; Price, 1960; Boardman, 1966) suggests that the matrix hole, mined chamber, and explosive cavity concepts possibly are practical there and, by extrapolation, also in similar intrusive masses throughout the Basin and Range province.

The conclusion that tuffs are favorable for shallow-depth mined disposal chambers and for nuclear cavity (chimney) disposal sites at various depths is based on preshot and postshot studies and on data extrapolated from Nevada Test Site (E. C. Jenkins and William Thordarson, written commun., 1972) and from central Nevada. The data indicate that tuffs, especially those that have been extensively zeolitized and (or) altered to clay, have very low permeabilities in zones as much as several hundred feet (a few hundred metres) thick. These zones occur both above and below the water table. Some potentially favorable zones are inferred to be present at Nevada Test Site (E. C. Jenkins and William Thordarson, written commun., 1972). They occur also in central Nevada (G. A. Dinwiddie, written commun., 1969). The most serious problem for waste disposal in tuffs is the presence of faults. Any potential sites would have to be carefully scrutinized for faults by surface mapping and (or) geophysical surveys and, wherever possible, by underground tunneling and horizontal drilling.

Lavas, carbonates, and alluvial deposits are generally not suitable for waste disposal because of their high porosities and permeabilities. Locally, however, alluvial deposits that have been derived from tuff have properties similar to tuff, and exploration may demonstrate that these are suitable for shallow-depth disposal.

A thick section of argillite was recently drilled at Nevada Test Site to a depth of 5,300 feet (1,620 m) (P. P. Orkild, oral commun., 1973). Hydraulic testing was limited to the upper 2,000 feet (610 m) of the hole and showed that permeable zones were limited to thin interbeds of quartzite and dolomite. The hole was drilled with mud below about 2,000 feet (610 m) because of caving problems and "made little or no water." The data suggest that argillite or shale is "possibly suitable" for exploded cavity waste disposal in the Basin and Range province. The low permeabilities of the argillite suggest that shale and (or) argillite are suitable also for shallow depth mined chambers or cavities with manmade structures in areas where the water table is deep, if caving problems can be solved.

Thick deposits of salt and (or) anhydrite occur in some basins in the province, especially in Arizona (fig. 4). These deposits are possibly suitable for waste disposal in shallow-depth mined chambers, matrix holes, and exploded cavities. The principal problem with these deposits seems to be whether they are tectonically stable. According to Eaton, Peterson, and Schumann (1972) the Luke salt body near Phoenix, Ariz., has fractures that apparently are fairly young. The fractures indicate that adjustments are still occurring, probably in direct response to large ground-water withdrawals (Eaton and others, 1972).

Winograd concept

The possibility that solid wastes can be safely stored in parts of the arid and semiarid southwest at depths of 100-2,000 feet (30.5-610 m) in a variety of rock types has been proposed by I. J. Winograd (written commun., 1972). Winograd suggested that thick unsaturated zones are ideally suited for solid-waste disposal because, at many places, evaporation exceeds precipitation by 4 to as much as 20 times, and that recharge on interfluves (areas between streams) within the arid zone is very small, if it occurs at all. Winograd believes that the formation of widespread caliche zones in arid areas throughout the world suggests that precipitation penetrates only a few feet into the ground prior to evaporation and deposition of $CaCO_3$ (caliche), and, therefore, the possibility of solidified wastes entering into solution and then being transported by ground-water flow is slight. He cited other evidences that indicate that moisture never penetrated below certain very shallow depths even during past periods of much heavier rainfall. If Winograd's analyses are correct, and they seem to be well documented, many areas in the arid southwest that are well above the water table may prove to be favorable sites for this concept of waste disposal. We feel, however, that rock media for above-the-water-table disposal must have very low permeabilities to assure that the wastes will continue to be safely contained in the event of increased precipitation and water-table rise.

Disposal in recharge areas

Maxey and Farvolden (1965) discuss the advantages of waste disposal in areas of recharge of drainage basins in arid lands. The principal advantage of such placement of wastes is to gain a factor of safety by making transit time to a potential aquifer as long as possible. Therefore, areas of thick unsaturated rock in areas of ground-water recharge would appear to offer a disposal environment that satisfies most requirements for the shallow-depth concepts of disposal of solid wastes. This setting is available at a few places, for instance beneath some flats and mesas at the Nevada Test Site.

RECOMMENDATIONS

Rocks and the geohydrologic environments that appear to satisfy the requirements of the various concepts are summarized in table 7.

If laboratory tests and field experiments demonstrate the feasibility of the disposal methods considered herein, the environments classified as potentially suitable for waste disposal should be further evaluated at State- and county-wide levels. If these studies define potentially suitable target areas, the follow-up studies should include: (1) detailed geologic mapping and seismic monitoring to delineate active fault zones and areas of crustal unrest, (2) comprehensive geophysical surveys (where applicable) and underground tunneling and drilling (where possible) to locate buried faults and to better define subsurface conditions, (3) exploratory drilling and comprehensive hydraulic testing to define the zones having the lowest permeabilities, and (4) determinations of physical and chemical properties of the potential host rock in order to predict what the interactions of waste and rock will be.

In areas where salt is the potential host, it will be necessary to evaluate whether or not the salt is tectonically stable. If explosive cavities are considered in salt, an evaluation of the potential for triggering salt diapirism will be necessary. According to R. E. Anderson (written commun., 1973) data on the existence of present-day diapirism (Gera, 1972) are restricted to a few domes located near the gulf coast. Farther inland, data suggest that the domes in northern Louisiana and Mississippi, for example, have not been active diapirically since late Tertiary time. Anderson also suggests that studies be initiated at

Table 7.--Summary of areas and rocks potentially suitable for various methods of waste disposal

Deep drill hole (30,000-50,000 ft or 9,140-15,240 m)	Matrix holes (1,000-20,000 ft or 305-6,100 m)	Mined chamber (1,000-10,000 ft or 305-3,050 m)	Exploded cavity (2,000-20,000 ft or 610-6,100 m)	Cavities with separate manmade structure (1,000-10,000 ft or 305-3,050 m)
1. Continental interior where the sedimentary cover is thin (less than about 5,000 ft or 1,520 m). 2. The Shield area of Minnesota, Wisconsin, and Michigan. 3. Metamorphic and igneous rocks of eastern metamorphic belt--principally the Piedmont physiographic province from New York to Georgia. 4. Isolated granitic plutons in Central Interior and in upwarps of Colorado Plateau. 5. Granitic stocks of New England States.	1. Suitable in essentially the same igneous and metamorphic terrains as deep drill hole and possibly in thick salt beds and in stable salt domes. 2. Possibly suitable in shale below 7,000 ft or 2,130 m in some sedimentary basins, depending on proof of hydrologic isolation. 3. Granitic stocks in the Basin and Range province.	1. Salt beds and stable salt domes above about 200 ft (61 m) elevation. 2. Tuff and shale for above-the-water table emplacement in arid and semi-arid climates. 3. Metamorphic and intrusive igneous rocks in same areas as listed for deep drill hole. 4. Granitic stocks in the Basin and Range province.	1. Metamorphic and intrusive igneous rocks in same areas as listed for deep drill hole. 2. Possibly suitable in thick salt beds and stable salt domes. 3. Possibly suitable in shale in some sedimentary basins below 7,000 ft (2,130 m), depending on proof of hydrologic isolation. 4. Tuff and granitic rocks in Great Basin.	Same as mined chamber.

Note: All methods are considered unfavorable in seismic risk zone 3. Items are not preferentially listed.

selected domes for the purpose of establishing movement rates for geologically significant time periods. These studies should include (1) detailed stratigraphic and structural studies of Pleistocene and Holocene deposits (especially terrace and flood-plain deposits), (2) microseismic investigations, (3) highly accurate repetitive areal geodetic measurements, and (4) measurements of vertical strain in drill holes.

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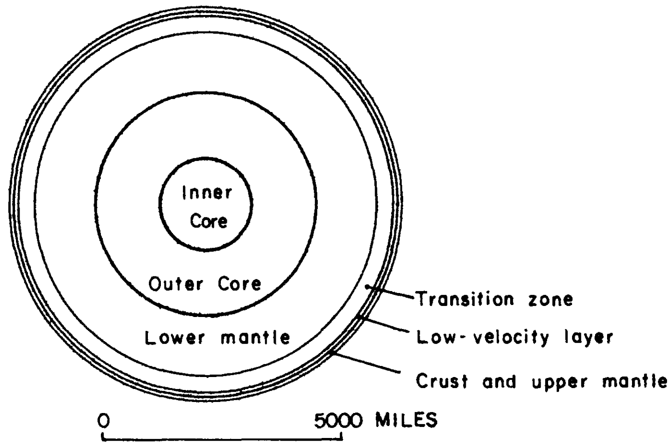
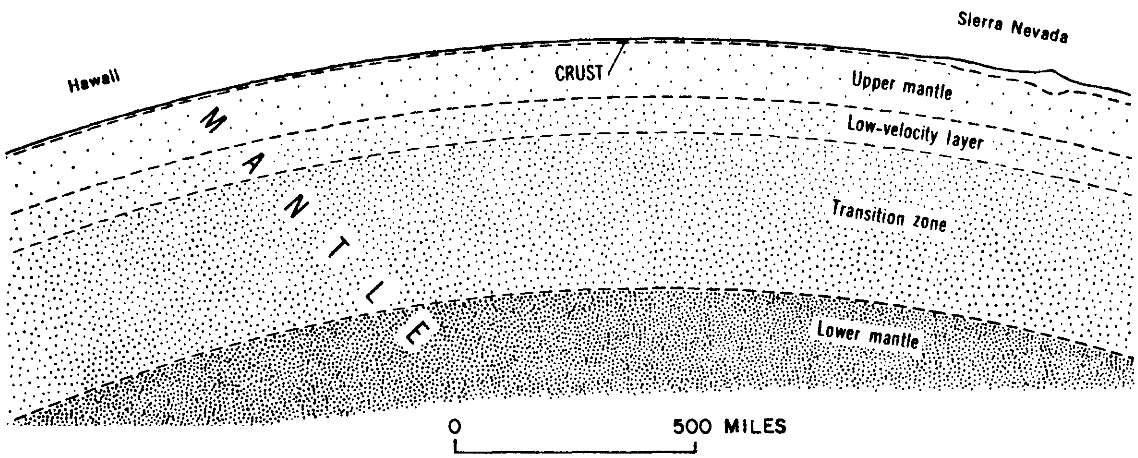
APPENDIX A

Elementary description of Earth's structural components

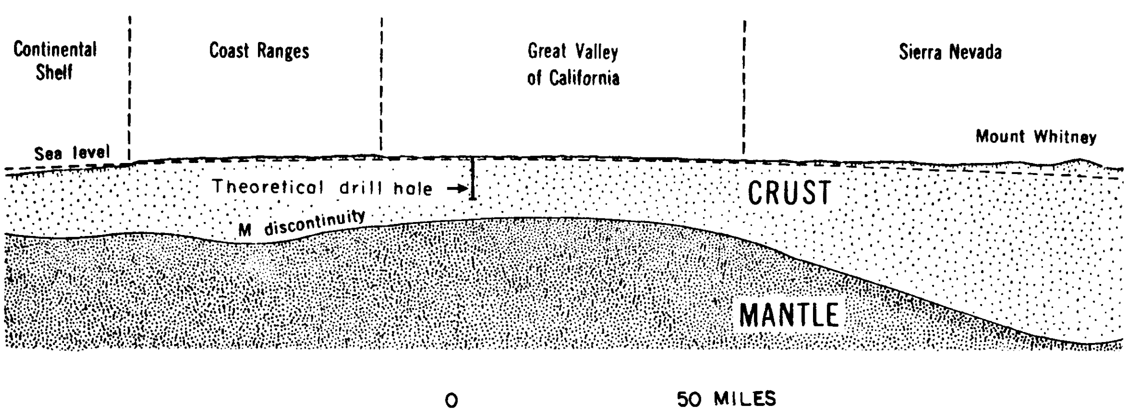
All the waste disposal concepts evaluated in this investigation involve placing wastes in the Earth's crust, which is the outermost layer or shell of the Earth (fig. 15). Knowledge that the Earth is made up of various layers is based principally on the behavior of seismic or earthquake waves as they pass through the Earth. The crust of the Earth ranges in thickness from about 5 miles (8 km) at some places under the oceans to more than 30 miles (48 km) under high mountain ranges, such as the Sierra Nevada (fig. 15) (Robertson, 1966). In the continental parts of the United States the crust everywhere exceeds the maximum thickness or depth considered for the deep drill-hole concept (50,000 ft or 15,240 m) (fig. 15). The continental crust is made up largely of light-colored igneous rocks (Appendix C) such as granite, and the oceanic crust is made up almost entirely of basalt, which is darker and slightly denser than granite. The crust overlies a layer called the mantle, which, in turn, overlies the Earth's core. The composition of the mantle as contrasted to the crust is little known. Knowledge of mantle composition is conjectured from studies of volcanic lava and of the composition of diamond pipes and from laboratory experiments on minerals and rocks. These studies and seismic data (Robertson, 1966) indicate that the rocks of the upper mantle are denser than the crustal material and are composed mostly of iron and magnesium silicate minerals. In the lower mantle, because of very high pressure, only the simple oxides of iron, magnesium, and silicon are thought to be present (Robertson, 1966).



CROSS SECTION OF THE WHOLE EARTH, SHOWING CORE, MANTLE, AND CRUST.



UPPER MANTLE AND CRUST BETWEEN HAWAII AND CALIFORNIA. THE CRUST IS VERY THIN RELATIVE TO THE REST OF THE EARTH.



CONTINENTAL CRUST UNDER CALIFORNIA, SHOWING CRUSTAL THICKENING UNDER THE SIERRA NEVADA AND 50,000 FOOT DRILL HOLE.

Figure 15.--Cross sections of the whole Earth and parts of the Earth's crust and mantle. Modified from Robertson (1966).

Below the mantle is the Earth's core, which is divided into an outer part and an inner part as shown on figure 15. The outer core is presumed to be liquid because it does not transmit shear waves (earthquake waves in which particle motion is across, or transverse to, the direction of travel) and because it sharply reduces the velocity of compressional waves (earthquake waves in which particle motion is back and forth parallel to the direction of travel). The inner core, detected because of its higher compressional wave velocity, is considered to be solid. The core occupies about 15 percent of the Earth's volume, the mantle about 84 percent, and the crust only about 1 percent (Robertson, 1966).

APPENDIX B

General Considerations

Hydrology

Flow systems--Hydrology, specifically ground-water hydrology, is one of the most important considerations when planning for the disposal of high-level radioactive wastes, because ground-water flow systems are the primary means by which wastes might regain contact with man's environment. Very basically, where a hydraulic gradient is developed by differences in head, ground water has the potential to move from areas of high static head toward areas of lower head. If this potential exists and if avenues for movement are open, a ground-water flow system is established.

Figure 16 illustrates basic patterns of ground-water flow in sedimentary basins under fairly uncomplicated conditions and shows how contaminants could regain contact with man's environment even if placed in the deeper parts of the basins. Water enters permeable rock in outcrop areas and travels downward, then laterally through the rock by gravity. In some basins, if permeable rock is overlain by relatively low permeability rock, artesian conditions can develop and result in especially hazardous conditions for waste disposal. The sedimentary basins in the United States are far more complicated than these diagrams indicate and it is apparent that a thorough knowledge of hydraulic conditions in any basin considered for waste disposal is absolutely essential.

Effect of stratification and faults--Ground-water flow systems can be much more complex than indicated on figure 16. The basic flow pattern through a basin usually is complicated, at least locally, by stratification and faulting. Stratification can change the direction of ground-water flow. Faults significantly affect flow patterns in any ground-water system. They either can be conduits for flow of water between transmissive zones or be obstructions to flow of water in an aquifer. Faults that are potential conduits of flow have been found at depths of several thousand feet. These faults are potentially hazardous to waste containment because they can serve as connections between burial sites and man's environment even in an otherwise dense rock of very low permeability. Therefore, any site selected for disposal of waste must be hydrologically isolated

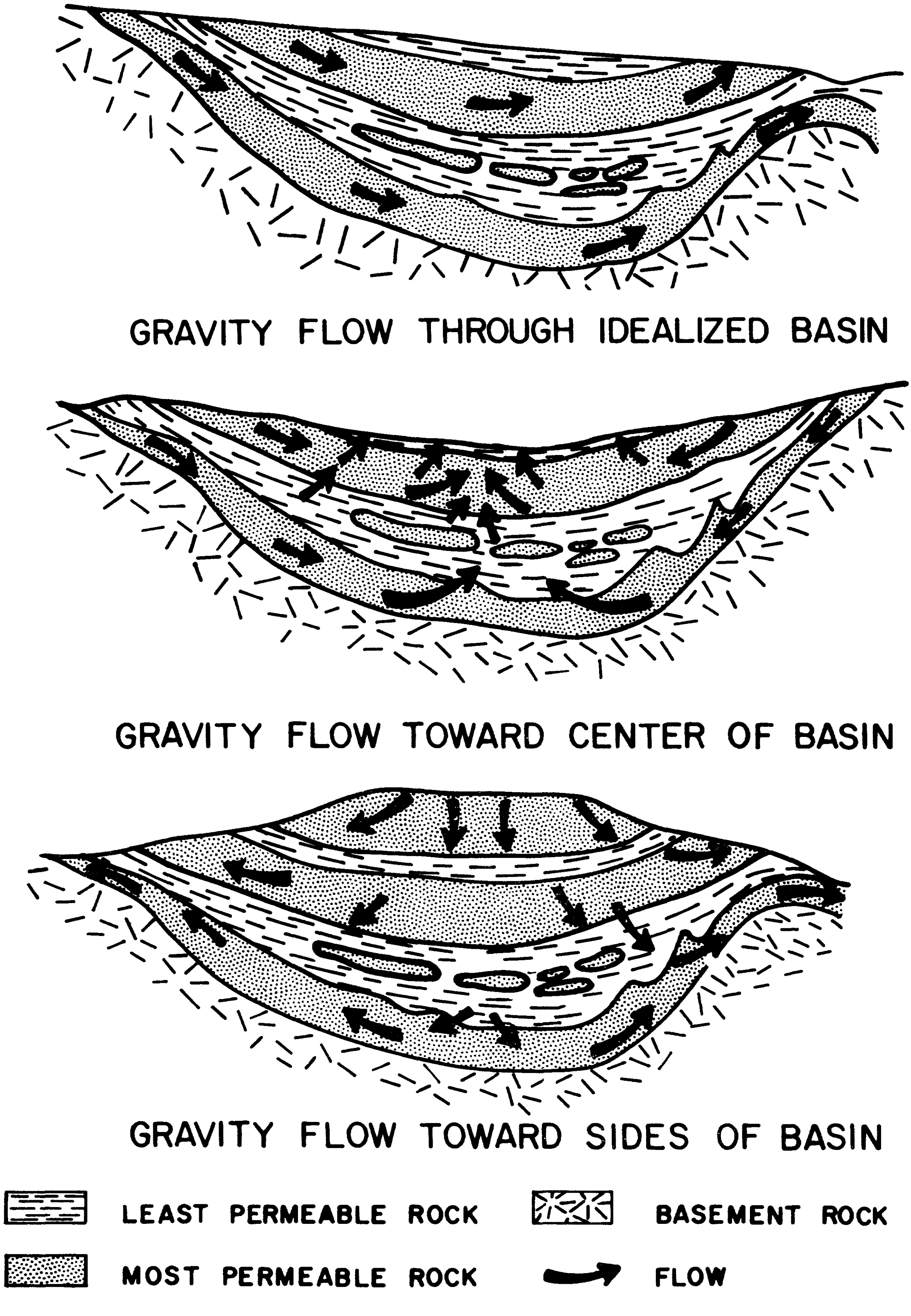


Figure 16.--Idealized gravity flow through basin. Modified from Drescher (1965).

from permeable fault systems. Thermal springs, commonly associated with volcanic rocks, can be surface expressions of faults. Certainly, thermal springs are an indication of permeability and fairly rapid ground-water circulation at depth.

