Open-file Report 77-776

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UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

THE PIERRE SHALE, NORTHERN GREAT PLAINS; A POTENTIAL ISOLATION MEDIUM FOR RADIOACTIVE WASTE

By

George W. Shurr

FOREWORD

In February 1976 the U.S. Energy Research and Development Administration (ERDA) announced a greatly expanded waste management program for defense and commercial radioactive waste. The commercial radioactive waste disposal program, which was named the National Waste Terminal Storage (NWTS) Program, represents the principal programmatic effort of ERDA for ultimate and final disposal of commercial radioactive waste. The U.S. Geological Survey, under the provisions of Interagency Agreement No. EY-76-C-05-4330, is participating in the NWTS Program by conducting studies in geologic formations of interest and by providing information on their properties and characteristics. This work was coordinated by the U.S. Geological Survey, Reston, Va., and the U.S. Energy Research and Development Administration (now U.S. Department of Energy), Oak Ridge, Tenn.

CONTENTS

ILLUSTRATIONS

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ABSTRACT

The purpose of this reconnaissance is to assess the potential of the Pierre Shale, of Late Cretaceous age, as a possible isolation medium for radioactive wastes. The regional stratigraphic and structural setting of the Pierre Shale in the northern Great Plains is summarized from subsurface data.

Geologic attributes mapped and employed in the identification of areas warranting further evaluation are: depth to the base of the Pierre Shale, shale thickness, overburden thickness, lithology and mineralogy of the shale, and penetrations by oil and gas wells. Three areas emerge as most favorable; each may contain many potential disposal sites. These large geologic study areas are further described on the basis of general structural and seismic considerations and are compared with respect to topography and mineral and water resources.

A large area in west-central South Dakota is recommended for extensive further study. A smaller area in northeastern Colorado also may warrant additional investigation. A relatively small area in north-central North Dakota is also delineated, but currently is not proposed for further studies.

INTRODUCTION

The Upper Cretaceous Pierre Shale, a well-known and widespread formation in the northern Great Plains, is under consideration as a possible geologic medium for the isolation of radioactive wastes. This preliminary reconnaissance study summarizes the regional geologic setting and character of the Pierre Shale and identifies three areas that meet current criteria, and that may warrant further geologic study. Each of the areas (fig. 1) may contain many potential isolation sites. The reconnaissance area lies between lat. 39° and 49° and long. 98° and 105°. Specific sites are not identified here because this report has the sole purpose of identifying large areas for subsequent detailed evaluation and exploration. Such exhaustive studies will precede a site-selection process within any of the three areas. In addition, this report has two ancillary purposes: (1) it should be useful in making comparisons with other potential isolation media elsewhere in the United States, and (2) it should help guide more detailed investigations in case such comparisons lead to selection of the Pierre Shale for further study.

This report starts with outlines of criteria and procedures employed in data collection. Available geologic data, as they apply to identification of geologic study areas, are then summarized. Preliminary study areas are defined and compared. Finally, some suggestions for further, more detailed studies are presented, with some specific recommendations.

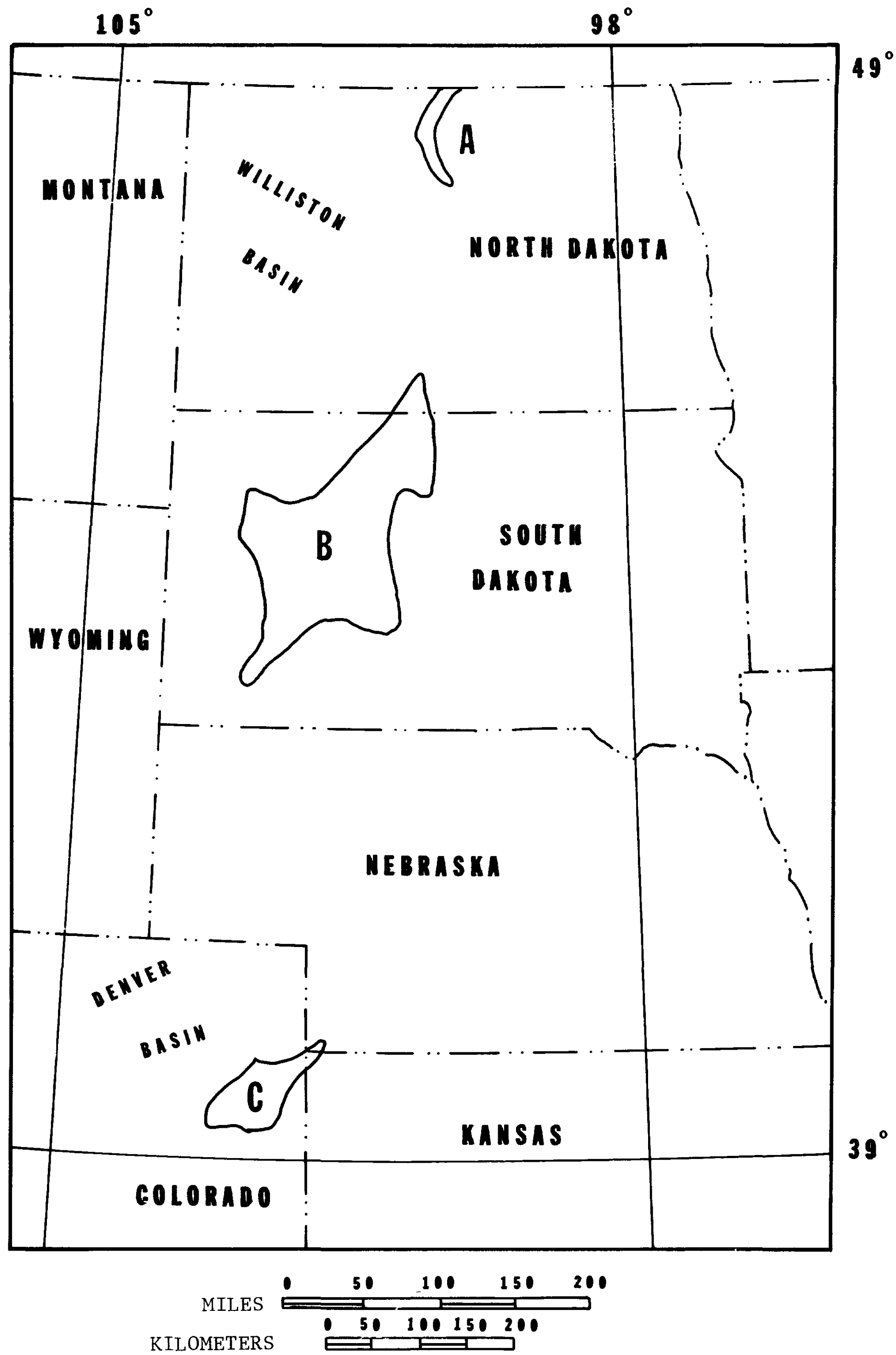


Figure 1.--Base map showing geologic study areas (A, B, and C) proposed for possible detailed evaluation.

Acknowledgments

This report has undergone substantial editing directed to an emphasis on waste-isolation aspects of the contents. The patient and helpful assistance of E. B. Eckel and H. W. Smedes is gratefully acknowledged.

CRITERIA

The criteria for potential underground sites for isolation of radioactive waste in shale have not been precisely defined. Many factors must be considered, each of them in relation to all the others. In this report, the Pierre Shale is the only geologic unit that is considered for a potential isolation medium, but the characteristics of the formation itself, and of its geologic setting, range widely from place to place. Consequently, only relatively small parts of the total mass of the Pierre may prove suitable for waste-isolation sites. For this investigation, the following criteria were applied:

1. *Depth.* Potential specific isolation horizon (the zone in which an isolation facility would be constructed) should be from 1,000 to 3,000 feet (305-914 m) below land surface; shallower depths may be considered, but are less desirable.

2. *Shale thickness.* Maximum thickness of the isolation medium is to be preferred. The minimum shale thickness acceptable is 500 feet (152 m).

3. *Overburden thickness.* Minimal thickness of sand, gravel, or other overlying material above the Pierre Shale is preferred. Maximum permitted is 2,500 feet (762 m) (in order to have at least 500 feet (152 m) of shale and be no more than 3,000 feet (914 m) deep).

4. *Lithology and mineralogy.* The entire Pierre section must be reasonably uniform shale, with few if any beds of sandstone or other permeable rocks. One or more potential isolation horizons, at least 50 feet (15 m) thick, must exist. Expandable clays in the shale are undesirable within the isolation horizon.

5. *Penetrations* (boreholes). Boreholes of any kind are undesirable, particularly if they penetrate to rocks beneath the Pierre Shale. It is recognized that some holes, either pre-existing or bored during detailed search for isolation sites, are necessary to provide geologic information at depth.

6. *Structure.* Beds should be nearly horizontal, having maximum dips of 5° and no known faults or folds within several miles of the isolation site.

7. *Seismicity.* Future seismic activity is highly undesirable; regions of recorded epicenters should be avoided.

8. *Topography.* Minimal topographic relief is desirable.

9. *Mineral and water resources.* It is undesirable to consider a potential site near exploitable mineral or water resources, either at or below the surface.

The three geologic study areas shown in figure 1 are identified on the basis of criteria 1-5. Criteria 6 and 7 are discussed for the area of regional reconnaissance and criteria 8-9 are described for each of the three geologic study areas. Hydrologic considerations for both surface and ground water are not included in this report. Investigations of the movement of ground water through the Pierre Shale are in progress.

