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SHALE, MUDSTONE, AND CLAYSTONE AS POTENTIAL HOST ROCKS FOR UNDERGROUND EMPLACEMENT OF WASTE

By

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ABSTRACT

In this report, the suitability of the argillaceous formations in the conterminous United States as host rocks for underground waste emplacement is reviewed in terms of available geologic information. The strata are considered mainly according to their dimensions, depth, composition, permeability, structural and seismic history, and to the extent of drilling in the area. Shale, mudstone, and claystone of marine origin, in areas of little structural deformation and seismic risk, are generally the most promising. These include the Ohio Shale of Devonian age in northern Ohio and the Devonian-Mississippian Ellsworth Shale and Mississippian Coldwater Shale in Michigan. In the Rocky Mountain states, the Pierre Shale and other thick shales of Late Cretaceous age are also potential host rocks.

INTRODUCTION

This report is one of a series prepared by the U.S. Geological Survey to summarize the available geologic and hydrologic knowledge of selected salt deposits and other impermeable sedimentary rocks and to help determine the suitability of these strata for waste emplacement. The series was assembled in response to separate but similar requests from the U.S. Atomic Energy Commission and the Advanced Research Projects Agency. Anticipating the difficulty of finding safe respositories for the disposal of nonradioactive but chemically noxious wastes, the Advanced Research Projects Agency asked the Geological Survey in 1971 to evaluate salt deposits and other impermeable rocks for potential underground emplacement sites.

In planning for the management of radioactive waste, the U.S. Atomic Energy Commission asked the Geological Survey in 1972 to summarize the available geologic and hydrologic knowledge of selected areas and rock types that seemed promising for subsurface repositories. The rock types chosen for study included salt and argillaceous sedimentary rocks (shale, claystone, and mudstone). Because many of the geologic and hydrologic factors involved in selecting sites for storage or disposal of wastes in subsurface impermeable rocks are the same whether the wastes are highly radioactive or nonradioactive but highly toxic, the results of the Geological Survey's investigations for the Atomic Energy Commission are of parallel interest to the Advanced Research Projects Agency (now the Defense Advanced Research Projects Agency). This report provides data sought by both agencies and is therefore being submitted to both.

The usefulness of thick bodies of impermeable argillaceous rocks as sites for the subsurface emplacement of chemically noxious or radioactive wastes may not have received adequate consideration because of the higher priority given to salt deposits. The low permeability, relatively high plasticity, large ion-exchange capacity, and widespread distribution of most shale, mudstone, and claystone are desirable properties in host rocks for underground waste emplacement. On the other hand, many argillaceous rocks include mineral constituents that may be unacceptable: some of the most extensive undeformed shales with relatively high plasticity contain much montmorillonite that may release water when heated; but many shales with little montmorillonite are less plastic, older, and therefore commonly more permeable as the result of tectonic deformation; other shales contain an unacceptable amount of organic matter that may yield combustible carbon compounds when heated. Note--the term shale as used hereafter in this report includes claystone and mudstone.

The purpose of this report is to provide a general review of the thick shale bodies in the conterminous United States as a first step in evaluating the potential of these rocks for underground waste emplacement. The report was compiled not only from geologic publications, but also from the unpublished information, personal knowledge, and experience of the authors and other Geological Survey personnel.

Sedimentary rocks underlie 75 percent of the total land area of the earth's crust and consist of 42 to 56 percent shale, as calculated from measured stratigraphic sections (Pettijohn, 1957, p. 7-11). The porosity of the average clay is 27 percent and of the average shale is 13 percent (Pettijohn, 1957, p. 353-354). The porosity of the average sand is 35 to 40 percent and of the average sandstone is 15 to 20 percent (Pettijohn, 1957, p. 87). More important, perhaps, is the fact that the permeability of shale is very low in comparison with the permeability of the average sandstone. The average composition of shale, determined from the analyses of 10,000 samples (Yaalon, 1962) is 59 percent clay minerals, 20 percent quartz and chert, 8 percent feldspar, 7 percent carbonates, 3 percent iron oxides, 1 percent organic material, and 2 percent other. The common clay minerals in shale are illite, chlorite mica, montmorillonite, and kaolinite (Grim, 1968, p. 554). Illite is probably the dominant clay mineral. Montmorillonite is abundant in the Mesozoic and Cenozoic sedimentary rocks of the United States but rare in the pre-Mesozoic rocks (Grim, 1968, p. 551-554).

Shales of marine origin have received more study during this investigation than nonmarine shales because the marine shales are generally more uniform in composition, hence are less likely to contain unexpected coarser-grained water-bearing beds and therefore are less permeable. The authors of this report have assumed that regions containing abundant faults or folds are generally less suitable because the rocks are commonly fractured and therefore have greater secondary permeability. An additional relevant factor is the location, frequency, and intensity of seismic activity. Regions characterized by frequent earthquakes or faults of Quaternary age are more likely than other areas to be subjected to significant diastrophism during the next several hundred thousand years. It does not follow that safe repository sites cannot be selected in these regions--only that greater care and discrimination will be required in their selection.

The geologic and hydrologic potential of a body of shale for a waste emplacement site is determined by the dimensions, lithology and mineralogy, mechanical and hydrologic properties, and structural and seismic history of the shale, and by the extent of drilling in the area. Table 1 includes a list of dominantly shale formations and selected pertinent descriptions of the formations. The table supplements this report, but many gaps in information are indicated by the blanks in the table. This report divides the conterminous United States into six geographic regions (fig. 1): Pacific Mountain System, Intermontane Plateaus, Rocky Mountain System, Interior Plains (includes Interior Highlands), Appalachian Highlands, and Atlantic Plain. The following notes refer to columns in table 1:

Thickness: It is assumed that excavation for waste storage or disposal would be limited to a depth range of about 500 to 2,000 feet

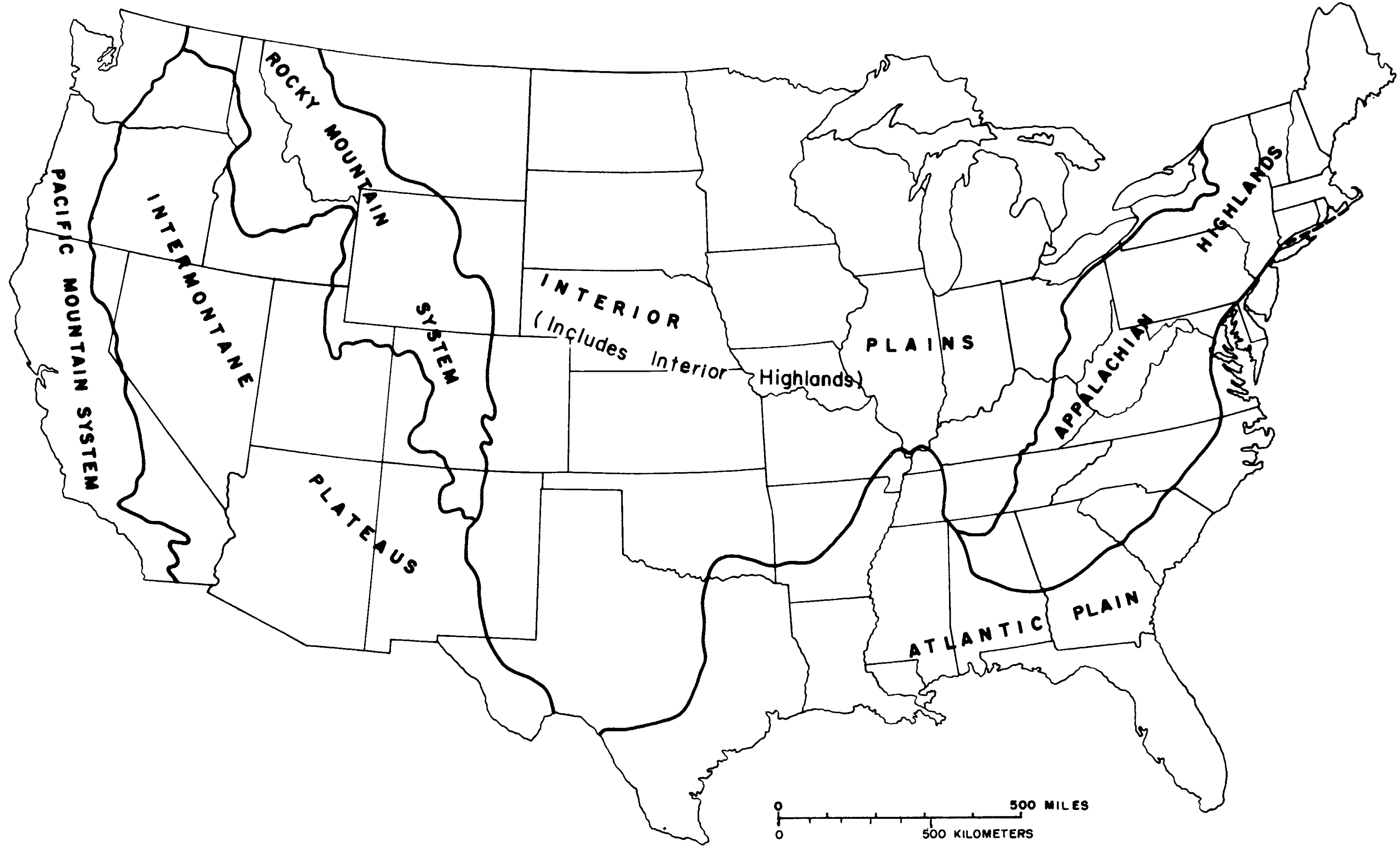


FIGURE 1.--PHYSICAL DIVISIONS OF THE UNITED STATES (MODIFIED FROM FENNEMAN, 1928)

below the surface. All shale bodies described in this report are more than 500 feet thick and nearly all have extensive outcrops.

Rock types: The shales referred to in this report are chiefly marine rocks that consist of more than 80 percent shale, mudstone, or claystone. As stated above, shales of marine origin have been selected because their composition and permeability are more uniform.

Minor constituents of rocks: The scope of this report does not permit detailed mineralogic descriptions of the various bodies of shale, but note is made of minor constituents that appear to be potentially relevant. Some shales are petroliferous, carbonaceous, or montmorillonitic. Montmorillonite-type minerals contain interlayered water that might be released upon heating. Heat may also produce gaseous or liquid carbon compounds from carbonaceous or petroliferous shales.

Estimated plasticity: This column is largely blank because the scope of the investigation does not permit the extensive testing that would be required to ascertain the physical properties of the shale bodies. An effort has been made, however, to estimate the relative plasticity of various shales. The comprehensive determination of mechanical properties for a given site rightfully comes much later in the site-investigation process.

