INTRODUCTION

The Bakken Formation, of Devonian and Mississippian age, is the source of a large portion of the oil discovered in the Williston basin (Dow, 1974; Williams, 1974), and is itself a reservoir rock in some areas (Von Osinski, 1970; Petroleum Information Corporation, 1980). For these reasons, even though it makes up less than 1 percent of the total rock column in the Williston basin, the Bakken Formation is of considerable economic importance, and knowledge of its physical characteristics is important for the understanding of the petroleum geology and potential of the basin.

This report provides a basic data set for the Bakken Formation, and characterizes and discusses selected physical properties of the Bakken Formation in the United States portion of the Williston basin (fig. 1). These properties include:

1) Thickness (upper, middle, and lower members, and total)
2) Depth (below sea level and below land surface)
3) Average density (upper, middle, and lower members)
4) Neutron-log porosity (upper, middle, and lower members)
5) Resistivity (upper, middle, and lower members)
6) Temperature

The data for this report are derived from wire-line logs from 252 locations in North Dakota and Montana (map A). The spacing of data locations is adequate except in the southeastern part of the study area, where few wells have been drilled to the Bakken Formation.

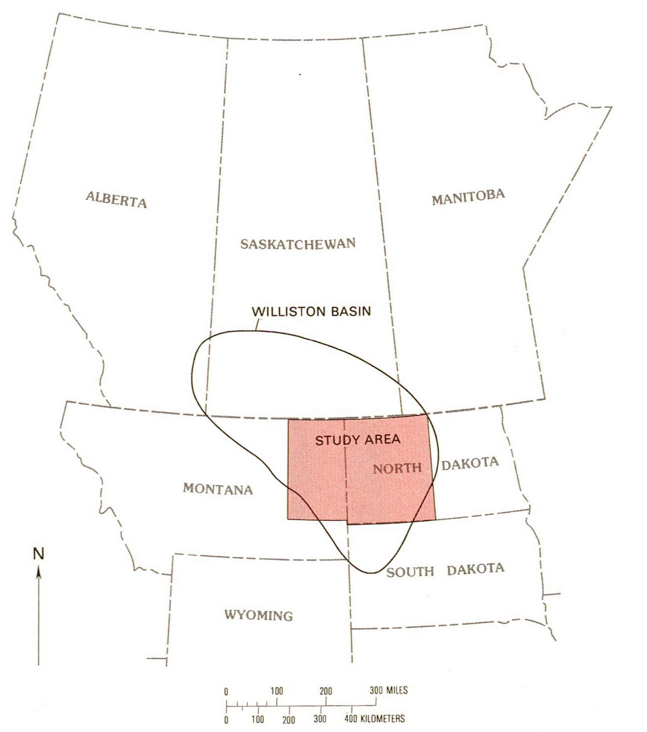

Figure 1.—LOCATION OF STUDY AREA. (Background map modified from Worsley and Fuzesy, 1978.)

GEOLOGIC SETTING

The Bakken Formation is formally defined (Nordquist, 1953) as the stratigraphic sequence between 9,615 ft (2,931 m) and 9,720 ft (2,963 m) in the Amerada Petroleum Corporation H. O. Bakken No. 1 Well, Williams County, North Dakota. In the type well, and throughout much of the basin, the Bakken Formation can be divided into three distinct members. Kume (1963) described the upper and lower members as dark-gray, slightly calcareous, fissile, pyritic shale, and the middle member separating them as brownish-gray to light-gray, very fine grained, calcareous sandstone, with rounded to subrounded quartz grains. No formal names have been assigned to these three members.

The Bakken Formation was deposited within a series of predominantly shallow-water carbonates and evaporites. It overlies the Devonian Three Forks Formation and is overlain by the Mississippian Lodgepole Limestone (McCabe, 1954). The Madison Group of which the Lodgepole Limestone is the basal formation, is the primary reservoir rock for oil expelled from the Bakken Formation (Dow, 1974; Williams, 1974).

The three members of the Bakken Formation exhibit an onlapping depositional relationship, so that the lower boundary of each successively younger member overlaps the older member below (map A). The sharp character change between members and the apparent transgression of the Bakken Formation may be due in part to vertical migration of a dysaerobic-anaerobic water boundary (Lineback and Davidson, 1982).

The high gamma-ray intensity and high density-log porosity (or equivalently, low formation density) of the upper and lower black-shale members create a log signature that is distinctive and easily recognized over much of the basin (fig. 2). This signature results from the association of uranium with the relatively low-density organic matter in the organic-matter-rich lower and upper members (Schmoker and Hester, 1983).

Along the eastern edge of the study area, however, where the upper member is thin and the Lodgepole Limestone and underlying Three Forks Formation contain shale, it becomes more difficult to pick the upper member of the Bakken Formation. Possible stratigraphic confusion may also arise in the area of Billings County, North Dakota, where a shaly interval in the basal part of the Lodgepole Limestone has a relatively high gamma-ray intensity and is sometimes referred to as "upper Bakken."

SELECTED PHYSICAL PROPERTIES

THICKNESS

Thicknesses of the Bakken Formation and its members were taken directly from wire-line logs using formation and member tops as shown in figure 2. Dips average less than 1 degree, so there is no significant difference between apparent and true formation thickness.

The Bakken Formation reaches a maximum thickness of nearly 140 ft (43 m) in west-central Mountrail County (map B). Isopachs generally parallel the southern boundary of the Williston basin, and open to the northwest into Canada. Formation thickness increases relatively uniformly across the basin from the Bakken's edge to its depocenter. A few local anomalies, particularly in the northeast corner of the study area, are superposed on the regional pattern. These local anomalies are probably caused by topographic variations in the Devonain Three Forks Formation, variations resulting from solution and collapse of underlying salts in the Middle Devonain Prairie Formation and from erosion of the Devonian Three Forks Formation prior to Bakken desposition (Webster, 1982a). Detailed mapping of these features is limited by the spacing of available data.

The regional features of the isopach map of the middle member of the Bakken Formation (map C) resemble those of the total-thickness map. The middle member has a maximum thickness of more than 70 ft (21 m), and accounts for a substantial part of the volume of the Bakken Formation. The lower black-shale member reaches a maximum thickness of about 45 ft (14 m), compared to 20 ft (6 m) for the upper black-shale member, but is smaller in areal extent (maps D and E). Isopach patterns of the lower and middle members are similar, implying a continuity of basic dynamics, whereas the isopach pattern of the upper member shows that sedimentation was shifted to the southeast and was limited primarily to the North Dakota part of the basin.

DEPTH

Within the study area, depth below sea level of the Bakken Formation ranges from less than 2,500 ft (760 m) in the northeast corner of Bottineau County to more than 8,500 ft (2,590 m) in central McKenzie County (map F). On the regional scale shown, contours are uniform and nearly circular, and depict the bowl-like structure of the Williston basin. The depocenter of the Bakken Formation (map B) is about 45 mi (72 km) northeast of, and more than 1,000 ft (300 m) higher than, the present structural center of the basin and indicates a regional tilting that has influenced the distribution of Bakken-sourced oil within the basin.