IDENTIFICATION OF GEOLOGIC STUDY AREAS

The three geologic study areas (A, B, C) shown in figure 1 are derived largely from facts in figures 5-9. The rocks within all three geologic study areas meet the following conditions:

1. Base of Pierre Shale is 1,000-3,000 feet (305-914 m) below land surface.
2. Thickness of Pierre Shale is greater than 500 feet (152 m). Specifically, the shale is 1,000 (305 m) or more feet thick.
3. Overburden thickness is less than 2,500 feet (762 m). Specifically, the overburden is less than 500 feet (152 m) thick.
4. Entire section of Pierre consists of shale or marly shale, with no known beds or lenses of sandstone.
5. Penetrations (boreholes) are fewer than 100 per cell of 15' lat by 15' long

The remaining criteria are described as attributes for each of the potential study areas and will be investigated in more detail in subsequent studies.

A relatively small part near the center of study-area B more than meets the limitations just listed. Within it, the Pierre is more than 1,500 feet (457 m) thick, overburden thickness is zero, and there are fewer than 10 penetrations per 15-minute cell. Though not shown separately in figure 1, this area currently is geologically the most promising for further evaluation.

Vast areas outside the three geologic study areas shown in figure 1 would also meet most or all of the requirements. However, the Pierre section is thinner, and the overburden is thicker than within the designated areas. Therefore, such areas may be less appropriate and would be investigated further only if no adequate isolation sites could be found within study-areas A, B, and C.

PROCEDURE

All but a tiny fraction of the area of regional reconnaissance shown in figure 1 is underlain, or was formerly underlain, by the Pierre Shale. An enormous amount of information on the Pierre within this area is available from drill-hole records, surface stratigraphic and structural studies, specialized chemical, mineralogic, geophysical investigations, and other sources. The problem was to narrow this mass of data to an objectively chosen sample that would be representative of the whole but small enough to be manipulated with reasonable time and effort. The final objective, of course, was to delineate one or more geologic study areas wherein the Pierre Shale best meets the present criteria for isolation sites as defined above.

The procedure adopted is based heavily on the subsurface records of boreholes drilled for oil and gas exploration or production, supplemented and refined by information from other sources.

A computer-based "Well History Control System," produced by the Petroleum Information Corp., was the primary basis for the study. As of June 1975, this compilation includes locations, drilling history, and geologic data for 34,000 wells in the study areas; of these, 33,000 penetrate the Pierre Shale. A computer scan of this data base narrowed the sample by selecting one well per township, for a total of 5,000 data points. This sample, still too large for easy manipulation, was then further reduced to 550 control points, spaced about 18 miles (29 km) apart, on which delineation of geologic study areas would be based. This reduction was accomplished by subjective evaluation of geophysical logs employing datums which were functional definitions for the top and base of the Pierre. The definitions were based upon 14 outcrops and a correlation grid of some 150 wells.

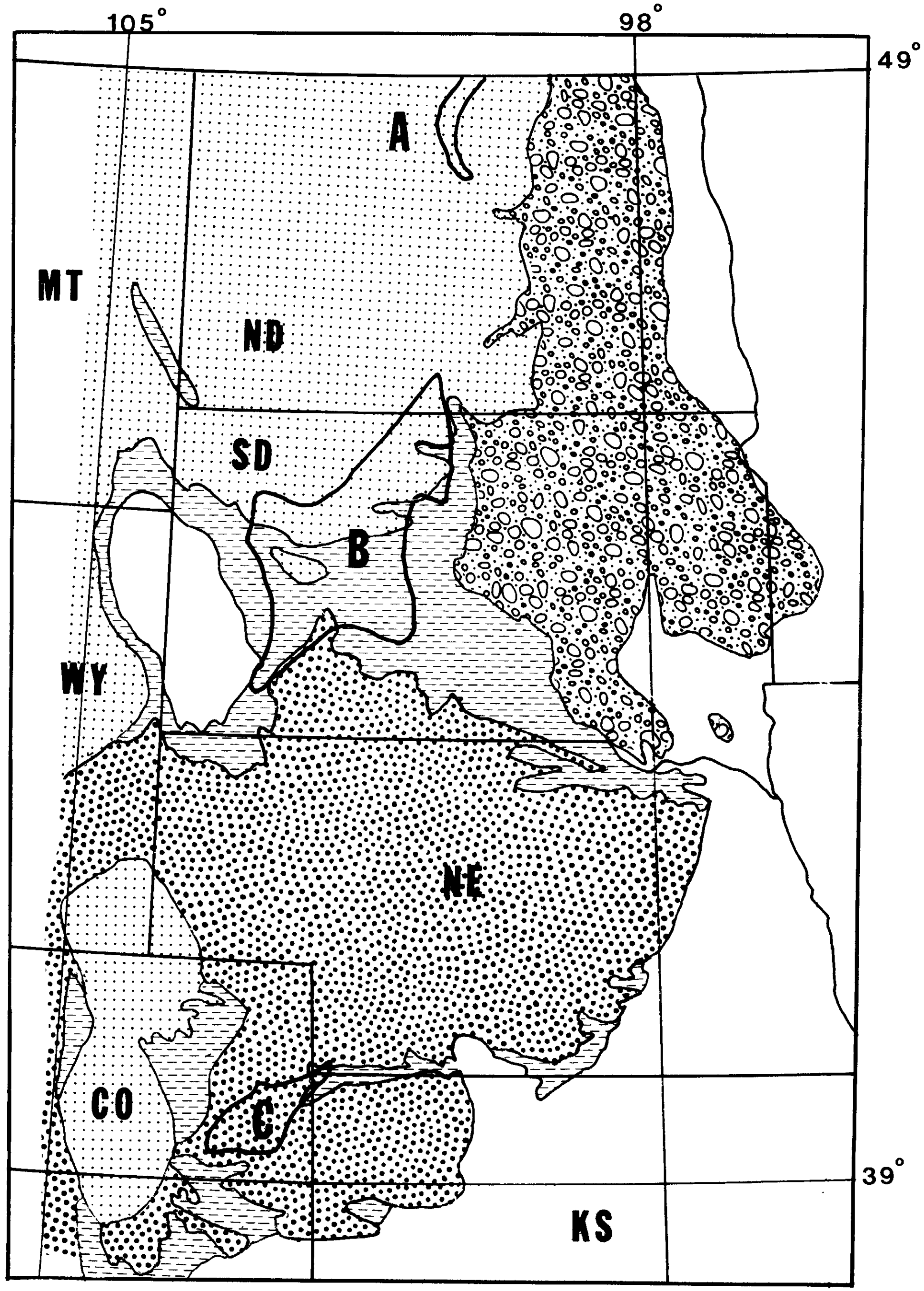
Thus the interpretations that follow are based on 550 data points that were objectively selected from a much larger array. Though the picture probably would not be changed appreciably had all available data been used, it should be emphasized that any or all parts of the original 33,000-well data base are available for any future detailed studies of selected areas. Data from the 550 control points, with a density of 1 control point per 420 mi^2 (1,087 km^2), were plotted on regional maps. Data from the well logs were processed by computer, using simple iterative calculations, and maps at a scale of 1:1,000,000 (16 mi/in; 10 km/cm) were plotted automatically. All contouring was done by hand. The contours were then transposed from the working copies to a base map showing county and State boundaries. These contour maps, shown in greatly reduced form in figures 5-9, were then employed in the defining of geologic study areas (fig. 1).

The initial extraction of study areas employed stratigraphic maps, such as thickness of shale and overburden, prepared as just described. These preliminary extractions were refined by use of available data on geologic structure (figs. 3A, 3B, 4). These data, however, are less accurate than those on stratigraphy because structural variations tend to be much smaller in area than stratigraphic ones. Control-point spacings employed in this reconnaissance do not adequately describe these structural variations. Finally, comparisons of the three identified geologic study areas employed additional data on other factors, such as seismicity, topography, and water and mineral resources that were not parts of the main data base.

STRATIGRAPHY AND STRUCTURAL SETTING OF THE PIERRE SHALE

That part of the northern Great Plains underlain by the Pierre Shale coincides in general with the area chosen for study in this reconnaissance (figs. 1, 2). The Pierre thins to a zero edge along the eastern and southern margins of the study area, and tectonic uplifts with erosional thinning define the southwest margin. Along the northwest margin of the study area, the shale of the Pierre gives way to sandstone units by facies changes. The northern limit of the study area is the international border. The extension of the Pierre into northwestern Kansas is not considered here because that area is not included in the computer data file on which the study was based.

Structurally, the area of this regional reconnaissance is marked by two major basins, or downwarps; these are the Williston Basin in the Dakotas and Montana, and the Denver Basin in Colorado and Nebraska. Both were areas of long-term deposition and minimal erosion; hence the Pierre Shale is thicker there than elsewhere. The two basins are separated by broad upwarps in South Dakota and Nebraska. The upwarps are not named on the illustrations, but figures 3A, 3B, and 4 show the regional structure.



EXPLANATION

- PLEISTOCENE GLACIAL MATERIAL OVER PIERRE SHALE
- TERTIARY SANDS AND CLAYS OVER PIERRE SHALE
- CRETACEOUS SANDSTONE OVER PIERRE SHALE
- PIERRE SHALE
- ROCKS OLDER THAN PIERRE SHALE

MILES 0 50 100 150 200
KILOMETERS 0 50 100 150 200

Figure 2.--Distribution of Pierre Shale and lithology and age of units overlying the Pierre. Compiled from State geologic maps and borehole records. A, B, and C are geologic study areas.