Problem of liquid- versus solid-waste emplacement--Ground-water flow systems are limiting factors for planning the disposal of high-level radioactive wastes. It is necessary to evaluate whether underground emplacement of liquid wastes is hydrologically feasible in any geologic environment and, if it is, to consider the relative hazards of liquid- and solid-waste emplacement.

Liquid-waste disposal presents some obvious problems. Any plan to inject or place liquid wastes within sedimentary rocks appears to be extremely hazardous even if these wastes first melt the host rock and then solidify with the rock. All sedimentary rock has some permeability--has some degree of ability to transmit water and thus to transmit contaminants. It seems, therefore, virtually inconceivable that large volumes of liquid wastes injected or placed in any sedimentary rock, with the possible exception of salt[1/], would not cause contaminated ground water to eventually migrate toward and regain contact with man's environment during a period of 1 m.y.

1/ Present knowledge is insufficient to indicate whether salt can be used for high-level radioactive liquid wastes (Galley, 1966, p. 21).

The alternatives to sedimentary rocks for liquid-waste disposal are dense, unfractured metamorphic and intrusive igneous rocks. Most of the metamorphic and intrusive igneous rocks are completely crystalline (see Appendix C), and the hydrologic implications are that interstitial porosity and permeability are very low and that any significant permeability established in these crystalline rocks is due to fractures. The crystalline rocks are weathered and fractured at shallow depths, but below a depth of several thousand feet (a few thousand metres) the likelihood of encountering water-bearing fractures, especially in the granitic type rocks, is low because lithostatic loading generally serves to keep fractures closed and to prevent formation of new tensile fractures. Therefore, the crystalline rocks seem to be much better hosts for all concepts of liquid-waste disposal than do sedimentary rocks. However, Secor (1965) has presented arguments indicating that appropriate fluid pressures of magnitudes that have been observed in deep oil tests could serve both to form tension fractures and to open up previously formed fractures at great depth. Such a process potentially provides paths for the migration of ground water. Determining the existence of the appropriate conditions would require hydrologic evaluation of the specific area, including deep drilling and studies of existing mines.

Fractures might also develop as a result of melting and subsequent expansion of the host rock by high-temperature liquid wastes whether placed in an exploded cavity or a deep drill hole. Whether or not such possible fracturing would extend far into the rock and form potential avenues for escape of contaminants can be evaluated only by laboratory and small-scale field experiments.

Disposal of high-level radioactive wastes as glassy or microcrystalline solids in the initial phases of disposal is, therefore, much more appealing. The main advantage is obvious, namely that the solidified wastes will have less heat generating capability and the radionuclides will not be subject to migration until such time that they are leached from the binding solids (Gera and Jacobs, 1972, p. 20-34).

Permeability of rock--Of principal concern for the safe emplacement of high-level radioactive waste is the permeability of the rock media. Permeability, as used in this report, is a measure of the ability of a rock to allow movement of water through its connected openings. Permeability (hydraulic conductivity) is described by Lohman and others (1972) as follows: "If the porous medium is isotropic and the fluid is homogeneous, the medium has a hydraulic conductivity of unit length per unit time if it will transmit in unit time a unit volume of water at the prevailing kinematic viscosity through a cross section of unit area, measured at right angles to the direction of flow, under a hydraulic gradient of unit change in head over unit length of flow path." Permeability is a property of rock that has been measured frequently and, as such, can be discussed with some confidence in terms of general rock types. Therefore, table 8 defines degrees of permeability for use in later discussion of geohydrologic environments and rock and soil types.

Table 8.--Degrees of permeability of various rock and soil types

Permeability, in centimetres per second[1/]	10^{2}	10^{1}	1.0	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-7}	10^{-8}	10^{-9}
Permeability, in gallons per day per square foot	10^{6}	10^{5}	10^{4}	10^{3}	10^{2}	10^{1}	1.0	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}

Degree of permeability	Very high	High	Moderate	Low	Very low

Soil type[2/]	Clean gravel	Clean sands; clean sand and gravel mixtures	Very fine sands; silts; mixtures of sand, silt, and clay; glacial till; stratified clay deposits; etc.	Homogeneous clays below zone of weathering

Rock type[3/]

- Shale
- (fractured) —— Sandstone
- (solution cavities) —— Limestone and dolomite —— (unfractured)
- (fractured or weathered) —— Volcanic rocks, excluding basalt
- (cavernous and fractured) —— Basalt —— (dense)
- (weathered) —— Metamorphic rocks
- Bedded salt
- (weathered) —— Granitic-type rocks

Probable yield, in gallons per minute	>3000	1000	100	10	<1.0

1/ Darcy units when multiplied by 1.04×10^{3}.
2/ From Terzaghi and Peck, 1960.
3/ Synthesized from references listed in table 1.

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U.S. Geological Survey

Transport of radionuclides in ground water--Radioactive contaminants migrate from an underground source of contamination through ground-water systems, but there is not a full understanding of the fixation processes and rates of movement of radionuclides. Fenske (1969) discusses the phenomena of the migration of radionuclides away from sites of nuclear explosions in terms of radionuclide transport in ground water. Important physical parameters of radionuclide transport include: (1) radioactive decay constants, (2) initial concentrations of contaminants, (3) dispersion and diffusion of radionuclides, (4) retardation of radionuclides by ionic sorption, and (5) velocity of ground water. These same parameters are pertinent to the problem of transport of radionuclides away from a waste-disposal site (Gera and Jacobs, 1972, p. 132-144).

Dispersion of radionuclides in a ground-water system is a reduction of original concentrations of radionuclides by mixing with the native, uncontaminated water. Dispersion is caused principally by variations in velocity within a ground-water system, and the greatest dispersion will be in a system with the greatest range in velocity wherein movement paths are tortuous. Therefore, dispersion will be greater in heterogeneous, anisotropic host rock than in homogeneous, isotropic media. Dispersion phenomena may retard or even slightly accelerate the first arrival of radionuclides as compared to average ground-water velocity. Heterogeneity and dispersion are unpredictable within the scope of general rock types and, therefore, will not be used in evaluation of environments for waste disposal in this report.

Retardation of radionuclides is any means by which the rate of migration of radionuclides is slowed to less than the rate of ground-water movement. The principal retarding effect is that of ion-exchange capacity. The net effect of ion exchange is reduction of concentration of radionuclides in solution when these ions are exchanged with ions from the host rock. Some experiments have been made to determine retarding effects of specific rock types on selected radionuclides. The results of these studies and an expanded discussion of retardation are presented in the next section, "Interaction between rock and radionuclides in water" (p. 153).

Because radionuclides migrate within ground-water flow systems, the rate of ground-water movement is one of the principal controlling factors of the extent of migration. Velocity of ground-water movement is controlled by effective porosity and permeability of the host rock and by hydraulic gradient. Within the scope of discussion of general rock types and geohydrologic environments, only permeability can be even generally evaluated. Therefore, in this report, during evaluation and discussion of suitability of geohydrologic environments for waste disposal, transport potential necessarily will be generalized in terms of permeability as classified in the section, "Permeability of rock" (p. 150).

The problem of transport of radioactive wastes in ground-water systems has been a subject of serious consideration by leading scientists since the very day that the problem was recognized. Theis (1955; 1956a, b; 1959), Nace (1960; 1961), and Piper (1969) have given excellent overviews of the intricacies of the problem, and pertinent discussions have been published by the National Academy of Sciences-National Research Council (1957).

Interaction between rock and radionuclides in water--Nearly all rocks exhibit the capability of sorbing cations (ion-exchange) such as cesium and strontium from solution. The sorbing capability is especially great in clay minerals. The gross effect of sorption is reduction of the velocity of cation travel to less than the velocity of the transporting water. The degree of velocity reduction (retardation) depends on the chemical nature of the species, the concentrations of competing species in solution, and the extent and nature of the host rock.

A side effect of sorption is that exchangeable ions are released from the host rock into solution. For instance, sorption of cesium or strontium ions by clay releases sodium or potassium ions into the water, and these released ions, together with ions originally present in the solution, can compete with waste material for available exchange sites. This is the reason that cation movement is only retarded and not stopped. Calcium and magnesium ions generally affect retardation of strontium ions the most, and sodium and potassium ions affect strontium retardation very little except at high concentrations. For example, disposal of strontium in dolomite would result in releasing calcium and magnesium ions to solution which then would compete with the remaining strontium ions, and the travel of strontium ions would not be retarded as much as they would through some other host rock.

The degree of retardation also depends on physical parameters such as bulk density and effective porosity of the host rock. Sorption is a phenomenon displayed by all solid substrates. The degree to which these substrates may accommodate sorbants depends in part on the nature of, but more significantly on the total surface area of, the substrate. The larger the surface area per unit mass for a given substrate the greater will be its sorption capacity. If the substrate particles are small enough, for example, colloidal, they may move with the ground water together with their sorbed materials, effectively increasing the transport velocity of the sorbants. Should these colloidal materials have a residual electrical charge, however, they in turn may be sorbed on bulkier substrates decreasing the effective sorbant velocities.

The preceding discussion has been focused on sorption of cations; however, sorption may or may not have as much effect on movement of anions such as bromides, iodides, and sulfides. Very little study, beyond laboratory conditions, has been conducted on anionic solutions. Most of these studies have been made with iodide. The movement of iodide has been measured at significantly higher rates than that of most cations under similar conditions; therefore, it is probable that the mechanisms that control retardation of cations do not readily apply to retardation of anions.

Another group that must be examined is the nonionic species. Triated water is in the nonionic group. The effect of host rocks on the movement of tritium, as tritiated water, has been studied with varying degrees of success. Although it is not well defined, it is an accepted fact that there is some measurable retardation of tritium; however, the leading edge of a pulse of tritiated water may move at the same rate as the water.

A distribution coefficient (K_d) is a measure of retardation potential of a host rock. Figure 17 illustrates ranges of distribution coefficients for some rock types measured under laboratory conditions; however, the rock samples were in "natural state"--as physically undisturbed as possible.

Ideally, when selecting a host rock for waste disposal, a match should be made between the waste and the host environment. Movement of cations should be significantly retarded in rocks containing clay or zeolites, which exhibit large surface areas capable of ion exchange. Anionic and nonionic wastes probably should be disposed in water-insoluble forms to minimize leaching by the formation water.

Possible climatic changes

Strong evidence is available that indicates extreme climatic changes in the geologically recent past. Therefore, the possibility of climatic changes in the future must be considered when selecting a site for long-term waste disposal. Of principal concern are those climatic changes that will drastically alter the present-day hydrologic

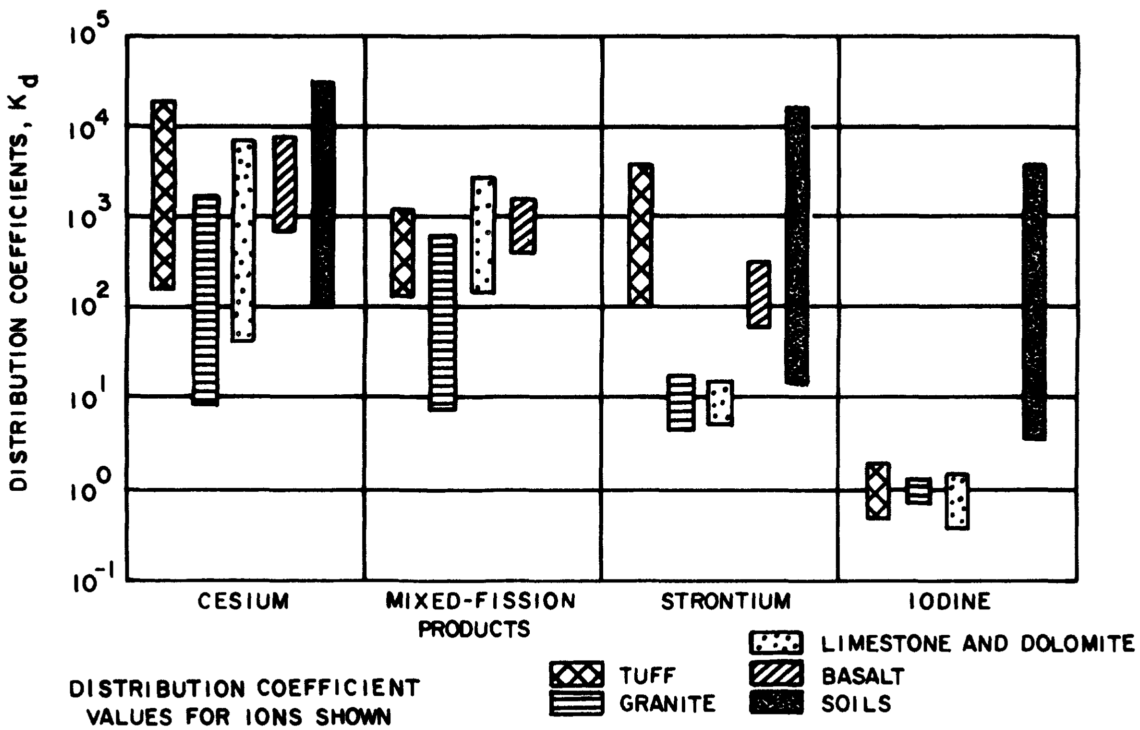

Figure 17.--Ranges of distribution coefficients for various rock types (From Grove, 1970).

regimen. These changes include: (1) a possible return of glaciation, (2) a warming trend that would cause a melting of polar icecaps and cause a subsequent rise in sea level, and (3) a return of pluvial (wet) climate to arid regions.

Possible return of glacial climate--Many geologists and climatologists are agreed that the present-day interglacial period will eventually end and an ice age will return. This conclusion is based on the apparent cyclic pattern of glacial activity during the past 1 m.y. and on evidence from pollen studies that indicate that warm intervals like the present one have been short lived in the geologic past. Some investigators (Kukla and Matthews, 1972) believe that we are in the final phase of the present interglacial period. Their conclusion is based on a comparison of the last interglacial with the present one. For example, pollen diagrams of the preceding interglacial lake beds so closely parallel the present interglacial records in composition and thickness that basically the same duration must be expected for both intervals (Kukla and Matthews, 1972). Kukla and Matthews further point out that cooling on a global scale is evident in certain key regions in arctic and subarctic latitudes. They feel that man's heat-generating activities are insufficient, at present, to alter the natural climatic changes, although continuing human input may eventually trigger or speed climatic change.

The causes of past climatic changes are unknown. Theories include changes in the Earth's magnetic field related to precessional torques, astronomical motions of the Earth (Kukla and Matthews, 1972), volcanism, changes in solar activity, veils of cosmic dust, and changes in atmospheric/ocean circulation (Flint, 1971). Whatever the causes, only slight changes in temperature are apparently required to cause a shift from interglacial to glacial climates. According to Flint (1971, p. 4) extreme glacial-interglacial temperatures over lands in low altitudes near coastlines may have been as little as 3° F less than present-day temperatures in mean-annual terms, increasing to 12° F or more inland.

It is evident that one or more possible returns to ice ages must be considered in evaluating potential sites for waste disposal and that areas covered by glaciers during past glacial epochs should be either avoided entirely or considered in terms only of concepts requiring several thousand feet of burial. The need for deep burial is to assure that the wastes will not be exhumed by glacial erosion. The deep fiords of Norway, British Columbia, and elsewhere provide unequivocal evidence of the power of glaciers to erode hard rocks to great depths. One fiord in Norway possibly was eroded to a depth of 2,400 m (7,870 ft) (Gera and Jacobs, 1972, p. 72). Areas that were covered by ice during maximum advances of continental sheets and alpine glaciers are shown on figure 18.

Changes, in addition to possible occurrence of ice cover and deep glacial erosion (Flint, 1971), that could affect potential sites in these areas include (1) drastic changes in drainage patterns including complete obliteration of preexisting valleys and the creation of new ones, (2) overall changes in the hydrologic cycle, (3) creation of

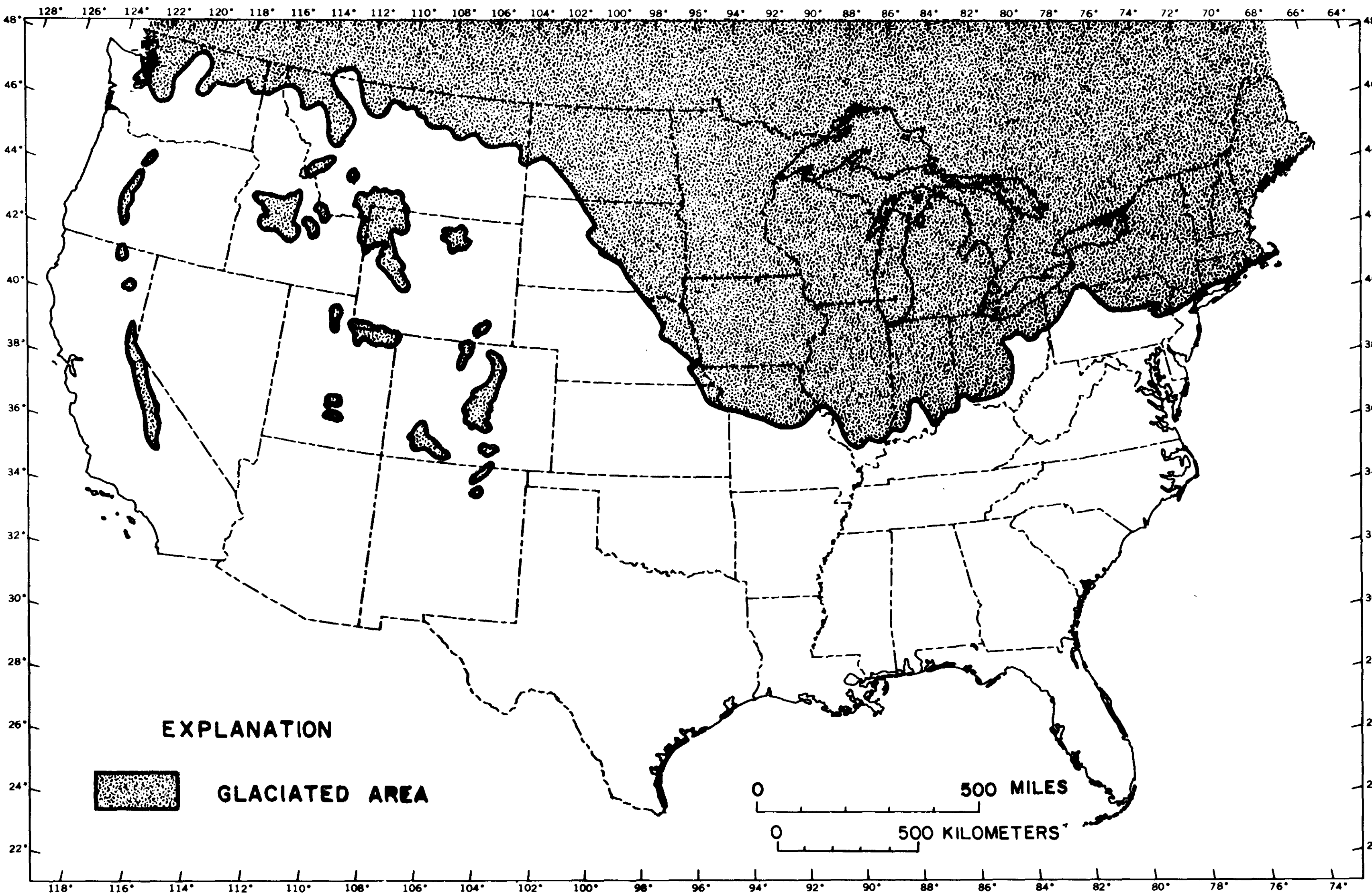

Figure 18.--Maximum extent of glaciation in the United States. Modified from Flint and others (1945).

new lakes by glacial damming and (or) ice melting, (4) cutting and filling of terrain adjacent to glaciers by glacial outwash streams, (5) disastrous flooding by bursting of glacial dams, (6) burial of vast areas under windblown sand and silt, and (7) possible fracturing of host rock or slipping along existing faults due to loading by lakes or glaciers.