Estimated abundance of fractures: A hydrologic description of any shale being considered for a waste emplacement site should include porosity, primary and secondary permeability, presence of water-bearing strata, etc. In this preliminary study, we determined only the probable abundance of fractures in the shale body and, for certain shales, the location, geologic structure, water yield, and civil importance of associated aquifers. The

Table 1.--Selected thick bodies of shale in the conterminous United States

Age and stratigraphic name	Map reference number (fig. 2C) and location	Thickness (in feet)	Rock types	Minor constituents of rocks	Estimated plasticity	Estimated abundance of fractures	Regional seismicity (0-3) **	Abundance of drill holes or mines
PACIFIC MOUNTAIN SYSTEM								
Oligocene sh. *	1.--Northwestern Washington	More than 10,000	Claystone and siltstone	Slightly tuffaceous			2-3	Locally abundant
Eocene Moody Sh. Mbr., Toledo Fm. *	2.--Northwestern Oregon	1,500-1,800	Mudstone and sandstone	Tuffaceous, montmorillonitic	Low	Abundant fractures	2	Sparse
Miocene Nye Mudstone *	3.--Northwestern Oregon	2,500	Mudstone and siltstone	Montmorillonitic	Moderate	Moderately abundant fractures	2	Sparse
Eocene-Oligocene Bastendorff Sh. *	4.--Southwestern Oregon	2,300	Shale and sandstone	Tuffaceous, montmorillonitic			1	Sparse
Eocene Capay Fm. *	5.--Sacramento Valley of California	300-2,500	Brown to gray shale; local sandstone at base				2-3	Locally abundant
Jurassic Knoxville Fm.	6.--Sacramento Valley of California	As much as 10,000	Shale and siltstone; local sandstone and conglomerate		Low	Abundant fractures	2-3	Locally abundant
Cretaceous Shasta Series	6.--Sacramento Valley of California	About 10,000	Mudstone and siltstone; less sandstone and conglomerate				2-3	Locally abundant
Paleocene Martinez Fm.	7.--Sacramento Valley of California	As much as 2,000	Claystone and sandstone; local conglomerate	Silty			2-3	Locally abundant
Cretaceous-Paleocene Moreno Fm.	8.--San Joaquin Valley of California	About 2,000 average	Brown and gray shale; local sandstone	Partly siliceous, partly calcareous			2-3	Locally abundant
Eocene Lodo Fm. *	9.--San Joaquin Valley of California	As much as 5,000	Siltstone and claystone; less sandstone				2-3	Locally abundant
Oligocene Tumey Sh.	10.--San Joaquin Valley of California	As much as 1,500	Basal sandstone (800 ft), shale (700 ft)				2-3	Locally abundant
Eocene Kreyenhagen Sh. *	11.--San Joaquin Valley of California	600-4,000	Claystone, siltstone, shale, diatomite; less sandstone	Diatomaceoua and gypsiferous ahale			2-3	Locally abundant
Miocene sh. *	12.--San Joaquin Valley of California	100-1,000 (buried)	Mudstone and sandstone	Silty, sandy			2-3	Locally abundant

				INTERMONTANE PLATEAUS				
Devonian-Mississippian Pilot Sh. *	13.--East-central Nevada, west-central Utah	As much as 1,200	Shale, limestone, and siltstone	Calcareous	Low	Abundant fractures	2-3	Sparse
Mississippian Doughnut Fm. *	14.--Northeastern and north-central Utah	As much as 500	Shale and limestone				1-2	
Mississippian Chainman Fm. *	15.--Eastern Nevada, eastern California, and western Utah	As much as 5,000	Shale, sandstone, and limestone		Low	Abundant fractures	2-3	Sparse
Cretaceous Mancos Sh. *	16.--Eastern Utah, northeastern Arizona, northwestern New Mexico, and western Colorado	0-5,000	Shale, siltstone, and sandstone	Montmorillonitic	Moderate to high	Sparse fractures	1-2	Locally abundant
Paleocene Nacimiento Fm. *	17.--Northwestern New Mexico	400-800	Claystone and mudstone		Moderate to high	Sparse fractures	1-2	Locally abundant
Pennsylvanian Panther Seep Fm. *	18.--South-central New Mexico	800-2,400	Shale, sandstone, and limestone	Silty and carbonaceous	Low		1-2	
				ROCKY MOUNTAIN SYSTEM				
Cretaceous Bearpaw Sh. *	19.--Eastern Montana	As much as 1,200	Shale, siltstone, sandstone, and bentonite	Montmorillonitic	Moderate to high	Sparse fractures	1	Locally abundant
Mississippian-Pennsylvanian Big Snowy Fm. *	20.--Central Montana	As much as 500	Shale, sandstone, and limestone	Calcareous	Low	Moderately abundant fractures	1-2	Locally abundant
Cambrian Wolsey Sh. *	21.--Western Montana and northwestern Wyoming	As much as 1,000	Shale, sandstone, and limestone		Low	Moderately abundant to abundant fractures	1-2-3	Locally abundant
Cambrian Park Sh. *	22.--Western Montana and northwestern Wyoming	As much as 600	Shale		Low	Moderately abundant to abundant fractures	1-2	Locally abundant
Mississippian Milligen Fm. *	23.--South-central Idaho	More than 5,500	Shale and limestone	Calcareous and carbonaceous	Low	Abundant fractures	2-3	Sparse
Cretaceous Pierre Sh. *	24.--Eastern Montana, eastern Wyoming, eastern Colorado, North Dakota, South Dakota, and Nebraska	Less than 500 to more than 5,000	Claystone, shale, mudstone, and bentonite	Montmorillonitic	Moderate to high	Sparse fractures	1	Locally abundant
Pennsylvanian sh. *	25.--North-central New Mexico	As much as 2,000	Shale		Low	Moderately abundant fractures	1	

* Strata referred to in text

** ESSA/Coast and Geodetic Survey, 1969
- 0 - no seismic risk
- 1 - minor seismic risk
- 2 - moderate seismic risk
- 3 - major seismic risk

(See fig. 2B of this report for outline of seismic areas in U.S.)

Table 1.--Selected thick bodies of shale in the conterminous United States--Continued

Age and stratigraphic name	Map reference number (fig. 2C) and location	Thickness (in feet)	Rock types	Minor constituents of rocks	Estimated plasticity	Estimated abundance of fractures	Regional seismicity (0-3) **	Abundance of drill holes or mines
INTERIOR PLAINS								
Devonian-Mississippian Ellsworth Sh. *	26.--Southern Michigan	As much as 600	Shale and siltstone		Low to moderate	Sparse to moderately abundant fractures	1	Locally abundant
Mississippian Coldwater Sh. *	27.--Southern Michigan	About 500 to more than 1,100	Shale, siltstone, sandstone, limestone and dolomite	Silty and calcareous	Low to moderate	Sparse to moderately abundant fractures	1	Locally abundant
Pennsylvanian Des Moines Series	28.--Kansas, Missouri, and Iowa	Locally more than 500	Shale, limestone, sandstone, and coal	Partly carbonaceous	Low to moderate	Sparse to moderately abundant fractures	1-2	Locally abundant
Mississippian Borden Gp. *	29.--Illinois and Indiana	As much as about 760	Siltstone, shale, and sandstone	Silty	Low to moderate	Moderately abundant fractures	1-2-3	Locally abundant
Pennsylvanian McLeansboro Gp.	30.--Southern Illinois	Locally more than 500	Shale, sandstone, limestone, and coal	Partly carbonaceous	Low to moderate	Sparse to moderately abundant fractures	1-2-3	Locally abundant
Pennsylvanian Kewanee Gp.	31.--Southern Illinois	Locally more than 500	Shale, sandstone, limestone, and coal	Partly carbonaceous	Low to moderate	Sparse to moderately abundant fractures	1-2-3	Locally abundant
Pennsylvanian Virgil Series	32.--Eastern Kansas	Locally more than 500	Shale and limestone		Low to moderate	Sparse to moderately abundant fractures	1-2	Locally abundant
Mississippian-Pennsylvanian Springer Fm.	33.--Oklahoma	Locally more than 4,000 (deeply buried)	Claystone, sandstone, and limestone		Low to moderate	Locally abundant fractures	1-2	Locally abundant
Pennsylvanian Des Moines Series	34.--Oklahoma and Texas	Locally more than 2,300	Claystone, sandstone, limestone, and coal	Partly carbonaceous	Low to moderate	Sparse to moderately abundant fractures	1-2	Locally abundant
Pennsylvanian Canyon and Cisco Gps. *	35.--Texas	Locally more than 500	Shale, limestone, sandstone, and coal		Low to moderate	Sparse to moderately abundant fractures	0-1	Locally abundant
Mississippian Barnett Sh. *	36.--Texas	Locally more than 500	Shale and limestone	Locally petroliferous	Low to moderate		0-1	Locally abundant
Pennsylvanian Smithwick Sh. *	37.--Central Texas	Locally more than 500	Shale, siltstone, and sandstone		Low to moderate	Moderately abundant fractures	0-1	Locally abundant
Pennsylvanian Atoka Fm.	38.--Oklahoma and Arkansas and Mississippi	Locally more than 5,000	Shale, siltstone, and sandstone	Slightly carbonaceous	Low to moderate	Moderately abundant to abundant fractures	1-2	Locally abundant
Pennsylvanian Bloyd Sh.	39.--Northwestern Arkansas	Locally more than 500	Shale and limestone		Low to moderate	Moderately abundant fractures	1	Locally abundant
Mississippian-Pennsylvanian Johns Valley Sh.	40.--West-central Arkansas	200-1,000	Shale, sandstone, and limestone	Scattered exotic pebbles and boulders	Low to moderate	Moderately abundant to abundant fractures	1	Sparse
Ordovician Mazarn Sh.	41.--West-central Arkansas	About 1,000	Shale, sandstone, and limestone. Veins of quartz and calcite		Low	Moderately abundant to abundant fractures	1	Sparse
Mississippian Stanley Sh.	42.--West-central Arkansas	6,000-12,000	Shale, siltstone, and sandstone	Locally siliceous	Low to moderate	Moderately abundant to abundant fractures	1	Sparse

ATLANTIC PLAIN AND APPALACHIAN HIGHLANDS								
Devonian Ohio Sh. *	43.--Northeastern Ohio	Average about 1,100	Shale, siltstone, and limestone	Locally calcareous and carbonaceous	Low to moderate	Sparse to moderately abundant fractures	1-2	Locally abundant
Ordovician Reedsville Sh.	44.--Northwestern Pennsylvania	About 830	Shale, siltstone, and limestone	Calcareous	Low to moderate	Moderately abundant fractures	1-2	Locally abundant
Ordovician Queenston Sh.	44.--Northwestern Pennsylvania	About 854	Shale	Partly silty and calcareous	Low to moderate		1-2	Locally abundant
Devonian Hamilton Gp. *	45.--South-central New York and north-central Pennsylvania	About 900	Shale and limestone	Locally calcareous and carbonaceous	Low to moderate	Sparse to moderately abundant fractures	1-2	Locally abundant
Ordovician Utica, Frankfort, and Pulaski Fms.	46.--South-central New York	About 1,200 (buried)	Shale and siltstone	Silty	Low to moderate	Moderately abundant fractures	1	Locally abundant
Ordovician Canajoharie Sh.	47.--Eastern New York	About 2,000	Shale, siltstone, and sandstone		Low to moderate	Moderately abundant fractures	1-2	Locally abundant
Ordovician Martinsburg Sh.	48.--Southeastern New York, northwestern New Jersey, and northeastern Pennsylvania	About 4,000-8,000	Shale, siltstone, and sandstone		Low	Abundant fractures	1	Sparse
Mississippian Hedges and Myers Sh.	49.--Western Maryland and northeastern West Virginia	About 970	Shale, sandstone, and coal	Partly carbonaceous and partly sandy	Low	Abundant fractures	1-2	Sparse
Paleocene Porters Creek Clay	50.--Louisiana, Mississippi, Alabama, Tennessee, and Missouri	As much as 600	Clay, sandstone, and limestone	Montmorillonitic	High	Sparse fractures	1-2-3	Locally abundant
Cretaceous Eagle Ford Sh.	51.--Texas and western Louisiana	Average about 475	Shale	Montmorillonitic	Moderate to high	Sparse fractures	0-1	Locally abundant
Mississippian Floyd Sh.	52.--Central Alabama and Mississippi	As much as 1,500	Shale, sandstone, and limestone		Low	Abundant fractures	1-2	
Miocene Hawthorn Fm.	53.--Georgia	As much as 500	Clay and sandstone	Partly sandy	High	Sparse fractures	1-2	Sparse

* Strata referred to in text
** ESSA/Coast and Geodetic Survey, 1969
0 - no seismic risk
1 - minor seismic risk
2 - moderate seismic risk
3 - major seismic risk
(See fig. 2B of this report for outline of seismic areas in U.S.)

possibility of ground water contamination precludes the location of waste repositories in some areas. Fractures commonly increase the secondary permeability of strata; consequently an estimate of fracture abundance is given for most of the shales in table 1. No estimate was given if the required information was not readily available.