The depth below ground surface of the Bakken Formation (map G) changes by more than 7,000 ft (2,100 m) within the study area. The otherwise more or less laterally homogeneous Bakken Formation varies with burial depth from thermally immature to mature, and has corresponding lateral changes in those physical and geochemical properties that are dependent upon the level of thermal maturity.

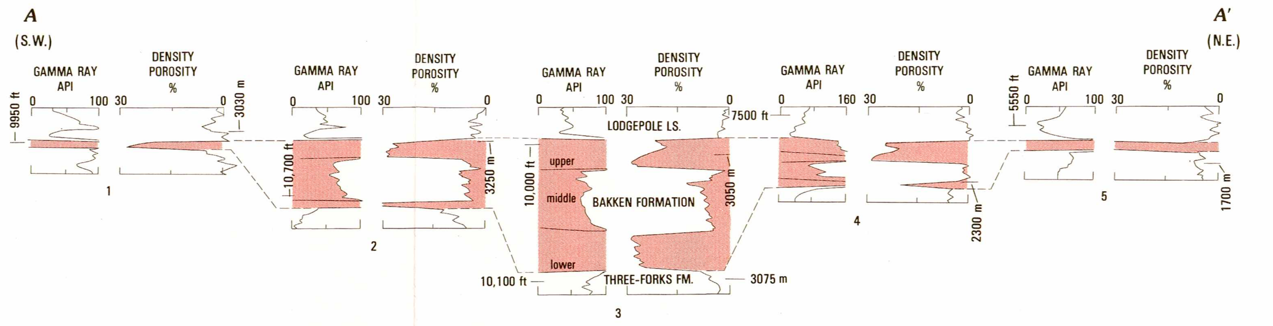

Figure 2.—PROFILE SHOWING GAMMA-RAY INTENSITY AND DENSITY-LOG POROSITY OF BAKKEN FORMATION (modified from Schmoker and Hester, 1983). Upper and lower members of Bakken Formation are characterized by high (off-scale) gamma-ray intensity and high density-log porosity. Profile location is shown on map A.

DENSITY

The average density of the lower black-shale member of the Bakken Formation (map H) is about 2.30 g/cm^3 in McKenzie County where the Bakken Formation is deepest, and tends to decrease to the east, north, and northwest in a pattern roughly correlating with that of decreasing formation temperature (Map O). This regional pattern is locally perturbed in the extreme northeast corner of the mapped area by a sharp density increase to 2.50 g/cm^3. The average-density contours of the upper black-shale member (map I) are similar in character, but do not increase sharply to the northeast.

The upper and lower members of the Bakken Formation are extremely rich in organic matter, even by the standards of good source rocks. Their average organic-carbon content is roughly 12 percent (Webster, 1982a, 1982b; Schmoker and Hester, 1983), far above a commonly accepted source-rock minimum of 0.5 percent for shales (Tissot and Welte, 1978). Because the density of the upper and lower members varies primarily in response to the abundance and distribution of this organic matter (Schmoker and Hester, 1983), the density log should not be interpreted as reflecting changes in porosity or mineralogy in these members, as is commonly done in more conventional sedimentary rocks.

The sharp increase in the density of the lower member along the northeast edge of the mapped area (map H) indicates a decrease in organic-matter content, suggesting locally anomalous depositional conditions. Perhaps organic material in this area near the shales's depositional edge was not well preserved, resulting in a lower organic-carbon content and also a more inert type of organic matter with poorer oil-generation potential (Schmoker and Hester, 1983)

The regional correlation between average density and formation temperature in the upper and lower black-shale members is thought to indicate a relation between organic matter content and thermal maturity. The data suggest that organic carbon has been depleted by the conversion of organic matter to oil and the subsequent explusion of the oil from the shale members, in a process that has proceeded longer and at higher rates in the hotter areas of the basin (Schmoker and Hester, 1983).

The average density of the middle member of the Bakken Formation can be interpreted in terms of porosity and rock type, since this member contains almost no organic matter. Contours of average density are mappable but do not show a distinct regional pattern. The histogram of average density of the middle member (fig. 3) resembles a normal distribution, with a mean of 2.64 g/cm^3 and with more than 90 percent of the measurements falling between 2.58 and 2.68 g/cm^3.

NEUTRON-LOG POROSITY

Neutron logs respond primarily to hydrogen. In many cases, essentially all hydrogen in a formation is in the pore fluid, and the neutron log gives an estimate of true formation porosity. Average neutron-log porosities of the upper and lower black-shale members of the Bakken Formation are between about 30 and 40 percent (maps J and K), but these values bear little relation to true porosity. Instead, maps J and K reflect the distribution of hydrogen in organic matter and in water bound to clay minerals.

The average neutron-log porosity of both lower and upper members is lowest near the deepest (map G) and hottest (map P) area of the basin, and tends to increase in directions of decreasing formation temperature. This pattern supports the hypothesis of the preceding section linking organic-matter content to thermal maturity. Conversion of organic matter to oil and subsequent oil explusion has depleted the hydrogen content of the shale members in an amount proportional to the level of thermal maturity. The initial hydrogen distribution has been altered by oil generation and expulsion to the pattern shown on maps J and K.

The middle member of the Bakken Formation contains little organic matter and has not acted as a source rock, but is of economic importance in that it may be a reservoir for oil produced from the Bakken Formation (Meissner, 1978). Contours of average neutron-log porosity of the middle member show local anomalies but no apparent regional pattern. The histogram of average neutron-log porosity (fig. 4) resembles a normal distribution, with a mean of 9.1 porosity units and with more than 80 percent of the measurements falling between 4 and 12 porosity units This distribution reflects the oil-storage capacity of the middle member, although neutron-log porosities may be biased upward by water bound to clay minerals in this fine-grained rock.

RESISTIVITY

Average resistivities of the lower and upper black-shale members of the Bakken Formation (maps L and M) tend to be either very high (greater than 100 ohm m) or rather low (less than 25 ohm m). High resistivities occur in a nearly continuous block covering a large area of the central Williston basin, and are separated from low resistivities in the eastern and northwestern parts of the study area by a narrow transition zone.