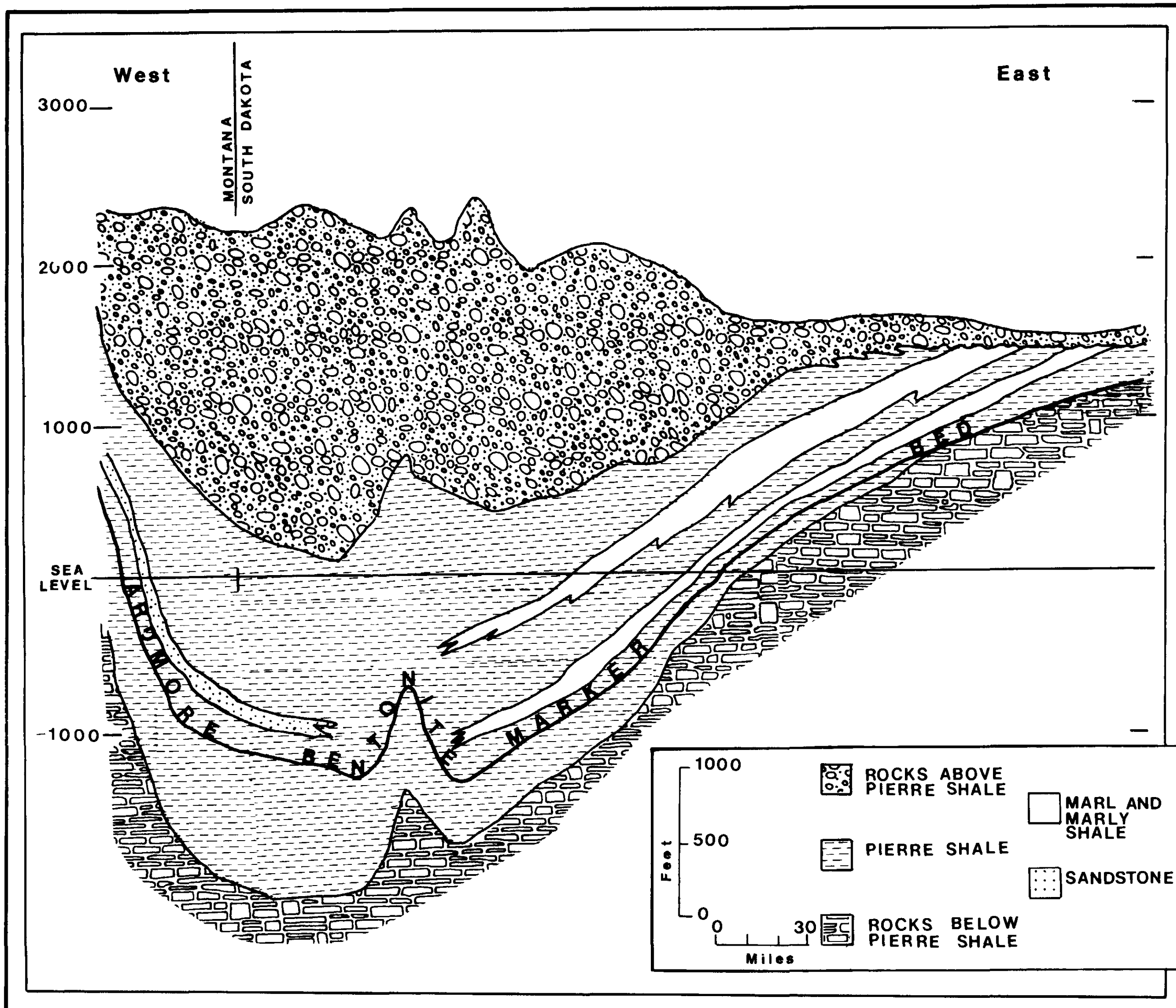


Figure 3A.--East-west cross section of Pierre Shale along lat 48° N. Vertical scale exaggerated 250X.

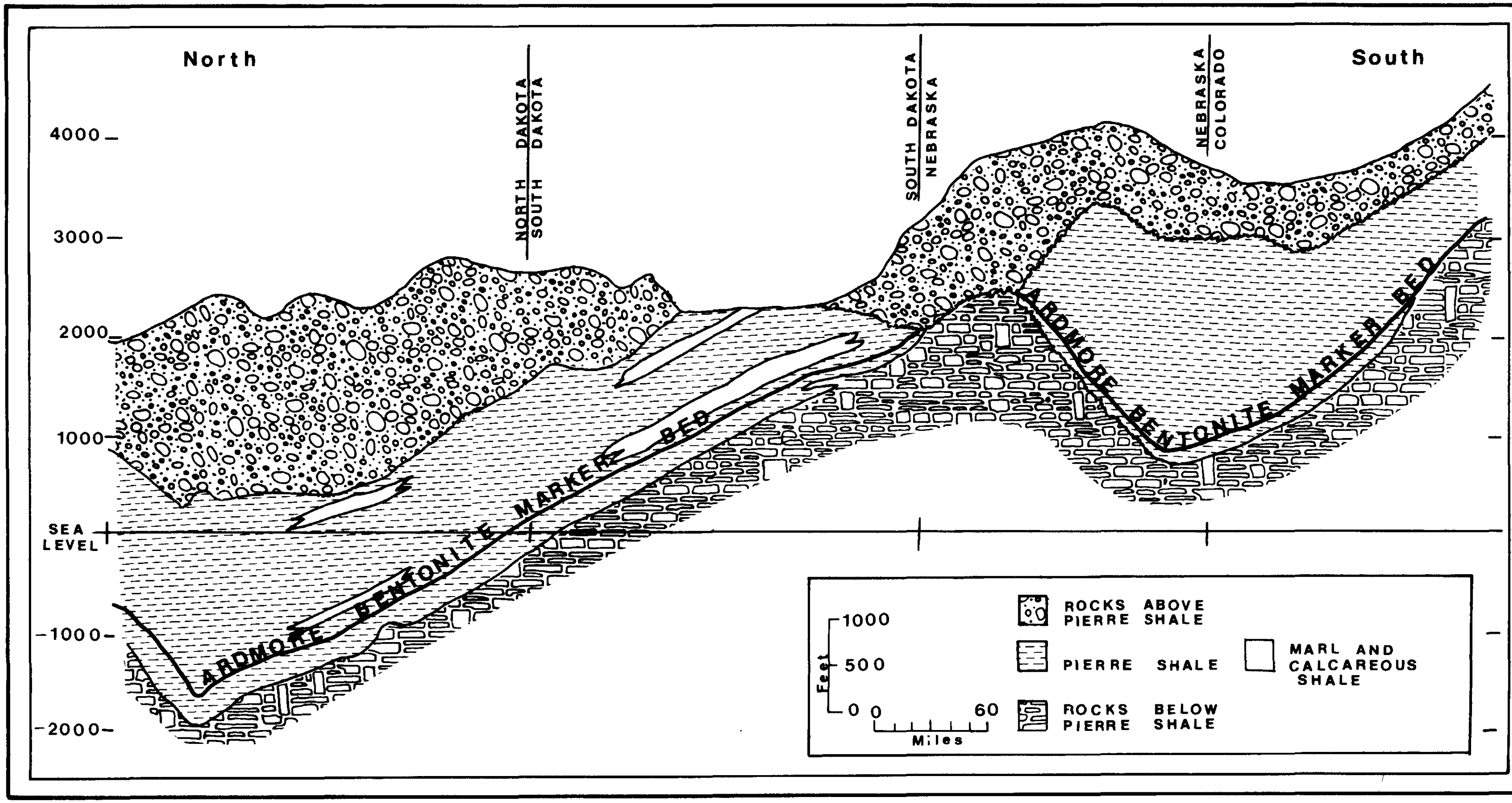


Figure 3B.--North-south cross section of Pierre Shale along long 102°30' W. Vertical scale exaggerated 250 X.

Faults, most of them with small displacements, occur around the edges of the Williston and Denver Basins. Several extensive lineaments that probably reflect faults in the basement rocks have been mapped in places. Their possible significance is discussed later in this report.

Various characteristics of the Pierre Shale, such as its stratigraphy, paleontology, lithology, and geochemistry, have been studied by many geologists over many years. The resultant voluminous literature provides necessary backup for interpretation of the 550 well records on which this study is based. The literature is well reviewed by Tourtelot (1962) and by Gill and Cobban (1973). Regional rock-stratigraphic and biostratigraphic relationships are described by Gill and Cobban (1966, 1973); by Gill, Cobban, and Schultz (1972a, b); and by Izett, Cobban, and Gill (1971). Geochemical and mineralogic aspects are reviewed and summarized by Tourtelot (1962) and L. G. Schultz (oral commun., 1976). Asquith (1970), DeGraw (1969, 1975), and Shurr (1975) present the results of subsurface investigations in the Pierre Shale. In the course of the present study, the following people provided unpublished data and offered helpful suggestions: W. A. Cobban, L. W. Kitely, E. A. Merewether, D. R. Rice, C. W. Spencer, and H. A. Tourtelot of the U.S. Geological Survey; J. C. Harksen and R. L. Stach of the South Dakota Geological Survey; H. M. DeGraw of the Nebraska Geological Survey.

Although the Pierre Shale is conventionally visualized as a uniform and featureless marine shale, it is far from homogenous. Marine beach and bar sandstones in the west pass eastward and downsection into clay shales and silty shales. Calcareous shale and marl are found toward the base of the Pierre and in higher stratigraphic units in the Dakotas. There are also units of organic-rich black shale and of siliceous shale. Minor lithologic discontinuities are represented by bentonite beds, thin beds of silt and sand, and zones of calcareous and ferruginous concretions. Fossils are commonly found in the concretions.