Sea-level changes related to climatic changes--The sea coasts of the world display a variety of erosional and sedimentary evidences that indicate sea levels have changed dramatically in Quaternary time (table 9 and fig. 19) and tide gages indicate that changes are currently in progress (Flint, 1971). In most areas it is not possible to determine whether the changes recorded on land or below the sea resulted from actual rise or fall of the sea or from crustal rise or fall of the land. However, coastlines that appear to have been stable for long periods of time display sea-erosion terraces as much as 500 feet (150 m) above the present level (Fairbridge, 1961, p. 131) and as much as 400 feet (120 m) below the present level (Nakagawa, 1967, p. 38). In addition to the obvious effect of advance and retreat of glacial ice, other significant causes of sea-level rise include: (1) movement of crust beneath the sea, (2) creation of volcanic masses beneath the sea, and (3) draining of inland seas and lakes as a result of crustal movements or erosional processes (Flint, 1971).

The processes listed above are all capable of causing significant changes in sea level, but for the 1-m.y. period considered in this investigation, the process of principal concern to waste disposal is

Table 9.--Major stratigraphic and time divisions

[By Geologic Names Committee, U.S. Geol. Survey, 1972]

Subdivisions in use by the U.S. Geological Survey			Age estimates commonly used for boundaries (in million years)	
Era or Erathem	System or Period	Series or Epoch	(A)	(B)
Cenozoic	Quaternary	Holocene		
		Pleistocene	1.5-2	1.8
	Tertiary	Pliocene	ca. 7	5.0
		Miocene	26	22.5
		Oligocene	37-38	37.5
		Eocene	53-54	53.5
		Paleocene	65	65
Mesozoic	Cretaceous	Upper (Late)		
		Lower (Early)	136	
	Jurassic	Upper (Late)		
		Middle (Middle)		
		Lower (Early)	190-195	
	Triassic	Upper (Late)		
		Middle (Middle)		
		Lower (Early)	225	
Paleozoic	Permian	Upper (Late)		
		Lower (Early)	280	
	Pennsylvanian	Upper (Late)		
		Middle (Middle)		
		Lower (Early)	320	
	Mississippian	Upper (Late)		
		Lower (Early)	345	
	Devonian	Upper (Late)		
		Middle (Middle)		
		Lower (Early)	395	
	Silurian	Upper (Late)		
		Middle (Middle)		
		Lower (Early)	430-440	
	Ordovician	Upper (Late)		
		Middle (Middle)		
		Lower (Early)	ca. 500	
	Cambrian	Upper (Late)		
		Middle (Middle)		
		Lower (Early)	570	

Time subdivisions of the Precambrian:

Precambrian

Precambrian Z--base of Cambrian to 800 m.y.
Precambrian Y--800 m.y. to 1,600 m.y.
Precambrian X--1,600 m.y. to 2,500 m.y.
Precambrian W--older than 2,500 m.y.

A--Geological Soc. of London, 1964
B--Berggren, 1972

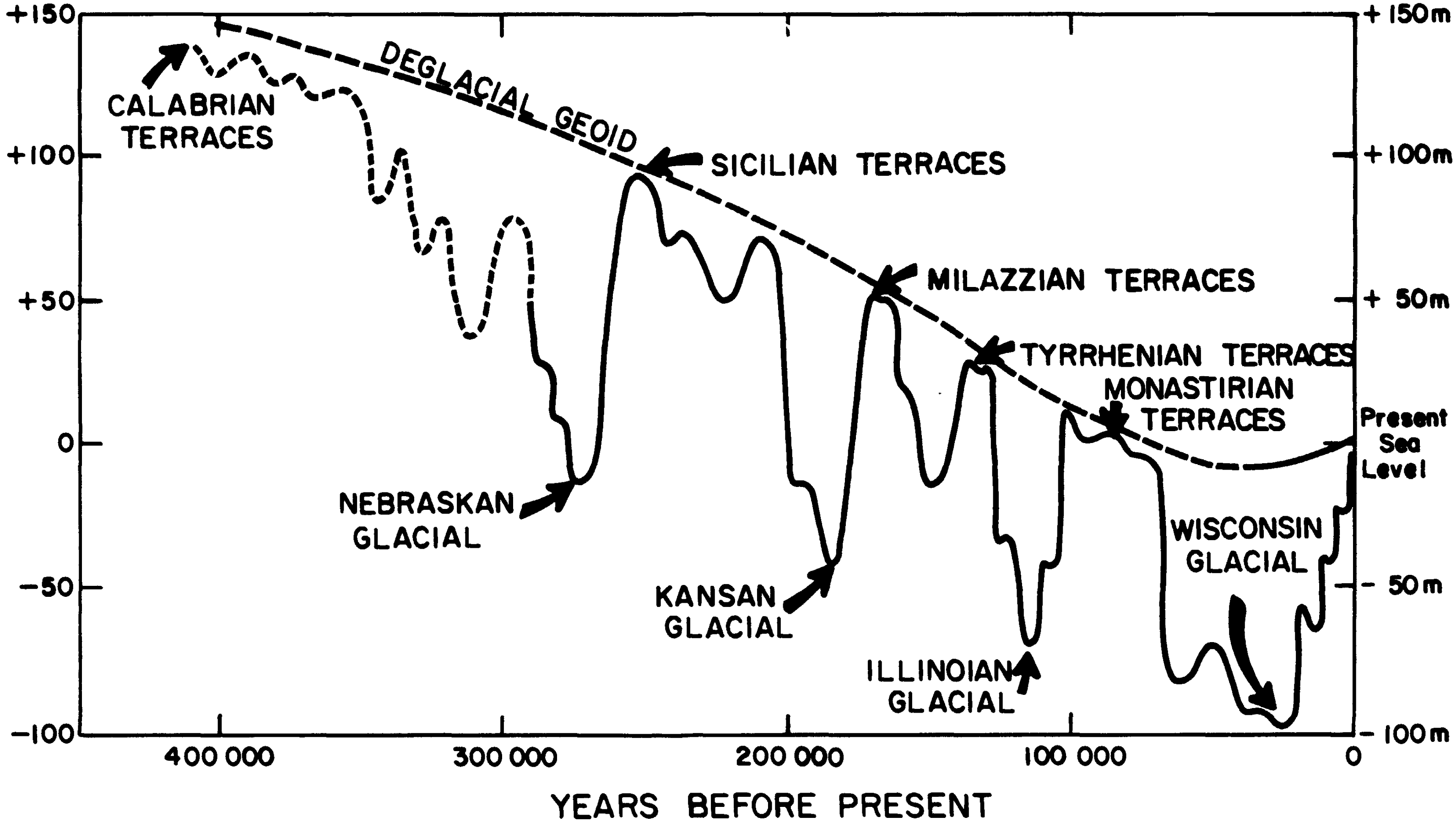

Figure 19.--Quaternary sea-level oscillations. Modified from Fairbridge (1961).

the possible melting of glacial ice. If all the ice now stored in the arctic and antarctic icecaps were melted, the sea level would rise about 200 feet (61 m) (Foster, 1969; Flint, 1971). Although many investigators (see preceding discussion) feel that this possibility is unlikely, others (Budyko, 1972) feel that it is almost a certainty, and all the ice could be melted by the year 2050. In view of the overall disagreement among expert climatologists and the lack of firm factual data for predicting climatic change it is necessary to consider the possibility that large parts of the coastal areas of the United States will be inundated during the next 1 m.y. Areas that will be inundated by 200-foot (61-m) and 500-foot (152-m) rises are shown on figure 20. All potential sites for waste disposal in these areas, especially those below the 200-foot (61-m) level, should be reviewed critically. These areas include, for example, the large salt domes along the gulf coast.

Return of pluvial climate--The arid and semiarid climate prevailing today in large parts of the Southwest creates conditions that are hydrologically attractive for waste disposal; however, the possibility of a return to pluvial climate should be considered when planning a site in these areas. A return of pluvial climate will predictably alter the present-day rates of erosion, but more significantly a return will mean an abundance of, or at least a significant increase in, surface and near-surface ground water. Such an increase would result in greater runoff and the possible development of new and "permanent" rivers and streams, development of lakes in topographically closed areas,

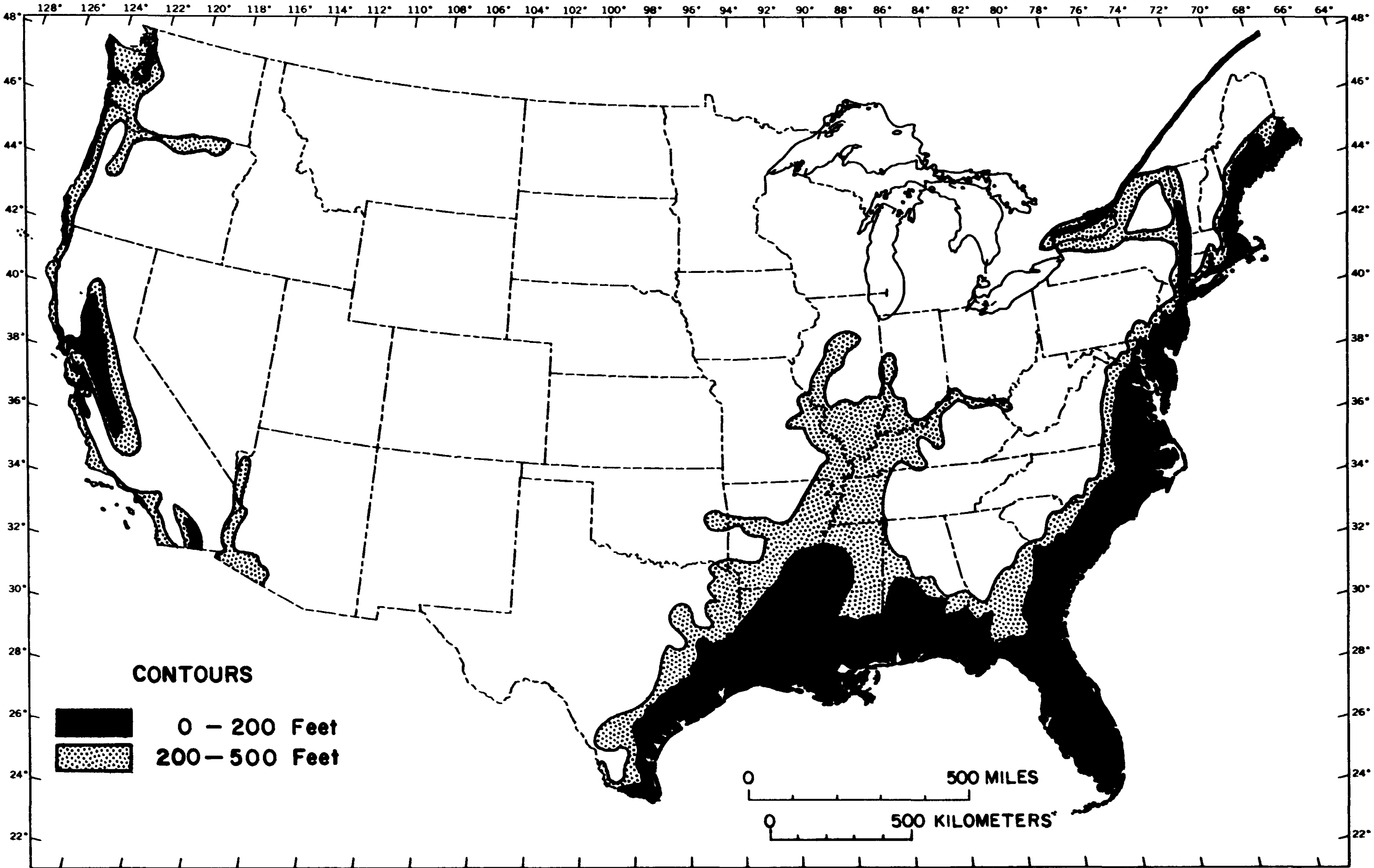

Figure 20.--Areas of the United States that would be inundated by 200- and 500-foot (61- and 150-m) sea-level rise. Modified from U.S.Geological Survey maps.

and greater recharge to the ground-water reservoirs. I. J. Winograd (written commun., 1973) concluded that valley floors of topographically closed basins could become flooded and should be avoided as sites for waste disposal. He further concluded that topographically high areas would continue to receive the most precipitation and that the water table is controlled more by geologic conditions and hydraulic parameters than by climate. The significance of Winograd's conclusions is that a return of pluvial climate presents some problems for waste disposal but that these problems can be overcome by adequate evaluation of hydrogeologic conditions and careful selection of sites for waste disposal in the arid or semiarid Southwest and elsewhere.

Effects of erosion and rates of denudation

The main process going on today on the Earth's surface is clearly erosion (Foster, 1969). This process is of obvious concern in planning for waste disposal. The waste products must be placed in position(s) where they will not be exhumed by erosional processes or covered by their ensuing products (if continued monitoring of the disposal site is required). The underlying cause of erosion is gravity--all materials tend to move downslope. This tendency is shown by landslides, gullies on hillsides, accumulations of rocks (talus) at the foot of cliffs and ridges, and similar examples. Agents of erosion are (1) rivers and streams, which are the most important agents, (2) landslides and other mass movements, (3) rain, which erodes by impact and by flowing over surfaces, (4) glaciers, which erode by grinding and plucking, (5) frost action, which loosens blocks of rock and gradually causes rock to disintegrate, (6) wind, which erodes by deflation and sand blasting, (7) shoreline erosion, and (8) chemical weathering. The overall effect of erosion is to eventually reduce irregular topography to a level plain.

The rate of erosion of the continents is approximately determined by measuring the amount of material carried by rivers. The average rate of erosion in the United States, determined in this way (Foster, 1969), is 200 feet (61 m) per 1 m.y. The lowest rate of erosion is 125 feet (40 m) per 1 m.y. in the basin of the Columbia River; the highest is 540 feet (165 m) per 1 m.y. in the basin of the Colorado River. The rates of erosion vary according to specific topographic location, rock hardness, rainfall, evaporation rates, type of vegetation, and other factors. The rates are sufficiently slow so that in most areas they do not constitute serious problems for waste disposal, but each site must be carefully evaluated. For excellent summaries of denudation rates and the problems of predicting these rates with respect to selecting a waste-disposal site see Gera and Jacobs (1972, p. 58-69) and Stewart (1973).

Significant erosional processes and their bearing on site selection

River erosion--Common sense dictates that a waste-disposal site should not be located in the vicinity of a river or large stream. Examples of rapid erosion in and adjacent to streams are plentiful throughout the world especially in semiarid and arid climates (fig. 21) and also in some humid regions where man's farming and industrial

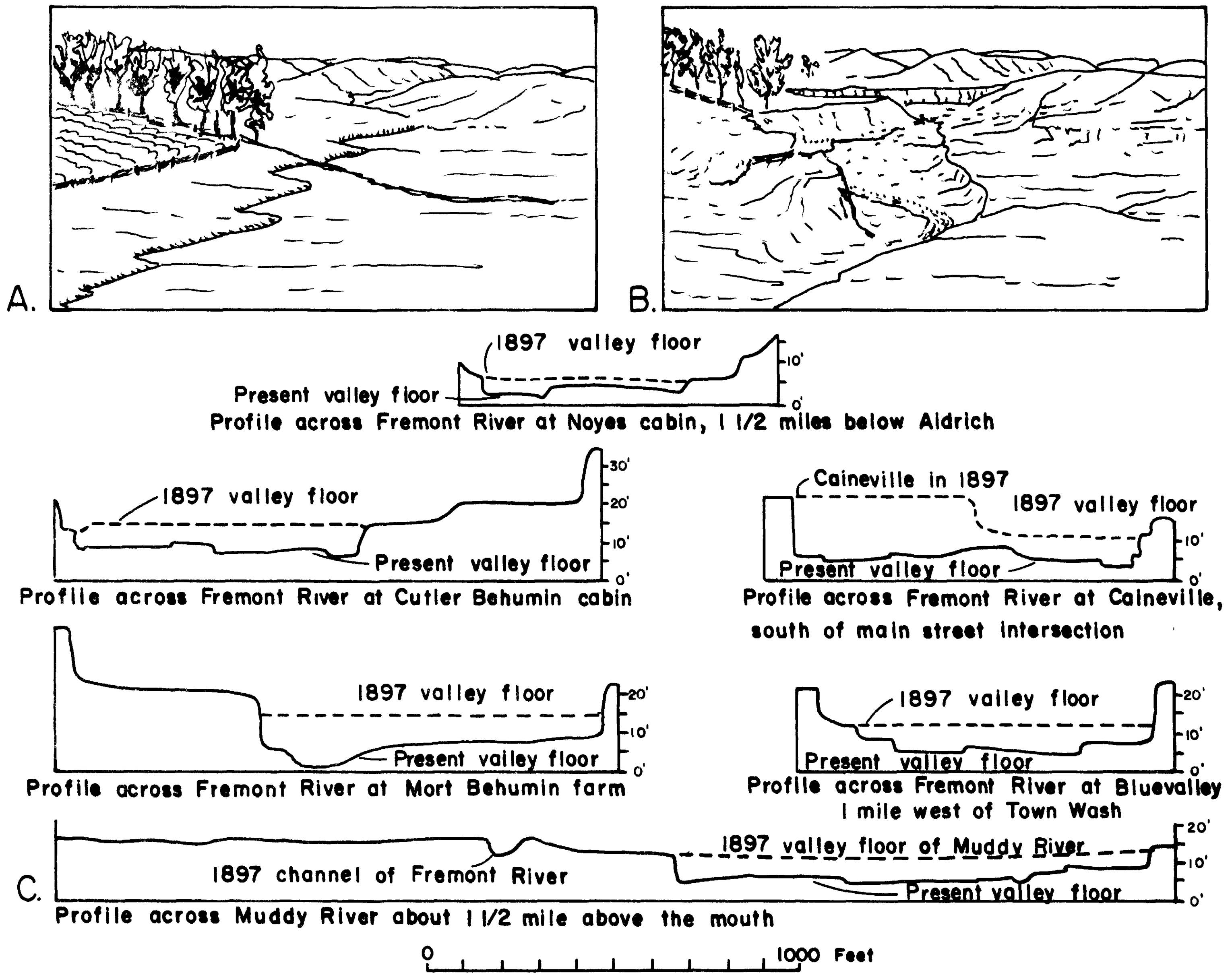

Figure 21.--Examples of river erosion in Henry Mountains region, Utah, since 1897. Climate change is the probable reason for this erosion. Parts A and B show Pleasant Creek at Notom. The part B (present day) is 20 feet deep. Part C shows cross sections of Fremont River. Modified from Hunt and others (1953).

activities have removed forest or other natural cover. In many areas it is not possible to predict erosion rates adjacent to a large stream with any degree of accuracy. This is because catastrophic flooding and rapid erosion may occur only a few times each century or may be initiated by a completely unpredictable climatic change. Such catastrophic flooding may cause a drastic change in the course of a stream or even the complete abandonment of one stream channel in favor of another. Rivers erode by several processes,and rapid downcutting can suddenly take place for a variety of reasons; for example, when a stream bed deepens itself and suddenly gains access to a soluble stratum. Relatively docile streams or those that seem to be completely controlled by man may become unmanageable as a result of climatic change or earthquake activity. When a disposal site is considered in an area where man has built a dam(s), one must keep in mind (1) that the life expectancy of these structures, either because of deterioration of the structure itself or because of the complete silting-up of the holding area, is commonly no more than a few hundred years, and (2) that the dams may, in some areas, be vulnerable to rupture by unexpectedly large earthquakes.

