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GEOLOGICAL SURVEY

# Preliminary Log-Derived Maps of the Bakken Formation, North Dakota and Montana Portions of Williston Basin

By

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This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards and stratigraphic nomenclature. Any use of trade names is for descriptive purposes only and does not imply endorsement by the U.S.G.S.

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ILLUSTRATIONS

# PRELIMINARY LOG-DERIVED MAPS OF THE BAKKEN FORMATION, NORTH DAKOTA AND MONTANA PORTIONS OF WILLISTON BASIN

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## INTRODUCTION

The Bakken Formation, of Devonian and Mississippian age, is the source of a large portion of the discovered oil in the Williston basin (Dow, 1974; Williams, 1974), and is itself a reservoir rock in some areas (Von Osinski, 1970; Petroleum Information Corp., 1980). For these reasons, even though it comprises less than 1% 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 Bakken-Formation data set, 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 (fig. 2). The spacing of data locations is adequate except in the southeastern part of the study area, where closer data spacing could not be realized because of few wells drilled to the Bakken Formation.

The maps and figures derived from the wire-line data are considered to be the primary contribution of this report, and are accompanied by a limited text that addresses some of the more significant map features and their implications.

## GEOLOGIC SETTING

The Bakken Formation, which does not outcrop, 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 Corp. H.O. Bakken No. 1, 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 sub-rounded quartz grains. No formal nomenclature has 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).

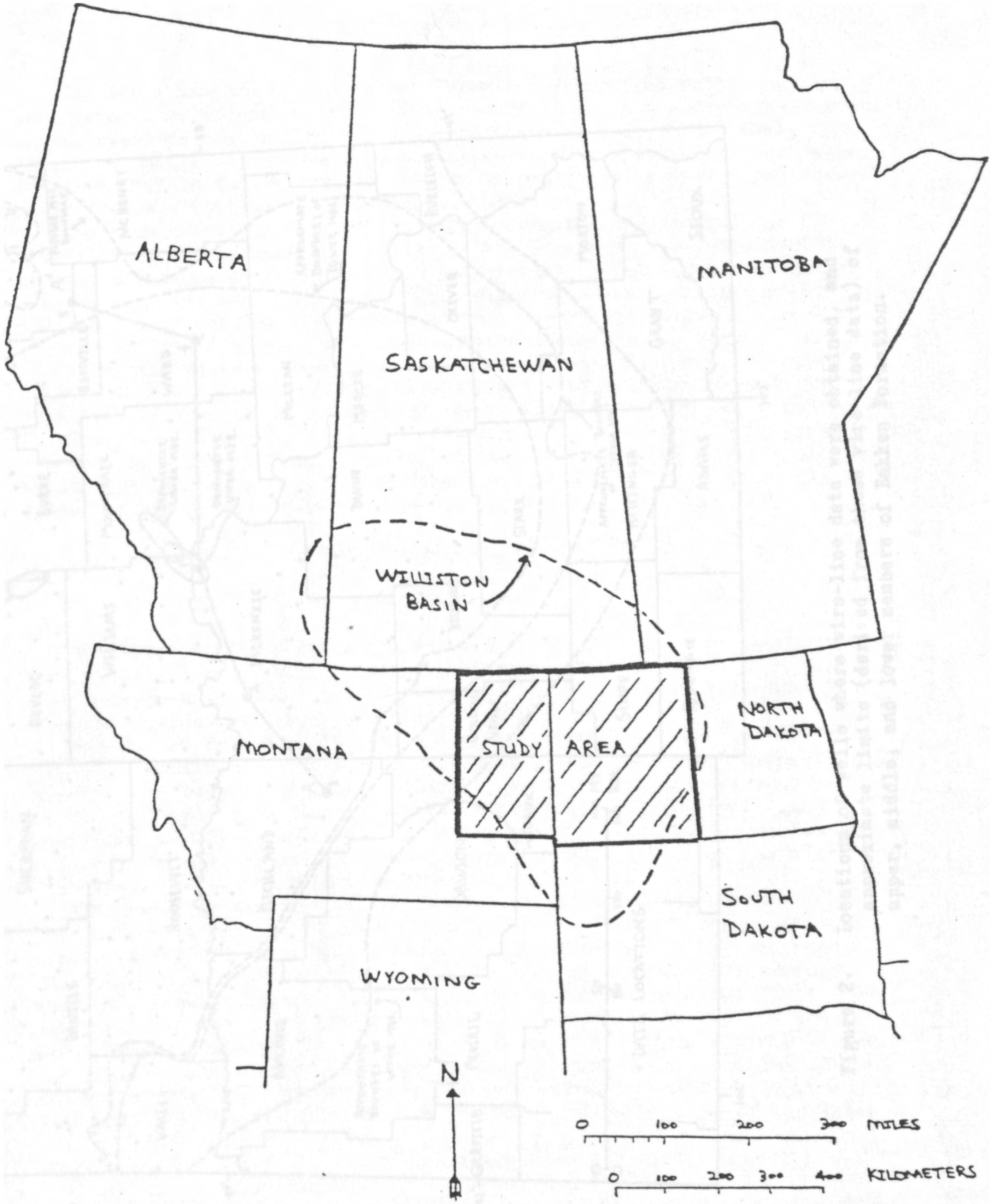


Figure 1. Regional setting of study area. (Background map modified from Worsley and Fuzesy, 1978.)