The formal rock-stratigraphic units recognized in outcrop and widely described in the literature often cannot be employed in subsurface studies. Instead, parastratigraphic units (Krumbein and Sloss, 1963) are defined on the basis of electric-log characteristics. Three stratigraphic datums are employed in this investigation: (1) the top of the Pierre Shale; (2) the base of the Pierre Shale; and (3) the Ardmore Bentonite Bed of the Pierre Shale.

Top of the Pierre Shale

The top of the Pierre Shale in the central portion of the Williston Basin is characterized by a facies relationship with rocks of the Fox Hills Sandstone. In this area the top of the Pierre is taken at the base of the lowest well-defined sandstone unit in the Fox Hills Sandstone. In the Denver Basin, the change downward from sandstone to shale is very gradational. Here, the top of the Pierre is arbitrarily defined for this report as the base of the silty and sandy transition member of the Pierre.

Along the eastern margins of the Williston and Denver Basins and in the area of the uplifts separating the basins, the top of the Pierre is erosional. Generally the overlying unit is coarse grained and the top of the shale is clearly shown on mechanical logs. However on the northern and eastern margins of the Denver Basin the top of the shale is difficult to recognize because the units above the Pierre are Tertiary clay or clay shale.

Base of the Pierre Shale

The base of the Pierre throughout most of the Williston Basin is gradational with the calcareous shale and marl of the underlying Upper Cretaceous Niobrara Formation. There is a slight increase in resistivity and self potential at the top of the Niobrara which is taken as the base of the Pierre. In the Denver Basin, the facies gradation is more abrupt and the Niobrara has a more distinctive signature on electric logs; hence, the base of the Pierre is more easily recognized. Similarly in the area of uplifts between the basins, the base of the Pierre has clear expression. This is a consequence of erosion at the top of the Niobrara, which has been documented in western Nebraska (DeGraw, 1975) and in south-central South Dakota (Shurr, 1970).

Ardmore Bentonite Bed of Pierre Shale

A series of thick bentonite beds is located near the base of the Pierre Shale and is virtually continuous throughout the study area (fig. 4). The beds are collectively termed the Ardmore Bentonite Bed of the Pembina Member of the Pierre Shale in North Dakota, the Ardmore Bentonite Bed of the Sharon Springs Member of Pierre Shale in the southern Black Hills (Spivey, 1940), and informally referred to as the "I" bentonite bed in the northern Black Hills (Knechtel and Patterson, 1962). The bentonites have expression on geophysical logs as units of low resistivity and spontaneous potential. The lowest of these units is a useful marker bed and is employed as a structural datum.

FEATURES APPLIED TO DEFINITION OF GEOLOGIC STUDY AREAS

The three geologic study areas shown in figure 1 lie on the margins of the downwarped basins, specifically: (1) the eastern flank of the Williston Basin in north-central North Dakota, (2) the southeast flank of the Williston Basin in central South Dakota, (3) the east flank of the Denver Basin in northeastern Colorado and southwestern Nebraska. Each geologic study area is very large and may contain many potential repository sites. Criteria employed in the selection of these geologic study areas are ranked on the basis of large-area exclusions down to small-area exclusions. This hierarchical arrangement is also employed in the discussions that follow on depth, shale thickness, overburden thickness, lithology, and penetrations. This means that large areas of less desirable depth are excluded first and smaller areas of high-density borehole penetrations are eliminated last.

Depth

Potential isolation horizons within the Pierre Shale, according to the criteria stated on page 3, should be at depths of 1,000-3,000 feet (305-914 m). Figure 5 shows those areas in which the base of the Pierre is 1,000-3,000 feet (305-914 m) below the land surface. To include depths of less than 1,000 feet (305 m), the geologic study areas shown in figure 1 and subsequent maps would enlarge eastward toward the edge of the shale unit.

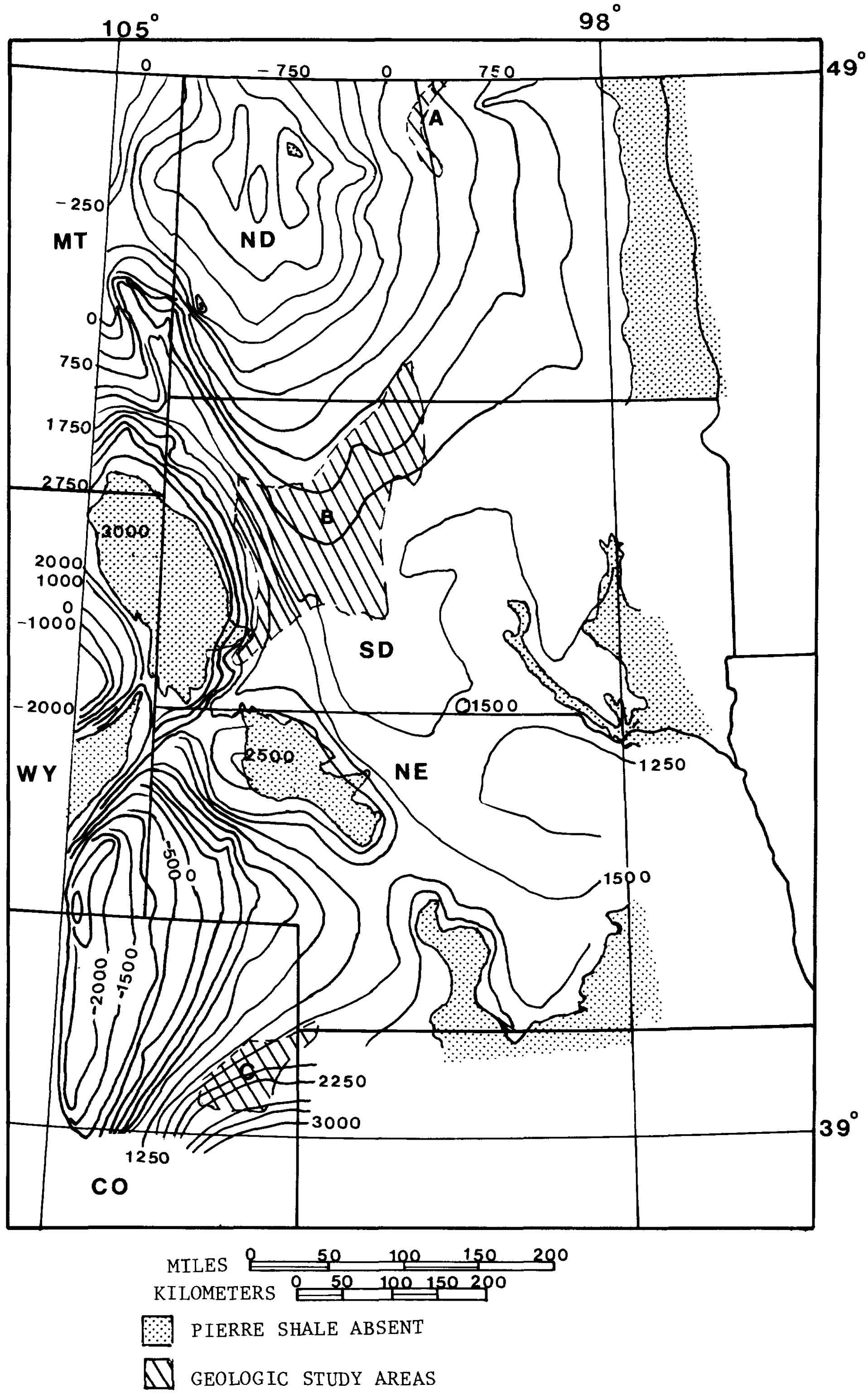


Figure 4.--Configuration of Ardmore Bentonite Bed marker unit in Pierre Shale. Contours denote depth of marker above and below sea level. Contour interval 250 feet, except in the Denver Basin where the interval is 500 feet.