Landslides--Landslides are of concern to waste-disposal planning in areas of moderate and rugged topographic relief. Areas to be avoided include: (1) slopes that may slide or creep, (2) areas that may be covered by a slide, (3) areas that may be flooded by damming of a river, and (4) areas that may be affected by a sea wave resulting from land sliding beneath the sea.

Landslides may be triggered in many ways. According to Foster (1969) the most common are (1) undercutting of a slope, (2) overloading of the slope so that it cannot support its new weight and, hence, must flow or slide, (3) vibrations from earthquakes or explosions that break the bond holding the slope in place, and (4) additional water which lessens the cohesion of the material.

Erosional processes in desert regions--The arid and semiarid parts of the United States are affected by erosional processes that differ significantly from those in humid regions. Rain may fall only once in many years in a particular spot but when it does it commonly is a cloudburst. The cloudburst causes flash floods that may erode large areas upslope and bury downslope areas under tons of material. These floods do not necessarily occur along well-established stream channels but may occur anywhere adjacent to mountainous areas.

A feature of drainage in desert areas that is especially significant to waste disposal is that in an area of interior drainage a basin will eventually fill to a level that will allow the ephemeral streams to flow over the lowest divide into an adjoining basin. Soon the divide is eroded and the first basin will be rapidly dissected because of the lowered base level (Foster, 1969).

Wind erosion is a significant erosional process in desert regions but, except for the possibility of covering a disposal site under dune sand, is of little concern to waste-disposal investigations.

A type of erosion that is of major concern in arid and semiarid climates is the retreating escarpment. Cliffs, for example, at the edges of mesas may retreat at rapid rates while losing little or no loss of height. Schumm (1963) reported average denudation rates for arid and semiarid terrain of 300-600 feet (90-180 m) per 1 m.y. and Melton (1965) reported slope retreat rates of 200-700 feet (61-210 m) per 1 m.y.

Glaciation--Glaciers are extremely important agents of erosion. They erode by plucking large blocks of bedrock and by abrasion. They deepen and widen valleys previously formed by streams and give rise to valleys with a "U" shape. Where tremendous thicknesses of ice occur, valleys are deepened to great depths; an example is the fiords of Norway. Glaciers also deposit large volumes of material that is called drift. Drift consists of material deposited in front of, on the sides, and beneath a moving active glacier and of deposits that are carried by the glacier and remain after the glacier is melted.

Long-term tectonic effects

Of concern to waste disposal in the Western United States is the knowledge that the Pacific Ocean and coastal California west of the San Andreas fault system is moving relatively northwestward with respect to the remainder of the United States at a rate that has been estimated at from 2 to 3 inches (5 to 8 cm) per year (Atwater, 1970). This movement breeds the earthquakes that shake California and is an example of tectonic activity that affects the entire globe. The science of this global tectonic activity is generally referred to as "plate tectonics."

Not only are southern California and the Pacific plate moving northwestward with respect to the North American plate but continents and ocean basins alike throughout the globe are slowly moving across the face of the Earth at rates that are extremely slow in terms of a man's lifetime but are exceedingly fast in terms of geologic time Knowledge gained on a global scale now allows earth scientists to divide the Earth's crust and uppermost mantle into some eight major geological plates or caps (Bolt, 1972). The plates move out from midoceanic ridges and plunge downward into the great deeps or troughs of the ocean (fig. 22) in zones referred to as subduction zones. The midoceanic ridges are linear "rift" zones where rock material from the Earth's interior wells up to form new crust and then spreads outward on both sides of the ridge. This process is referred to as "sea-floor spreading." That the floor is indeed spreading has been confirmed by magnetic and fossil data which show that the ocean floor is youngest at the midoceanic ridges or divides and becomes progressively older outward in both directions. The continents gradually move away from the spreading ridges. It is inferred that about 200 m.y. ago the continents were all part of a single land mass or supercontinent.

Subduction zones (fig. 22) and other plate-junction zones are belts of major earthquake and volcanic activity. Of principal concern to this investigation is the junction of the Pacific and the North American plates along the San Andreas fault, which connects offset segments of the East Pacific Rise. The significance of movement along this junction from the standpoint of waste disposal is the fact that

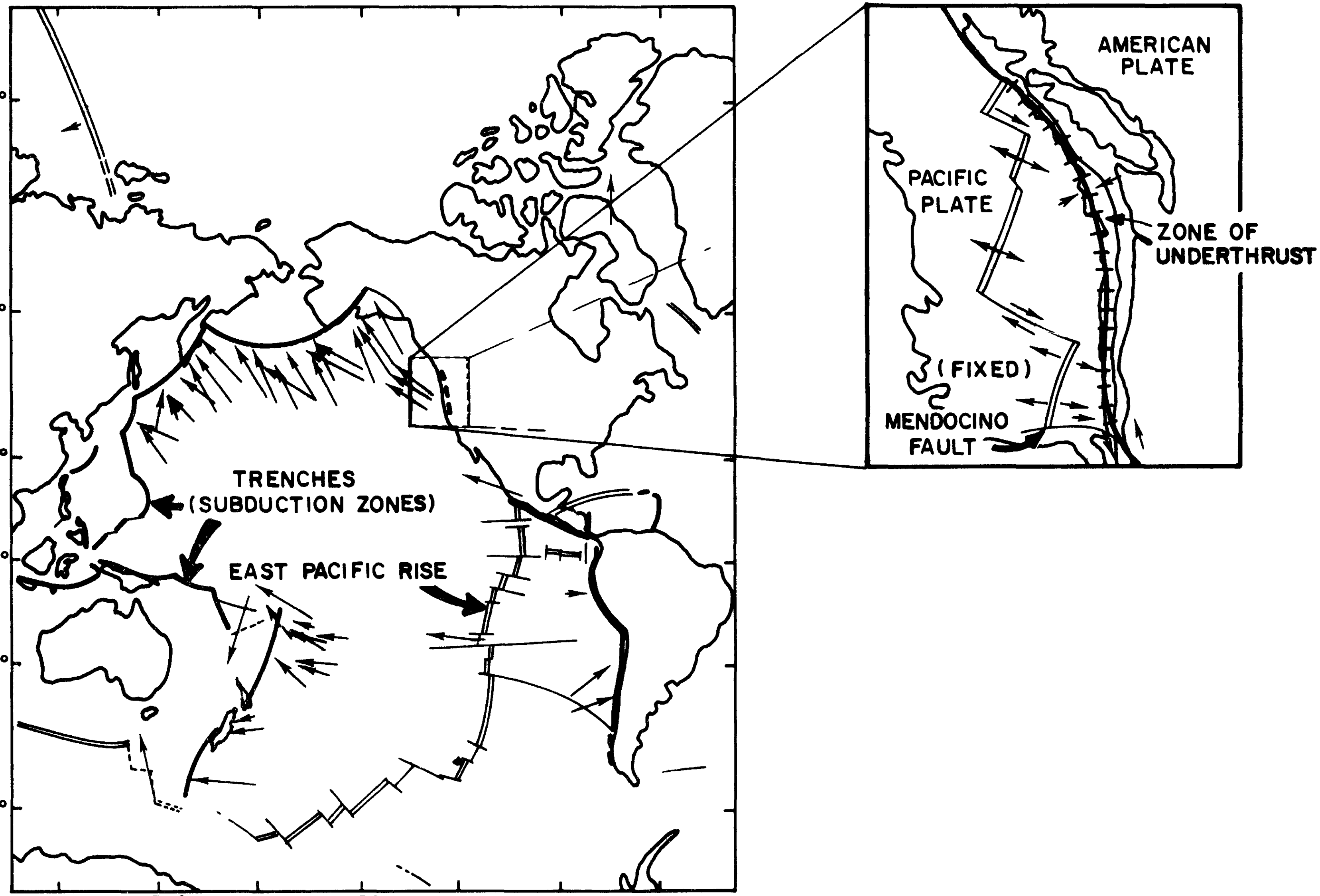

Figure 22.--Summary map of slip vectors in the Pacific area. Modified from Isacks and others (1968) and Atwater (1970).

at the present rate southern California west of the San Andreas fault will move northwestward relative to the remainder of the continent at least 30 miles (50 km) in a 1-m.y. period. Whether the coastal region of southern California will remain essentially intact during this movement or whether large parts will be demolished by a combination of sea-wave erosion and fault movements is a moot question. Certainly the coastal region of southern California is an unfavorable location for waste disposal.

The San Andreas fault projects northward offshore to intercept the east-trending Mendocino fracture zone. It is not clear what happens to the San Andreas at this junction. At least neither the Mendocino fracture zone nor the San Andreas system offsets the other (Gilluly, 1970). North of the junction, the East Pacific Rise is present (fig. 22) and is spreading at a rate of 5.8 cm or 2.3 in. per year (Atwater, 1970). This motion and the possibility that the coasts of Oregon and Washington are being underthrust by the ocean floor (Silver, 1969a, b; 1971) indicate that the lack of major earthquakes in that locality may not be a permanent condition. The development of tight folds in the Columbia Plateau and the indication of continuing crustal unrest in that region may be related directly or indirectly to the interaction of the oceanic and continental plates, and the next 1 m.y. may see an increase in tectonic activity in the northwestern part of the United States.

Seismic risk and its bearing on site selection

Most of the major earthquakes of the world occur in the belts along the boundaries between the global tectonic plates. As mentioned in the preceding discussion, one such boundary is that between the Pacific and North American plates along the west coast of the United States. The greatest number of damaging earthquakes that have occurred in California and western Nevada have been attributed to tectonic activity along this belt. Most fault movements in this zone in California are horizontal or strike-slip, rather than vertical or up-down, the most notable fault zone having horizontal movement being the San Andreas. Movement along the San Andreas fault system and other major fault systems in the Western United States is sporadic rather than constant because of friction and interlocking of the fault blocks.

Earthquake activity farther east than western Nevada or the Idaho batholith is probably unrelated to the active zone at the boundary between the Pacific and North American plates. This activity includes the earthquakes of the New Madrid, Mo., area (1811-1812) and Charleston, S.C. (1886), which were both major damaging earthquakes. Intraplate tectonism and magmatism have been demonstrated in oceanic plates; earthquakes and igneous activity that occur within the North American plate show that intraplate tectonism and magmatism occur in the continental plates as well (Gilluly, 1971, p. 2391), though the mechanism for their origin is unknown.

Seismic risk as a function of historic earthquake activity and strain release patterns--Earthquakes are described in terms of both magnitude and intensity. Magnitude is a logarithmic scale based on the amplitude of instrumentally recorded seismic waves. Several scales in common use, depending on the type of seismic waves used, are:

(1) The Richter or local magnitude scale based on recordings of short-period surface waves recorded at distances of less than 600 km,

(2) The surface-wave magnitude (Ms) scale based on the amplitudes of surface waves with periods near 20 seconds that are recorded at distances greater than about 2,000 km (1,240 mi),

(3) The body-wave magnitude (m_b) scale based on amplitude/period ratios and corrections for distance and focal depth for waves recorded at distances greater than about 2,000 km.

All the scales result in numbers that are independent of the distances of the recording stations from the earthquake (Richter, 1958).

In contrast, intensity is a number that expresses various effects of an earthquake at a particular location and thus depends, among other things, on the distance of the location from the earthquake, the magnitude of the earthquake (which is an indication of the energy released at the earthquake focus), the duration of the quake, and, most significantly, local geology. The intensity scale in use in the United States is the Modified Mercalli Intensity Scale of 1931 (M.M.). Assignment of an intensity value to a particular location is based on the degree of damage and various subjective criteria (see table 10).

Table 10.--Abridged version of Modified Mercalli Intensity Scale of 1931 /Coffman and von Hake, 1972, p. 4-7/

I. Not felt except by a very few under specially favorable circumstances. (I)

II. Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing. (I to II)

III. Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognize it as an earthquake. Standing motorcars may rock slightly. Vibration like passing of truck. Duration estimated. (III)

IV. During the day, felt indoors by many, outdoors by few. At night, some awakened. Dishes, windows, doors disturbed; walls made creaking sound. Sensation like heavy truck striking building. Standing motorcars rocked noticeably. (IV to V)

V. Felt by nearly everyone, many awakened. Some dishes, windows, etc., broken; a few instances of cracked plaster; unstable objects overturned. Disturbances of trees, poles, and other tall objects sometimes noticed. Pendulum clocks may stop. (V to VI)

VI. Felt by all, many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Damage slight. (VI to VII)

VII. Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable in poorly built or badly designed structures; some chimneys broken. Noticed by persons driving motorcars. (VIII-)

Table 10.--Abridged version of Modified Mercalli Intensity Scale of 1931--Continued

VIII. Damage slight in specially designed structures; considerable in ordinary, substantial buildings, with partial collapse; great in poorly built structures. Panel walls thrown out of frame structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water. Persons driving motorcars disturbed. (VIII+ to IX)

IX. Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb; great in substantial buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken. (IX+)

X. Some well-built wooden structures destroyed; most masonry and frame structures destroyed with their foundations; ground badly cracked. Rails bent. Landslides considerable from river banks and steep slopes. Shifted sand and mud. Water splashed (slopped) over banks. (X)

XI. Few, if any, (masonry) structures remain standing. Bridges destroyed. Broad fissures in ground. Underground pipelines completely out of service. Earth slumps and land slips in soft ground. Rails bent greatly.

XII. Damage total. Waves seen on ground surfaces. Lines of sight and level distorted. Objects thrown upward into air.

Richter magnitudes of six and greater have been recorded for earthquakes since around 1900, but records for smaller earthquakes are less complete (Algermissen, 1969, p. 17). Modified Mercalli intensities, however, have been assigned by the Coast and Geodetic Survey and other investigators to nearly all significant earthquakes known to have occurred in the United States. The historical record of seismicity in the country, therefore, does provide some guidelines to the relative seismicity of various regions (Algermissen, 1969, p. 17). Figure 23 shows the locations of damaging earthquakes (intensity VII and greater) known to have occurred in the United States from historical times through 1970. Some of the strongest of these earthquakes are listed in table 11.

The relative strain release throughout the United States has been used as an index of current tectonic activity (Algermissen, 1969, p. 16). Strain release is proportional to the square root of the energy released; the energy released is determined from the magnitude of the earthquake. Using this index, Algermissen (1969, p. 16) has divided the conterminous United States into four areas having different rates of strain release, on the basis of data compiled from earthquakes between 1900 and 1965. The areas and

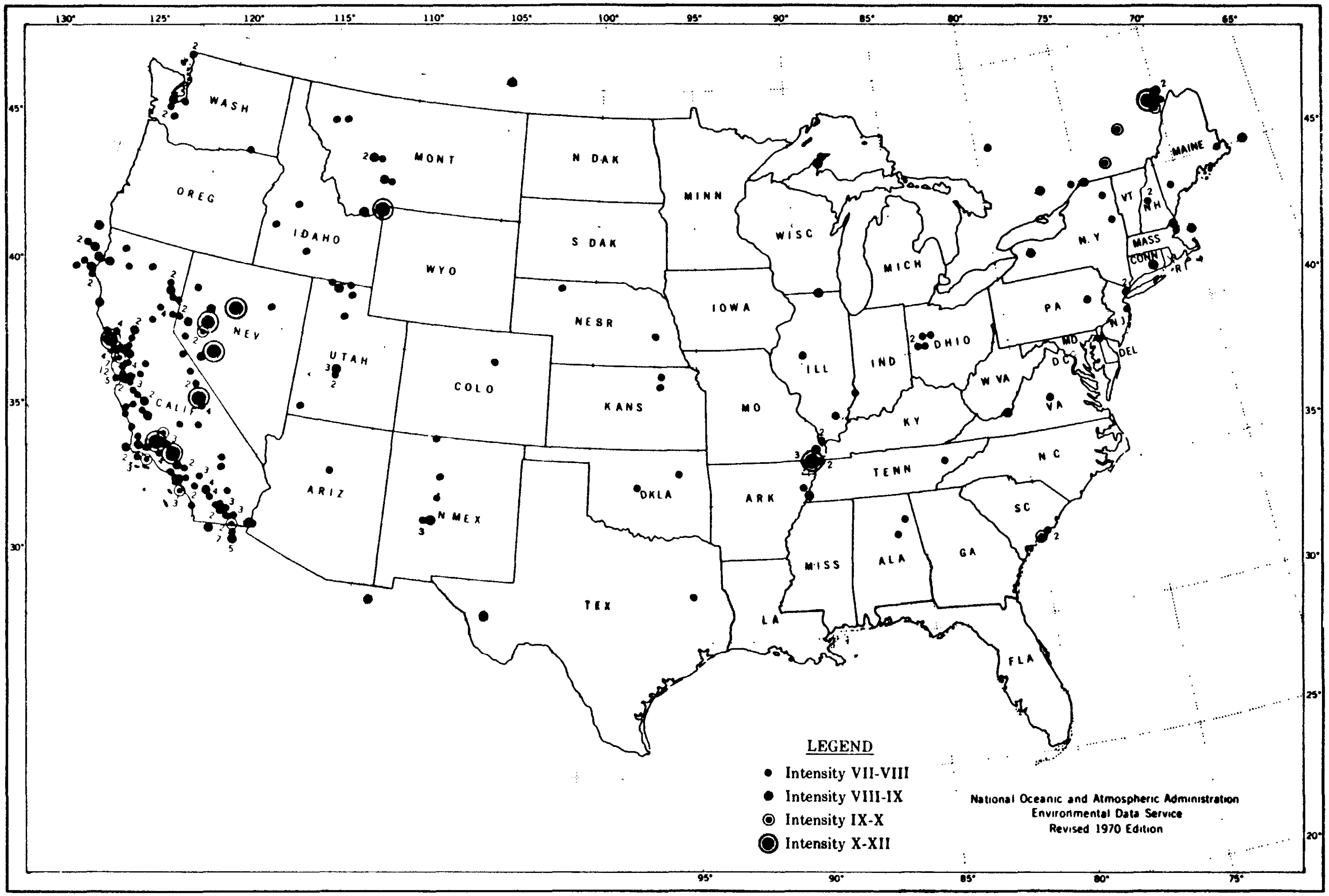

Figure 23.--Damaging earthquakes in and near the United States from earliest history through 1970. Modified from Coffman and von Hake (1972).