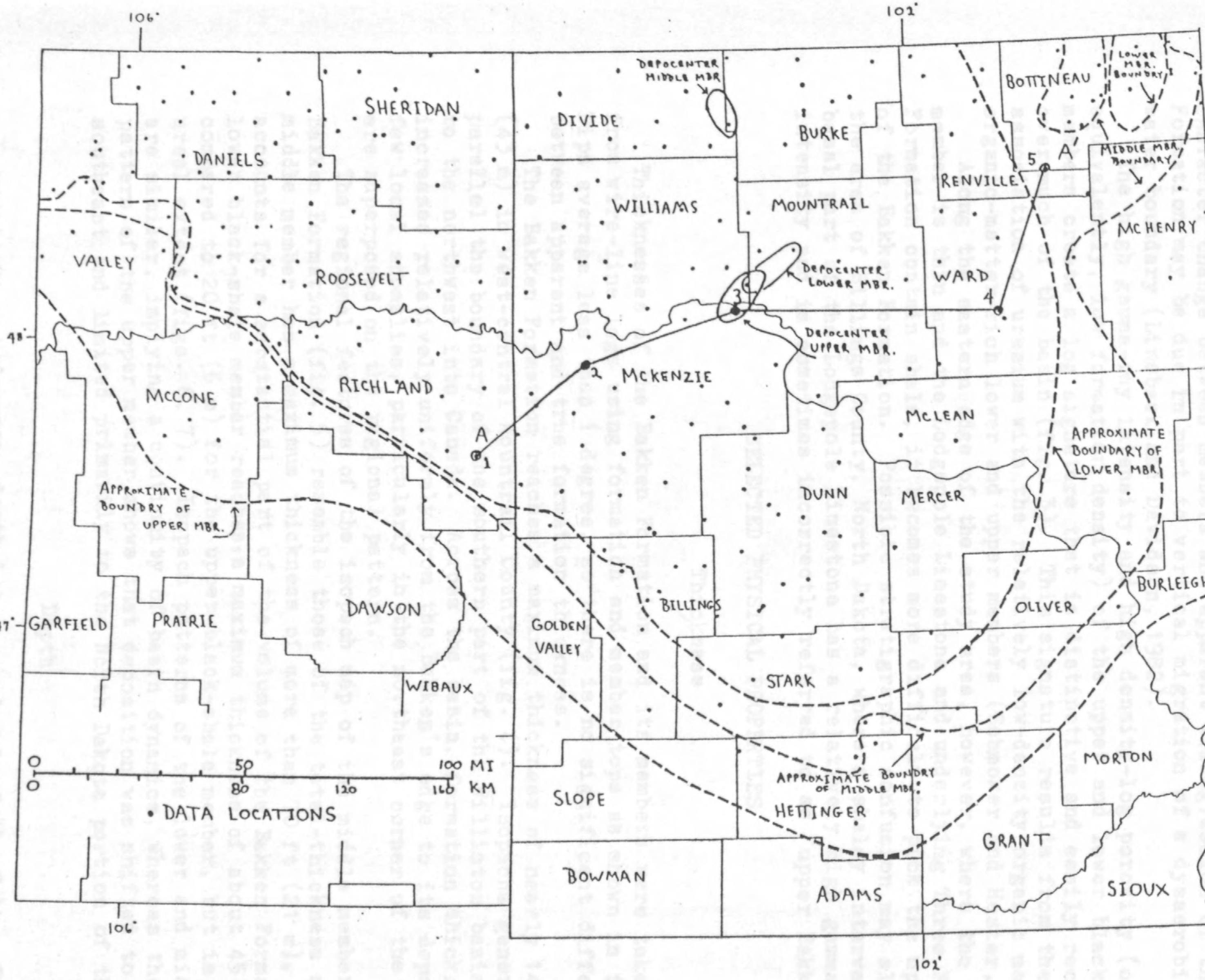


Figure 2. Locations of wells where wire-line data were obtained, and approximate limits (derived from these wire-line data) of upper, middle, and lower members of Bakken Formation.

The three members of the Bakken Formation exhibit an onlapping depositional relationship, so that the boundary of each successively younger member overlaps that of the older member below (fig. 2). The sharp character change between members and 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. 3). 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, in press).

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 shaley interval in the basal part of the Lodgepole Limestone has a relatively high gamma-ray intensity and is sometimes incorrectly 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 3. 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 (fig. 4). Isopachs generally parallel the boundary of the southern part of the Williston basin, and open to the northwest into Canada. Across the basin, formation thickness increases relatively uniformly 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.

The regional features of the isopach map of the middle member of the Bakken Formation (fig. 5) 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 (figs. 6, 7). Isopach patterns of the lower and middle members are similar, implying a continuity of basin dynamics, whereas the isopach pattern of the upper member shows that deposition was shifted to the southeast and limited primarily to the North Dakota portion 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 (fig. 8). 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 (fig. 4) is about 45 mi (72 km) northeast of, and more