Regional seismicity: Data on structural history, Quaternary faults, and relative seismicity of regions containing shale are noted in the text and in figures 2A, 2B, and 2C (in pocket). Strata with a history of intense structural deformation generally contain many fractures that not only increase the permeability but also decrease the strength of the rocks. Rock strength may be a critical factor in planning underground workings. The seismic risk of the areas containing the shales listed on table 1 ranges from zone 0, reflecting no reasonable expectancy of earthquake damage, to zones 1, 2, or 3, reflecting expectancy of minor to severe earthquake damage. The degree of seismic risk in different parts of the United States is shown on figure 2B (ESSA/Coast and Geodetic Survey, 1969).

Abundance of drill holes or mines in area: Drill holes and other man-made underground openings modify the natural pattern of ground-water circulation and may jeopardize the isolation from ground water required for safe underground emplacement of waste. Shales in extensively developed oil and gas fields, for example, probably are poor risks as sites for waste emplacement.

PACIFIC MOUNTAIN SYSTEM

The volcanic and seismic activity that characterizes much of California, Oregon, and Washington (figs. 2A and 2B) demands greater caution in selecting a site for waste emplacement in the thick Tertiary shales found in that region. In central and southern California, the Kreyenhagen Shale and the Lodo and Capay Formations of Eocene age, and other shale bodies of Miocene age (11, 9, and 5 of table 1) are sufficiently thick and impermeable (Repenning, 1960, p. 57), but are in a region of major seismic risk and complex structure (figs. 2A, B, C). In western Oregon the Moody Shale Member of the Toledo Formation (Eocene), the Bastendorff Shale (Eocene and Oligocene), and the Nye Mudstone (Miocene) (2, 4, and 3 of table 1) are more than 500 feet thick (Baldwin, 1959, p. 14, 18, 26-28), but are generally montmorillonitic. Clay-rich strata of Oligocene age in northwestern Washington (1 of table 1) are more than 10,000 feet thick and contain only a small amount of pyroclastic material (Snavely and Wagner, 1963, p. 19), but moderate to major earthquake damage may be expected in the area.

INTERMONTANE PLATEAUS

Formations of Paleozoic age

The thick Paleozoic shale formations in California, Nevada, Utah, and New Mexico (fig. 2C) have undergone mild to intense structural deformation and most are in regions of moderate to major seismic risk (figs. 2A and 2B). Examples are the Devonian-Mississippian Pilot Shale, Mississippian Chainman Formation, and other Paleozoic clay-rich strata in Nevada and eastern California (13 and 15 of table 1). The Mississippian Doughnut Formation which crops out in northeastern and north-central Utah (fig. 2C and 14 of table 1) is deeply buried by younger rocks where it is thick and of uniform lithology. In south-central New Mexico, the Panther Seep Formation of Pennsylvanian age (18 of table 1) is dominantly shale with sandstone and limestone interbeds, and is about 800 to 2,400 feet thick (Kottlowski and others, 1956, p. 42-47). Problems may arise, however, from the interbedded permeable sandstone and limestone and the numerous faults in the area.

Formations of Mesozoic age

The Mancos Shale of Cretaceous age (16 of table 1) crops out in eastern Utah, northeastern Arizona, northwestern New Mexico, and western Colorado. It is 0-5,000 feet thick, nearly impermeable, and occurs mainly in areas of minor seismic risk and mild structural deformation. The shale is composed largely of montmorillonitic clay, and if the problems caused by this clay can be solved, some of these strata may deserve serious consideration. The Mancos and its lateral equivalents in the Rocky Mountain System and Interior Plains are more completely described in the Rocky Mountain section of this report.

ROCKY MOUNTAIN SYSTEM

Formations of Paleozoic age

Thick Paleozoic formations consisting mainly of shale crop out in Montana, Idaho, Wyoming, Utah, Colorado, and New Mexico. The Paleozoic strata with most suitable characteristics are mainly of

Cambrian and Mississippian age. The Wolsey Shale and Park Shale of Cambrian age (21 and 22 of table 1) and lateral equivalents in western Montana, eastern Idaho, and western Wyoming (not shown on fig. 2C) are each more than 500 feet thick in some areas, but include scattered permeable beds of sandstone and limestone. Both formations were folded and fractured during the Laramide Orogeny. Most of the outcrops are within regions of moderate to major seismic risk.

The Mississippian-Pennsylvanian Big Snowy Formation of Montana, Mississippian Milligen Formation of Idaho, and Mississippian Doughnut Formation of northeastern Utah (fig. 2C; 20, 23, and 14 of table 1) are each more than 500 feet thick and are dominantly shale in some areas. The Milligen is located in an area of moderate to major seismic risk and complex geologic structure. The Big Snowy and Doughnut Formations are characterized by relatively high permeabilities. They include subordinate calcareous and sandy rocks and have been fractured and deformed by regional tectonism.

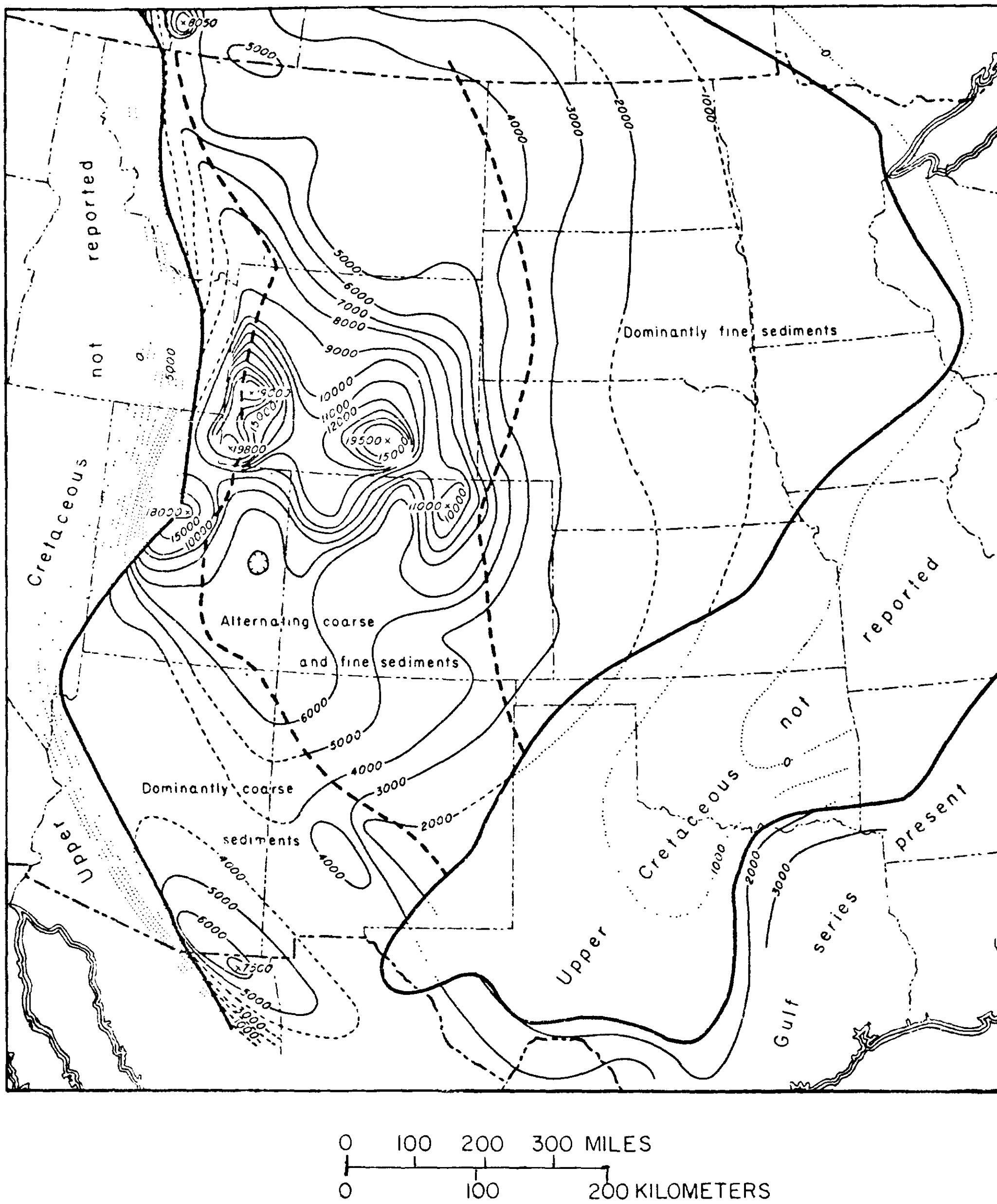
An unnamed shale sequence of Pennsylvanian age in north-central New Mexico (fig. 2C; 25 of table 1) is as much as 2,000 feet thick (Bachman, unpub.) and is within a region of minor seismic risk. Thrust faulting in the area, however, has probably caused an increase in the permeability of the shale.

Formations of Mesozoic age

The Rocky Mountain System and Interior Plains (figs. 1 and 2C) contain thousands of square miles of structurally undeformed Mesozoic rocks in areas of low population density and seismic stability (zones 0 or 1 of fig. 2B). The regions are partly underlain by thick sequences of Cretaceous shale which have been described in many reports. Except for the possible problems associated with a high content of montmorillonite, these rocks seem well suited for waste storage or disposal.

As much as 19,000 feet of alternating marine and nonmarine rocks of Late Cretaceous age were deposited in a 1,250,000-square-mile area in the Great Plains and Rocky Mountain states (fig. 3). Gilluly (1949, p. 573) estimated that about 875,000 cubic miles of sediment were delivered to this area. We estimate that of this volume as much as 500,000 cubic miles consisted of marine clay, silt, and mud. These fine-grained sediments are now represented by the Colorado and Graneros Shales, the Benton Formation, and the Mancos, Carlile, Pierre, Steele, Clagett, Bearpaw, and Lewis Shales (fig. 4).

Pierre Shale.--The Pierre Shale (24 of table 1) and its lateral equivalents, the Bearpaw, Clagett, Lewis, and Steele Shales, are representative of most of the Cretaceous Shales of the region and are therefore selected for brief discussion. The Pierre (fig. 5) has a volume of about 175,000 cubic miles, an outcrop area of about 90,000 square miles, and is concealed beneath younger strata in an area of about 370,000 square miles (Tourtelot, 1962, p. 3-4). It consists of thick sequences of claystone, shale, bentonitic mudstone, and many thin beds of bentonite. It ranges from less than 500 feet thick in the eastern Dakotas to more than 5,000 feet thick in southeastern



—— LIMIT OF UPPER CRETACEOUS DEPOSITS

---- LIMIT OF LITHOLOGIC FACIES

—— ACCEPTED THICKNESS, IN FEET

---- PARTLY INFERRED THICKNESS, IN FEET

.... WHOLLY INFERRED THICKNESS, IN FEET

FIGURE 3.--THICKNESS OF UPPER CRETACEOUS DEPOSITS, ROCKY MOUNTAIN SYSTEM AND INTERIOR PLAINS (REESIDE, 1944, MAP 2).