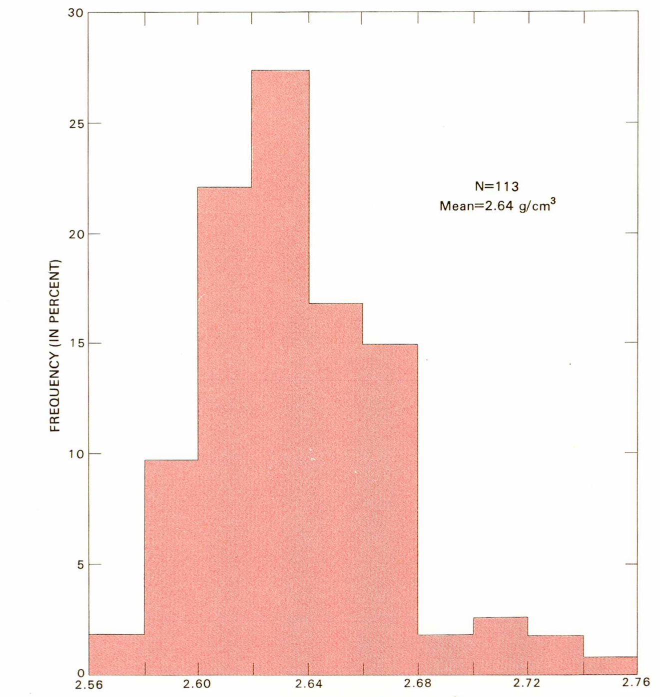

Figure 3.—FREQUENCY DISTRIBUTION OF AVERAGE DENSITY OF MIDDLE MEMBER OF BAKKEN FORMATION. Data are from well locations within middle-member boundary shown on map A.

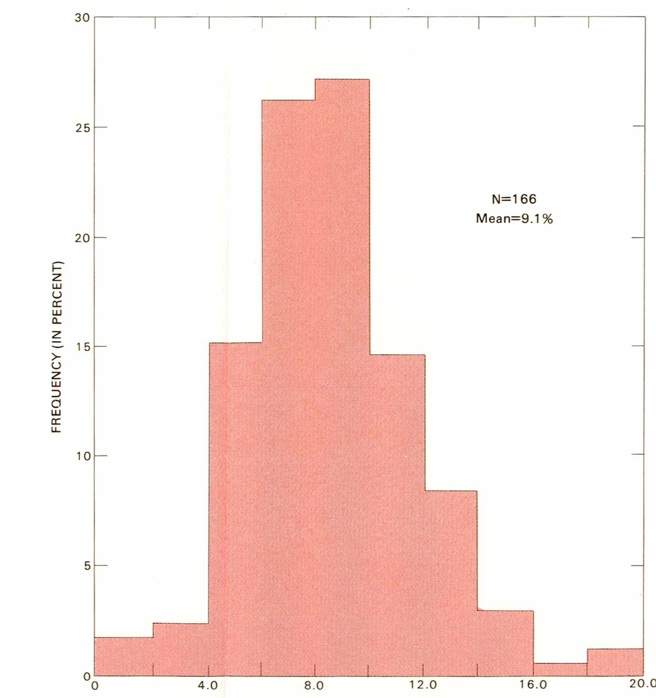

Figure 4.—FREQUENCY DISTRIBUTION OF AVERAGE NEUTRON-LOG POROSITY OF MIDDLE MEMBER OF BAKKEN FORMATION. Data are from well locations within middle-member boundary shown on map A.

The high resistivities are due to the replacement of saline (conductive) formation water with nonconductive oil generated from organic matter in the upper and lower members, while the low resistivities reflect normal, water-saturated shale (Meissner, 1978). In these laterally impermeable shale members, the transition between the two resistivity domains corresponds to a transition from thermally mature shale to immature shale that has not generated oil. Meissner (1978), working with relatively limited wire-line data, defined a mature-immature transition line in the eastern part of the study area; the larger data set developed here permits contouring zones of transition for both the lower and upper members (maps L and M).

The resistivity transition zones are well defined in the eastern portion of the map area, where they trend approximately north-south and average about 15 mi (24 km) in width. The transition zone of the lower member is roughly 15 mi (24 km) west of that of the upper member, and Meissner's boundary represents an approximate average of the two. The transition from high to low resistivities in the northwest part of the map area implies a maturity boundary in Montana, in addition to the eastern boundary described by Meissner (1978). In Montana, the transition zone of the lower member (map L) also lies basinward of that of the upper member (map M). For reasons not apparent to the authors, the area of apparent oil saturation of the lower member is less than that of the upper member.

Average resistivities of the middle member of the Bakken Formation range from less than 10 ohm m to a little over 30 ohm m (map N). A partial ring of higher resistivity values roughly follows the edge of the central region where significant oil saturation is expected. Resistivity decreases basinward from this ring.

In the central basin, oil expulsion from the shale members should be greatest and the water saturation of the middle member at a minimum. In this area, water is not recovered from the Bakken Formation during drill-stem tests (Meissner, 1978). Thus, the decrease in average resistivity of the middle member toward the central part of the basin is difficult to quantitatively explain, and could be a function of several factors. Minor changes in lithology, such as variations in dispersed-shale content associated with regionally varying depositional environments, could change the basic formation resistivity (Schlumberger, 1972), as well as the percentage of immovable water, to produce the observed resistivity pattern. A decrease basinward of the resistivity of residual formation water due to changing salinities and temperatures, could contribute to the observed resistivity pattern, as could increased invasion of the formation by high-salinity drilling mud in the deeper wells of the central basin.

TEMPERATURE

The temperature of the Bakken Formation in the study area (map O) ranges from about 125°F to more than 250°F (50-120°C). In a number of regions, isotherms cut across contours of constant burial depth (map G), indicating lateral variations in the thermal gradient.

The resistivity transition zones shown on maps L and M tend to parallel the isotherms, although not precisely. Because the resistivity transition zones are thought to define the boundary between thermally mature and immature regions, it follows that present-day temperatures are reasonably indicative of the level of thermal maturity, as was assumed in previous sections. As a general approximation, the 175°F (80°C) isotherm defines the region of thermal maturity. Consequently, it can be assumed that little of the Bakken Formation in the Canadian part of the Williston basin is thermally mature (map O).