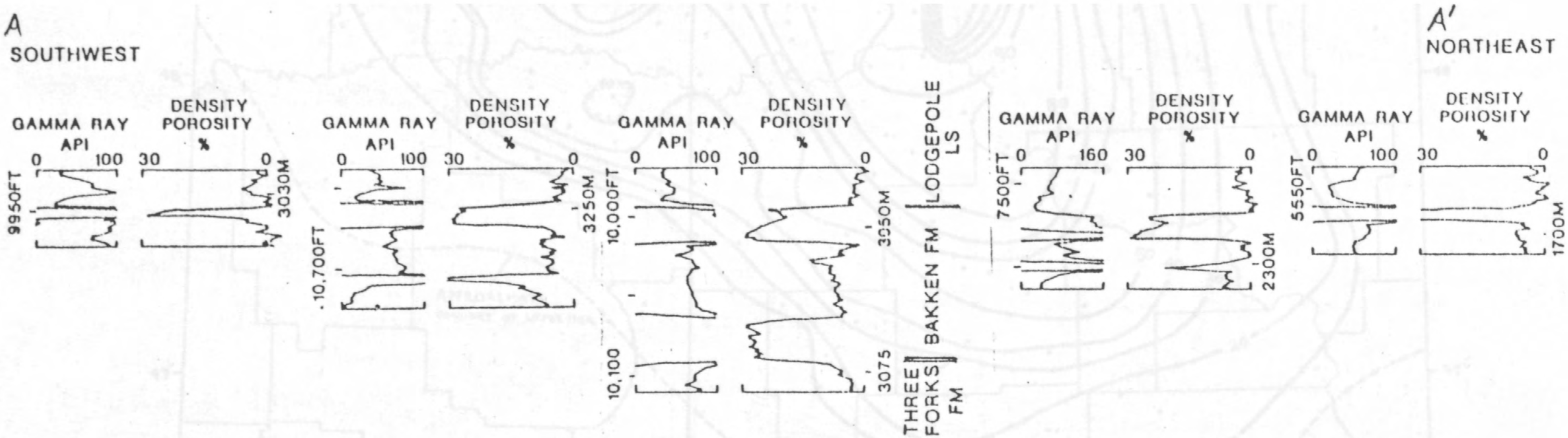


Figure 3. Profile showing gamma-ray intensity and density-log porosity of Bakken Formation (modified from Schmoker and Hester, in press). Upper and lower members of Bakken Formation are characterized by high (off-scale) gamma-ray intensity and high density-log porosity. Profile location is shown on Figure 2.

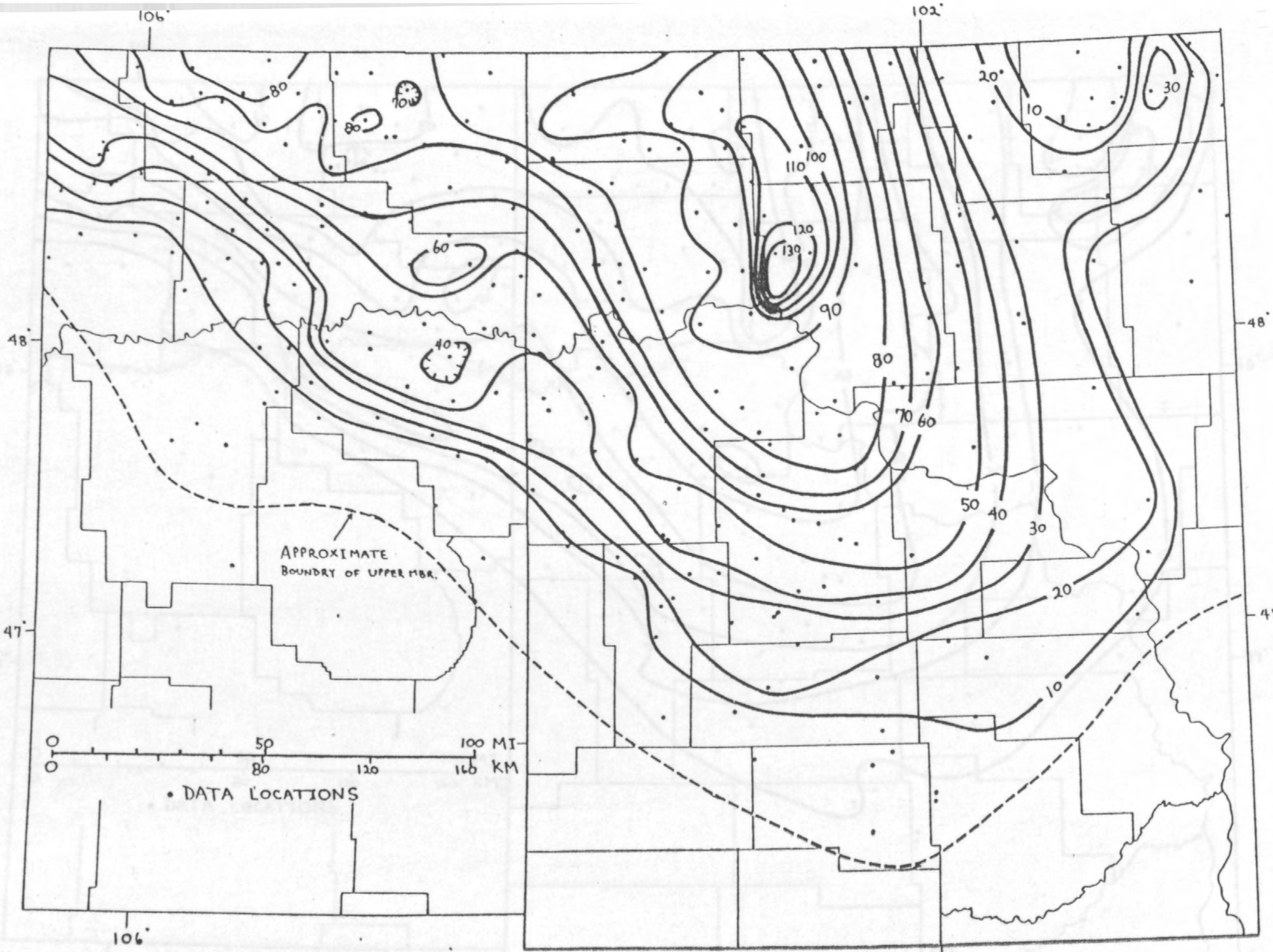


Figure 4. Thickness of Bakken Formation. Contour interval = 10 ft.
1 ft = 0.3048 m.