Table 11.--Prominent earthquakes in the United States through 1970
(Coffman and von Hake, 1972, p. 6)

Date			Locality	N. Lat (degrees)	W. Long (degrees)	Area (sq. mi.)	Modified Mercalli Intensity Scale
1663	Feb.	5	St. Lawrence River region	47.6	70.1	750,000	X
1755	Nov.	18	East of Cape Ann, Mass	42.5	70.0	300,000	VIII
1811	Dec.	16					
1812	Jan.	23	Near New Madrid, Mo	36.6	89.6	2,000,000	XII
1812	Feb.	7					
1812	Dec.	21	Off coast of southern California	34	120	....	X
1836	June	10	San Francisco Bay	38	122	....	IX-X
1838	June		San Francisco region	37 1/2	122 1/2	....	X
1853	Nov.	9	Near Fort Yuma, Ariz	33	114 1/2	....	VIII-IX
1857	Jan.	9	Near Fort Tejon, Calif	35	119	....	X-XI
1865	Oct.	1	Fort Humboldt and Eureka, Calif	41	124 1/2	....	VIII-IX
1865	Oct.	8	Santa Cruz Mts., Calif	37	122	....	VIII-IX
1868	Apr.	2	Near south coast of Hawaii	19	155 1/2	....	X
1868	Oct.	21	Hayward, Calif	37 1/2	122	....	IX-X
1872	Mar.	26	Owens Valley, Calif	36 1/2	118	125,000	X-XI
1886	Aug.	31	Northwest of Charleston, S.C	32.9	80.0	2,000,000	IX-X
1892	Feb.	23	Northern Baja California	31 1/2	116 1/2	....	VIII-IX (U.S.)
1892	Apr.	19	Vacaville, Calif	38 1/2	122 1/2	....	IX
1892	Apr.	21	Winters, Calif	38 1/2	122	....	IX
1893	Apr.	4	Northwest of Los Angeles, Calif	34 1/2	118 1/2	....	VIII-IX
1895	Oct.	31	Charleston, Mo	37.0	89.4	1,000,000	VIII
1898	Apr.	14	Mendocino County, Calif	39	124	....	VIII-IX
1899	Sept.	3	Yakutat Bay, Alaska	60	142	....	XI
1899	Sept.	10	....do	60	140	....	XI
1899	Dec.	25	San Jacinto and Hemet, Calif	33 1/2	116 1/2	100,000	IX
1906	Apr.	18	Northwest of San Francisco, Calif	38	123	375,000	XI
1915	Oct.	2	Pleasant Valley, Nev	40 1/2	117 1/2	500,000	X
1918	Apr.	21	Riverside County, Calif	33 3/4	117	150,000	IX
1921	Sept.	29	Elsinore, Utah	38.8	112.2	....	VIII
1921	Oct.	1					
1922	Mar.	10	Cholame Valley, Calif	35 3/4	120 1/4	100,000	IX

Table 11.--Prominent earthquakes in the United States through 1970--Continued

Date		Locality	N. Lat	W. Long	Area	Modified Mercalli Intensity Scale
			degrees	degrees	sq. mi.	
1925 Feb.	28	St. Lawrence River region	47.6	70.1	2,000,000	VIII
1925 June	27	Helena, Mont.	46.0	111.2	310,000	VIII
1925 June	29	Santa Barbara, Calif.	34.3	119.8	....	VIII-IX
1927 Nov.	4	West of Point Arguello, Calif.	34 1/2	121 1/2	....	IX-X
1931 Aug.	16	Western Texas	30.6	104.1	450,000	VIII
1932 Dec.	20	Western Nevada	38.7	117.8	500,000	X
1933 Mar.	10	Long Beach, Calif.	33.6	118.0	100,000	IX
1934 Jan.	30	Southeast of Hawthorne, Nev.	38.3	118.4	110,000	VIII-IX
1934 Mar.	12	Near Kosmo, Utah	41.7	112.8	170,000	VIII
1935 Oct.	18	Northeast of Helena, Mont.	46.6	112.0	230,000	VIII
1935 Oct.	31	....do	46.6	112.0	140,000	VIII
1940 May	18	Southeast of El Centro, Calif.	32.7	115.5	60,000	X
1949 Apr.	13	Western Washington	47.1	122.7	150,000	VIII
1952 July	21	Kern County, Calif.	35.0	119.0	160,000	XI
1954 July	6	East of Fallon, Nev.	39.4	118.5	130,000	IX
1954 Aug.	23	....do	39.6	118.5	150,000	IX
1954 Dec.	16	Dixie Valley, Nev.	39.3	118.2	200,000	X
1958 July	9	Southeastern Alaska	58.6	137.1	100,000	XI
1959 Aug.	17	Near Hebgen Lake, Mont.	44.8	111.1	600,000	X
1964 Mar.	27	Southern Alaska	61.0	147.8	700,000	IX-X
1965 Apr.	29	Northwestern Washington	47.4	122.3	130,000	VIII

number of equivalent magnitude 4 earthquakes during this period are listed below:

Area	No. Equiv. Mag. 4 earthquakes/1,000 km^2 in 66-yr period1/	No. Equiv. Mag. 4 earthquakes/1,000 km^2 in 66-yr period2/
Pacific West-west of long 114° W.	12.	13.
Rocky Mountains-long 106°-114° W.	2.0	2.6
Central Plains-long 92°-106° W.	.14	.38
Eastern U.S.-east of long 92° W.	.74	1.1

1/ Total equivalent number of magnitude 4 earthquakes in each area divided by total area.

2/ Only those parts of each area considered in which more than 0.25 equivalent magnitude 4 earthquakes occurred.

The data in the first column show that the strain release in the Pacific West during the 66-year period was approximately six times greater than in the Rocky Mountain area, 86 times greater than in the Central Plains, and 16 times greater than in the Eastern United States. Data of the second column show that the strain release in the Pacific West was respectively 5, 34, and 12 times greater than in the other areas. From the standpoint of strain release, the Pacific West is most active, and the Central Plains the least active. Recurrences of earthquakes, as summarized in tables 12 and 13, also indicate this.

Table 12.--Recurrence of earthquakes in conterminous United States per 100 years for modified Mercalli intensities V-VIII

[Modified from Algermissen, 1969, table 1]

Area[1/]	Approximate seismic risk zone	Earthquakes per 100 years			
		V	VI	VII	VIII
California, western Nevada (combined).	3,2	2,290	646	182	51.3
California.	3,2	1,660	479	138	39.8
Western Nevada.	3,2	1,510	417	115	31.6
Montana, Idaho, Utah, Arizona.	3,2	407	112	30.9	8.5
Mississippi Valley, St. Lawrence Valley.	3,2,1	162	51.3	16.2	5.1
Puget Sound, Washington.	3,2	224	53.7	12.9	3.1
East Coast.	3,2,1	132	34.7	9.1	2.4
Wyoming, Colorado, New Mexico.	3,2,1	182	38.0	7.9	1.7
Nebraska, Kansas, Oklahoma.	2,1	34.7	11.2	3.6	1.2
Oklahoma, north Texas.	2,1	22.4	6.3	1.8	(0.5)

1/ Areas arranged in order of decreasing number of modified Mercalli intensity VII earthquakes.

Table 13.--Recurrence of earthquakes in conterminous United States per 100 years per 100,000 km^2 (38,600 mi^2) intensities V-VIII

[Modified from Algermissen, 1969, table 2]

Area 1/	Approximate seismic risk zone	Earthquakes per 100 years 2/			
		V	VI	VII	VIII
California, western Nevada (combined)	3,2	300	84.6	23.8	6.72
Montana, Idaho, Utah, Arizona	3,2	64.4	17.7	4.89	1.35
Puget Sound, Washington	3,2	68.0	16.3	3.92	.94
Mississippi Valley, St. Lawrence Valley	3,2,1	24.2	7.65	2.42	.76
Nebraska, Kansas, Oklahoma	2,1	13.0	4.20	1.35	.45
Wyoming, Colorado, New Mexico	3,2,1	32.8	6.85	1.42	.31
Oklahoma, north Texas	2,1	13.3	3.73	1.07	.30
East Coast	3,2,1	12.8	3.39	.88	.23

1/ Areas arranged in order of decreasing number of modified Mercalli intensity VII earthquakes.

2/ The recurrences of table 5 have been divided by the area of each region.

Although the Eastern United States is an area of relatively low seismicity at present, it is also characterized by low attenuation of seismic waves. According to Nuttli (1972, p. 212) the low attenuation can result in a 100-fold increase in the total damage over the amount that would be expected in California for an earthquake of the same surface-wave magnitude. The low attenuation properties of the Eastern United States seem to be as much responsible for the large area affected by the Charleston and New Madrid earthquakes as the magnitudes of the quakes.

It is interesting to note that the relative amounts of strain release in the four areas of conterminous United States correspond, to some degree, with the distribution of principal horizontal and vertical faults (fig. 24). The Pacific West, which has currently active horizontal and associated vertical faults, had the greatest rate of strain release between 1900 and 1965. The Rocky Mountains, which have had relatively less fault movement during historical time, had considerably greater rates than the Eastern United States, in which older, inactive faults, such as the Triassic graben boundary faults, occur. The area east of long 92° W. appears to be seismically more active, based on strain release rates, than the Central Plains region, the greater part of which has deeply buried vertical faults, long since inactive, as indicated by younger undisturbed sedimentary rocks near the surface. The distribution of damaging earthquakes (fig. 23) also corresponds in some degree to the four areas and the distribution of horizontal and vertical faults (fig. 24). The seismic activity in

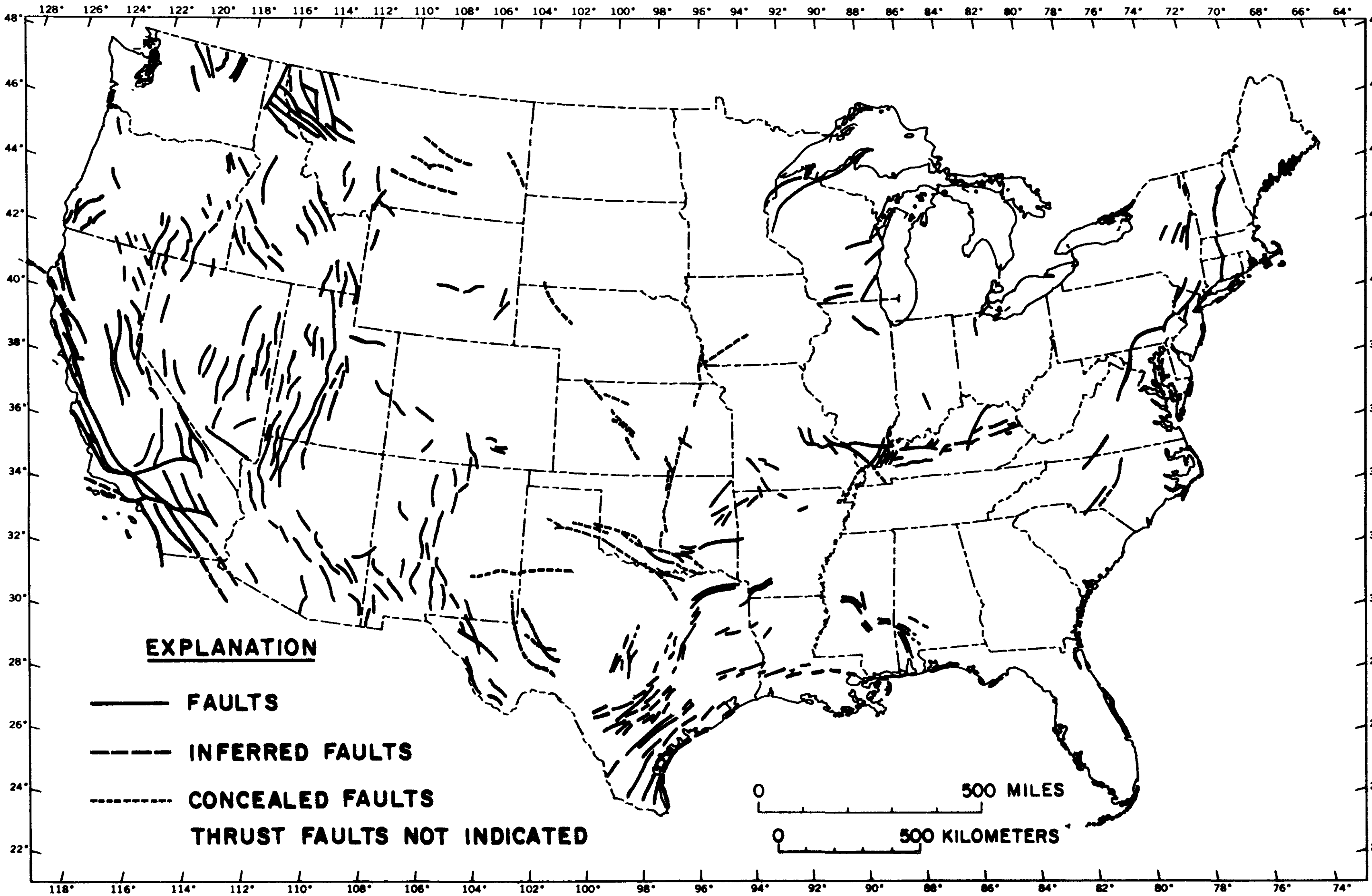

Figure 24.--Principal faults in the United States. Modified from King, P. B. (1967).

the Mississippi Valley, for instance, may be associated with the vertical faults in the region. Little is known about the origin of damaging earthquakes in coastal plain areas in the Eastern United States, such as those recorded at Charleston, S.C. Zietz and Zen (1973, p. 25) speculated that the Charleston earthquake may be associated with a continental extension of a fracture zone apparently active in the early opening of the Atlantic Ocean.

The seismic risk map, figure 25, is based on the distribution of modified Mercalli intensities associated with the known seismic history of the United States, strain release in the United States since 1900, and the association of strain release patterns with large-scale geologic features believed to be related to recent seismic activity (Algermissen, 1969, p. 20). Zones of seismic risk, rated 0-3, in order of increasing risk, based on no damage to major damage, are shown on this map. Areas of seismic risk 3 correspond to areas that have had the most numerous and most damaging earthquakes.

It is important to note that "...frequency of occurrence of damaging earthquakes was not considered in assigning ratings to the various zones on the risk map..." (Algermissen, 1969), and thus, the seismic risk map indicates the maximum expected events and not how often such events are expected to occur. Difficulties in evaluating the adequacy of historical seismic data as the basis for assigning risk have made seismic zoning a controversial subject, but most workers seem to agree that reliable assignment of risk requires an understanding of local and regional tectonic processes responsible for

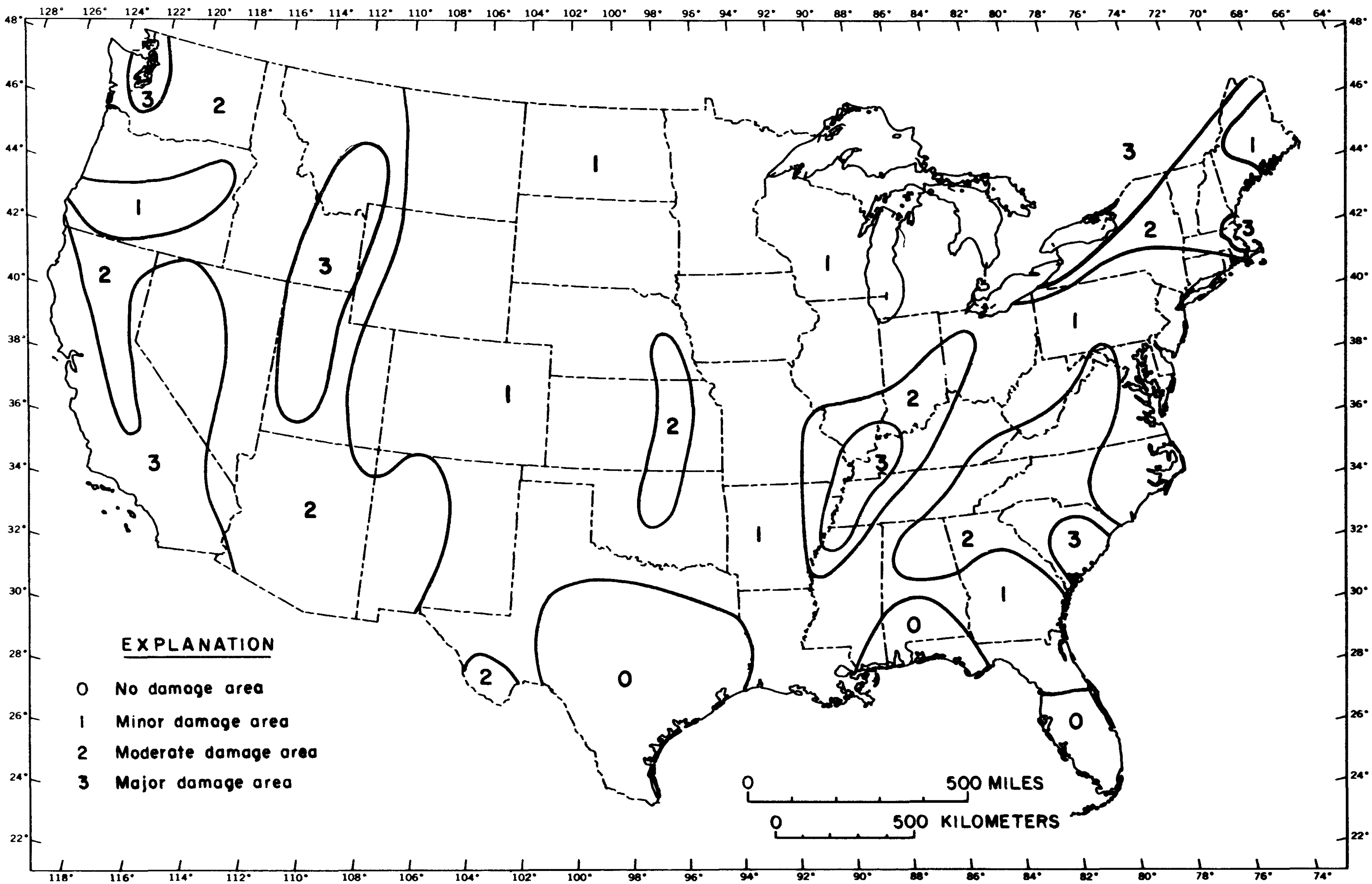

Figure 25.--Seismic risk map of the United States. Modified from Algermissen (1969).

earthquakes. Papers in the proceedings of the International Conference on Microzonation for Safer Construction, Research, and Application (1972) give an idea of currently recognized difficulties and methods of evaluating seismic risk.