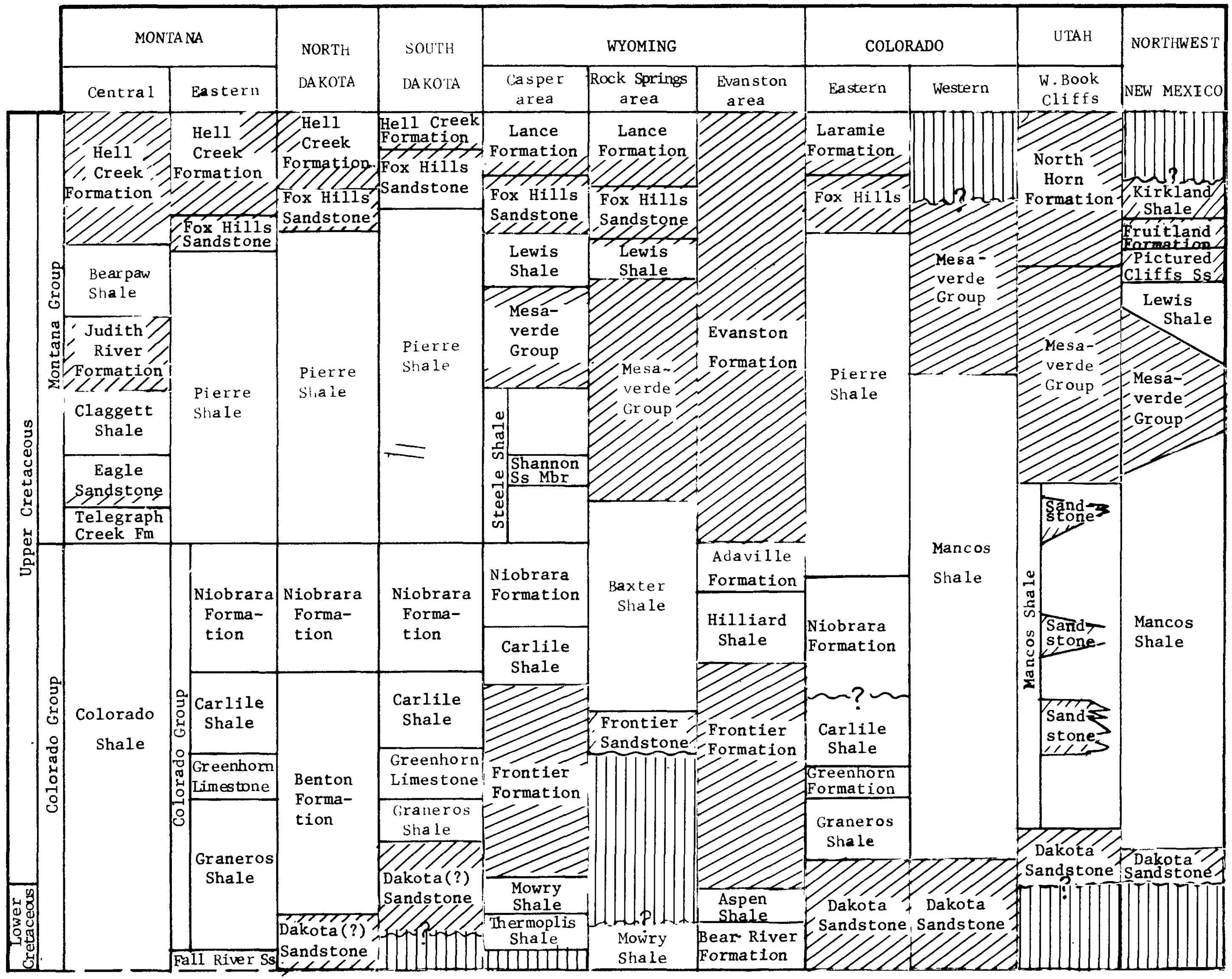


FIGURE 4.--CORRELATION CHART OF UPPER CRETACEOUS FORMATIONS OF GREAT PLAINS AND ROCKY MOUNTAINS (MODIFIED FROM COBBAN AND REESIDE, 1952). VERTICAL LINES INDICATE DEPOSITIONAL HIATUS; SLANTED LINES INDICATE NONMARINE ROCKS AND MARINE SANDSTONE; UNLINED BOXES INDICATE MARINE SHALE, AND LESS CHALKY SHALE AND LIMESTONE.

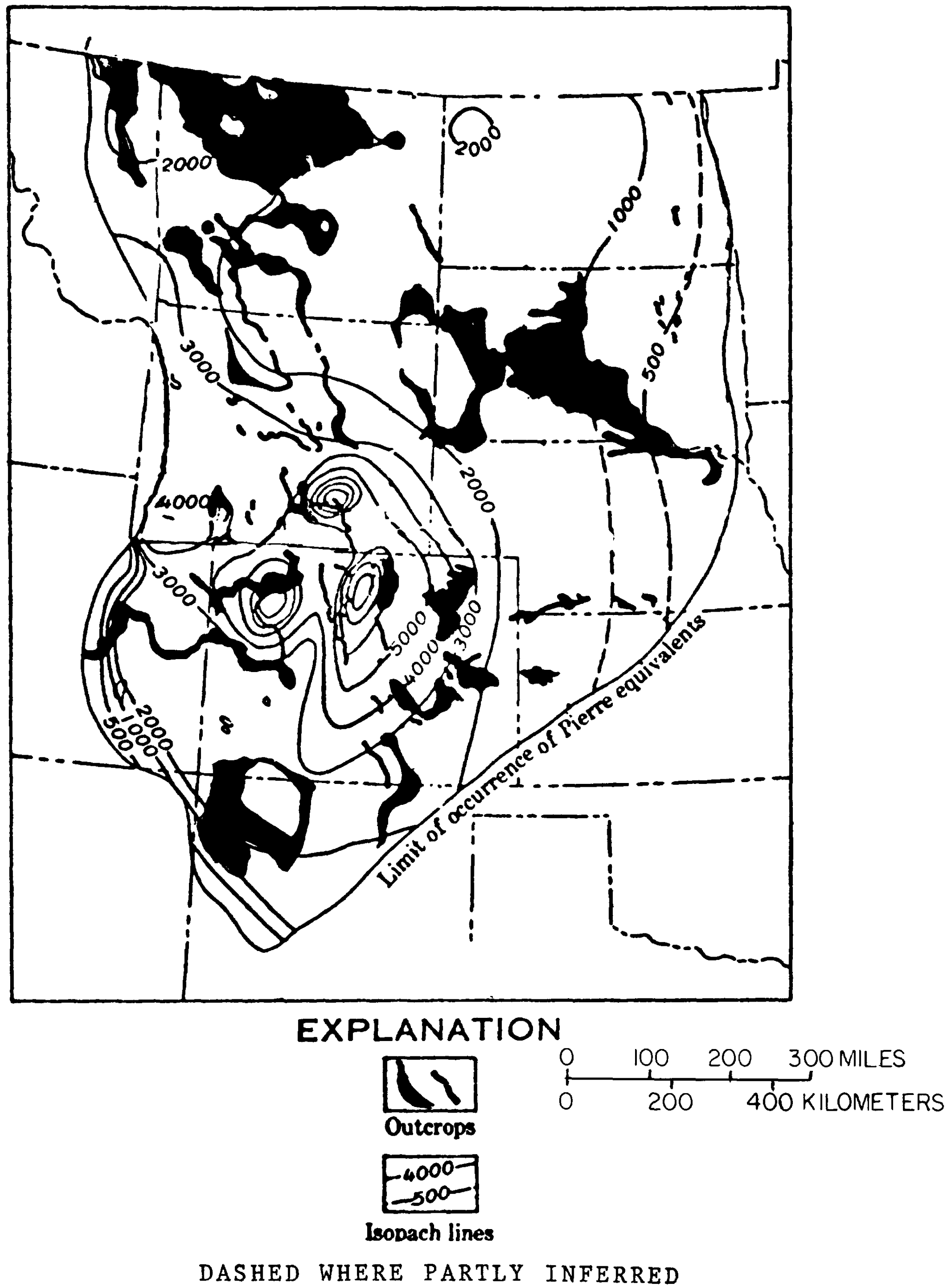


FIGURE 5.--DISTRIBUTION AND THICKNESS OF PIERRE SHALE AND EQUIVALENT ROCKS IN THE WESTERN INTERIOR OF THE UNITED STATES (TOURTELOT, 1962).

Wyoming and central Colorado. The Pierre is largely devoid of aquifers and, although highly porous locally, is essentially impermeable and does not yield water to wells. The moisture content as determined from core samples decreases with depth of burial; it is as much as 35 percent in near-surface weathered beds and as little as 15 percent where deeply buried (Fleming, Spencer, and Banks, 1970, p. 164).

The mineralogy of the Pierre Shale is probably typical of the clayey Cretaceous formations in the Great Plains and Rocky Mountain regions. Tourtelot, Schultz, and Gill (1960, p. B449) report that most samples of the Pierre from the Black Hills and Missouri River areas consist of 65 to 80 percent clay minerals, 15 to 25 percent quartz, a few percent feldspar, and small amounts of calcite, dolomite, biotite, pyrite, gypsum, jarosite, clinoptilolite, and organic material. The clay minerals consist of 25 to 45 percent montmorillonite, 35 to 45 percent mixed-layer illite-montmorillonite, 15 to 25 percent illite, and about 5 percent each of kaolinite and chlorite.

Many areas underlain by the Pierre would invite further study if the montmorillonite in the shale could be tolerated. For example, near the northern end of the Black Hills in Carter County, Montana, the outcropping Pierre is about 2,100 feet thick, generally impermeable, and has a gentle dip (figs. 6 and 7). In this area the seismic risk is minor and holes drilled for oil and gas are sparse. The thick shale sequences of the Pierre do not yield water except in the uppermost 20-30 feet of the formation, where a small amount is obtained from a few wells. The few clayey and silty sandstones in the formation contain minor amounts of water. The calcareous shale of the Niobrara Formation

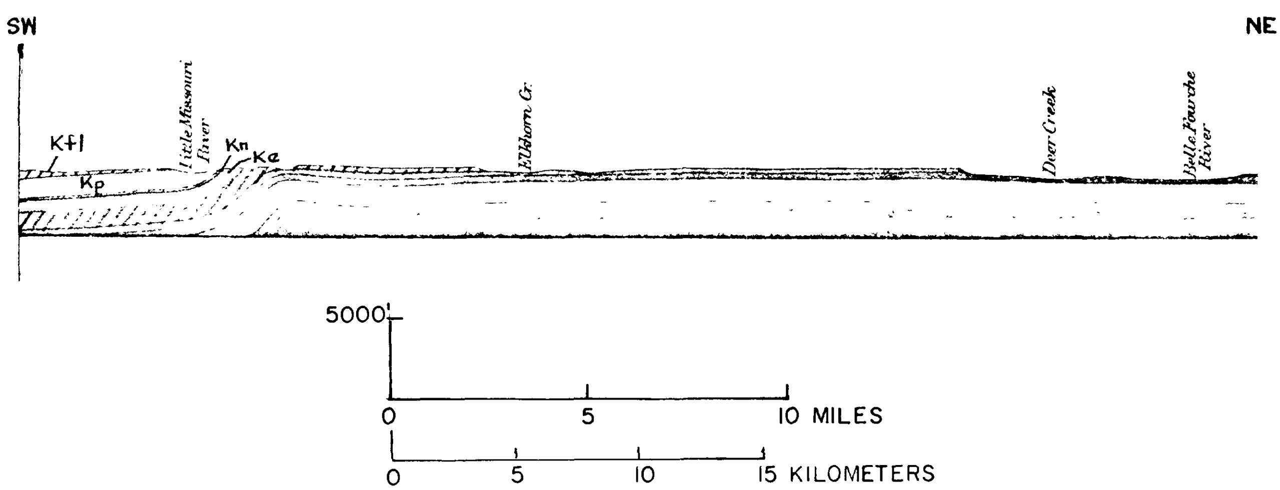


Figure 6.--Generalized section showing structure of formations on the northwestern flank of the Black Hills in northeastern Wyoming. Ke, Carlile Shale; Kn, Niobrara Formation; Kp, Pierre Shale; Kfl, Fox Hills Sandstone and Lance Formation. Vertical exaggeration 2 1/8 X (modified from Darton, 1909, plate XV, section 1).