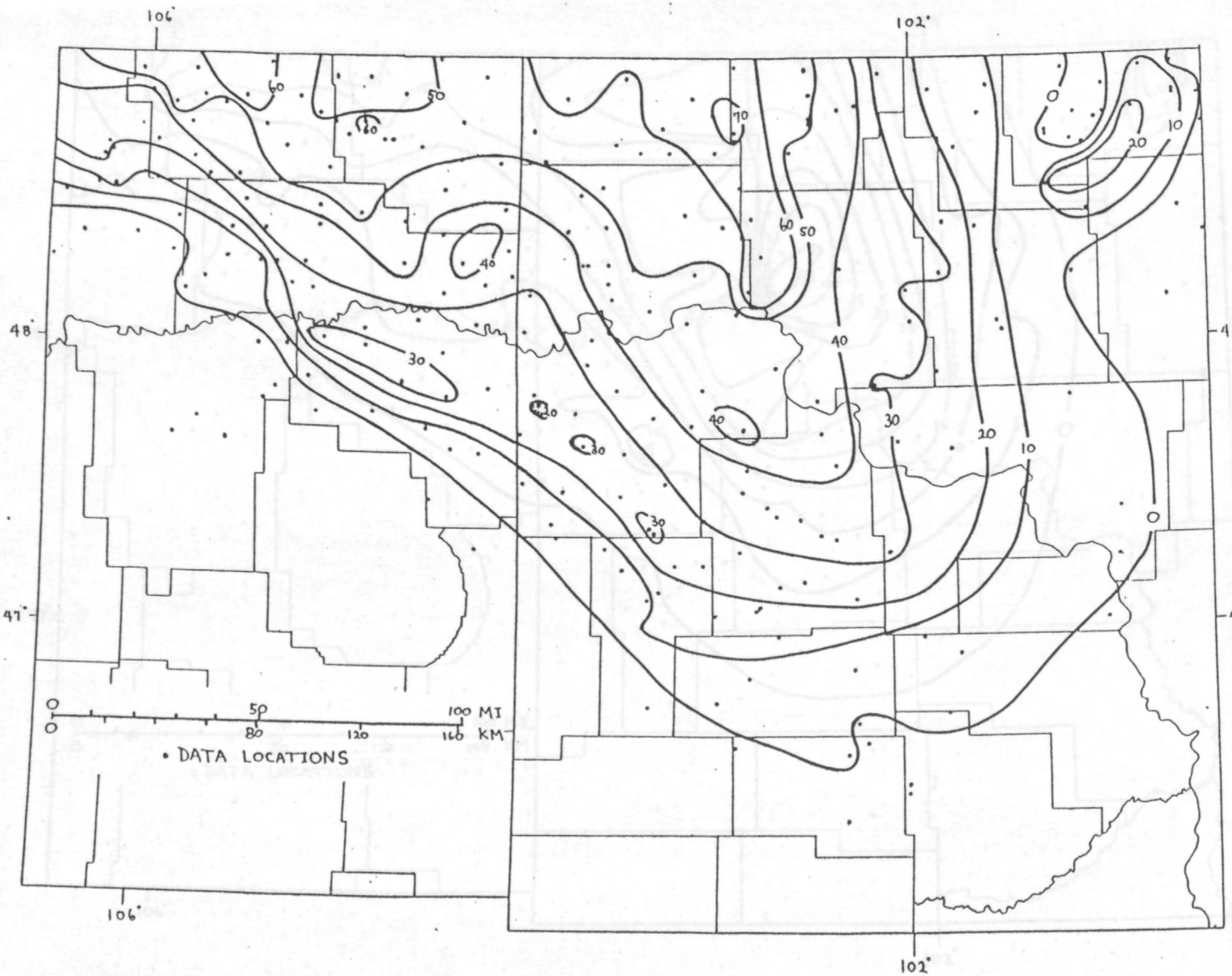


Figure 5. Thickness of middle member of Bakken Formation. Contour interval = 10 ft. 1 ft = 0.3048 m.