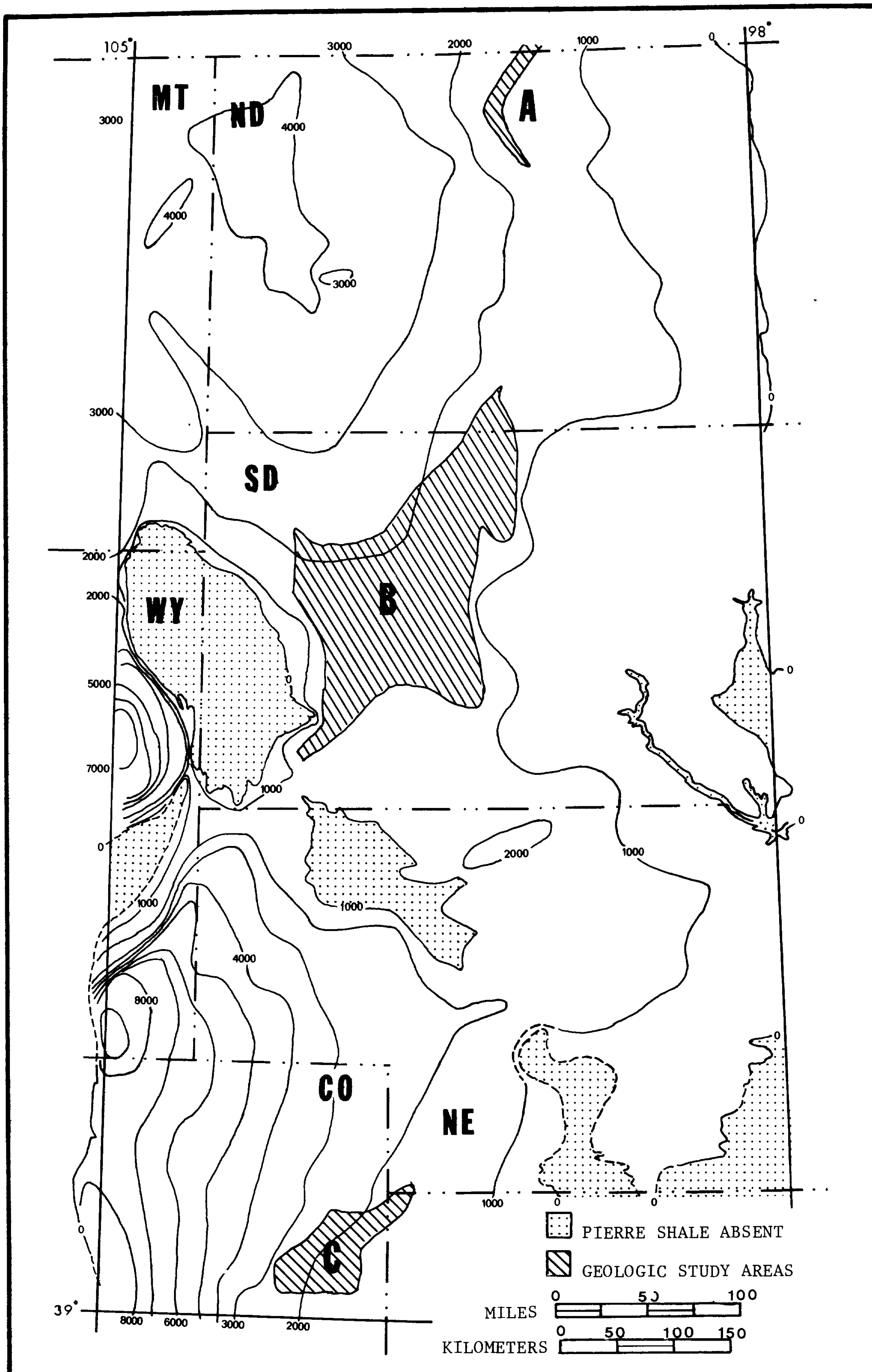


Figure 5.--Depth from surface to base of Pierre Shale. Contour interval 1,000 feet.

Areas in which the base of the Pierre Shale is at depths of 1,000-3,000 feet (305-914 m) lie along the eastern and southern flanks of the Denver and Williston Basins. Depths increase toward the basin centers and decrease toward uplifts such as the Black Hills. Depths also increase westward into Wyoming (in the Powder River Basin outside the delimited area) and into a minor basin in north-central Nebraska. A very narrow area of appropriate depth lies along the Front Range at the western edge of the Denver Basin. It is not included in figure 5 because of scale limitations and will not be further considered because of limitations imposed by geologic structure.

Shale thickness

The thickness of the Pierre Shale throughout the area of regional reconnaissance is shown in figure 6. Thickness data are minimums in areas where well records start below the top of the Pierre. Shale thickness is equivalent to the overburden thickness (fig. 7) subtracted from the depth to the base of the Pierre (fig. 5). Areas of maximum shale thickness are located in the Williston and Denver Basin.

Within the area of currently acceptable depths (that is, 1,000-3,000 ft; 305-914 m), the maximum shale thickness available is slightly over 2,500 feet (762 m). This thickness is found at the western end of the Colorado study area. Shale thicknesses between 1,000 and 1,500 feet (305-457 m) are relatively widespread in the central Dakotas; narrower bands where thicknesses range from 1,000 to 2,000 feet (305-610 m) are found in Colorado and western Nebraska.

Overburden thickness

The thickness of overburden lying above the top of the Pierre Shale is shown in figure 7. Values of zero overburden thickness represent areas of outcrop, such as those in central South Dakota. Much of the Pierre Shale outcrop in Colorado (fig. 2) is not shown on figure 7 because the uppermost, or transition member, has been excluded from the stratigraphic definition of the Pierre used in this report. In areas where the depth to the base of the Pierre is 1,000-3,000 feet (305-914 m), the maximum overburden thickness is generally about 1,500 feet (457 m). This is well below the maximum of 2,500 feet (762 m) which currently could be tolerated and still have 500 feet (152 m) of shale available within the acceptable depth range. Intermediate values of overburden thickness, for example 500-1,000 feet (152-305 m) are widespread.

The lithologic character of stratigraphic units immediately above the Pierre Shale is indicated in figure 2. Glacial sediments constitute the overburden in the eastern Dakotas, and Tertiary sandstones and claystones cover the Pierre Shale throughout Nebraska. In the Williston and Denver Basins, Cretaceous and Tertiary clastic units overlie the Pierre.

Lithology and mineralogy

The lithologic character of the Pierre Shale is shown in figure 8. The rock-stratigraphic unit known as Pierre Shale is indeed dominated by clay shale, but it includes wide areas and thicknesses of sandstones and siltstones. In addition, much of the shale is calcareous (marly), siliceous, or organic rich; hence, it may not fit the concept of a

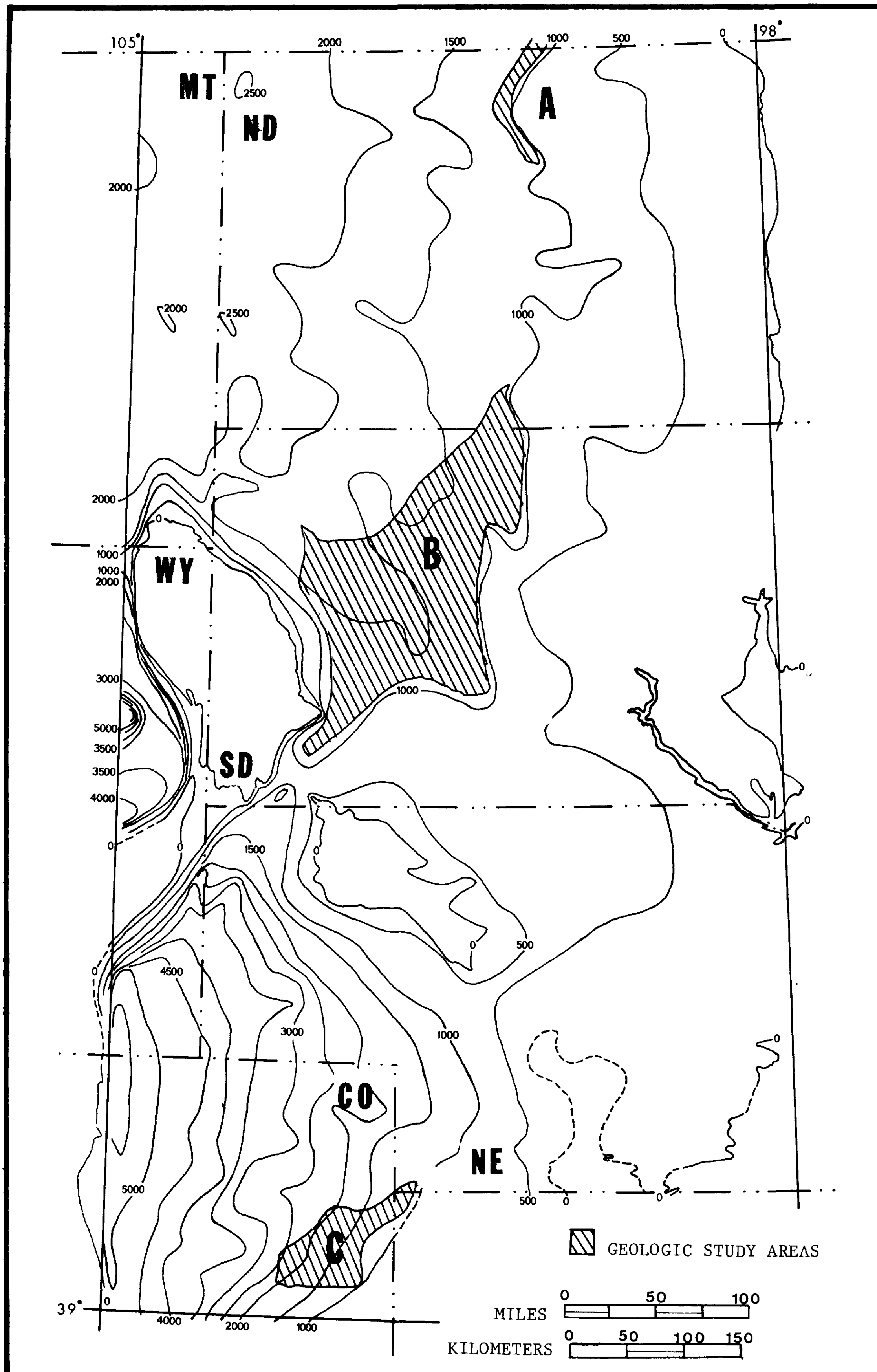


Figure 6.--Thickness of the Pierre Shale. Contour interval 500 feet.