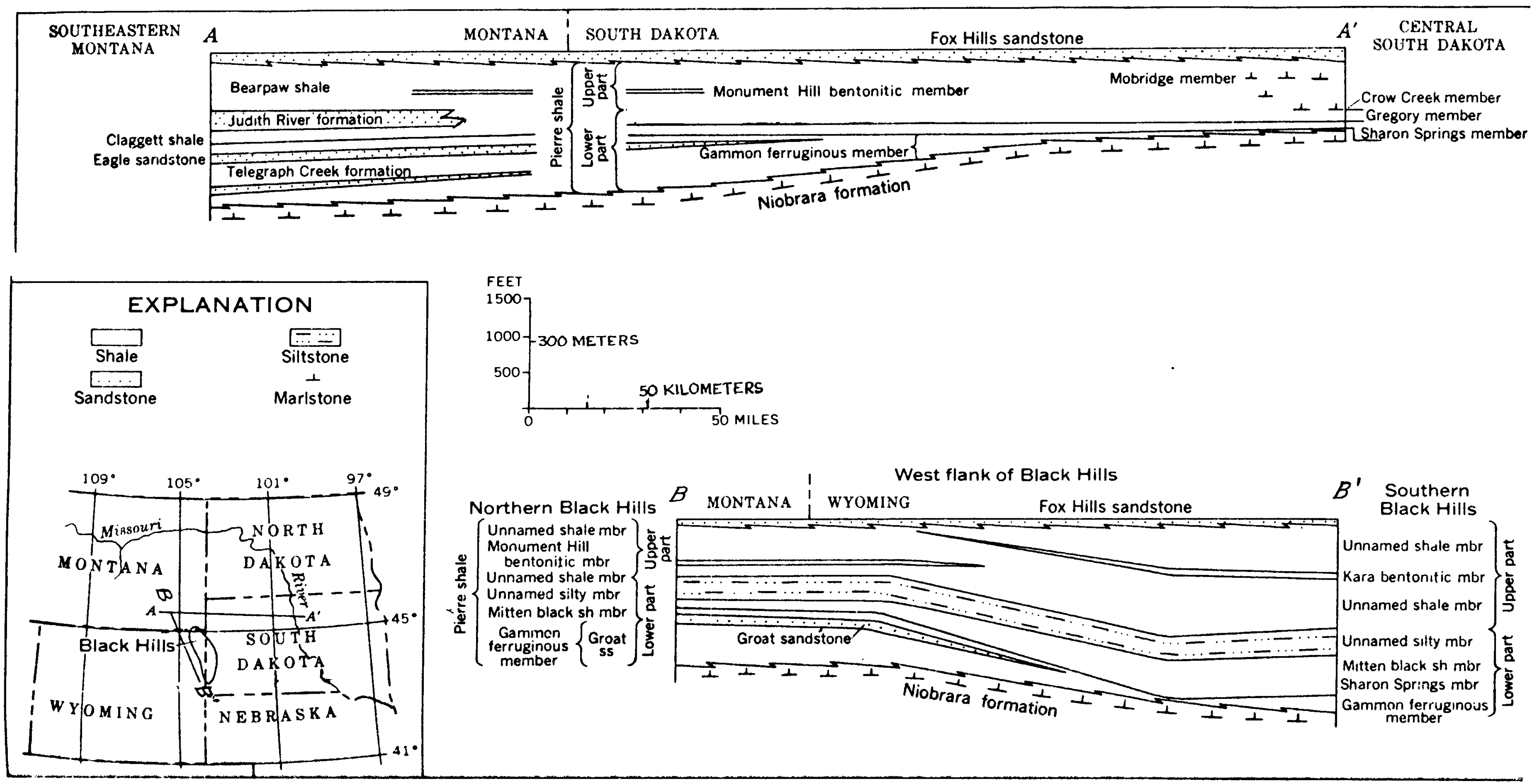


Figure 7.--Generalized sections showing relations of Pierre Shale and equivalent rocks in South Dakota, Wyoming, and Montana (modified from Tourtelot, Schultz, and Gill, 1960, fig. 205.1).

which directly underlies the Pierre may contain a small amount of water at a few localities. The Cretaceous Fox Hills Sandstone and Lance Formation, and the Tertiary Fort Union Formation, which overlie the Pierre, are a multiple aquifer system. Water wells that penetrate this system are common in the area and yield as much as 500 gallons per minute. The water in all aquifers of the area is under high artesian pressure

Bearpaw Shale.--The Bearpaw Shale is the westward equivalent of the upper part of the Pierre Shale in Montana and southern Canada. The 29 samples from the Bearpaw analyzed by Scott and Brooker (1968, p. 13) contain an average of 5 percent sand, 41 percent clay, and 54 percent silt. The clay fractions contained an average of 77 percent montmorillonite, 18 percent illite, and 5 percent chlorite. From these and other data it seems unlikely that thick sequences of clayey Cretaceous rocks containing less than 10 percent montmorillonite can be found in this region.

INTERIOR PLAINS

Formations of Paleozoic age

In much of the midcontinent part of the United States, Paleozoic shale, mudstone, and claystone generally do not contain much montmorillonitic clay, but they are less than 500 feet thick. In scattered structural basins, however, the clay-rich formations are much thicker. The structural deformation of the region ranges from slight to intense and the seismic risk ranges from none to major.

In western and northern Texas and western Oklahoma several formations of Mississippian and Pennsylvanian age are dominantly shale and more than 500 feet thick, but they are deeply buried beneath younger rocks.

The Mississippian and Pennsylvanian formations of central and eastern Texas include thick clayey strata but most are not suitable for underground storage facilities. The Mississippian Barnett Shale (36 of table 1) does not crop out. The Pennsylvanian Smithwick Shale (37 of table 1) has been faulted where it crops out and is generally buried by younger Pennsylvanian and Mesozoic rocks. It is 1,700-2,000 feet deep in western Hamilton County and may be as shallow as 1,400 feet near Ft. Worth in western Tarrant County, Texas. Where mainly shale, the Strawn, Canyon, and Cisco Groups of Pennsylvanian age either do not crop out or contain scattered permeable sandstone and limestone beds (Turner, 1957, p. 61-75).

In central and eastern Oklahoma, several formations of Ordovician, Devonian-Mississippian, Mississippian, Mississippian-Pennsylvanian, and Pennsylvanian age contain bodies of shale more than 500 feet thick (MacLachlan, 1964, fig. 4). Most of the shale, however, is deeply buried or intensely faulted and folded. In large areas of eastern Oklahoma thick shaly strata of middle and upper Pennsylvanian age crop out, but they contain beds of coal, sandstone, and limestone (Branson, 1962, p. 437-449), and have been deformed by mild folding and faulting.

The Pennsylvanian shale in parts of eastern Kansas, western Missouri, and southern Iowa has the mineralogy, thickness, structural setting, and seismic history considered favorable for underground storage sites. The subordinate amounts of sandstone, limestone, and coal interbedded with the shale, however, introduce undesirable characteristics that probably preclude further consideration of these rocks.

In Arkansas, shale sequences of Paleozoic age, like those in eastern Oklahoma, are abundant and widespread. The thick pre-Pennsylvanian rocks have been strongly deformed by folding and faulting and in eastern and southern Arkansas are deeply buried. The thick Pennsylvanian strata that crop out in northwestern Arkansas are less deformed in some areas but they contain scattered beds of permeable sandstone.

The Paleozoic rocks in southern Illinois and southern Indiana, in the Illinois basin, include thick shale-rich formations of Mississippian and Pennsylvanian age that also have potential disadvantages. Most of the area underlain by the formations is in a region of moderate to major seismic risk. In other parts of the area the potential host rocks include minor amounts of more permeable siltstone, sandstone, and limestone, as well as potentially combustible carbonaceous beds. In this area the most suitable rocks for an underground repository are probably in the Mississippian Borden Group (29 of table 1) which crops out in west-central Indiana. An undesirable characteristic of the group is the large amount of siltstone it contains.

The clay mineralogy of the Paleozoic sedimentary rocks in the Illinois basin has been described in several reports and is probably similar to the clay mineralogy of Paleozoic rocks in the nearby Michigan and Appalachian basins. Grim, Bradley, and White reported (1957, p. 5) that clays of Ordovician through Pennsylvanian age from widely separated localities in Illinois are dominantly illite but commonly include kaolinite and a chloritic clay mineral. Minor quantities of montmorillonite were found in one shale. Clay minerals in marine Mississippian shales of the Illinois basin are mainly illite but generally contain chlorite (Smooth, 1960, p. 3). The shales contain little or no kaolinite.

Michigan basin.--In southern Michigan, northern Indiana, and northwestern Ohio, thick shale sequences of Devonian and Mississippian age (fig. 8) underlie Pleistocene glacial deposits on the flanks of a large structural depression named the Michigan basin (figs. 2C and 9). The glacial deposits range from about 50 feet to 800 feet in thickness (Sanford, 1967, p. 974) and are permeable. Throughout much of the basin, wells in the glacial deposits yield more than 100 gallons of water per minute. The Paleozoic rocks have been mildly folded and are in a region of minor seismic risk. The most promising strata for waste emplacement are parts of the Devonian-Mississippian Antrim and Ellsworth Shales and the Mississippian Sunbury and Coldwater Shales (fig. 8). The Marshall Formation, one of the main aquifers of the Michigan basin, overlies the Coldwater Shale.

The Antrim is mainly dark-gray to black bituminous shale and is as much as 650 feet thick (Sanford, 1967, p. 993). From east to west across the Michigan basin, the Antrim is partly replaced by the overlying Ellsworth, which is mostly gray marine shale. The Ellsworth (26 of table 1) is as much as 600 feet thick where buried and about

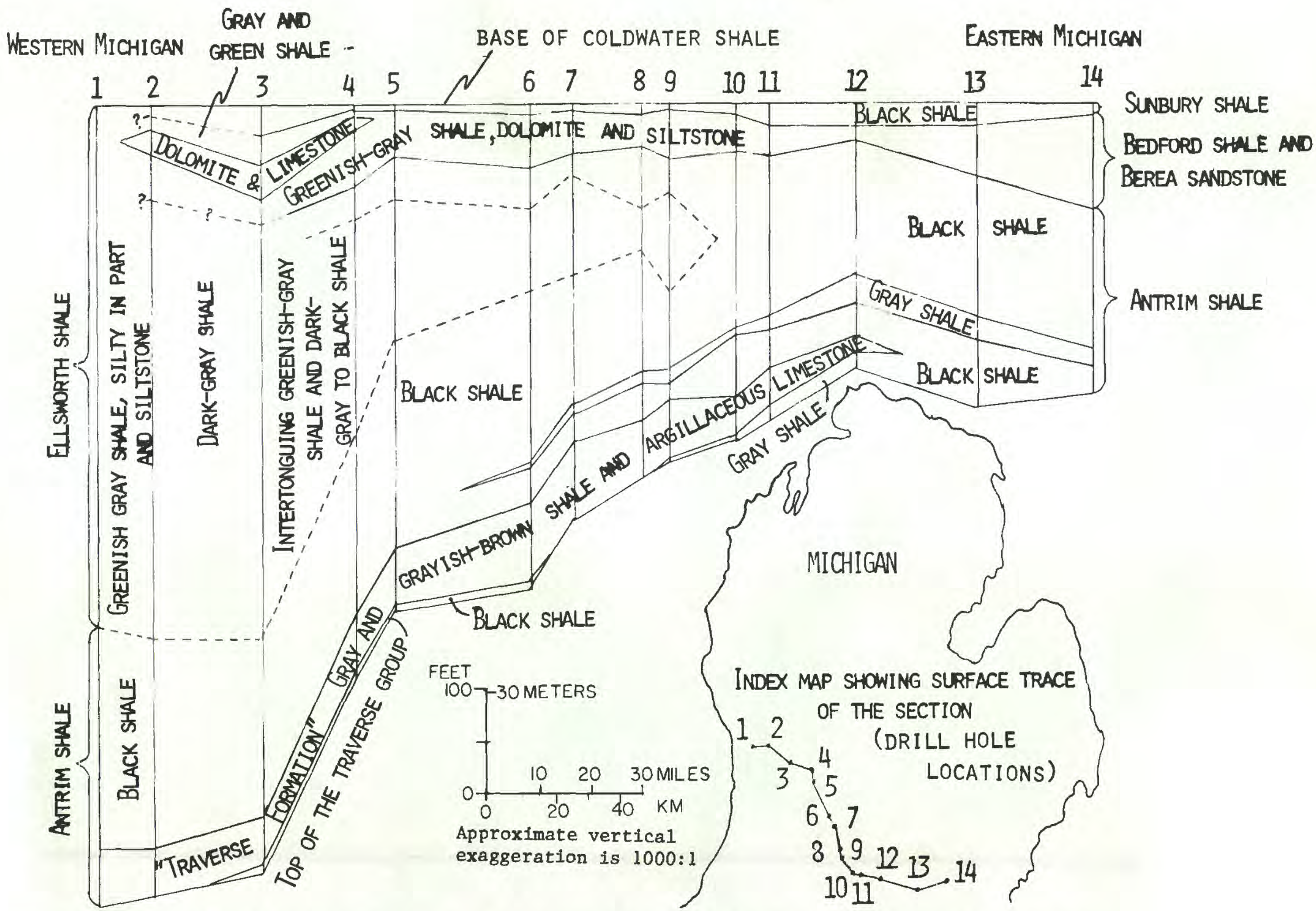


FIGURE 8.--SECTION SHOWING THE RELATION OF THE ANTRIM SHALE AND ELLSWORTH SHALE IN WESTERN MICHIGAN TO THE ANTRIM SHALE, BEDFORD SHALE AND BEREA SANDSTONE, AND SUNBURY SHALE IN EASTERN MICHIGAN (MODIFIED FROM COHEE, MACHA, AND HOLK, 1951).