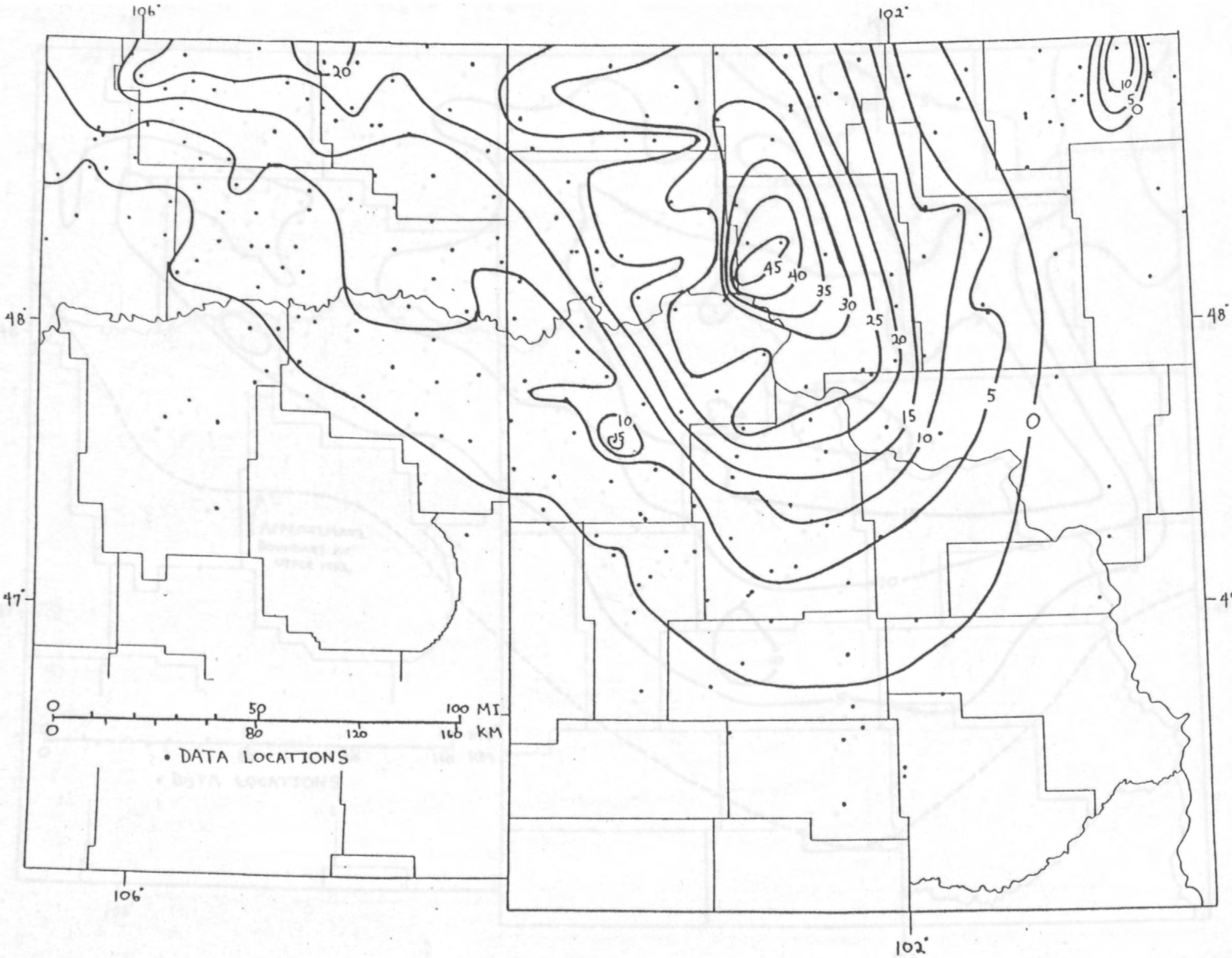


Figure 6. Thickness of lower black-shale member of Bakken Formation. Contour interval = 5 ft. 1 ft = 0.3048 m.

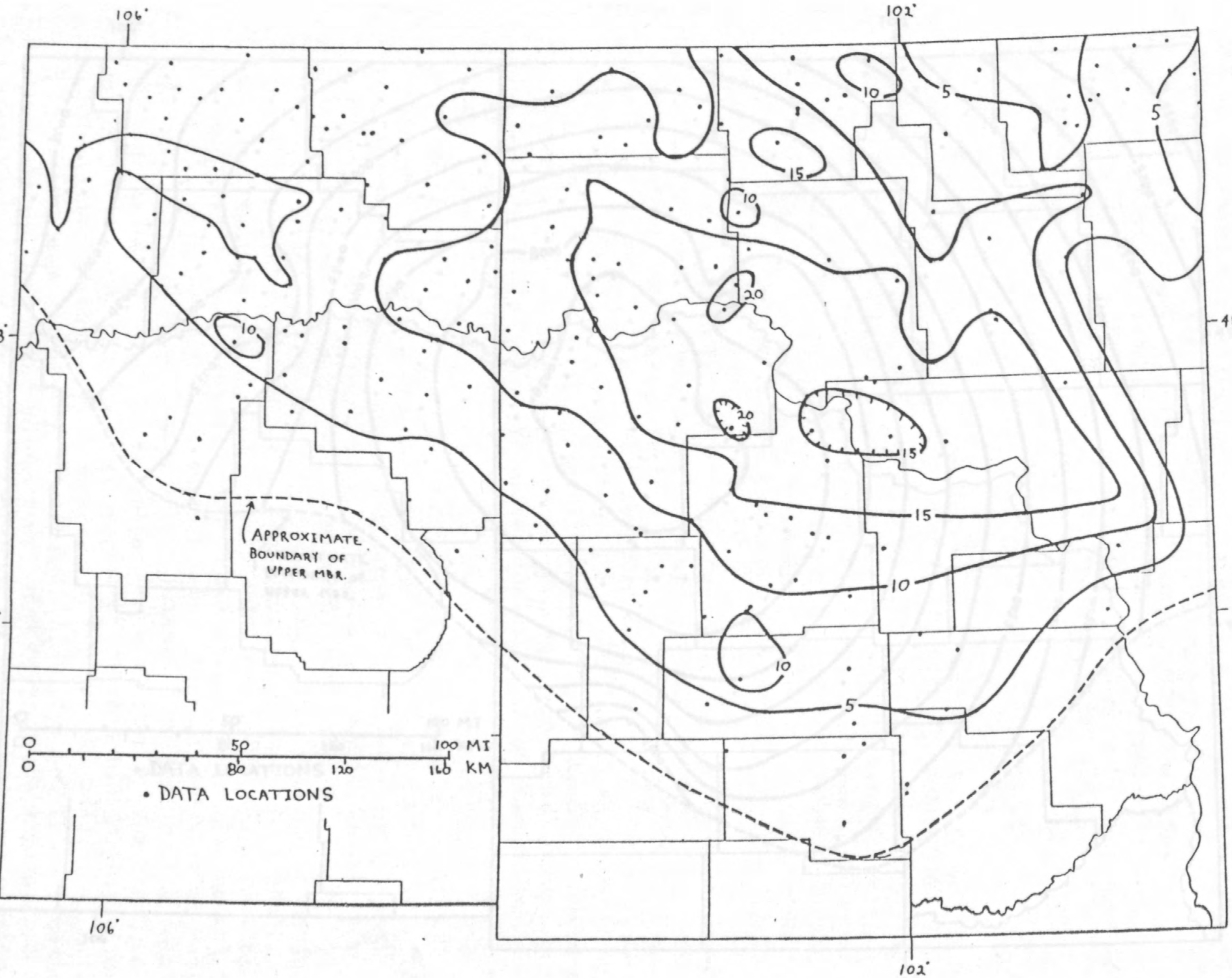


Figure 7. Thickness of upper black-shale member of Bakken Formation. Contour interval = 5 ft. 1 ft = 0.3048 m.