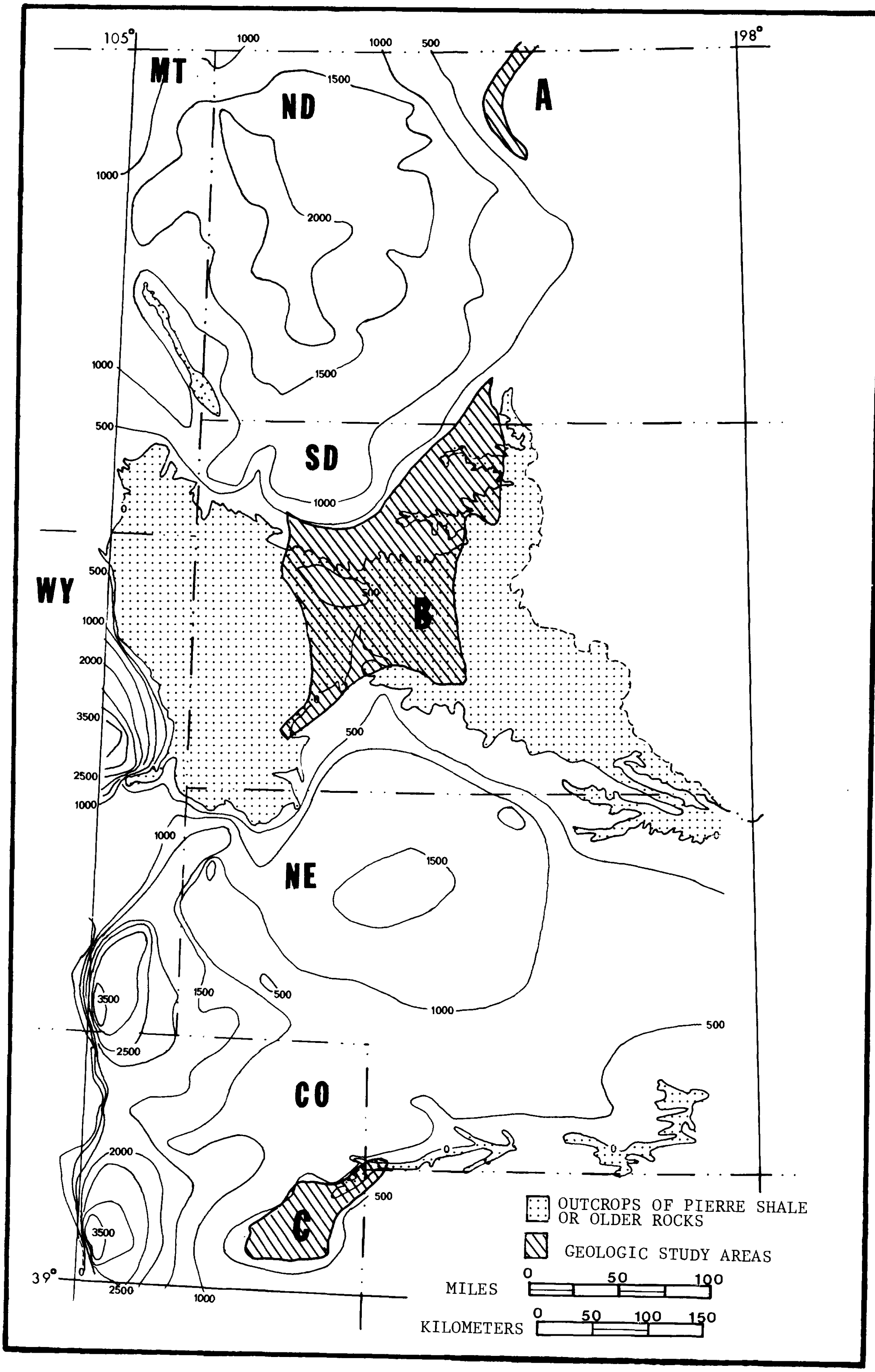


Figure 7.--Thickness of overlying rock above Pierre Shale (upper transition member excluded). See figure 2 for character of overburden materials. Contour interval 500 feet.

low-strength material commonly associated with the term shale. Data on strengths in the calcareous, siliceous, and organic-rich shales doubtless will need to be acquired during more detailed studies.

In general, sandstones are found in the western third of the regional study area and marls are distributed in the eastern third. The western sandstones are associated with thick Pierre Shale sections and the marls occur where the Pierre is thin. Widespread calcareous shales and marls are not excluded from geologic study areas, but those areas in which the shale contains one or more sandstone units are excluded (fig. 8). Permeable sandstone may make a potential isolation facility difficult to isolate from ground-water movement. This constraint eliminated only small portions on the western side of the area of allowable depths (fig. 5).

The gross mineralogy of the shale in the Pierre Shale has been described by Tourtelot, Schultz, and Gill (1960), Tourtelot (1962), and L. G. Schultz (oral commun., 1976). In general, the shale is dominantly composed of clay minerals but may contain as much as 25 percent quartz, a few percent feldspar, and minor amounts of calcite, dolomite, biotite, pyrite, jarosite, clinoptilolite, and organic matter. However, marls and calcareous shales may have as much as 75 percent calcium or magnesium carbonate; siliceous shales have as much as 40 percent cristobalite; and organic-rich shales contain as much as 15 percent organic matter.

Among the clay minerals, mixed-layer illite-montmorillonite is the dominant constituent; there are minor amounts of kaolinite and chlorite. Lesser amounts of illite and montmorillonite are present in approximately equal proportions. Geographically, illite and montmorillonite percentages increase eastward and mixed-layer illite-montmorillonite percentages decrease in that direction. Stratigraphically, illite and mixed-layer illite-montmorillonite components are more abundant in the lower part of the section, whereas montmorillonite increases upward through the unit.

Penetrations

The distribution of oil and gas wells that penetrate the Pierre Shale is shown for the area of regional reconnaissance in figure 9. Logarithmic contours summarize the number of penetrations found within cells whose dimensions are 15 minutes of latitude and longitude. The vast majority of the oil and gas borings penetrate deeper than the base of the Pierre. It should be emphasized that water wells or test drilling for resources other than oil and gas are not included in the penetration data; many of these are shallow holes which do not even enter the Pierre.

Within the area of acceptable depths, broad areas occur that have fewer than 10 penetrations in each 15-minute cell (fig. 9). Contours enclosing more than 100 penetrations per cell are localized in the vicinity of producing oil and gas fields. Exclusion of these localized areas from potential target areas not only minimizes the number of wells penetrating the Pierre, but also reduces potential interference with the development of natural resources.

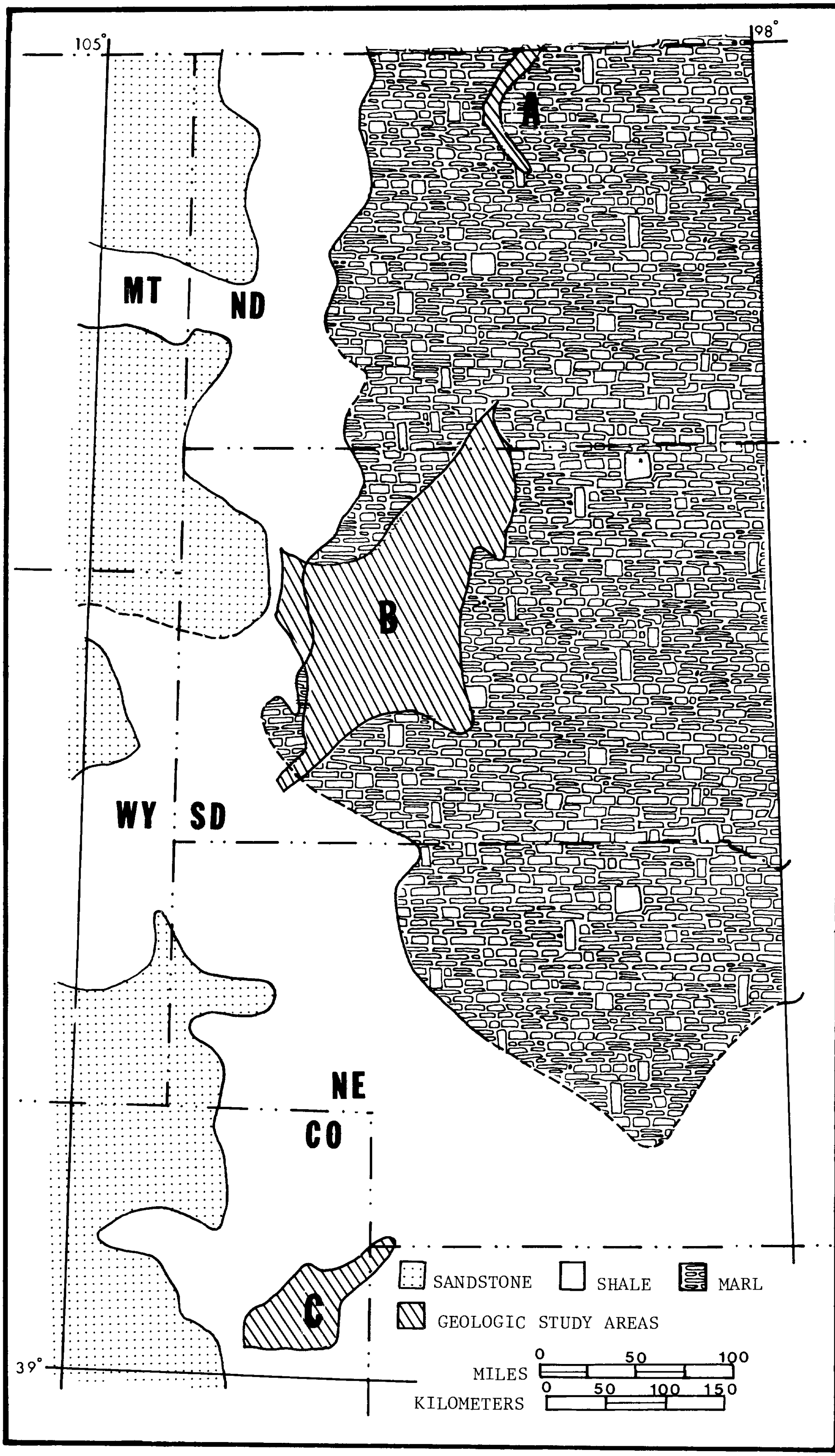


Figure 8.--Gross lithology of the Pierre Shale, showing limits of abundant sandstone to west and of marly beds to east.