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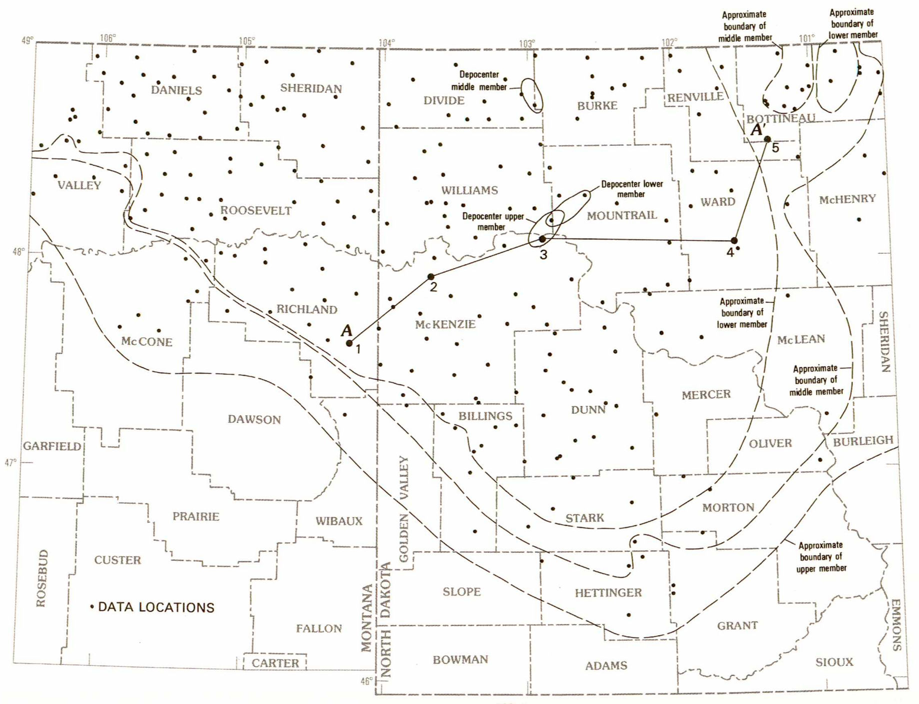
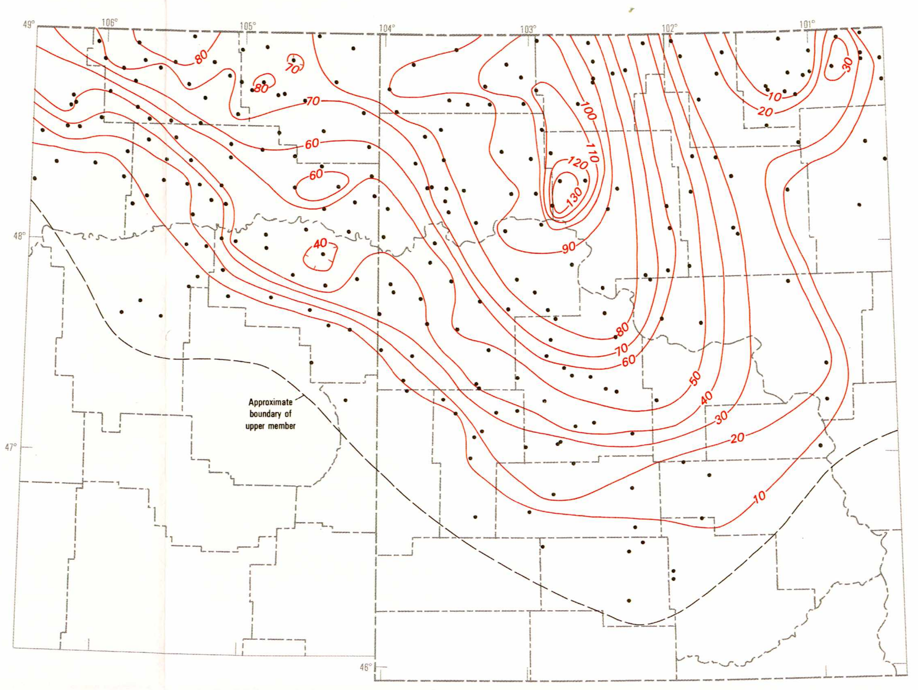
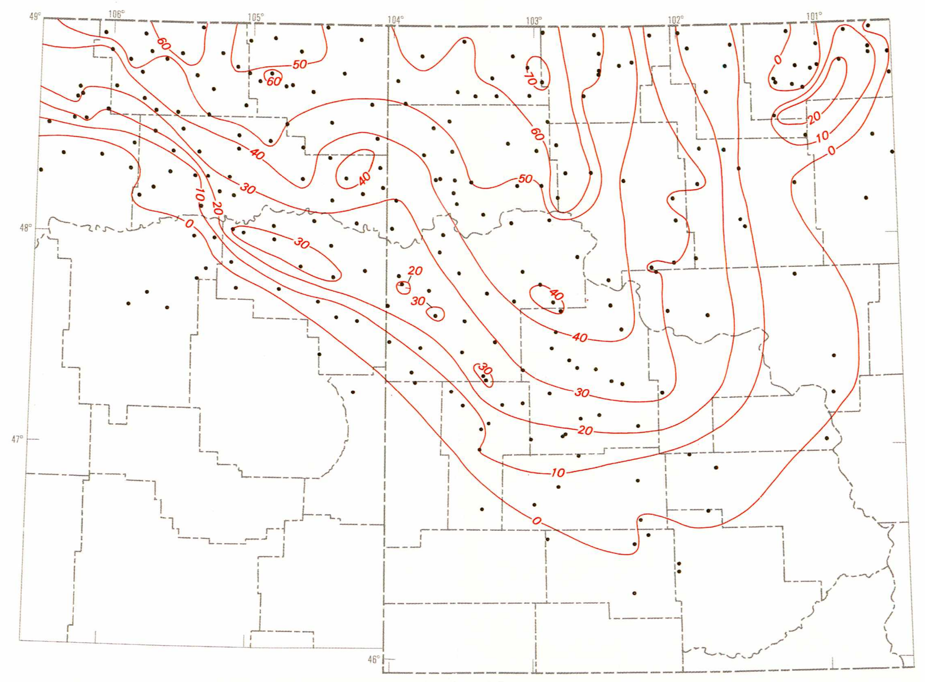


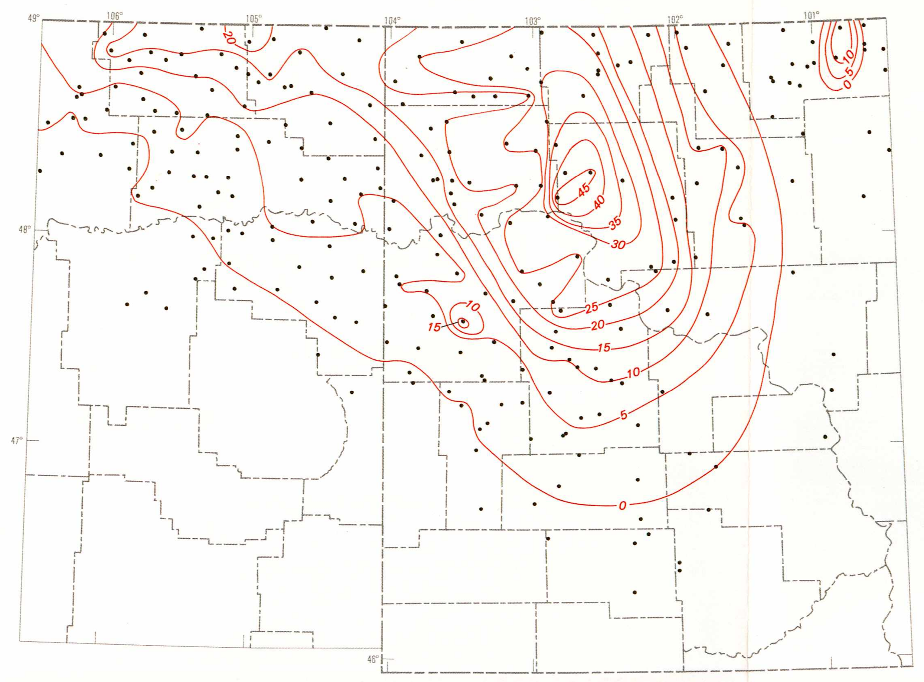
Map A.—LOCATIONS OF WELLS WHERE WIRE-LINE DATA WERE OBTAINED, AND APPROXIMATE LIMITS (DERIVED FROM THESE WIRE-LINE DATA) OF UPPER, MIDDLE, AND LOWER MEMBERS OF BAKKEN FORMATION.