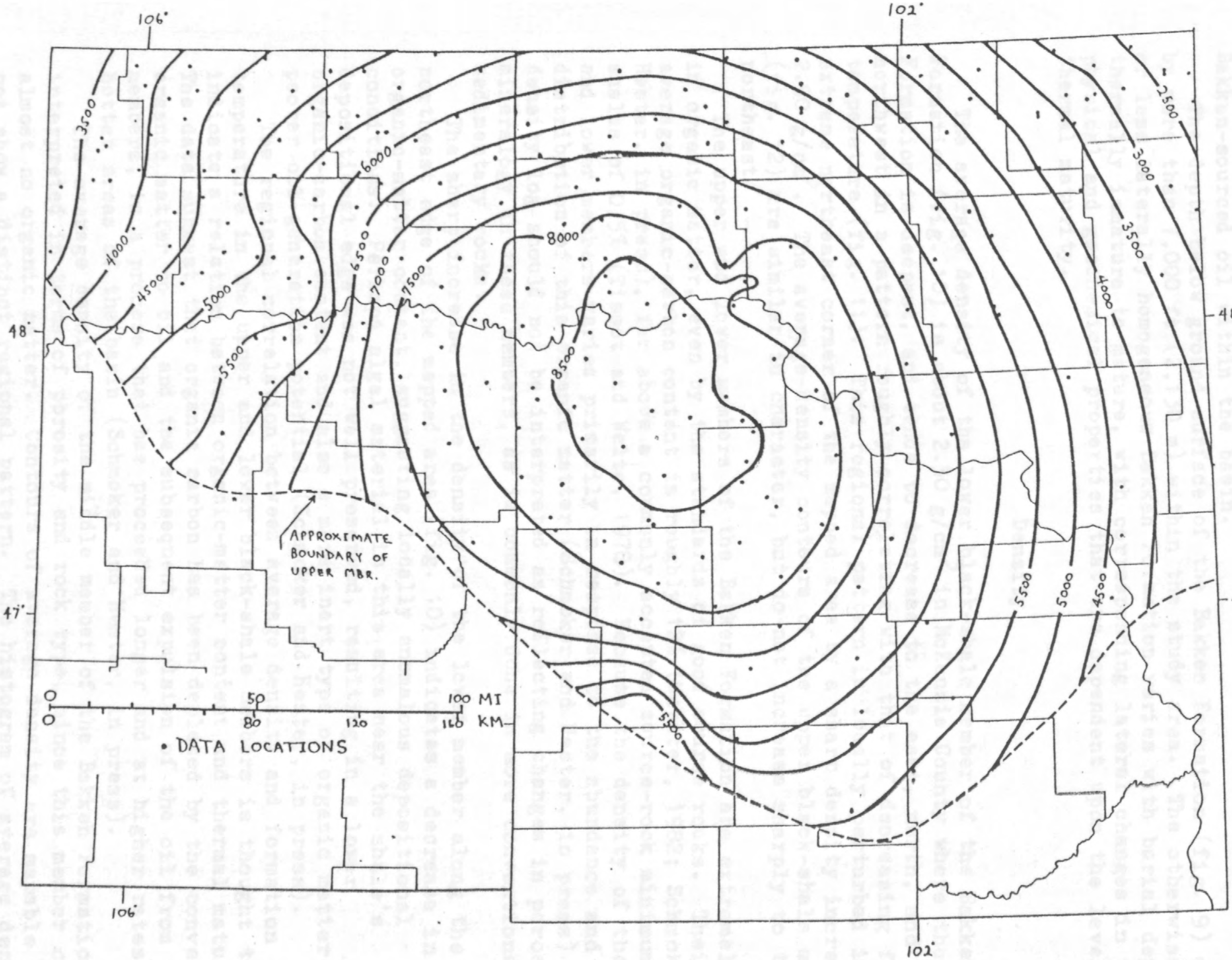


Figure 8. Depth below sea level of top of Bakken Formation. Contour interval = 500 ft. 1 ft = 0.3048 m.

than 1,000 ft (300 m) higher than, the present structural center of the basin, indicating a regional tilting that has influenced the distribution of Bakken-sourced oil within the basin.

The depth below ground surface of the Bakken Formation (fig. 9) changes by more than 7,000 ft (2,130 m) within the study area. The otherwise more or less laterally homogeneous Bakken Formation varies with burial depth from thermally immature to mature, with corresponding lateral changes in those physical and geochemical properties that are dependent upon the level of thermal maturity.

## Density

The average density of the lower black-shale member of the Bakken Formation (fig. 10) 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 (fig. 11). 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 (fig. 12) 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% (Webster, 1982; Schmoker and Hester, in press), far above a commonly accepted source-rock minimum for shales of 0.5% (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, in press) 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 (fig. 10) indicates a decrease in organic-matter content, suggesting locally anomalous depositional conditions. Perhaps algal material in this area near the shale'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, in press).

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 expulsion 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, in press).

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 mapable but do not show a distinct regional pattern. The histogram of average density of the middle member (fig. 13) resembles a normal distribution, with a mean of 2.64 g/cm$^3$ and with more than 90% of the measurements falling between 2.58 and 2.68 g/cm$^3$.