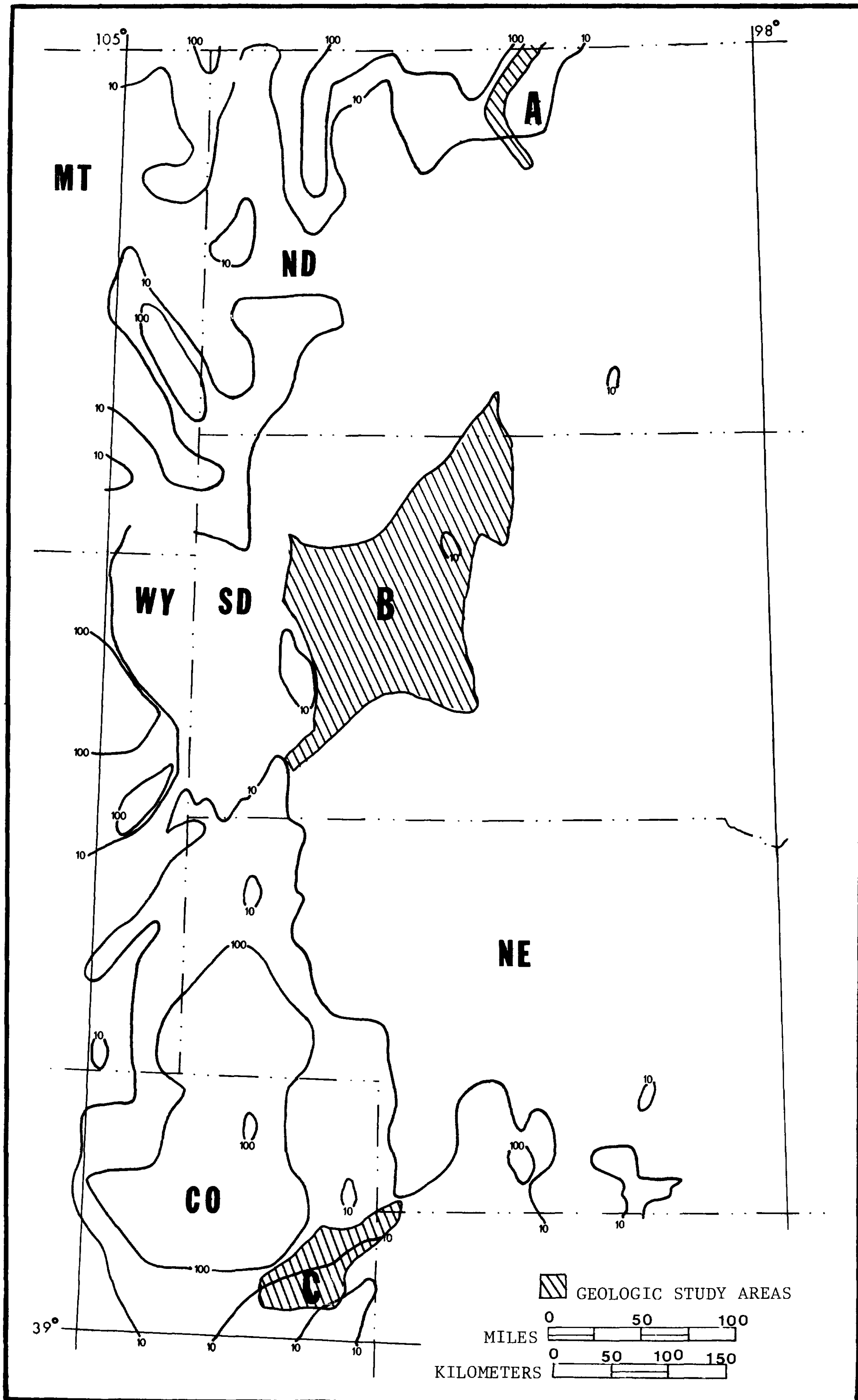


Figure 9.--Spatial frequency of oil and gas wells that penetrate the Pierre Shale; contours based on cells of 15' lat by 15' long from records of 33,000 wells. Contours are logarithmic.

TECTONIC AND SEISMIC CONSIDERATIONS

The geologic study areas shown in figure 1 are defined largely on the basis of stratigraphic data collected specifically for this regional study. In contrast, the tectonic and seismic considerations draw heavily upon published information to augment structural data extracted from the stratigraphic studies.

Structure

Figure 4 shows the elevation above and below sea level of the Ardmore Bentonite Bed, a key marker horizon within the Pierre Shale. Only major tectonic elements, generally having large areal expression but small structural dips, are conspicuous on this regional map. In the Williston Basin of North Dakota and South Dakota, the Pierre structure datum is more than 1,000 feet (305 m) below sea level. The minimum elevation of this datum in the Denver Basin of Colorado and Nebraska is more than 3,000 feet (914 m) below sea level. These downwarps are separated by the Black Hills uplift and Chadron Arch, which are stippled in figure 4 and outlined by the contour of 2,000 feet (610 m) above sea level.

Regional dips in all three geologic study areas are less than 20 ft/mi (4 m/km), and no faults having significant displacements are known.

Smaller structural features, some having dips in excess of 100 ft/mi (0.2 m/km), are not delineated in figure 4 because of the large separation of control points. Most of the smaller folds lie off the northern and southern ends of the Black Hills. Known faults commonly are located near the uplifts at the margins of the basins and are often associated with minor folds. The possible existence of large-scale faults is discussed under the heading of "Lineaments."

Lineaments

The term "lineaments" is used here to denote linear surface features, such as drainage elements, vegetation patterns, or landforms that can be recognized on aerial photos and satellite images. While the exact structural nature of lineaments is not clear, it is possible that some are surface expressions marking zones of weakness which bound adjoining basement blocks. There is disagreement on the relative importance of vertical and horizontal displacements on these faults (for example, see Stone, 1976). However, it is widely recognized that fundamental faults in the crystalline basement may control the development of structures within the overlying sedimentary rocks.

Published regional maps of lineaments include portions of the study area. A lineament-fracture pattern delineated from the Tectonic Map of North America (King, 1969) includes six named lineaments in the total area of regional reconnaissance (Thomas, 1976). Fischer and others (1976) mapped linear and curvilinear features on LANDSAT satellite images for the United States; their maps are small, but show lineaments in all the study areas. Satellite images were employed by Saunders and others (1973) to map more-limited areas. They show one major and three minor lineaments in the Colorado study area (C), and at least six lineaments in the North Dakota study area (A). Only a part of the South Dakota study area is included in the mapping by Saunders and others (1973), but four lineaments are recognized. Based upon tectonic studies, Stone (1976) showed an extension of the Nashfork-Hartville fault trend from the southwest into the South Dakota study area.

Lineaments have been mapped in the northwestern part of the regional study area (Thomas, 1974; Shurr, 1975), and mapping is currently in progress in Nebraska (Rex Peterson, Nebraska Geological Survey, oral commun., 1976). The completed studies in Montana and the Dakotas demonstrate a correspondence of lineaments with patterns on stratigraphic maps. These patterns include the erosional edges of sedimentary units, thickness patterns within the units, and lithologic variations within the units. Thus, lineaments are important in the selection of isolation sites for radioactive wastes as the lineaments provide clues to fracture porosity associated with structural features and to possible controls on sedimentary textures that influence porosity and permeability. Obviously, lineaments and their possible significance must be investigated in any more-detailed delineation of isolation sites.

Seismicity

The seismicity of the area of regional reconnaissance is described in a report by Docekal (1970). The maximum intensity experienced in the regional study area is VIII (Modified Mercalli Scale); most seismic events occurred at intensities of less than V. No epicenters lie within the North Dakota and Colorado study areas where the maximum intensities have been less than III. The South Dakota study area includes epicenters, largely because earthquakes are more common on the uplifts separating the Denver and Williston Basins than they are within the basins. Intensities have been as high as VI, but the majority of the intensities in the South Dakota area have been III or less. Docekal's data support a general seismic-risk classification of "Minor Damage" (Environmental Science Services Administration and U.S. Coast and Geodetic Survey, 1969).

COMPARISONS OF GEOLOGIC STUDY AREAS

The primary objective of this regional reconnaissance is to define potential geologic study areas on the basis of regional geologic attributes. Other characteristics of these three study areas will now be described and compared employing published synthesis.

Topography

Most of the North Dakota study area (A) is shown on the Minot (U.S. Geological Survey, 1954-64) topographic map, with a small part on the McClusky (1954-67) sheet. These maps are at a scale of 1:250,000. In general, the highest elevations (2,500 ft; 762 m) are in the northeast corner near the Turtle Mountains. Elevations decrease southwestward into the valley of the Souris River (less than 1,450 ft (442 m) elev.) and then rise to slightly higher values over most of the area. Regional relief is greatest, approximately 175 ft/mi (33 m/km), in the Turtle Mountains; but widely distributed values of less than 10 ft/mi (2 m/km) characterize most of the target area.