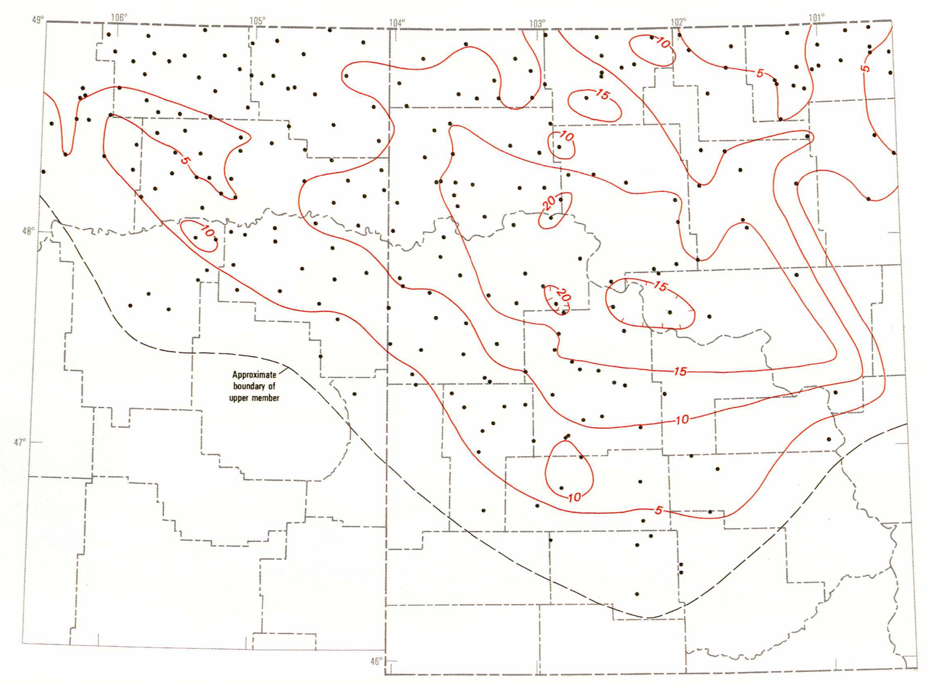
Map B.—THICKNESS OF BAKKEN FORMATION. Contour interval=10 ft (1 ft=0.3048 m); hachures indicate closed area of decreasing thickness.



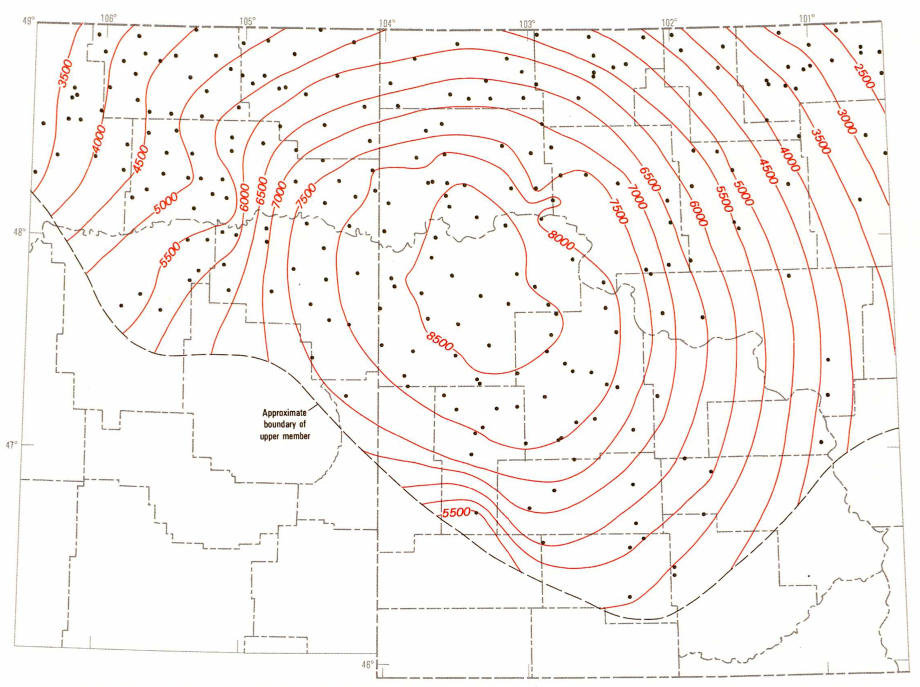
Map C.—THICKNESS OF MIDDLE MEMBER OF BAKKEN FORMATION. Contour interval=10 ft (1 ft=0.3048 m); hachures indicate closed area of decreasing thickness.



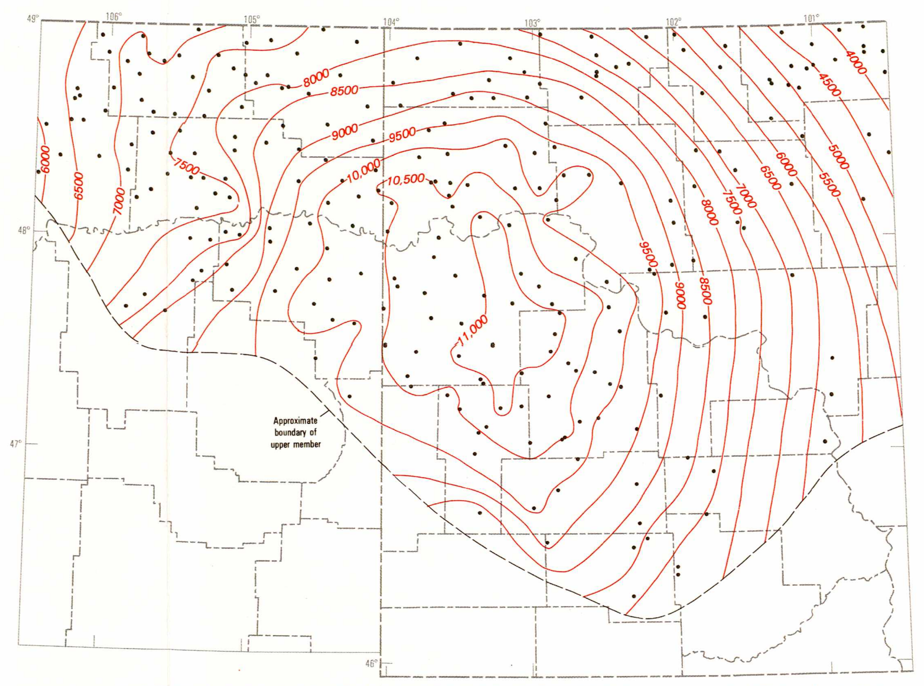
Map D.—THICKNESS OF LOWER BLACK-SHALE MEMBER OF BAKKEN FORMATION. Contour interval=5 ft (1 ft=0.3048 m).