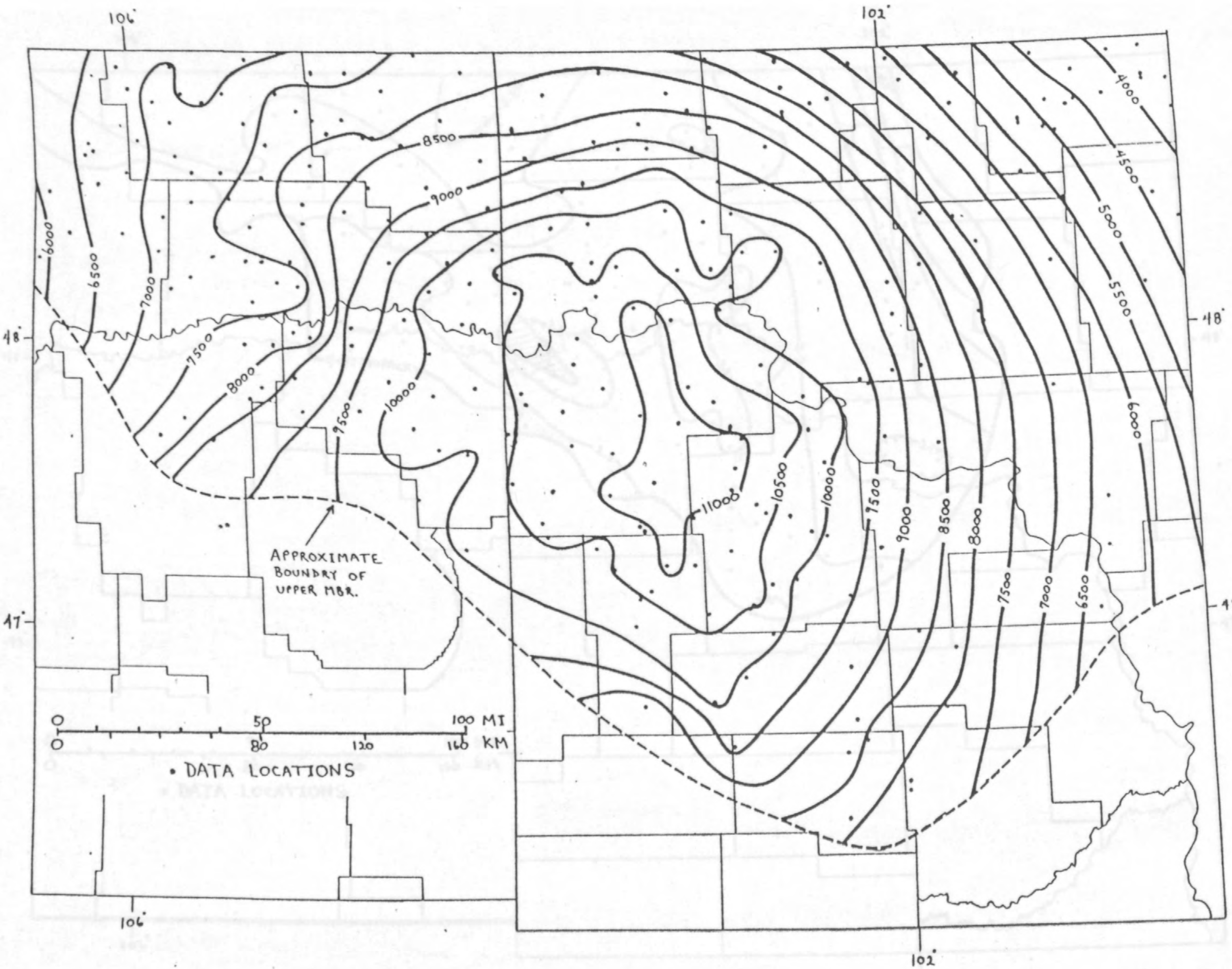


Figure 9. Depth below ground surface of top of Bakken Formation.
Contour interval = 500 ft. 1 ft = 0.3048 m.