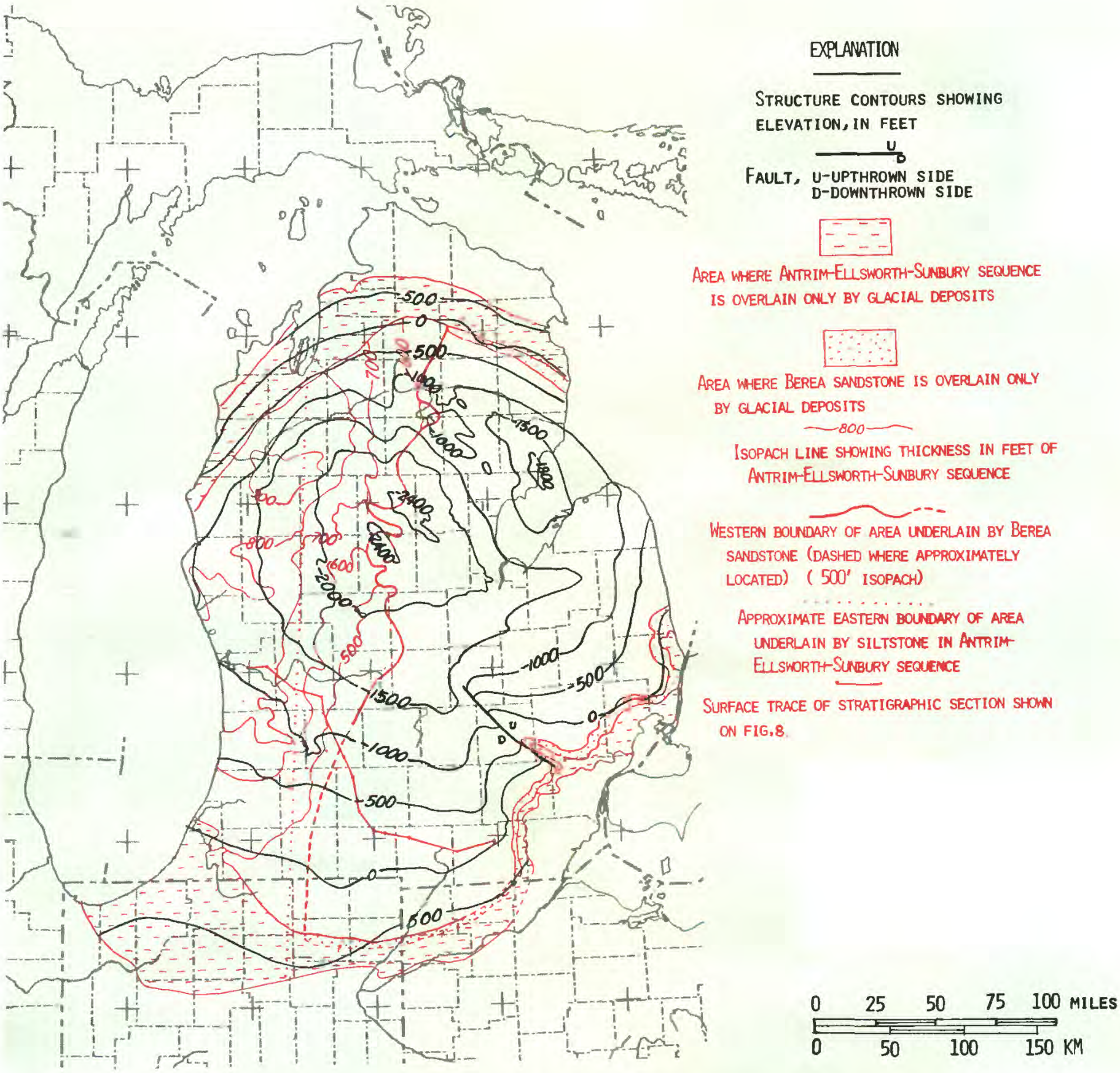


FIGURE 9.- ISOPACH MAP OF ANTRIM-ELLSWORTH-SUNBURY SEQUENCE AND STRUCTURE MAP ON BASE OF ANTRIM SHALE, MICHIGAN BASIN.
(MODIFIED FROM COHEE, MACHA, AND HOLK, 1951)

500 feet thick where it underlies glacial drift in western Michigan. The Sunbury Formation, which disconformably overlies the Ellsworth, is about 60 feet thick in western Michigan and consists of black shale. West of the area underlain by the Berea Sandstone, in the western part of the basin (fig. 9), the Antrim, Ellsworth, and Sunbury Shales have a combined thickness of as much as 950 feet. Siltstone is common in this sequence in the western part of the southern peninsula of Michigan. The depth of the top of the sequence, west of the area underlain by the Berea Sandstone, is about 2,800 feet (fig. 10). Holes drilled for oil and gas are abundant in many parts of the Michigan basin; the oil and gas fields are shown in figure 11.

The Mississippian Coldwater Shale (27 of table 1) overlies the Sunbury at most places but locally it rests on the Ellsworth or Antrim. The Coldwater is dominantly silty and calcareous gray shale interbedded with small amounts of siltstone, sandstone, limestone, and dolomite (DeWitt, 1960, p. 69). It directly underlies glacial deposits on the flanks of the Michigan basin and dips generally toward the center of the basin (fig. 12). The thickness of the formation increases from about 500 feet, on the west side of the southern peninsula, to more than 1,100 feet, on the northeast side of the peninsula (fig. 12). In the southeastern part of the basin the lower part of the Coldwater contains a 20- to 30-foot-thick sandstone bed and in the northeastern part of the basin the upper part of the formation includes lenses of sandstone (fig. 12). Locally, the sandstone lenses yield small

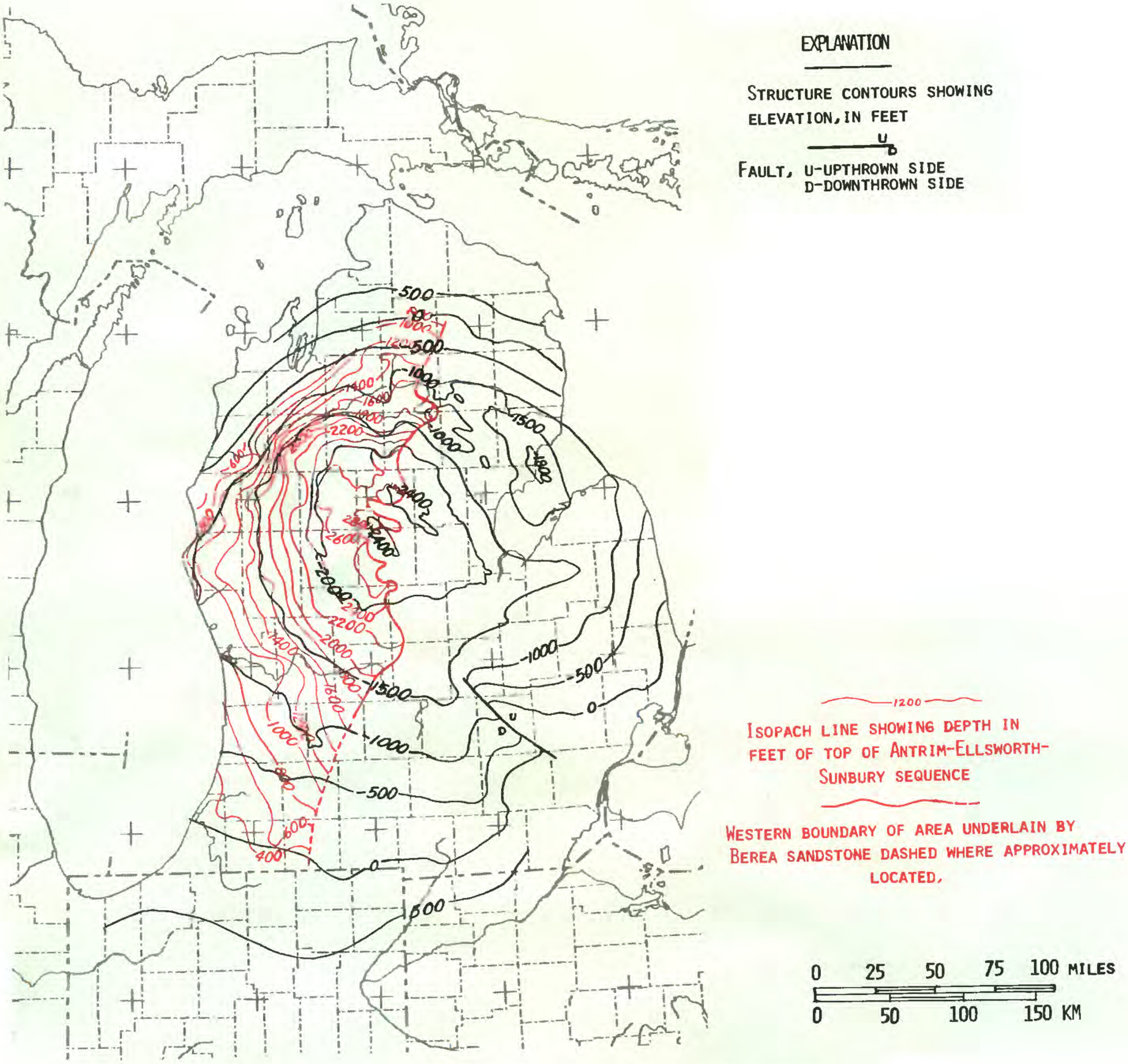


FIGURE 10.-Depth to top of Antrim-Ellsworth-Sunbury sequence and structure map on base of Antrim Shale, Michigan Basin. (Modified from Cohee, Macha, and Holk, 1951)