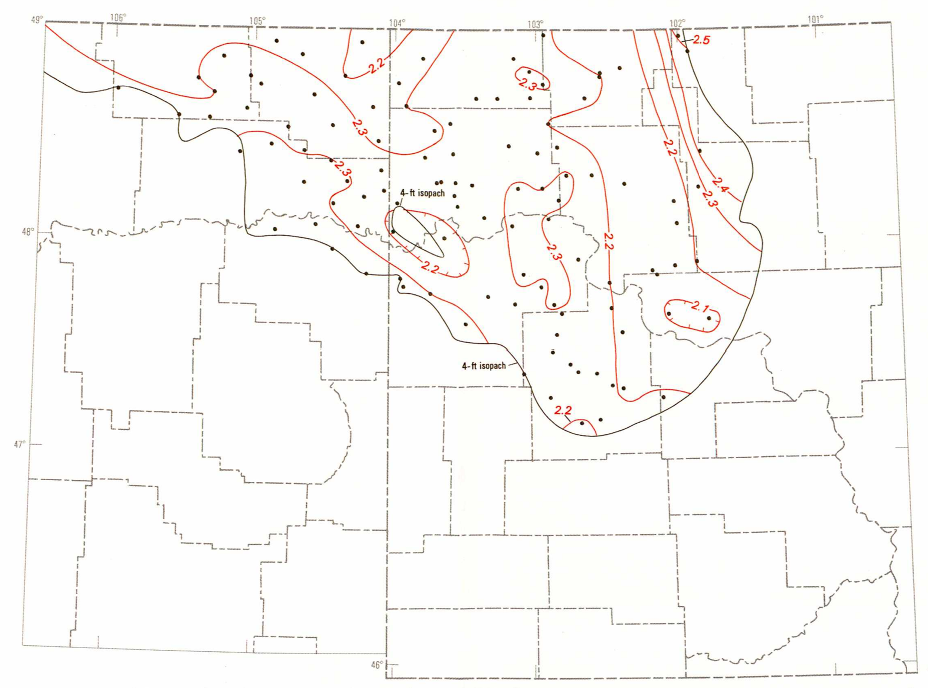
Map E.—THICKNESS OF UPPER BLACK-SHALE MEMBER OF BAKKEN FORMATION. Contour interval=5 ft (1 ft=0.3048 m); hachures indicate closed area of decreasing thickness.



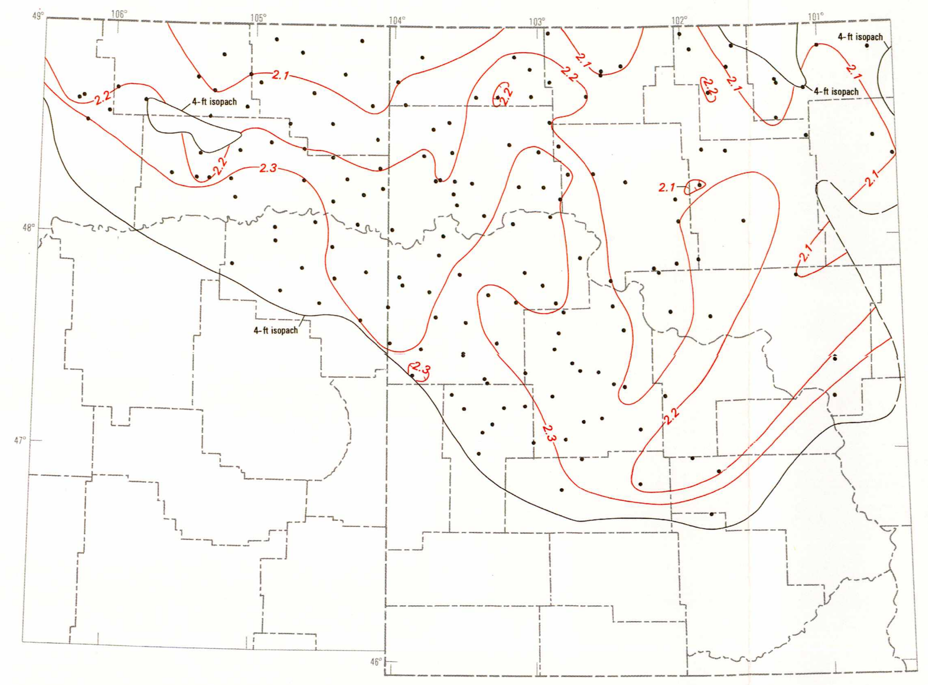
Map F.—DEPTH BELOW SEA LEVEL OF TOP OF BAKKEN FORMATION. Contour interval=500 ft (1 ft=0.3048 m).



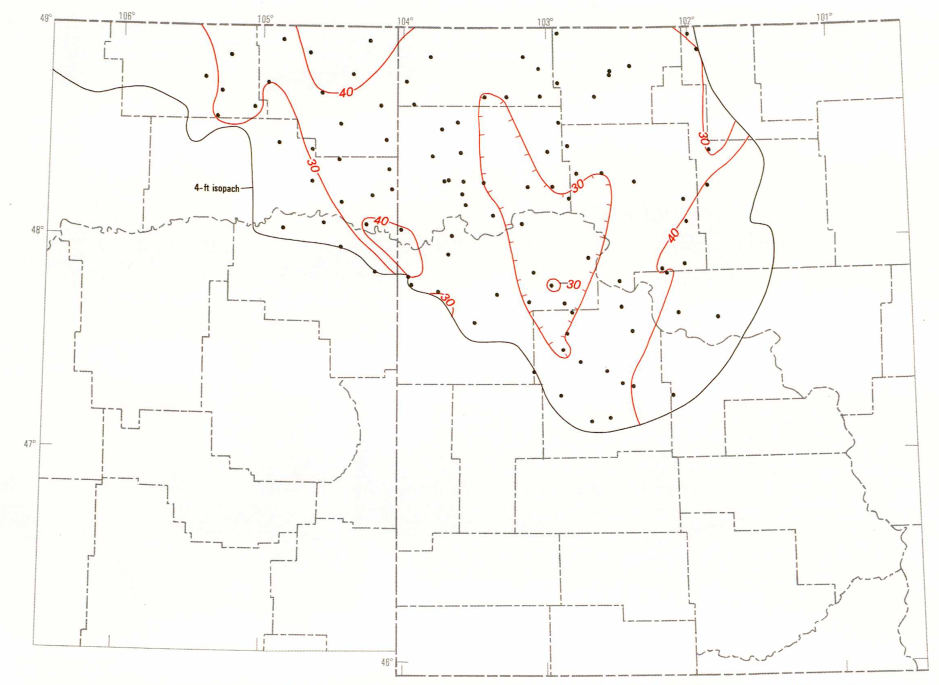
Map G.—DEPTH BELOW GROUND SURFACE OF TOP OF BAKKEN FORMATION. Contour interval=500 ft (1 ft=0.3048 m).