It is also necessary to note that the seismic risk map depicts the estimated damage potential at the ground surface. For seismic waves arriving nearly normal to the surface, surface motion is about twice that of points within the Earth (Rodean, 1971, p. 91). Because of these and other probable differences between the characteristics of seismic waves at the surface and at the depths considered in this report for waste facilities, additional studies should be made to determine the response of underground facilities to seismic waves and to define criteria for acceptable ground motions.

In lieu of more comprehensive seismic risk studies and criteria for acceptable ground motions, it is necessary, for the purposes of this investigation, to infer that areas of seismic risk zone 3 are unsuitable for underground as well as surface facilities. Areas in seismic risk zone 2 and less are considered to be suitable if zones of active faulting are avoided.

APPENDIX C

Rock media

This part of the report briefly describes the principal rocks found in the various geologic environments in the United States and presents tables of physical property data that we consider to be significant to waste disposal. The rocks include (in one location or another) all the principal types found in the Earth's crust. These are subdivided into three main categories: sedimentary, igneous, and metamorphic.

Sedimentary rocks

Sedimentary rocks are those that are deposited on the Earth's surface by the action of water, wind, accumulation of organic remains, or chemical precipitation. They are formed by the destruction (physical or chemical) of preexisting rocks, either igneous, sedimentary, or metamorphic. The principal sedimentary rocks are shown in table 14.

Among the various sedimentary rocks there are extreme variations in physical properties, but, in general, the sedimentary rocks tend to be the weakest rocks in the crust and, exclusive of salt, have the greatest ability to store and transmit ground water. Although sedimentary rocks are estimated to constitute only 5 percent of the volume of the Earth's crust they are the rocks most likely to be encountered on the Earth's surface.

Table 14.--Principal sedimentary rocks

Method of formation	Rock	Description
Mechanical	Conglomerate	Almost entirely cemented gravel.
	Sandstone	Cemented sand.
	Shale	Cemented mud and clay.
Chemical	Carbonate (limestone and dolomite)	Chemically precipitated but commonly reworked grains of calcite and dolomite with admixtures of mud and sand.
	Salt	---
Organic	Limestone, coal	Fossiliferous calcite reconstituted plant remains.

Description of principal sedimentary rocks and summary of properties significant to waste disposal--Sandstone and conglomerate consist of grains of quartz, feldspar, and rock fragments cemented together with silica, calcium, carbonate, clay, or combinations of these ingredients. Sandstone and conglomerate vary considerably in physical properties, but, in general, they are strong rocks that will support unpropped excavations. They are generally drilled with ease and mined with a minimum of problems and hazards. They unfortunately are often porous, and the pore spaces commonly are interconnected to allow rapid transmission of water. Because of their high porosities and permeabilities, they are generally unfavorable for waste disposal.

Shale is a general term for lithified clay and mud. Most shale contains some sand. Some geologists restrict the term to rock that breaks or weathers to tiny flat fragments a fraction of an inch thick that are parallel to original bedding planes. It is not so restricted in this report. Most shale is weak and will not support unpropped excavations. It commonly contains swelling clays. It creeps in outcrop and "flows" under loading. It is, in general, a poor foundation rock and it is extremely difficult to drill and mine. The amount of "chimneying" above an underground nuclear blast in shale can be predicted to be extreme unless strong interbeds of sandstone or limestone are present. Shale, however, has the lowest permeability of sedimentary rocks, it has the highest ion-exchange capacity, and, under certain conditions, it may be a suitable host for waste disposal.

Carbonate rocks are called limestone if composed predominantly of calcite ($CaCO_3$); they are called dolomite if abundant $CaMg(CO_3)_2$ is present. Carbonate rocks are water soluble in a variety of temperature-pressure conditions in the shallow subsurface and, consequently, form the famous cave areas of the world. In some areas, for example, in the Basin and Range province, the carbonate rocks at great depths can be prolific water bearers with extremely high permeability. In other areas, for example, the Balmat-Edwards area of New York State, carbonate rocks have very low permeability even in the shallow subsurface (Park and MacDiarmid, 1964). They are strong rocks but their locally high permeability and chemical instability make these rocks generally unfavorable for waste storage or disposal.

Salt (NaCl) forms in basins that become isolated or partly isolated from the sea. It occurs in relatively pure beds or in thin layers interbedded with sediments and other evaporites. Salt has many properties that seem to make it an ideal medium for waste disposal. These properties, according to a report prepared by a committee on radioactive waste management (National Academy of Sciences, 1970), are:

1. Natural plasticity that will effectively seal the containers in cells and will relieve stress concentrations produced by the mining operations.

2. High compressive strength.

3. Thermal conductivities that permit the dissipation of larger quantities of heat than any other rock.

4. Gamma-ray shielding properties similar to concrete.

5. Almost zero porosity and permeability which allow complete isolation from the biosphere.

In addition to the National Academy of Sciences, National Research Council (1970) many other investigations on the feasibility of using salt for repositories for radioactive waste have been completed (see selected references). However, these investigations have thus far been concerned only with shallow depth burial concepts. At shallow depth (about 3,000 ft, 910 m, or less) the natural plasticity of salt is not considered to pose problems for either chamber construction or long-term storage of wastes. At depths greater than about 3,000 feet (910 m), however, the ability of salt to flow may pose serious and possibly prohibitive problems for waste disposal either in drill holes or in cavities. For this reason some observations on deformation of salt seem to be in order. The following discussion is taken directly from Pierce and Rich (1962, p. 75):

> "Balk (1949, p. 1822-23) has summarized a report by Busch (1907) of measurements of plastic salt deformation in the Neu-Stassfurt mine in Germany. Busch's attention to salt movement was aroused by the inward bending of the walls of a newly excavated shaft, and a series of measurements was taken. It was found that at a depth of 750 meters (2,460 feet) salt was extruded at a rate of as

much as 0.9 millimeter per day. Holes were drilled in the salt at different depths in the mine, and the holes were filled with lead bars that just fitted when inserted. It was found that at a depth of 500 meters (1,640 feet) the bars jammed after a few months; at 300-meter depth (984 feet), the bars jammed after 2 years; and above 250-meter depth (820 feet) the holes stayed open.

"Balk (1949), in discussing mines in Gulf Coast salt domes, reports that timbers more than 6 inches thick were bent and broken by movement of the salt, and that drill holes were appreciably reduced in diameter.

"Dellwig (1958) conducted measurements on the flowage of salt in the pillars of the American Salt Co. mine at Lyons, Kansas. The salt layer being mined is 9 feet thick and 1,000 feet below the surface. During an interval of about a year the salt flowed outward from the center of the pillar, so that the distance to surrounding pillars was decreased by about three-tenths of a foot. As this flowage took place, the lower part of the salt bed also moved, forcing the floor of the mine to buckle up in a broad arch. It should be noted that the flowage of salt in mine pillars is related not only to the weight of the overlying rock or the depth below the surface, but to the ratio of the area of the mined-out space to the area of the supporting pillars.

"E. C. Robertson (written commun., 1958) says that 'As an approximation, large plastic flow probably will begin to predominate over fracturing in workings in salt at 3,000 to 4,000 feet depth.'"

Many holes, however, have been drilled in salt to depths of at least 13,000 feet (3,960 m) (Pierce and Rich, 1962) and no serious drilling problems have been reported. Nevertheless, the possibility exists that large-diameter holes not filled with drilling mud and large mined or explosion-induced cavities will not remain open for any appreciable period at depths below a few thousand feet.

Another problem to evaluate is the high solubility of salt and the attendant danger of exposing the wastes if the salt is attacked by ground water. Dissolution of salt formations at shallow depths by circulating ground water is a common phenomenon. To ensure the long-term containment of the waste in the salt, it is necessary to establish the nature and rates of salt removal near the site.

Igneous rocks

Igneous rocks are those formed by the solidification of molten rock. They include intrusive or plutonic rocks that solidified below the Earth's surface at various depths and extrusive or volcanic rocks that solidified after being erupted onto the Earth's surface. The intrusive rocks are fine, medium, or coarse grained depending upon the depth of intrusion, rate of cooling, and presence of gaseous constituents. The extrusive rocks are fine grained or glassy (with or without crystals) and are subdivided into (1) lava--rock formed from liquid magma that flowed directly onto the Earth's surface and (2) tuff--rock formed from eruptive ash that either flowed directly onto the Earth's surface from a volcanic vent (ash-flow tuff) or fell from the atmosphere after being explosively erupted into the air from a volcanic vent (ash-fall tuff). Igneous rocks are commonly classified on the basis of their texture (grain size), minerals present, and the abundance of silica (SiO_2). A general classification and the principal mineral assemblages are shown in table 15.

The igneous rocks vary individually in hardness and strength dependent upon crystal size, the mode of eruption, and the presence or absence of voids. The plutonic (intrusive) rocks have low porosities and permeabilities, whereas, the volcanic (extrusive) rocks vary in these properties from very low to extremely high.

<u>Description of principal igneous rocks and summary of properties significant to waste disposal</u>--Plutonic igneous rocks which consist of granite, granodiorite, diorite, gabbro, and other varieties can be generally regarded as a single rock type from the standpoint of mechanical strength and overall suitability for waste disposal. The granitic rocks, however, have the lowest melting points and are somewhat weaker. Because of low porosities and permeabilities and high mechanical strengths, the plutonic rocks in some terranes may be favorable for waste disposal.

Table 15.--A classification of igneous rocks

Texture	>66 percent silica (acid)	52-66 percent silica (intermediate)		<52 percent silica (basic)
Plutonic (medium- and coarse-grained)	Granite------------	Granodiorite----	Diorite------	Gabbro
Volcanic (fine-grained or glassy lava or tuff)	Rhyolite-----------	Quartz latite and rhyodacite	Dacite and andesite	Basalt and basaltic andesite
	Major minerals--quartz, potassium, feldspar, mica.	Major minerals--quartz, sodium-calcium feldspar, mica, amphibole.	Major minerals--calcium-sodium feldspar, mica, amphibole.	Major minerals--calcium-sodium feldspar, pyroxene, olivine.

Volcanic igneous rocks are the fine-grained (extrusive) equivalents of the plutonic (intrusive) rocks. Although some volcanic rocks are chemically identical to some plutonic rocks, their physical properties are, in general, decidedly different, and, although lavas and tuffs may have identical chemical compositions, they nearly always differ enormously in physical properties.

Throughout the United States lava occurs that varies in composition from rhyolite to basalt, and, although the various lavas have many features in common, they display some inherent differences that are significant to waste disposal. Rocks that are rich in SiO_2 or contain intermediate amounts of SiO_2 are erupted at lower temperatures than the basalts and other similar low-silica lavas, and they are much more viscous. Because of greater viscosity, these lavas move across the Earth's surface slowly, congealing and freezing on the flanks, at top, and base and become flow contorted and brecciated. The brecciation increases the porosity and permeability of the rock and, consequently, many of the silicic lavas are prolific water bearers. Although they are strong rocks, except where they are extensively brecciated, and, although they are easily mined and drilled, most silicic lavas are generally unfavorable for waste disposal or storage. The basaltic and other low-silica lavas are erupted at higher temperatures and are more fluid. They commonly solidify without extensive brecciation except at top and base. Individual flows, however, are thin (less than 200 ft or 61 m) and the brecciated contacts between flows are consistently zones of high porosities and permeabilities. The basalt lavas, therefore, although constituting some of the strongest rocks known, are unfavorable for waste disposal or storage.

Tuff solidifies from soft ash by a process called welding, which is a result of heat and load pressure, and by bonding of matrix material by secondary processes during burial beneath the water table. The degree of welding is the principal factor that controls the hardness of the tuff. Densely welded tuff has physical properties that are similar to those of lava. Partially or nonwelded tuff is similar to soft sandstone. Porosity in tuff is dependent on the degree of welding and the amount of alteration or secondary crystallization that occurred during and after cooling, including zeolitization. Although most tuff has more than 20 percent open pore space (porosity), it, nevertheless, tends to have lower permeability than most lava because the pore spaces are not extensively interconnected. Tuff is easily drilled and mined, and it has the highest ion-exchange capacity of all the igneous rocks. Where sufficiently thick and not faulted, tuff should provide an excellent medium for waste disposal.

Metamorphic rocks

Metamorphic rocks are formed from original igneous, sedimentary, or other metamorphic rocks through alterations produced by pressure, heat, or introduction of other materials at depths below the surface zones of weathering and cementation. They are more or less reconstructed in place while remaining virtually solid. New minerals and textures come into being and are stable under conditions that produce the change (Stokes and Varnes, 1955, p. 91). Grain sizes, compositions, and derivations of the principal metamorphic rocks are given in table 16. Quartzite, marble, and amphibolite are unfoliated to faintly foliated, whereas the other types are foliated, cleaved, or banded, and some types (especially slate) tend to split in well-defined thin layers. All these rocks are considered to be stronger than their sedimentary equivalents and have lower permeabilities, but, in general, they are weaker and have higher permeabilities than most intrusive igneous rocks.

In general, there are often no sharp boundaries between the various types of metamorphic rocks. Within a small area several rock types may occur; therefore, locating a particular metamorphic type at depth may require more intense surface and subsurface investigations than would normally be required for intrusive igneous (plutonic) rocks.

Description of principal metamorphic rocks and summary of properties significant to waste disposal--Quartzite is made up of interlocking grains of quartz. It is essentially extremely well cemented quartz sandstone. When fractured, quartzite breaks across the grains in contrast to sandstone which breaks around the mineral grains. Quartzite is very hard, chemically inert, and has the greatest thermal conductivity and thermal expansion of the principal rock types discussed. Most quartzite has very low porosity and permeability. Its susceptibility to fracturing, however, increases its permeability, especially at shallow depths. At greater depths in fractures, quartzite would tend to be closed.

Table 16.--Principal metamorphic rocks

Rock type	Grain size	Chief minerals	Derivation
Gneiss--------	Coarse to medium grained	Quartz, feldspar, mica, hornblende	Granite, mica, schist, shale
Quartzite-----	----do.---------	Quartz------------	Sandstone
Amphibolite---	----do.---------	Hornblende, plagioclase; minor garnet and quartz	Basalt, gabbro, tuff
Marble--------	Coarse to fine grained	Calcite, dolomite--	Limestone, dolomite
Schist--------	----do.---------	Mica, quartz, feldspar	Shale, igneous rocks
Phyllite------	Fine grained----	Mica, quartz, kaolinite	Shale, tuff
Slate---------	Very fine grained	Mica, kaolinite---	Shale, tuff

Marble is recrystallized limestone or dolomite and its chemical and physical properties do not differ markedly from these sedimentary rock types. Marble has the greatest solubility of the metamorphic rocks and is chemically unstable in an acid environment. Because of its potential for locally high permeability in most geohydrologic environments, marble is generally unsuitable for waste disposal.

Most amphibolite is a coarse-grained rock consisting of amphibole and plagioclase and lesser amounts of garnet, quartz, and epidote. It is principally derived from basalt, gabbro, and rock of similar composition. Of the principal metamorphic rocks, amphibolite has the greatest strength and should be less susceptible to fracturing than quartzite, and, therefore, less permeable at shallow depths. Amphibolite also has the highest density and magnetic susceptibility of the common metamorphic rocks, which could be advantageous in determining their distribution through geophysical methods. The potential for very low permeability indicates that amphibolite may be suitable for waste disposal.

Gneiss has distinct layers or lenses of different minerals. The mineral composition, although variable, consists of abundant feldspar and moderate amounts of quartz, amphibole, garnet, and mica. Gneiss forms from numerous parent rocks, igneous, sedimentary, or metamorphic. It is second to amphibolite in strength and second to quartzite in thermal conductivity. Because gneiss varies considerably in mineralogy and origin, its physical and chemical properties will not be consistent. Therefore, some varieties of gneiss may prove to be more favorable for waste disposal than others. Gneiss, in general, has very low permeability.

Schist is a crystalline metamorphic rock having closely spaced foliation. It tends to split readily into thin flakes or slabs. There is a complete gradation between schist and gneiss to schist and slate. The names of the varieties of schist are based chiefly on the mineral responsible for the foliation, that is, biotite schist, chlorite schist, and graphite schist. Schist has lower themal conductivity than quartzite, amphibolite, and gneiss, and has the least strength of any of the principal metamorphic rocks. Because of its wide variation in mineralogy and origin, schist should vary considerably with respect to physical and chemical properties, and its favorability for waste disposal will depend on the rock type in question.

Phyllite is fine-grained foliated rock that is intermediate between mica schist and slate. Practically all phyllite is derived from fine-grained sedimentary rocks by mechanical deformation and recrystallization. Fracturing is intermediate between the rather splintery fissility of schist and the smooth, even cleavage of slate. Both phyllite and slate are highly foliated and, because of their excellent foliation, split into thin sheets.

Slate is homogeneous metamorphic rock so fine grained that no mineral grains are visible to the naked eye. Some slate splits into slabs having plane surfaces almost as smooth as the cleavage planes of minerals. Slate is harder than shale, although the difference is slight. Slate and phyllite have the greatest ion-exchange capacities of the common metamorphic rocks. Slate locally may be suitable waste disposal rock from the standpoint of permeability, especially at great depths where open fractures along cleavage planes may be at a minimum. Slate has the least thermal conductivity, but its thermal expansion is nearly as high as for quartzite.

Chemical compositions and additional physical and hydrologic properties of principal rock types (sedimentary, igneous, and metamorphic) are given in table 17 (in pocket).

APPENDIX D

Glossary of geohydrologic terms

Technical terms, particularly those having somewhat obscure meanings, are defined in this glossary. For terms not defined in this glossary the reader is referred to the "Glossary of Geology and Related Sciences," compiled by the American Geological Institute, and Webster's New World Dictionary, College Edition.

In some instances, definitions have been enlarged beyond the standard textbook definitions. No attempt has been made to cite the source of definitions and those definitions that have been enlarged may deviate slightly from the standard definitions.

Alluvial fan.--A sloping, fan-shaped mass of loose rock material deposited by a stream at the place where it emerges from an upland onto a broad valley or a plain.

Alluvium.--All detrital material deposited permanently or in transit by streams.

Amphibole.--A group of dark, rock-forming, ferromagnesian silicate minerals which are closely related in crystal form and composition and which have abundant and wide distribution in igneous and metamorphic rocks.

Anorthosite.--A granular plutonic igneous rock composed almost exclusively of soda-lime feldspar.

Anion.--An ion that is negatively charged.

Anticline.--A fold, the core of which contains stratigraphically older rocks, and, which, in simplest form, is elongate and convex upward with the two limbs dipping away from each other.

Aquifer.--A formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs.

Aquitard.--A natural rock or fine-grained unconsolidated unit of low permeability which is stratigraphically adjacent to one or more aquifers and through which water movement is markedly retarded or impeded.

Argillite.--A compact rock, derived from claystone, siltstone, or shale, which has undergone a somewhat higher degree of induration than is present in these sedimentary rock types but which is less clearly laminated than shale, does not have the fissility of shale, and lacks the cleavage distinctive of slate.

Artesian.--When pertaining to an aquifer is one that is confined so that its hydraulic head rises above the top of the aquifer unit; thus an artesian water body is one that is confined under hydraulic pressure.

Basement.--A complex of undifferentiated rocks that underlies the oldest identifiable rocks in the area.