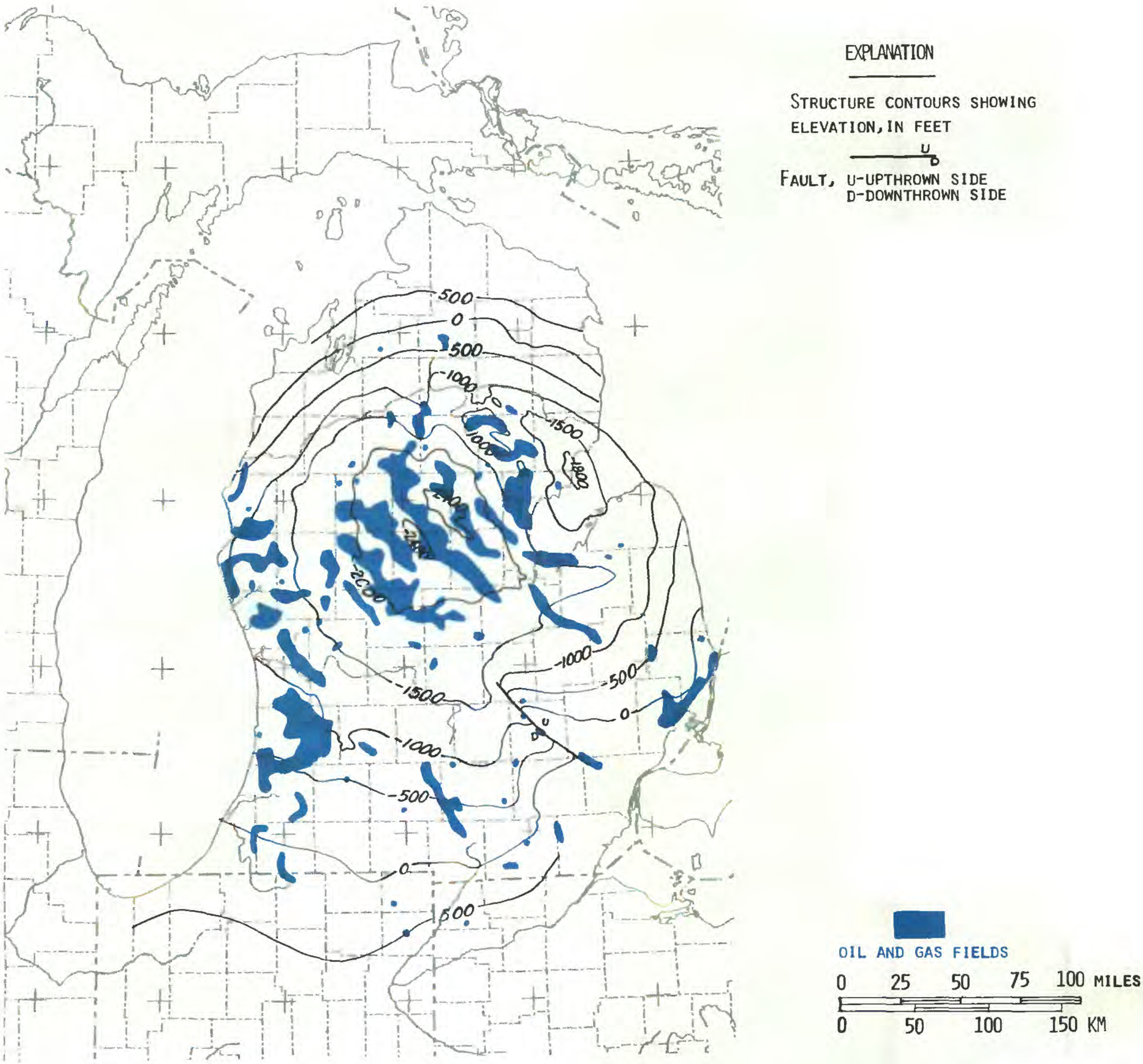


FIGURE 11.- OIL AND GAS FIELDS IN MICHIGAN BASIN AND STRUCTURE MAP ON BASE OF ANTRIM SHALE. (MODIFIED FROM COHEE, MACHA, AND HOLK, 1951)

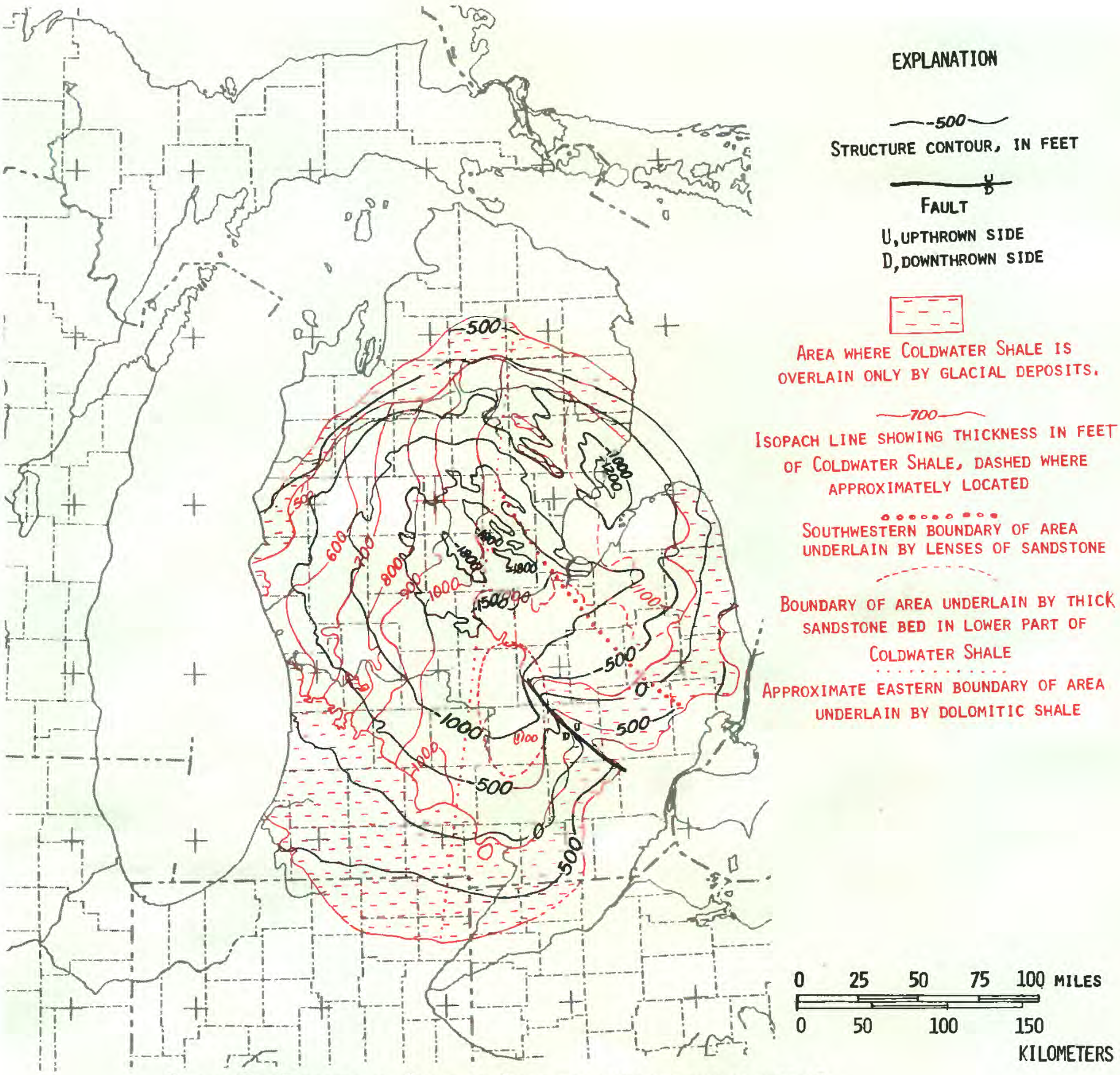


FIGURE 12.- THICKNESS OF COLDWATER SHALE AND STRUCTURE MAP ON BASE OF COLDWATER SHALE, MICHIGAN BASIN. (MODIFIED FROM COHEE, MACHA, AND, HOLK, 1951)

quantities of mineralized water. Beds of dolomitic shale and sandy dolomite are abundant in the Coldwater in western Michigan (fig. 12). The maximum depth of the top of the formation is about 1,800 feet (fig. 13).

The Ellsworth Formation and the Coldwater Shale of the Michigan basin may provide suitable sites for underground repositories. In the northern part of the southern peninsula, the Ellsworth is mainly shale, more than 500 feet thick (fig. 9), and not deeply buried (fig. 10). In the southeastern part of the basin the Coldwater has the required lithology, thickness, and depth locally (figs. 12 and 13). Development drilling of oil and gas fields (fig. 14) are a limiting factor in some areas, however. The shafts of salt mines near Detroit and gypsum mines near Grand Rapids, Mich., as noted by the U.S. Army Corps of Engineers (1956, p. 24), penetrate shales and should offer the opportunity for in situ observation of those argillaceous rocks.

Formations of Mesozoic age

The thick Upper Cretaceous shale sequences of the western part of the Interior Plains are generally continuous with the Upper Cretaceous shale sequences of the Rocky Mountain System and are described in the Rocky Mountain section of this report. As in the Rocky Mountains, these rocks are highly montmorillonitic.

ATLANTIC PLAIN

The Gulf Coast, Mississippi Embayment, and Atlantic Coast regions of the Atlantic Plain (fig. 1) are underlain by thick clay-rich strata

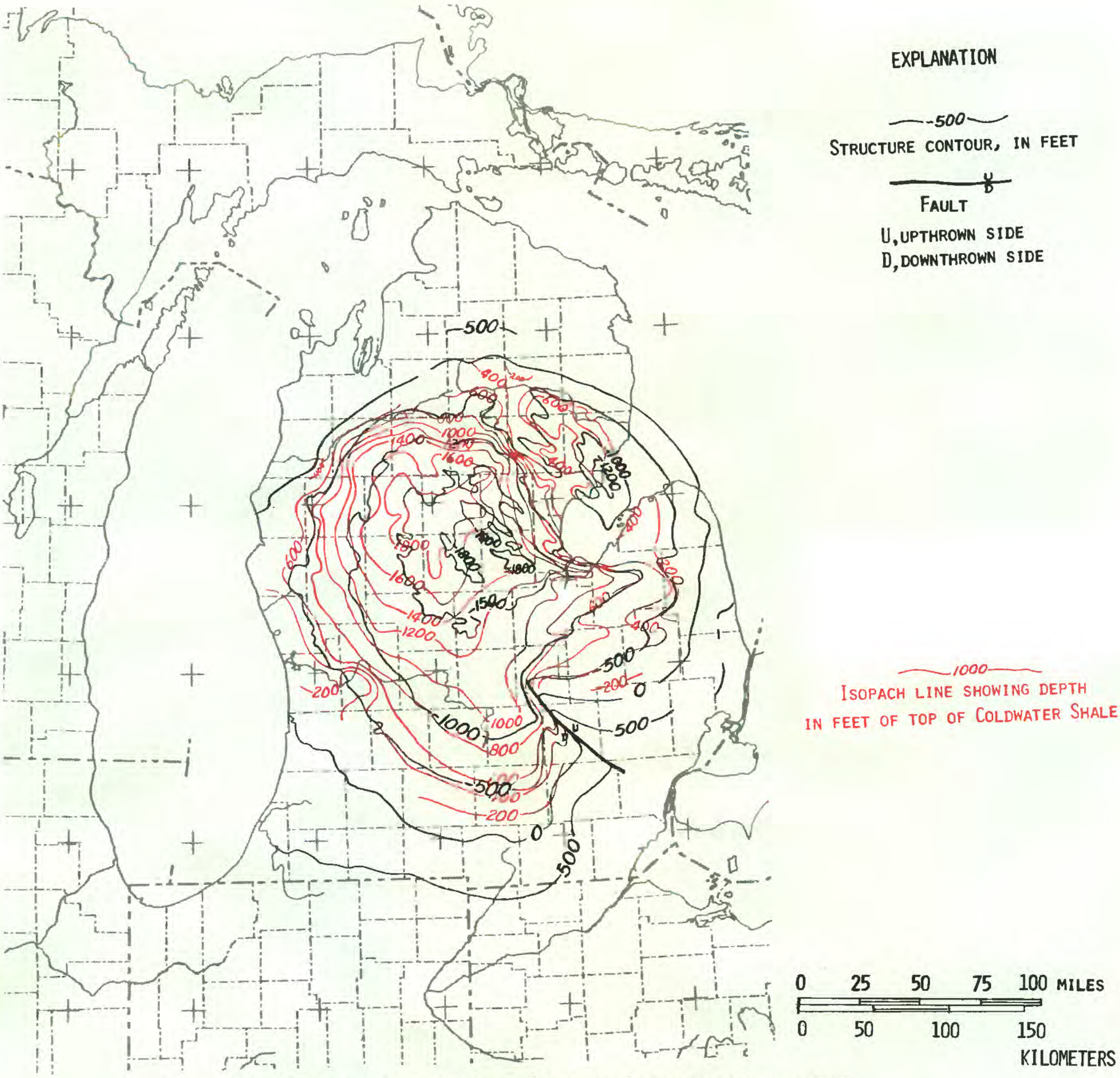


FIGURE 13.- DEPTH TO TOP OF COLDWATER SHALE AND STRUCTURE MAP ON BASE OF COLDWATER SHALE, MICHIGAN BASIN. (MODIFIED FROM COHEE, MACHA, AND HOLK, 1951)