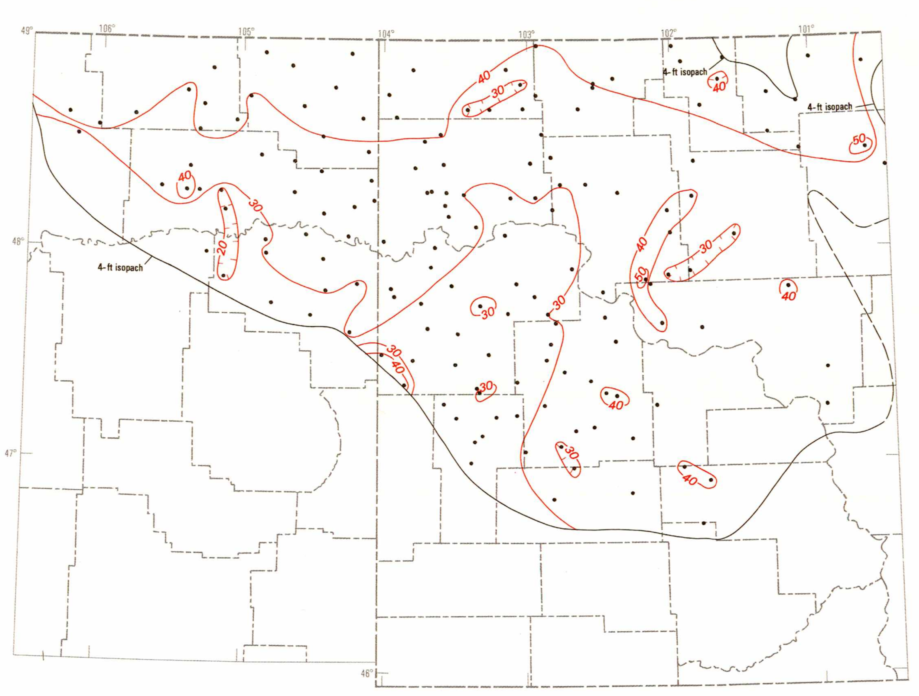
Map H.—AVERAGE DENSITY OF LOWER BLACK-SHALE MEMBER OF BAKKEN FORMATION. Contour interval=0.10 g/cm^3; hachures indicate closed area of lower density; 4-ft (1.2-m) isopach marks minimum thickness for accurate density-log response.



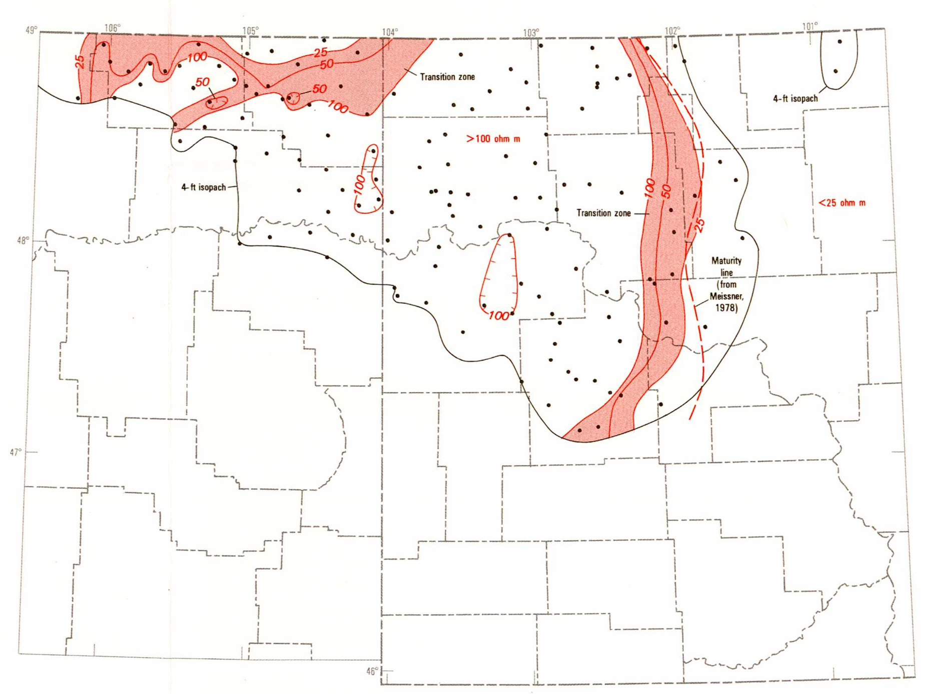
Map I.—AVERAGE DENSITY OF UPPER BLACK-SHALE MEMBER OF BAKKEN FORMATION. Contour interval=0.10 g/cm^3; hachures indicate closed area of lower density; 4-ft (1.2-m) isopach marks minimum thickness for accurate density-log response; dashed where approximately located.



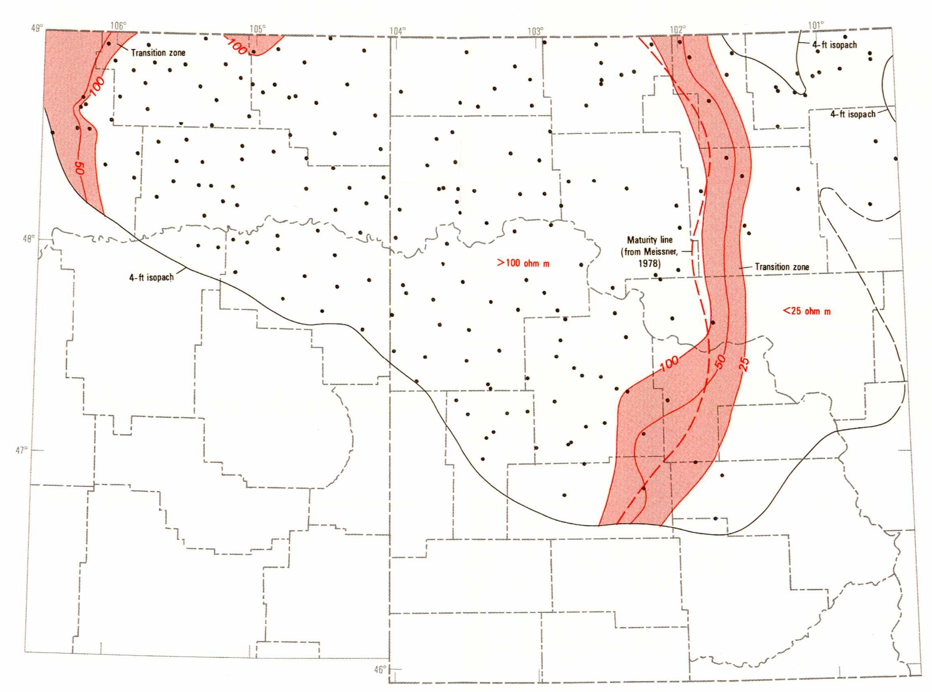
Map J.—AVERAGE NEURTON-LOG POROSITY OF LOWER BLACK-SHALE MEMBER OF BAKKEN FORMATION. Contour interval=10 porosity units; hachures indicate closed area of lower porosity; 4-ft (1.2-m) isopach marks minimum thickness for accurate neutron-log response.