Basin.--A depressed area generally having no surface outlet; a segment of the Earth's crust that has been downwarped by the accumulation of sediments on it; a synclinal tract or area in which the rocks dip toward a central point and in which folding occurred subsequent to deposition; an elongate, fault-bordered intermountain area.

Batholith.--An igneous intrusion greater than 40 mi^2 in surface exposure, composed predominantly of granitic rocks.

Bauxite.--A rock composed of an impure mixture of earthy hydrous aluminum oxides and hydroxides. It is the principal commercial source of aluminum.

Bentonitic.--Pertaining to rock containing bentonite, a clay formed from the decomposition of volcanic ash.

Biotite.--A complex silicate of aluminum, potassium, magnesium, and iron with hydroxyl that is a widely distributed and important rock-forming mineral of the mica group.

Block-faulting.--A type of vertical faulting in which the crust is divided into structural or fault blocks of different elevations and orientations.

Brackish.--A somewhat general term applied to mineralized water of concentrations intermediate between those of brine and those of fresh water.

Breccia.--A coarse-grained clastic rock composed of large, angular, and broken rock fragments cemented together in a finer grained matrix.

Caliche.--Calcareous material that forms on or near the surface of stony soils of arid and semiarid regions; thought to be genetically associated locally with the capillary fringe of the water table; it is inferred to form when evaporation exceeds precipitation.

Caprock.--A low-permeability body of anhydrite and gypsum which overlies a salt body or plug in a salt dome.

Cation.--An ion that is positively charged.

Chimneying.--The process of progressive collapse of rock overlying an explosion-produced cavity resulting in a tall underground cylinder (chimney).

Chlorite.--A group of green hydrous silicate minerals containing magnesium and iron, with or without aluminum; these minerals are widely distributed, especially in metamorphic rocks.

Clastic.--Pertaining to or the state of being a rock or sediment composed principally of broken fragments derived from preexisting rocks or minerals.

Cleavage.--The property or tendency of a rock to split along secondary, alined fractures or other closely spaced planar surfaces produced by deformation or metamorphism.

Coal measures.--A succession of sedimentary rocks (or measures) consisting of clays or shales, sandstones, limestones, and conglomerates with interstratified beds of coal; a group of coal seams interbedded with the above strata.

Conglomerate.--A coarse-grained clastic sedimentary rock composed of rounded to subangular fragments larger than 2 mm in diameter, such as granules, pebbles, cobbles, and boulders, set in a fine-grained matrix of sand, silt, or cementing materials, such as calcium carbonate, iron oxide, and silica. The consolidated equivalent of gravel.

Consolidated (material).--In geology, natural materials that have been made firm, cohesive, and hard.

Crystalline rock.--An inexact but convenient term designating an igneous or metamorphic rock, as opposed to a sedimentary rock.

Depositional environment (sedimentary environment).--A geographically restricted environment where sediment accumulates under similar physical, chemical, and biological conditions.

Diagenesis.--Process involving physical and chemical changes in sediment after deposition that converts the sediment to consolidated rock.

Diamond pipe.--Term used for an occurrence of kimberlite (peridotite that has been converted to a hydrous magnesian silicate) in volcanic pipes large enough and sufficiently diamond bearing to be minable.

Diapirism.--The piercing of overlying rocks by a mobile core, such as a salt body or an igneous intrusion.

Discharge.--In ground-water hydrology, water that issues naturally or is withdrawn from an aquifer.

Dome.--A dome-shaped landform or rock mass; a large igneous intrusion whose surface is convex upward with sides sloping away at low but gradually increasing angles; an uplift or an anticlinal structure, either circular or elliptical in outline, in which the rock dips gently away in all directions, that is, a salt dome.

Dunite.--A coarse-grained plutonic igneous rock composed almost entirely of olivine.

Ephemeral stream.--A water course carrying surface water part of the time but dry or having only underflow in the streambed materials the other part of the time.

Epidote.--A basic orthosilicate mineral containing calcium, aluminum, and varying amounts of iron, and commonly occurring in metamorphic rocks.

Fault.--A fracture or fracture zone along which there has been displacement of the sides relative to one another parallel to the fracture.

Fault block.--A crustal unit bounded by faults, either completely or partly.

Fault system.--A system of parallel or nearly parallel faults that are related to a particular deformational episode.

Feldspar.--Any of an important group of rock-forming minerals that are silicates of alumina and some other base, such as potash, soda, or lime.

Flood-plain deposit.--Sandy and clayey sediment deposited by river water that spread out over a flood plain.

Foliation.--A general term for a planar arrangement of textural or structural features in any rock type, but most commonly applied to metamorphic rocks, such as cleavage in slate or schistosity in a metamorphic rock.

Garnet.--An important group of silicate minerals rich in alumina, iron, lime, and magnesia, which occur chiefly as accessory constituents of metamorphic rocks and, less commonly, of igneous rocks.

Geohydrologic.--Of or pertaining to geology and hydrology. An abbreviation combining the adjectives geologic and hydrologic.

Geoid.--The figure of the Earth considered as a mean sea-level surface extended continuously through the continents.

Geothermal.--Pertaining to the heat of the interior of the Earth.

Glacial outwash gravel.--Gravel removed or "washed out" from a glacier by meltwater streams and deposited in front or beyond the margin of an active glacier.

Graben.--An elongate, relatively depressed crustal unit or block bounded by faults on its long sides.

Granitic.--Of or pertaining to granite. Granitelike.

Granitoid.--A textural term indicating grain size and mineral distribution typical of granite.

Hornblende.--A common member of the amphibole group of minerals.

Hydraulic gradient.--The change in static head per unit of lateral distance in a given direction.

Hydrostatic pressure.--The pressure exerted by the water at any given point in a body of water at rest.

Hydrothermal.--A term applied to heated or hot magmatic emanations rich in water and applied to the rocks, ore deposits, alteration products, and springs produced by hydrothermal processes.

Ion exchange.--Replacement of ions adsorbed on a solid--such as a clay particle--or exposed at the surface of a solid by ions from solution, usually in natural water. The phenomenon is known to occur when natural water moves through clays, zeolitic rocks, and other materials of the Earth's crust.

Interfluve.--The area between adjacent streams flowing in the same general direction.

Interstices.--In geology, small openings between solid particles in a rock or unconsolidated material; may be a void or pore and often contains ground water. Interstitial permeability is used to differentiate interconnected pore permeability from fracture permeability.

Iron formation.--A chemical sedimentary rock, typically thin bedded and (or) finely laminated, containing at least 15 percent iron of sedimentary origin.

Isopach.--A line drawn on a map through points of equal thickness of a designated stratigraphic unit or group of stratigraphic units.

Joint.--A fracture or parting in a rock, without displacement.

Kaolinite.--The mineral characteristic of kaolin; a group of minerals consisting mainly of hydrous aluminum silicate and closely related in chemical composition and crystal structure.

Laccolith.--A concordant igneous intrusion having a known or assumed flat floor and a postulated dikelike feeder somewhere beneath its thickest point.

Lithification.--The conversion of unconsolidated sediment into solid rock by processes such as compaction, cementation, and crystallization.

Lithology.--The character of a rock: its structure, color, mineral composition, grain size, and arrangement of its component parts.

Loess.--An unconsolidated or weakly consolidated sedimentary deposit which is composed dominantly of silt-sized rock and mineral particles and which is deposited by wind.

Low-angle fault.--A fault, the dip of which is no more than 45°.

Mafic.--Pertaining to or composed dominantly of magnesium rock-forming silicates.

Magmatism.--The development, movement, and solidification to igneous rock, of magma, a naturally occurring mobile rock material, generated within the Earth and capable of intrusion and extrusion.

Matrix-hole concept.--A type of radioactive-waste repository consisting of several geometrically spaced drill holes.

Mesa.--An isolated nearly level landmass standing distinctly above the surrounding country, bounded by steeply sloping erosion scarps on all sides and capped by layers of resistant nearly horizontal rocks.

Metallic.--Of or belonging to metals; contains metals, more particularly, valuable metals that are the object of mining ore.

Mica.--A group of silicate minerals of aluminum and other bases, especially potassium, magnesium, and iron, and characterized by great perfection of cleavage in one direction, that produces thin, tough, elastic plates or laminae.

Monocline.--A unit of strata that dips from the horizontal in one direction only and is not part of an anticline or syncline.

Nepheline syenite.--A plutonic rock composed almost entirely of alkali-feldspar and nepheline which is a silicate mineral containing appreciable amounts of potash, soda, and alumina.

Olivine.--An olive-green, common rock-forming ferromagnesian silicate mineral of mafic, ultramafic, and low-silica igneous rocks.

Outcrop.--A part of a body of rock that appears, bare and exposed, at the surface of the ground.

Permeability (permeable).--The relative ease with which a porous medium can transmit a liquid under a hydraulic gradient.

Plagioclase.--The group of common rock-forming feldspar minerals that contain varying mixtures of sodium and calcium.

Playa.--A flat-floored area composed of thin evenly stratified sheets of fine clay, silt, or sand, and representing the lowermost or central part of a shallow completely closed or undrained desert lake basin in which water accumulates after a rain and is evaporated, usually leaving deposits of soluble salts.

Peridotite.--A coarse-grained plutonic igneous rock composed chiefly of the mineral olivine but also containing considerable amounts of other ferromagnesian minerals.

Pluton.--A body of intrusive igneous rock of any shape or size.

Pluvial.--Pertaining to a period of time in which rainfall or precipitation is abundant.

Porosity.--That property of a rock or soil which enables the rock or soil to contain water in voids or interstices, usually expressed in percentage or as a decimal fraction of void volume as compared to total volume.

Pyroxene.--A group of dark rock-forming silicate minerals closely related in crystal form and analogous in chemical composition to the amphiboles; found chiefly in igneous rocks.

Pyroxenite.--An ultramafic plutonic igneous rock chiefly composed of pyroxene.

Quartz monzonite.--A coarse-grained igneous rock, intermediate in composition between granite and granodiorite, which contains quartz and about equal amounts of the alkali and soda-lime feldspars.

Recharge.--In hydrology, a source or means for replenishment of water withdrawn or discharged from an aquifer. An aquifer in hydraulic equilibrium will discharge a quantity of water about equal to the amount of recharge.

Rift.--A long fairly narrow depression formed along lines of multiple fracture.

Rift valley.--An elongate narrow trough or valley formed by the sinking of a strip of the Earth's crust between two more or less parallel nearly vertical faults.

Rift zone.--A system of crustal fractures.

Rise (marine).--A broad, elongate, and smooth elevation of the ocean floor.

Sedimentary basin.--A geologically depressed area that has thick sediments in the interior and thinner sediments at the edges.

Seismicity.--The phenomenon of Earth movements as manifested by earthquakes.

Shield.--A continental segment of the Earth's crust which has been relatively stable over a long period of time and which has exposed crystalline rocks mostly of Precambrian age; in general, representing the oldest rocks of the continent.

Sill.--A tabular igneous intrusion that parallels the planar structure of the surrounding rock.

Sink hole.--A funnel-shaped depression in the land surface generally in a limestone region often connected to a subterranean passage developed by solution.

Static head.--The height above a standard datum of the surface of a column of water (or other liquid) that can be supported by the static pressure at a given point.

Stock.--An igneous intrusion less than 40 mi^2 (100 km^2) in surface exposure.

Strain.--Deformation resulting from applied stress; proportional to stress.

Stratum.--A single layer of homogeneous or gradational lithology, deposited parallel to the original dip of the formation.

Strike-slip fault.--A fault, the actual movement of which is parallel to the strike of the fault.

Syncline.--A fold, the core of which contains stratigraphically younger rocks, and which, in simplest form, is elongate and concave upward with the two limbs dipping toward each other.

Tectonic.--Pertaining to the forces involved in, or the rock structures and external forms resulting from, the deformation of the Earth's crust.

Tectonism (diastrophism).--Crustal movement produced by Earth forces, such as the formation of plateaus and mountain ranges; the structural behavior of an element of the Earth's crust during, or between, major cycles of sedimentation.

Terrace.--A long, narrow, relatively level or gently inclined surface, generally less broad than a plain, bounded along one edge by a steeper descending slope and along the other by a steeper ascending slope, and containing unconsolidated material.

Thrust fault.--A fault having a dip of 45° or less in which the upper rock mass appears to have moved upward relative to the lower rock mass.

Transmissivity.--Volume of water flowing through a 1-foot width of aquifer of given thickness under a unit gradient (1 ft vertically for each 1 ft laterally) and at the viscosity prevailing in the field. Mathematically, it is the product of permeability and aquifer thickness.

Ultramafic.--Pertaining to igneous rocks composed chiefly of ferromagnesian dark minerals.

Underthrust.--A type of thrust fault in which the lower rock mass has been actively moved under the upper, passive rock mass.

Uplift.--A structurally high area in the crust, produced by positive movements that raise or upthrust the rocks, as in a dome or arch.

Upwarping.--Uplift of a regional area of the Earth's crust.

Wastes, radioactive.--Definitions of levels.

Level	ORNL (μCi/ml)	ORNL (X MPC)	HANFORD (μCi/ml)	AICE (X MPC)
Low	10^{-5} to 10^{-2}	10 to 10^4	$<5X10^{-5}$	$<10^4$
Intermediate	10^{-2} to 1	10^4 to 10^6	$5X10^{-5}$ to 100	10^4 to 10^8
High	>1	$>10^6$	>100	$>10^8$

ORNL = Oak Ridge National Laboratory.
HANFORD = Atomic Energy Commission, Richland, Wash.
AICE = American Institute of Chemical Engineers.
MPC = maximum permissible concentration.
μCi/ml = microcuries per millilitre.

Water table.--That surface of an unconfined water body at which the pressure is atmospheric.

Zeolite.--Any of a large group of minerals that are hydrous silicates of aluminum with sodium and calcium or, rarely, with barium and strontium.

Zeolitization.--The process by which feldspars and other alumino silicates of a rock are altered to zeolites.

Table 17.—Chemical compositions (in percent) and physical and hydrologic properties of principal rock types

	Sandstone 1/	Shale 2/	Limestone 3/	Dolomite 4/	Granite 5/	Granodiorite 6/	Diorite 7/	Gabbro 8/	Rhyolite 9/	Quartz latite 10/	Dacite 11/	Andesite 12/	Basalt 13/	Quartzite 14/	Amphibolite 15/	Gneiss 16/	Schist 17/	Phyllite 18/	Slate 19/	Salt	Marble	Tuff
SiO_2	78.66	58.10	5.19	4.08	70.18	65.01	56.77	48.24	72.80	67.43	65.68	59.59	49.06	83.30	50.39	64.17	65.74	61.78	61.90			
TiO_2	.25	.65	.06	---	.39	.57	.84	.97	.33	.85	.57	.77	1.36	.49	1.88	1.03	.55	.73	.82			
Al_2O_3	4.78	15.40	.81	.83	14.47	15.94	16.67	17.88	13.49	16.15	16.25	17.31	15.70	7.44	14.67	15.90	17.35	16.54	16.34			
Fe_2O_3	1.08	4.02	.54	.13	1.57	1.74	3.16	3.16	1.45	4.04	2.38	3.33	5.38	3.69	4.02	2.31	1.90	2.43	2.73			
FeO	.30	2.45	---	.95	1.78	2.65	4.40	5.95	.88	1.20	1.90	3.13	6.37	.62	8.34	4.36	3.35	5.45	3.63			
MnO	Trace	Trace	.05	.14	.12	.07	.13	.13	.08	.09	.06	.18	.31	<Trace	<.28	<.15	.03	.07	Trace			
MgO	1.17	2.44	7.90	9.28	.88	1.91	4.17	7.51	.38	1.74	1.41	2.75	6.17	.92	5.85	2.63	1.90	2.35	2.99			
CaO	5.52	3.11	42.61	29.48	1.99	4.42	6.74	10.99	1.20	4.24	3.46	5.80	8.95	.53	9.12	3.40	1.25	1.94	1.07			
Na_2O	.45	1.30	.05	---	3.48	3.70	3.39	2.55	3.38	3.34	3.97	3.58	3.11	1.58	2.84	2.62	1.78	1.89	2.57			
K_2O	1.32	3.24	.33	---	4.11	2.75	2.12	.89	4.46	3.75	2.67	2.04	1.52	1.62	.96	1.87	3.28	4.14	3.15			
P_2O_5	.08	.17	.04	---	.19	.20	.25	.28	.08	.27	.15	.26	.45	.21	.24	.15	.12	.27	.04			
H_2O	1.64	5.00	.77	.41	.84	1.04	1.36	1.45	1.47	1.90	1.50	1.26	1.62	1.16	1.54	1.15	2.01	2.32	3.84			
CO_2	5.04	2.63	41.58	4.42	---	---	---	---	---	---	---	---	---	---	Trace	<.03	None	---	.59			
Grain size (mm) 20/	0.05-0.8	<0.01	0.001-0.85	3.5-4.0	0.1-12.0	---	0.2-10.0	<1.0-3.0	---	---	---	0.3-1.6	0.01-80.0	<0.3	0.1-2.0	0.1-18.0	0.04->6.0	0.01-3.0	>0.03-0.12	10-40	<1-8.5	0.12-0.25
Mohs' hardness 20/	2.42-6.13	3.16-5.68	2.79-4.84	3.26	5.83-6.5	---	4.68-6.37	5.68-6.14	---	---	---	6.17-6.25	3.95-6.21	5.75	4.74-6.37	5.26-6.58	5.2-5.68	3.47-5.11	3.79-4.32	---	3.7-4.32	---
Specific gravity (avg) 20/	2.06-3.26	2.4-2.92	2.44-2.83	2.72-2.84	2.61-2.65	21/ 2.68-2.98	1.0-3.03	2.81-2.93	21/ 2.26-2.50	---	---	2.57	2.04-3.01	2.75	3.01-3.12	2.65-3.36	2.68-2.75	2.18-3.24	2.74-2.[illegible]3	2.5	2.72-3.2	21/ 2.42-2.55
Compressive strength (psi) 20/	2,270-34,100	4,970-34,800	9,700-29,500	46,700	8,250-35,400	---	9,310-48,300	18,300-40,200	21/ 17,200-42,000	---	---	18,710-19,130	2,470-52,000	91,200	30,400-74,900	22,200-36,400	1,160-23,500	97[illegible]-1[illegible],300	22,500-30,400	1,080-5,000	18,400-33,000	21/ 40,000
Modulus of elasticity (10^6 psi) 20/	0.87-7.02	6.73-9.87	4.1-10.73	12.3	3.85-6.41	---	[illegible].4-12.2	12.3	---	---	---	---	0.91-13.9	12.3	6.74-15.1	3.48-15.0	2.6-8.7	2.[illegible]-11.1	11.0-13.65	---	7.15-11.9	---
Interstitial porosity (percent)	22/ 0-51	23/ 0.7-22/ 45	22/ 0-32		Granitic and other plutonic rocks: 24/25/ 0.05-3.0				Volcanic rocks excluding basalt: 26/ <1-23/ 48				27/ 0.9-28/ 37	Metamorphic rocks: 24/27/ 0.02-2.4						26/ <1	21/ 0.9-2.3	21/ 29.1-47.5
Interstitial permeability (gpd/sq ft)	29/ 2×10^{-3}-30/ 220	23/ 7×10^{-7}-4	23/ 2×10^{-5}-28/ 6		Granitic and other plutonic rocks: 31/ 9×10^{-7}-5×10^{-6}				Volcanic rocks excluding basalt: 23/ 2×10^{-6}-18				30/ 4×10^{-5}-0.9	Metamorphic rocks: 31/ 1×10^{-6}-0.05						26/ 1.3×10^{-4}-0.07	---	---
Production rates from wells (gpm)	32/ <0.1-26/ 870	29/ <0.1-33/ 64	32/ <0.1-33/ 2,950		Granitic and other plutonic rocks: 26/ 0-63				Volcanic rocks excluding basalt: 23/ <1-700				27/ 10-5,300	Metamorphic rocks: 34/ <1-26/ 56						---	---	---
Types of principal permeability 23/26/27/	Interstitial, fracture	Fracture	Interstitial, fracture, solution		Granitic and other plutonic rocks: fractures				Volcanic rocks excluding basalt: fractures, interstitial				fractures, interstitial	Metamorphic rocks: Fractures						---	---	---
Solubility 27/	Low	Low	Moderate		Granitic and other plutonic rocks: Low				Volcanic rocks excluding basalt: low				low	Metamorphic rocks: Low						High	---	---
Cation-exchange capacity 35/ (milliequivalents/100 g)	---	10.0-41.0	---	---	---	---	---	---	---	---	---	---	0.5-2.8	0.6-5.3	---	---	---	---	---	---	---	32-49
Thermal conductivity 36/ (10^{-3} cal/cm sec °C)	3.5-10.2	2.8-6.9	4.7-8.0	9.6-12	6.2-9.0	6.2-8.3	37/ 5.53	37/ 4.16	7.4-8.8	---	---	37/ 3.06	37/ 3.45-4.09	8.7-19.2	6.1-9.1	4.6-11.4	4.1-8.9	6.5-14.0	---	36/ 12.75-17.2	37/ 5.2-7.14	---
Thermal expansion, 20°-100°C 38/ (avg linear expansion coefficient ΔL/LΔT)	$10\pm2\times10^{-6}$	---	$8\pm4\times10^{-6}$	---	$8\pm3\times10^{-6}$	---	$7\pm2\times10^{-6}$	$5.4\pm1\times10^{-6}$	$8\pm3\times10^{-6}$	---	---	$7\pm2\times10^{-6}$	$5.4\pm1\times10^{-6}$	11×10^{-6}	---	---	---	---	$9\pm1\times10^{-6}$	---	$7\pm2\times10^{-6}$	---
Incipient melting (°C) 39/	---	---	---	---	Below 700	---	---	---	---	---	---	1095-1098	1040-1072	---	---	---	---	---	---	---	---	---