The study area in South Dakota (B) covers large parts of the areas shown on the McIntosh (U.S. Geological Survey, 1953-64), Pierre (1954-67), and Rapid City (1953-64) topographic maps and smaller parts of the Bismarck, N. Dak. (1954-66), Lemmon (1954-63), Martin (1955-67), and Hot Springs (1955-67) maps. These maps are also at a scale of 1:250,000. Maximum elevations (3,400 ft; 1,036 m) within the study area are near the southeast flank of the Black Hills, and minimum elevations (1,600 ft; 488 m) are in the east near the mouths of tributaries to the

Missouri River. Five major tributaries flow east to the Missouri; from north to south these are the Grand, Moreau, Cheyenne, Bad, and White Rivers. Local relief is greatest (several hundreds of feet per mile) along these stream valleys. The uplands separating the valleys tend to have low relief (less than 10 ft/mi; 2 m/km).

The Colorado study area is mainly in the area shown on the Limon (U.S. Geological Survey, 1954-64) topographic map, with small segments in the Goodland, Kans. (1954), McCook, Neb. (1954-66), and Sterling, Colo. (1954-64) maps. These maps are at a scale of 1:250,000. Maximum elevations of 5,500 feet (1,676 m) in the southwest corner of the study area decrease to less than 3,300 feet (1,006 m) in the northeast corner. The area is drained by the northeastward-flowing Arikaree River and South Fork of the Republican River. In the study area, maximum relief (more than 400 ft/mi; 76 m/km) is found on the walls of these stream valleys, and minimum relief (less than 20 ft/mi; 4 m/km) is characteristic of the valley floors. Broad uplands of low relief (less than 50 ft/mi; 10 m/km) separate the two drainages and occupy the central part of the study area.

Mineral and water resources

The mineral and water resources of North Dakota have been recently summarized in a report to the Senate Committee on Interior and Insular Affairs (U.S. Geological Survey, 1973). Although the North Dakota area (A) is small, developed and potential resources are very near or within the area. The method adopted for summarizing the number of oil wells that penetrate the Pierre Shale (fig. 9) did not specifically exclude developed oil fields. Consequently, in the central part of the North Dakota area (A), along the Bottineau-McHenry County line, there is petroleum production from Paleozoic carbonates. Oil and gas may also exist in Cretaceous sandstones underlying the area, but there is no production from these units.

Low-sulfur lignite-coal resources (Fort Union Formation of Paleocene age and Hell Creek Formation of Late Cretaceous age) closely border the North Dakota area on the west, but no strippable reserves are known to be located within the area. Deposits of leonhardite, an oxidized lignite that is a possible source of chemicals and has other nonfuel uses, are known within the area but there is only limited commercial development as yet. Peat deposits are a part of Pleistocene and Holocene sediments. One peat mine has operated intermittently near the northeast corner of the study area. Bedded salt at minable depths and thicknesses is present in Paleozoic rocks beneath the study area. Units of the Prairie Formation (Middle Devonian) and Madison Group (Mississippian) present attractive potentials for salt mining. Sand and gravel are important resources along the Souris River in the central part of the area. To the northeast, manganese nodules occur in minor amounts in glacial drift.

Aquifers underlying the North Dakota geologic study area (A), both above and below the Pierre Shale, include Paleozoic rocks, the Dakota Sandstone (Lower Cretaceous), the Fox Hills Sandstone and Hell Creek Formation and even some units in the Pierre Shale. Yields from wells in the Pierre are generally less than 5 gal/min (19 l/min), but sustained pumping of more than 300 gal/min (1,136 l/min) has been reported from a few wells within the study area. The study area is in a part of the Garrison Diversion Conservancy District, which will be the locale of a major irrigation development using surface water. The annual precipitation averages 16-18 inches (41-46 cm), the median annual runoff is 0.5-1.0 inch (1-3 cm), and the prevalent dissolved constituent of surface water is bicarbonate.

Although the South Dakota geologic study area (B) is large, mineral resources are not particularly diversified (U.S. Geological Survey, 1975). Known horizons of hydrocarbons (Red River Formation of Late Ordovician age, and Minnelusa Formation of Early Pennsylvanian to Early Permian age) extend into the study area from areas of production in the northwestern corner of the State, but are only slightly developed. There is one unnamed oil field that has a single producing well. Water temperatures indicate that geothermal potentials in excess of 100° F (38° C) exist in eight aquifers below the Pierre Shale.

The South Dakota study area is, in part, underlain by coal-bearing rocks of the Hell Creek Formation (Cretaceous) and Ludlow Member of Fort Union Formation (Paleocene). Coal in the Hell Creek was mined until recently in the Isabel-Firesteel Field of Dewey and Ziebach Counties, but it is the Ludlow that has the best potential for strip mining in a small northern part of the area.

The Pierre Shale, which crops out extensively, has been considered as a possible source of aluminum, but at the present time other kinds of aluminum-bearing rocks are considered to be more promising for development. A calcareous unit in the upper part of the Pierre, just to the northeast of the study area near Mobridge, was tested for suitability as a possible cement source but was never developed. A black shale unit has been investigated as a source of uranium. Sand and gravel are important economic materials along the major east-west drainages. Gravels consisting of iron-manganese concretions from the Hell Creek Formation have been considered as a possible source of iron ore.

Twelve separate aquifers, ranging from Cambrian to Cretaceous in age, have been identified within the South Dakota study area. Six have artesian conditions, although pressures have declined markedly in the last 70 years. The water quality is poor as iron and manganese occur in major amounts. Dissolved solids in surface waters range from 1,800 to 2,500 mg/l; sulfates and chlorides of calcium and magnesium are the predominant chemical constituents. Suspended loads in streams are high--as much as 30,000 mg/l. The average annual precipitation ranges from 14 to 16 inches (36-41 cm) and the mean annual runoff is less than 1 inch (3 cm).

Mineral and water resources of Colorado are summarized in a report by the U.S. Geological Survey (1969). Oil and gas production within the Colorado geologic study area (C) is from stratigraphic traps in the Dakota Sandstone (Lower Cretaceous). Several fields are within the study area and production is from moderate depths (approximately 4,000 ft; 1,219 m). Salt in Permian rocks underlies the area but the great depths and discontinuous nature of the salt units probably preclude extensive development. Sand and gravel are produced from Quaternary alluvium and from the Ogallala Formation of Miocene age.

Ground water is an extremely important resource in the Colorado study area. The Ogallala Formation is the major aquifer and has yields averaging 1,000 gal/min (3,785 l/min). The quality of this water is good (dissolved solids ranged from 100-500 ppm) and it is an important source for irrigation. Present withdrawal rates are less than recharge rates, but expansion of irrigation is likely to change this condition. The average annual precipitation is 16-20 inches (41-51 cm) and the average annual runoff is about one-quarter inch (0.6 cm). Dissolved solids in surface waters are generally less than 350 ppm; the prevalent chemical constituent is calcium-magnesium bicarbonate. Suspended sediment loads in streams range from 30,000 to 50,000 ppm.

Overview

Considering only the total area of each geologic study area, and hence the number of potential sites each one might encompass, the South Dakota study area is the most attractive and the North Dakota study area is least desirable.

A review of geologic attributes strengthens this ranking. Clay shale intervals are thicker in the South Dakota and Colorado areas than in North Dakota. South Dakota has extensive shale outcrops, Colorado has exposures of intermediate extent, and the North Dakota area has none. Although the area is small, more lineaments are mapped in the North Dakota area than in the other two areas.

Hydrocarbon development is very limited in South Dakota. Oil fields in North Dakota are large and extensively developed; those in Colorado are moderately developed. Vast segments of the South Dakota study area are unpenetrated by oil and gas exploration drill holes. Bedded salt of economic potential underlies North Dakota. Salt in the Colorado area is probably too deeply buried for economic development; there is none in South Dakota.

Areas of low topographic relief are widespread in South Dakota and Colorado, but the small North Dakota area is cut twice by a major drainage.

RECOMMENDATIONS FOR FURTHER STUDY

On the basis of these studies of definition, refinement, and comparisons, it is recommended that the South Dakota area warrants evaluation in greater detail. The Colorado area may also be retained and investigated further. However, the North Dakota area probably can be eliminated from further consideration.

The geologic study areas chosen for further evaluation should be thoroughly studied, and several potential locales should be identified in each area. These studies should be carried to completion before more site-specific investigations are attempted.

The regional reconnaissance study described here employs widely spaced data points and, as a consequence, the delineation of tectonic features is limited. Although they are not well understood in a structural sense, lineaments are of particular concern. Satellite images and aerial photographs should be employed to map linear features in large areas around the study areas under investigation. These lineaments should then be evaluated and, if possible, their significance with respect to siting should be ranked. Topographic, geophysical, structural, and stratigraphic data may be useful in the evaluation of lineaments.

All subsurface data available within the study areas should be integrated with stratigraphic studies. The internal stratigraphy of the Pierre Shale should be established for the study areas. In addition, studies of geology and of ground-water conditions above and below the Pierre are essential. Specific potential sites will ideally have few or no penetrations of the Pierre

Shale; therefore, correlations between boreholes both in and outside the study areas will be essential tools in predicting variations of thickness and lithology within the areas.

As geologic investigations progress toward the consideration of potential locales, other aspects of the study areas must also be evaluated. The hydrology of the Pierre Shale is particularly critical. The meteorology and climatology of the study areas also may be of importance. Engineering properties of the shale at construction depths and of the shale in the specific locales will need to be investigated. Demographic and economic aspects of the South Dakota and Colorado areas must be investigated. Some of these aspects, such as land availability, may be as critical as geologic criteria in the selection of specific sites.

Field and laboratory geologic studies will require extensive geophysical, engineering geologic, and drilling support.

Finally, it is recommended that State agencies, particularly the geological surveys, be involved in a substantive manner. If work progresses toward the possible detailed examination of specific potential sites, the expertise of professionals familiar with local situations must be drawn upon more completely than was possible for this reconnaissance.

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GPO 843-320