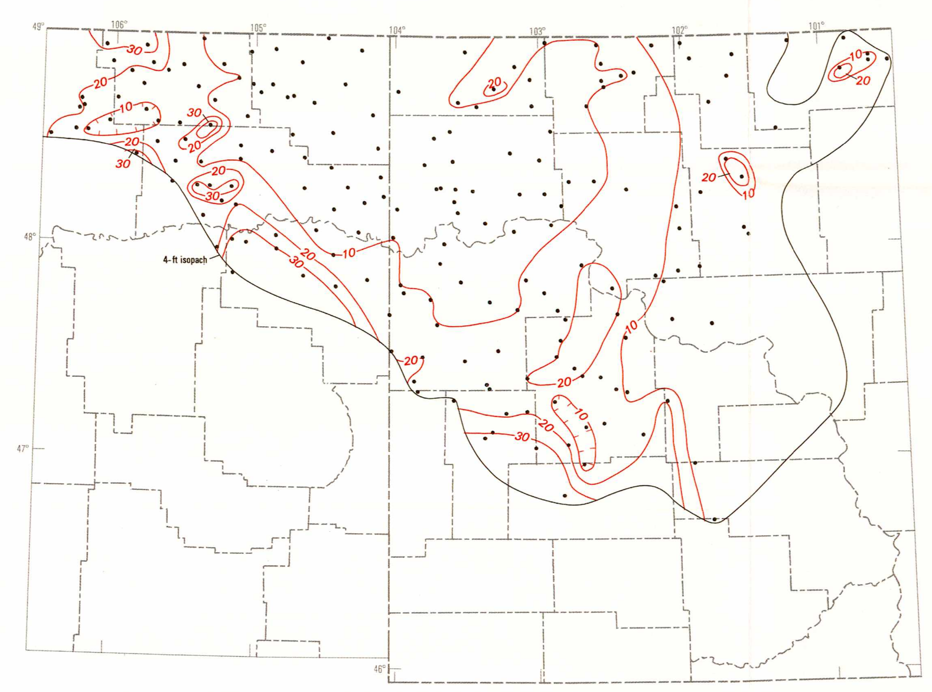
Map K.—AVERAGE NEUTRON-LOG POROSITY OF UPPER BLACK-SHALE MEMBER OF BAKKEN FORMATION. Contour interval=10 porosity units; hachures indicate closed area of lower porosity; 4-ft (1.2-m) isopach marks minimum thickness for accurate neutron-log response; dashed where approximately located.



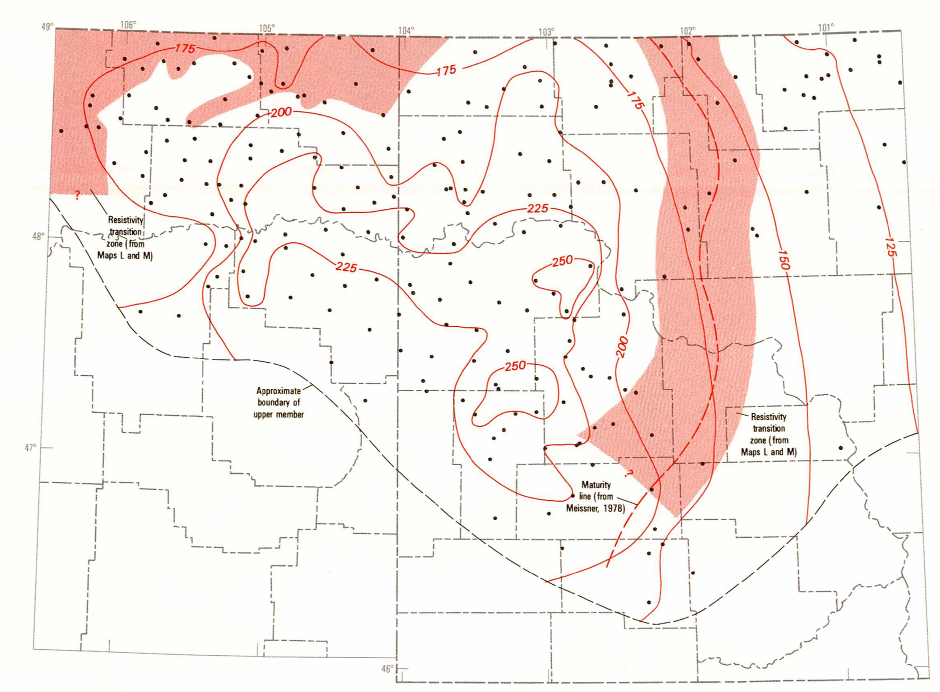
Map L.—AVERAGE RESISTIVITY (UNCORRECTED) OF LOWER BLACK-SHALE MEMBER OF BAKKEN FORMATION. Contour interval, in ohm m, is variable; hachures indicate closed area of lower resistivity; 4-ft (1.2-m) isopach marks minimum thickness shown on maps H through K.



Map M.—AVERAGE RESISTIVITY (UNCORRECTED) OF UPPER BLACK-SHALE MEMBER OF BAKKEN FORMATION. Contour interval, in ohm m, is variable; 4-ft (1.2-m) isopach marks minimum thickness shown on maps H through K; dashed where approximately located.



Map N.—AVERAGE RESISTIVITY (UNCORRECTED) OF MIDDLE MEMBER OF BAKKEN FORMATION. Contour interval=10 ohm m; hachures indicate closed area of lower resistivity; 4-ft (1.2-m) isopach marks minimum thickness shown on maps H through K.



Map O—PRESENT-DAY TEMPERATURE OF BAKKEN FORMATION. Contour interval=25°F; °F=1.8°C+32. Data obtained from bottom-hole temperatures corrected using an empirical equation developed by the American Association of Petroleum Geologists Geothermal Survey of North America Committee and referenced by Wallace and others (1979). Resistivity transition zones from maps L and M. Queries (?) indicate minimum thickness for accurate resistivity-log response.

Base from U.S. Geological Survey Map 2-A, 1972

SCALE 1:2 500 000
50 0 50 100 150 200 250 MILES
50 0 50 100 150 200 250 KILOMETERS

SELECTED PHYSICAL PROPERTIES OF THE BAKKEN FORMATION, NORTH DAKOTA AND MONTANA PART OF THE WILLISTON BASIN

By
Timothy C. Hester and James W. Schmoker

1985

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