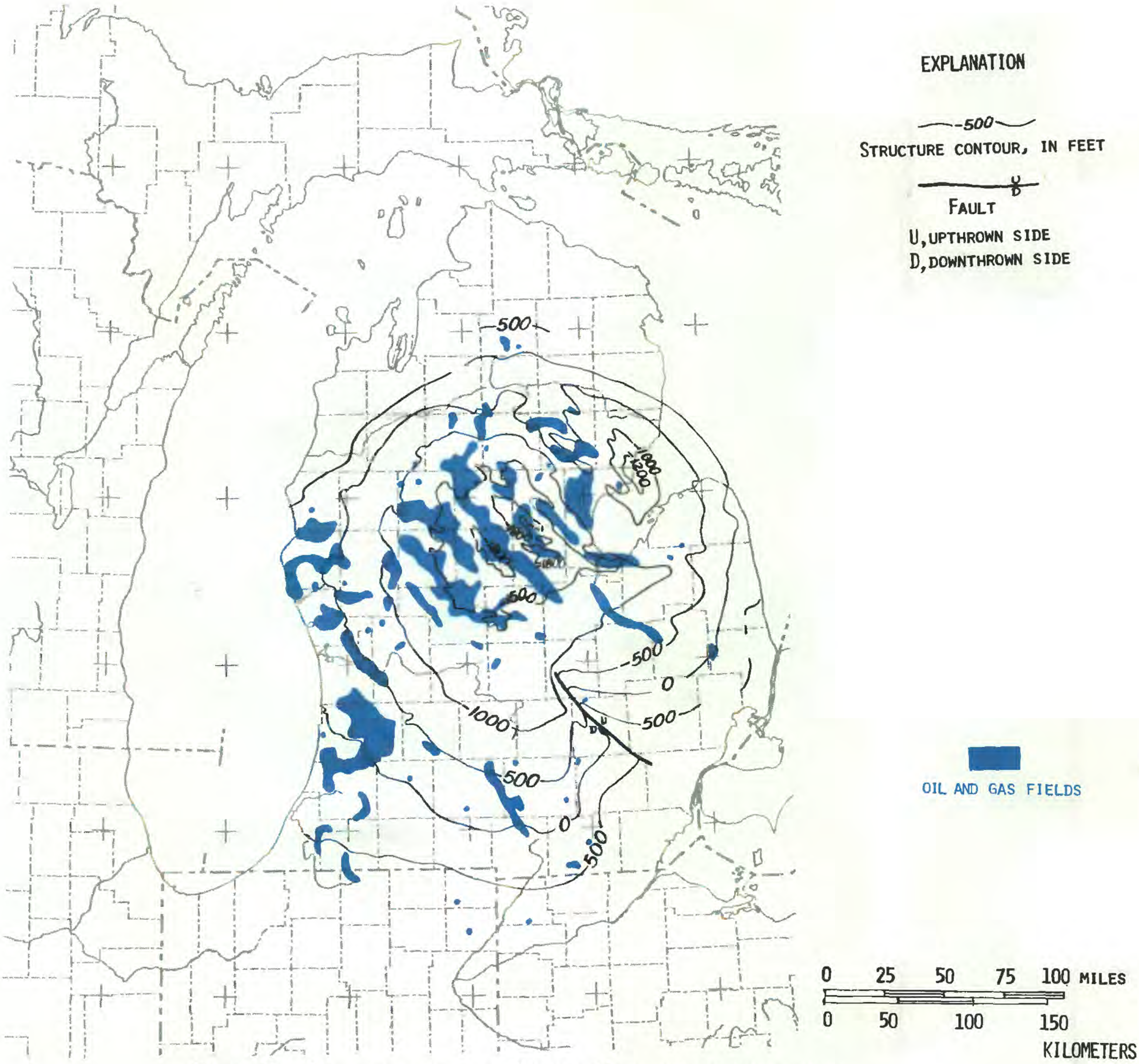


FIGURE 14.- OIL AND GAS FIELDS IN MICHIGAN BASIN AND STRUCTURE MAP ON BASE OF COLDWATER SHALE. (MODIFIED FROM COHEE, MACHA, AND HOLK, 1951)

of Paleozoic, Mesozoic, and Cenozoic age. In eastern Arkansas and northern Mississippi, Mississippian and Pennsylvanian shales which were found in oil and gas wells, are deeply buried, tectonically deformed, and in an area of active petroleum exploration.

Poorly indurated and commonly lenticular sandstone, limestone, and claystone strata of Cretaceous and Tertiary age crop out on the Atlantic Plain and, in general, dip gently toward the sea (Le Grand, 1962, p. 10-16). In much of the region the geologic structure is simple and the seismic risk is low (0 or 1, fig. 2B). Most of the claystone intertongues locally with sandstone or conglomerate and the rocks at shallow depths, in all but the southwestern part of the Atlantic Plain, are saturated with groundwater. The clay sequences along the Gulf Coast and Mississippi Embayment (fig. 2C) contain a large percentage of montmorillonite, are generally interbedded with important aquifers, and in many areas have been penetrated by wells drilled for oil and gas. Along the Atlantic Coast, the Cretaceous and Tertiary clays probably contain less montmorillonite but they are commonly interstratified with aquifers. The Atlantic Coast has not been intensively drilled for oil and gas but is considered promising for future exploration. Only the most suitable formations in the region are noted in table 1 (50, 52, and 53) and figure 2C.

APPALACHIAN HIGHLANDS

The Appalachian Highlands (fig. 1) contain thick bodies of Paleozoic shale (Colton, 1961, p. 35-102) which are strongly folded and faulted in the Appalachian Mountains and less deformed in the adjoining plateaus west of the mountains (figs. 2A and 2C). Many of these formations crop out on the flanks of a structural depression named the Appalachian basin in the northern part of the Appalachian Highlands. Large parts of the highlands region are characterized by complex geologic structure, moderate to major seismic risk and numerous oil and gas fields (fig. 15). Permeable formations in the Appalachian region are saturated with ground water at shallow depths and water wells yield as much as 300-600 gallons per minute. The most promising host rocks for waste repositories are of Ordovician, Devonian, and Mississippian age.

An Ordovician clastic sequence that is mainly shale crops out in the eastern part of the Appalachian basin, underlies a thick sequence of younger Paleozoic rocks in the middle of the basin, and crops out on the west flank of the basin in the eastern part of the adjacent Interior Plains (figs. 15 and 16). The thickness, depth, and structural setting are appropriate in southwestern Ohio but the strata are about 50 percent carbonate rocks (fig. 16). In Virginia, Maryland, and central Pennsylvania, the Ordovician shale has been severely deformed and probably contains water-bearing fractures. The shales in eastern New York, northwestern New Jersey, and eastern Pennsylvania are very thick and may be more suitable locally. The area contains an outcropping shaly sequence that ranges from 2,000 to 8,000 feet thick (47 and 48 of table 1).

The Devonian clastic sequence in the northern part of the Appalachian Highlands is dominantly shale and generally more than 500 feet thick (Colton, 1961, fig. 15). It crops out on the north and east flanks of the Appalachian basin in New York, Pennsylvania, Maryland, West Virginia, Virginia, and Tennessee and on the west flank of the basin in Kentucky and Ohio (figs. 17 and 18). On the east flank of the basin, sandstone and limestone are interbedded with the shale and the rocks are structurally contorted. On the north and west flanks of the basin, the sequence contains less sandstone and limestone, is less deformed, and is probably more appropriate for waste storage. Parts of New York and Pennsylvania, however, are in a region of major seismic risk. The shale and thin limestones of the Hamilton Group (45 of table 1) or the shale and siltstone of the Genesee, Sonyea, and West Falls Formations in northwestern Pennsylvania may provide acceptable storage sites, though oil and gas fields (fig. 17) have been extensively drilled in the area. In northeastern Ohio, the characteristics of the Ohio Shale (43 of table 1) seem to meet the geologic requirements for waste repositories except where the strata are petroliferous or include too many thin beds of limestone and siltstone. Many oil and gas wells have been drilled in parts of the region. The Ohio Shale yields small amounts of water to wells in the upper 30 feet of the formation, where it is weathered or is overlain by glacial deposits.

Formations of Mississippian and Pennsylvanian age in the Appalachian region contain thick shaly strata in several areas, but there are problems. Where the structural deformation, thickness, depth, and seismic risk are acceptable, the shales contain deleterious beds of sandstone, limestone, carbonaceous shale, and coal (Colton, 1961, p. 70-81).

Some of the limestone and salt mines in New York (U.S. Army Corps of Engineers, 1956, p. 26-27), including the limestone mines near Kingston, may penetrate shale that should receive additional study. In part of northwestern Pennsylvania and in central and northern Ohio, the nonpetroliferous shales in the formations of Middle and Late Devonian age may be acceptable for underground repositories, but selection of sites in these areas would be strongly influenced by the location of oil and gas wells. The limestone mines in Pennsylvania and the limestone and gypsum mines in Ohio, described by the U.S. Army Corps of Engineers (1956, table 2, p. 27), should be investigated. For example, the shaft of a limestone mine near Barberton, Ohio, passes through a shale sequence that is more than 1,600 feet thick (Colton, 1961, p. 64).

SUMMARY

Most of the shales, mudstones, and claystones in the United States are probably not suitable as host rocks for the underground emplacement of waste. Many shale bodies are too thin or deeply buried and have mineral constituents that may be unacceptable. The argillaceous strata of Mesozoic and Cenozoic age, which are widespread in the Pacific and Rocky Mountain Systems and the Atlantic Plain, generally contain large amounts of montmorillonite, which may release water when heated. Many of the Devonian, Mississippian, and Pennsylvanian shales in the eastern half of the nation contain large amounts of organic matter and may yield carbon compounds when heated. The shale bodies that are underlain or overlain by important aquifers and have been penetrated locally by oil and gas wells, as in the Atlantic Plain, have little site potential. Those clayey rocks that have been structurally deformed are also less suitable hosts for subsurface waste emplacement. Strata in the orogenic belts of the United States, the Appalachian Mountains, Ouachita Mountains, Rocky Mountains and other regions, are largely unacceptable because of abundant fractures that increase the permeability and decrease the strength of the rocks. Parts of many western and eastern states are characterized as areas of major seismic risk.

The argillaceous sedimentary rocks in a few areas of the United States fulfill many of the geologic requirements for repository strata and more detailed investigations may indicate that some of these sequences are acceptable. The Devonian-Mississippian Ellsworth Shale and Mississippian Coldwater Shale in Michigan are promising potential host rocks. In central and northern Ohio, parts of the Devonian Ohio Shale seem to have the necessary characteristics. In eastern New York and northwestern New Jersey some of the Ordovician shales may also qualify for emplacement sites if the rocks are not severely fractured. The thick Upper Cretaceous shale bodies in the Rocky Mountain System would probably be suitable host rocks if the problem posed by montmorillonite could be solved.

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