1/ Composite analysis of 253 samples (Clarke, 1924, p. 547) (includes 0.07 percent SO_3, trace Cl).
2/ Average of 78 analyses (Pettijohn, 1957, p. 344) (includes 0.64 percent SO_3).
3/ Composite analysis of 345 samples (Clarke, 1924, p. 564) (includes 0.05 percent SO_3, 0.02 percent Cl).
4/ Average of 5 analyses (Clarke, 1924, p. 579).
5/ Average of 546 analyses (Daly, 1933, p. 9).
6/ Average of 40 analyses (Daly, 1933, p. 15).
7/ Average of 70 analyses (Daly, 1933, p. 16).
8/ Average of 41 analyses (Daly, 1933, p. 17).
9/ Average of 126 analyses (Daly, 1933, p. 9).
10/ Average of 12 analyses (Daly, 1933, p. 13).
11/ Average of 90 analyses (Daly, 1933, p. 15).
12/ Average of 87 analyses (Daly, 1933, p. 16).
13/ Average of 198 analyses (Daly, 1933, p. 17).
14/ Average of 3 analyses (Clarke, 1924, p. 619).
15/ Average of 3 analyses (Clarke, 1924, p. 603).
16/ Average of 7 analyses (Clarke, 1924, p. 630) (includes 0.03 percent S).
17/ Average of 5 analyses (Clarke, 1924, p. 631) (includes 0.03 percent SO_3, 0.58 percent C).
18/ Average of 4 analyses (Mehnert, 1969, p. 278) (includes 0.01 percent S).
19/ Average of 22 analyses (Clarke, 1924, p. 631) (includes 0.11 percent FeS_2)
20/ Wuerker (1969, tables 1-5).
21/ Judd (1969, Appendix B).
22/ Manger (1963).
23/ Winograd and others (1971).
24/ Talobre (1957).
25/ Izett (1960).
26/ Davis and DeWiest (1966).
27/ Meinzer (1923).
28/ Mundorff and others (1964).
29/ Levorsen (1954).
30/ Morris and Johnson (1967).
31/ Johnson (1963).
32/ O'Connor (1971).
33/ Cederstrom (1972).
34/ McConaghy and others (1964).
35/ Carroll (1959, table 3).
36/ Clark (1966, tables 21-1 and 21-2).
37/ Daly (1933, table 12).
38/ Clark (1966, table 6-10).
39/ Daly (1933, table 16a).

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Table 1.--Sedimentary basins

Basin	Map No. number (fig. 2)	Area (sq. mi.)	Maximum depth (feet)	Folds	Faults	Ground water: Water levels, range in depth above (+) or below (-) land surface in feet	Ground water: Type of pressure producing water level	Oil and gas: Range in depth to producing formations in feet	Oil and gas: Type of production	Sediments and rocks: Shale 2/	Sediments and rocks: Coal	Sediments and rocks: Sandstone or conglomerate	Sediments and rocks: Limestone or dolomite	Sediments and rocks: Evaporites (salt unless specified)	Remarks
Atlantic Coastal Plain	1	95,000	10,000	Four scattered	Rare, covered	1/2/+119 to -73	Water table and artesian	---	None9/	20 percent silts and clays, 50-300 feet thick1/	None83/	Abundant	Abundant in Florida.	Florida6/	Hot water, 3,005 feet deep in Georgia1/
Eastern Triassic basins, eight	2	8 basins 300-4,000 each	3/20,000	---	Near margins and center6/	7/8/0 to -165	do.	---	None9/	Minor3/	Abundant bituminous83/	Abundant8/	None8/	None9/	Basalt flows8/
Appalachian basin	3	6/207,000	10/5,000-19,000	---	Thrust and normal10/	2/+1 to -146	do.	11/600-11,600	Oil and gas	800-8,000 feet crop out12/	Abundant bituminous13/83/	---	---	500 feet thick 500-4,000 feet deep14/	Volcanic rocks13/
Gulf Coastal Plain:															
Florida	4a	40,000	17/>20,000	Minor	Minor	2/+125 to -148	do.	11/13/11,000-16,000	Oil13/	---	None83/	---	Abundant	30 inches thick and 11,000-12,000 feet deep17/	Gravity data indicate igneous intrusion20/. Artesian springs. One thermal spring16/
Alabama	4b	40,000	30,000	One salt dome and one gentle fold 6/	Many in W. part 6/	2/-7 to -323	do.	18/2,600-19/17,100	Oil	Abundant	Some lignite83/	Abundant	Moderate to abundant.	Deep and one dome	Gravity data indicate igneous intrusion20/
Mississippi	4c	60,000	>30,000	Salt domes and gentle folds. Igneous dome?6/	Many in S. part	2/+103 to -243	do.	11/4,900-21,300	Oil and gas	do.	do.	do.	do.	Deep and domes	Igneous intrusions20/
Desha	4d	5,000	>20,000	Some gentle folds6/	Some near S. and SW. margins6/	21/+46 to -29	do.	11/10,451	do.	do.	do.	do.	do.	do.	Do.
Louisiana	4e	65,000	>40,000	Salt domes and gentle folds6/	Many6/	21/+25 to -179	do.	11/15/300-17,800	do.	do.	do.	do.	do.	0-130 feet thick and 3,000-10,000 feet deep41/	Do.
Tyler	4f	5,900	>26,300	Many6/	Some on folds6/	12/+3 to -287	do.	11/15/870-13,300	do.	do.	Some bituminous83/	do.	do.	Stable domes4/	---
Texas Gulf	4g	85,000	>40,000	Salt domes and gentle folds	Many parallel coast6/	21/+38 to -195	do.	11/15/160-15,600	do.	Abundant, maximum 490 feet thick.	Some lignite83/	do.	do.	Moving domes4/	Igneous intrusions20/. High temp. in south15/
Michigan basin, including Canada	5	122,000 including Canada	23/14,000	Trend NW. en echelon23/	Largest 500-foot throw, normal23/	1/+2 to -49	do.	11/15/700-7,400	do.	200-400 feet thick and 1,000-5,000 feet deep14/	<1 percent of section. Some23/	23 percent of section23/	47 percent of section23/	12 percent of section23/. 0-300 feet thick and 1,000-3,000 feet deep16/	Salty water below 2,000-2,300 feet23/. Many drill holes23/
Illinois basin	6	55,000	17/15,000	About 8 on E. and S.6/	Many in S.6/	1/2/24/-5 to -[illegible]2	do.	11/15/300-5,200	do.	Partly carbonaceous, 760 feet crops out12/	Abundant bituminous83/	---	---	---	---
Forest City basin	7	15,000	5,000	Many gentle folds25/	---	26/27/Flowing to -160	do.	11/910-3,230	do.	Abundant, partly carbonaceous.12/25/	[illegible]	Abundant25/	Abundant25/	None or little25/	---
Salina basin	8	20,000	28/4,500	Many gentle folds28/	---	29/30/Flowing to -265	do.	18/1,400-3,381	Oil	600-700 feet thick and 0-900 feet deep in Permian14/ 100-300 feet thick and 3,000 feet deep in Pennsylvanian14/	Some lignite84/	Abundant28/	Abundant28/	0-300 feet thick and 500-1,500 feet deep14/	Artesian spring from Dakota sandstone on a fault.
McAlester-Arkansas basin	9	10,000	17/20,000	Many folds and domes, especially in S.	Many	12/-10 to -18	do.	11/18/32/825-7,700	Oil and gas	Carbonaceous, 1,000-12,000 feet crops out12/	Some bituminous83/	Abundant	Abundant	---	---
Anadarko basin	10	35,000	33,000	On E., W., and S. margins	Near folds	21/31/32/-1 to -239	do.	11/18/33/200-24,600	do.	500-4,000 feet thick12/	None83/	do.	do.	800 feet thick	Possible deep solution of salt34/35/ Saline springs36/
Fort Worth basin	11	5,000	37/17,000	Some gentle folds6/	N. and E. sides; buried38/	39/-4 to -580	do.	11/15/37/900-8,900	do.	Thick and 1,400 feet deep12/	Some bituminous83/	---	---	---	---
Val Verde basin	12	3,000	15/25,000	---	N. and S. margins; buried38/	21/-21 to -493	do.	15/40/1,500-22,000	do.	---	None83/	---	---	---	---
Midland basin	13	8,000	17/20,000	Some gentle folds6/	S. and W. margins; buried38/	21/0 to -250	do.	11/15/2,800-14,000	do.	Abundant	do.	Abundant	Abundant	50-700 feet thick and 60 percent salt4/	Shallow formations discharge as springs.
Delaware basin	14	7,000	15/25,000	do.	On margins; some buried38/	21/41/42/+65 to -502	do.	2,500-23,000	do.	do.	do.	do.	do.	1,700 feet thick and 2,500 feet deep4/	---
Palo Duro basin	15	10,000	17/10,000	do.	N. and S. margins; buried38/	21/-44 to -325	do.	---	Sparse and oil and gas9/15/	do.	do.	do.	do.	---	---
Dalhart basin	16	3,000	17/7,000	do.	SE. margin; buried38/	21/-34 to -332	do.	9/15/18/600-6,200	Sparse oil	---	do.	---	---	---	---
Denver basin	17	44/60,000	44/14,000-15,000	---	E. margin61/	45/46/47/+86 to -470	do.	18/48/1,000-9,200	Oil and gas	1,000-8,000 feet thick14/	Abundant subbituminous83/	---	---	80-170 feet thick and 4,100-6,000 feet deep44/	Oil in stratigraphic traps44/
Powder River basin	18	44/20,000	44/17,000-20,000	Minor on N. and E. flanks; sharpe on S. and W. flanks44/	Reverse faults on SE. edge. Faults near folds6/	45/49/Flowing to -222	Artesian	900-15,000	do.	Bentonitic and 2,500 feet thick.	Thick and <120 feet deep. Abundant subbituminous50/	Approx. 50 percent of section.	Abundant	6,000-14,000 feet deep	80 percent of oil from stratigraphic traps44/ One thermal spring16/
Williston basin, including Canada	19	225,000 including Canada	17,000	11 in W. half51/	About 5 near folds51/	24/+1 to -112	Artesian	11/3,000-12,800	do.	1,200 feet crops out, montmorillonitic12/	Abundant lignite. Thick and 0-120 feet deep50/83/	Abundant	---	100-400 feet thick and >4,000 feet deep44/	Saline springs in E51/
Rio Grande basins, six	20	6 basins 1,000-3,000 each	15,000-20,000	---	Many on margins and center including thrust6/12/	42/-5 to -497	Water table and artesian?	---	None15/	800-2,400 feet crops out. 45 percent of section12/	Some bituminous84/	Interbeds in shale. 16 percent of section	37 percent of section.	2 percent of section	Thermal springs16/
SW. New Mexico basins, six	21	6 basins 100-600 each	52/>10,000	---	---	42/-24 to -272	do.	---	None15/	do.	None83/	---	---	---	Igneous intrusions53/
San Juan basin	22	54/20,000	44/14,000-15,000	Tight NE half and gentle SW half. Igneous domes.	Many in NE half near or along folds. High-angle reverse54/	55/56/57/+92 to -500	Water table and artesian	11/900-11,000	Oil and gas	2,000 feet thick and 0-2,000 feet deep14/	Abundant subbituminous83/	34 percent sandstone in upper 5,000 feet54/	---	<1 percent gypsum	Igneous intrusions. Thermal springs16/
Black Mesa basin	23	8,000	44/8,000-10,000	Some broad gentle folds6/	Many in W., one in center6/	57/58/Flowing to -1,118	do.	---	None15/	---	Some subbituminous83/	---	---	---	Igneous intrusions6/
Kaiparowits basin	24	3,000	44/12,000-15,000	do.	---	57/59/60/+80 to -880	do.	15/6,700	Minor oil in N.	---	do.	---	---	---	---
San Luis basin	25	4,000	44/15,000-20,000	---	Many on margins6/	61/+61 to -238	do.	---	Spare oil and gas. Some CO_2 9/.	---	do.	---	---	---	Thermal springs16/
Paradox basin	26	44/19,000	44/20,000-25,000	Tight in NE. half and gentle in SW. half, NW. trend. Igneous domes.	Many in NE. half on or near folds.	56/62/-1 to -800	do.	48/2,000-9,600	Oil and gas in E.	---	do.	---	---	4,000-12,000 feet thick and 0-8,000 feet deep4/	Igneous intrusions. One thermal spring16/
Piceance basin	27	44/3,900	44/27,000	N. and S. ends6/	E. and E. sides.44/ Small normal14/	62/63/0 to -673	do.	11/18/500-8,800	Gas	---	Some bituminous83/	---	---	---	Oil shale64/. Thermal springs on E.16/
Uinta basin	28	44/8,000	44/30,000-32,000	---	N. side44/	45/+11 to -25	do.	11/2,000-13,000	Oil and gas. Some CO_2 9/64/.	Abundant	Some bituminous64/	Abundant	Some in Paleozoic.	---	Oil shale and gilsonite64/
North and Middle Parks	29	4,000	44/15,000-20,000	In N. part of N. Park6/	Many6/	49/62/-2 to -2[illegible]0	do.	11/2,600-29,000	Oil and gas in N. Park.	Contains sandstone and is 200-5,000 feet thick49/	Some subbituminous83/	Abundant49/	Minor49/	---	Thermal springs16/
Laramie basin	30	44/2,000	44/10,000-15,000	Many on margins and center6/	Many on margins6/	45/65/-1 to -6[illegible]	do.	18/800-5,400	Oil and gas	---	do.	---	---	---	One thermal spring16/
Hanna basin	31	44/1,000	44/25,000-30,000	Some on margins, one in center6/	Some on N. and S. margins6/	Flowing to -118	do.	---	Sparse gas15/	---	Abundant subbituminous84/	---	---	---	---
Washakie and Sand Wash basins	32	3,000	44/>30,000	Two in W. part 6/	Many	65/Flowing to -395	do.	11/65/1,100-10,500	Oil and gas	Mowry shale, 150-525 feet thick and 0->11,000 feet deep65/	do.	Abundant65/	Minor65/	None65/	---
Red Desert basin	33	2,000	44/>30,000	Two on S. and E. margins6/44/	Some on N. margin6/44/	65/+51 to -151	do.	11/65/3,800	Oil	do.	do.	do.	do.	do.	---
Green River basin	34	44/21,000	44/>30,000	Some on margins6/	Thrusts on E. and W. sides44/	66/+290 to -249	do.	11/15/300-18,000	Oil and gas	---	do.	---	Lower one-third of section67/	---	---
Jackson Hole	35	44/2,000	44/20,000-25,000	Well-developed anticlines67/	Many6/	68/Flowing to -88	do.	---	None15/	---	Some subbituminous83/	---	---	---	---
Wind River basin	36	3,000	44/25,000-30,000	Anticlines in E. and NW parts6/	N. and E. sides44/	69/Flowing to -480	do.	11/15/300-14,000	Oil and gas	---	do.	---	---	---	Thermal springs16/
Bighorn basin	37	4,000	44/20,000-25,000	Steep W. side6/	N. and W. sides44/	70/-1 to -120	do.	11/15/1,400-12,900	do.	600-1,000 feet crops out12/	do.	---	---	---	Lavas and breccias44/ Thermal springs16/
Crazy Mountain basin	38	1,000	44/>30,000	Tight on margins and gentle in center71/.	Many on margins and W. center. Some thrusts71/	72/73/Flowing to -120	do.	1,000-5,500	do.	---	Some bituminous?84/	---	12 percent of section	---	Many intrusions and dikes71/
Western Montana basins, eight	39	8 basins 300-600 each	74/52,000?	Many on margins38/	Many on margins38/	75/Flowing to -145	do.	---	None9/	Mostly siltite74/	Some subbituminous83/	Fine- to medium-grained quartzite74/	Upper one-third of section74/	---	Abundant volcanic and granitic rocks in S.75/ Thermal springs16/
SW. Utah basin	40	1,500	12,000	Two anticlines76/77/	Large on E.	78/-1 to -102	do.	77/475-800	Minor oil	200 feet thick including 3 feet of limestone79/	Some lignite84/	---	---	---	Thermal springs16/.
San Joaquin basin	41	14,000	80/32,000	Many on W. and E.80/	Many on margins38/	81/82/-10 to -200	do.	11/15/18/600-11,000	Oil and gas	100-10,000 feet crops out12/80/	Some subbituminous84/	---	---	---	Thermal springs16/. Land subsidence.
Sacramento basin	42	11,000	80/53,000	Many on W. and E.18/80/	Many on margins38/80/	82/-13 to -70	do.	11/2,000-9,000	Mostly gas	do.	Some lignite84/	---	---	---	Intrusive near center. Volcanic rocks in E. Land subsidence. Thermal springs16/

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