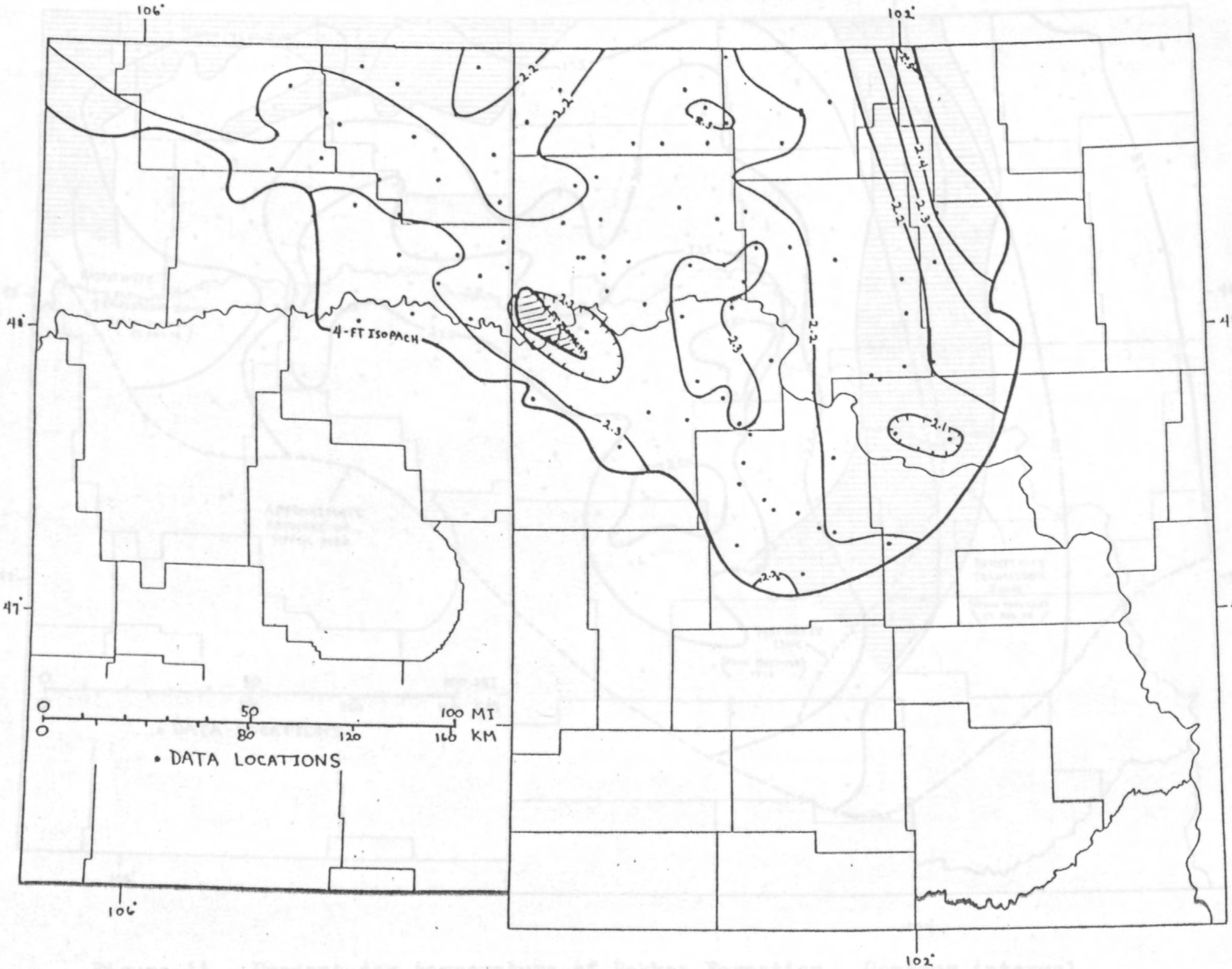


Figure 10. Average density of lower black-shale member of Bakken Formation. Contour interval = 0.10 $g/cm^3$. Four-ft (1.2-m) isopach marks minimum thickness for accurate density-log response.

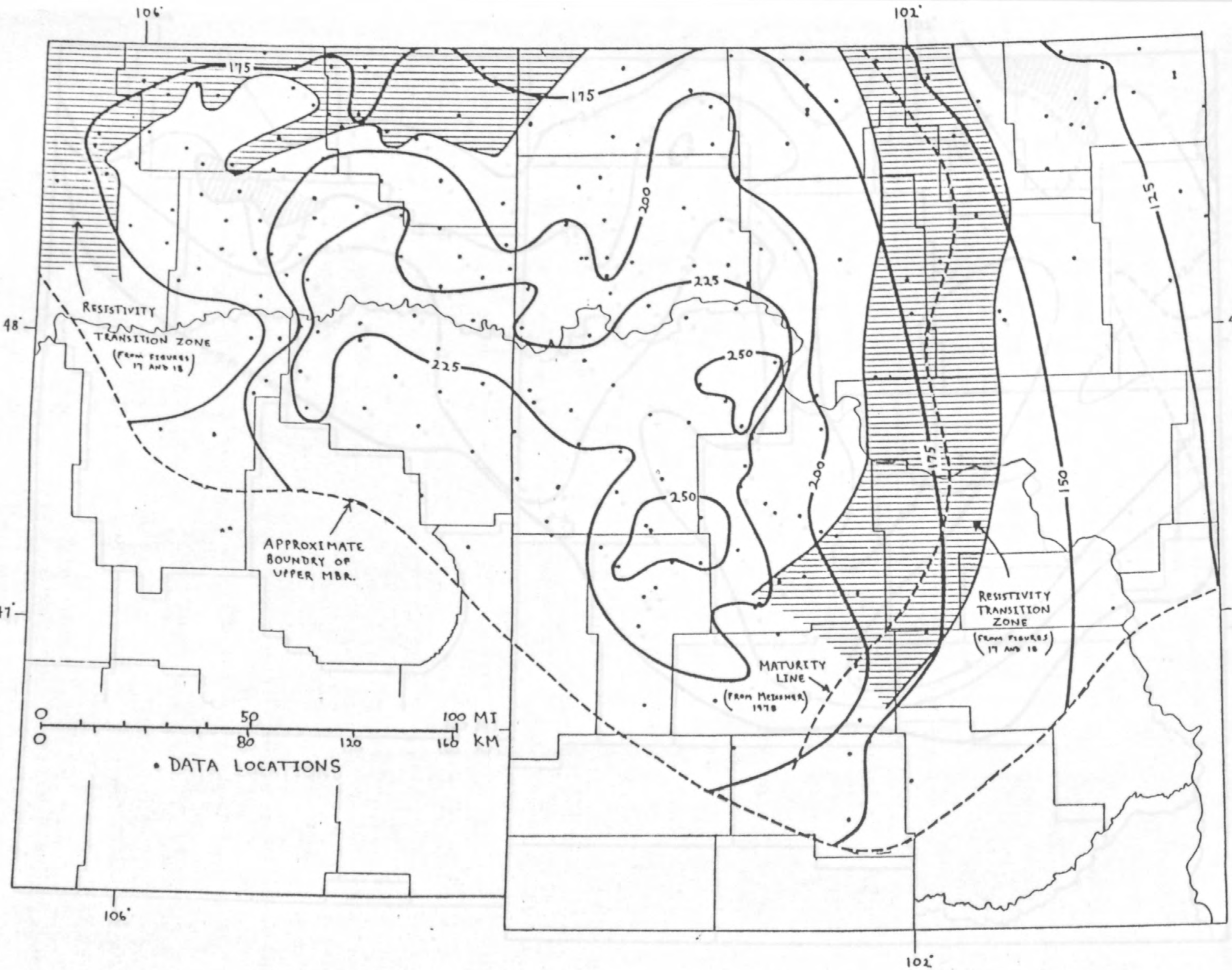


Figure 11. Present-day temperature of Bakken Formation. Contour interval = 25°F. Data obtained from bottom-hole temperatures corrected using an empirical equation developed by the American Association of Petroleum Geologists Geothermal Survey of North America Committee and referenced by Wallace and others (1979). °F = 1.8°C + 32. Resistivity-transition zones from figs. 17 and 18.

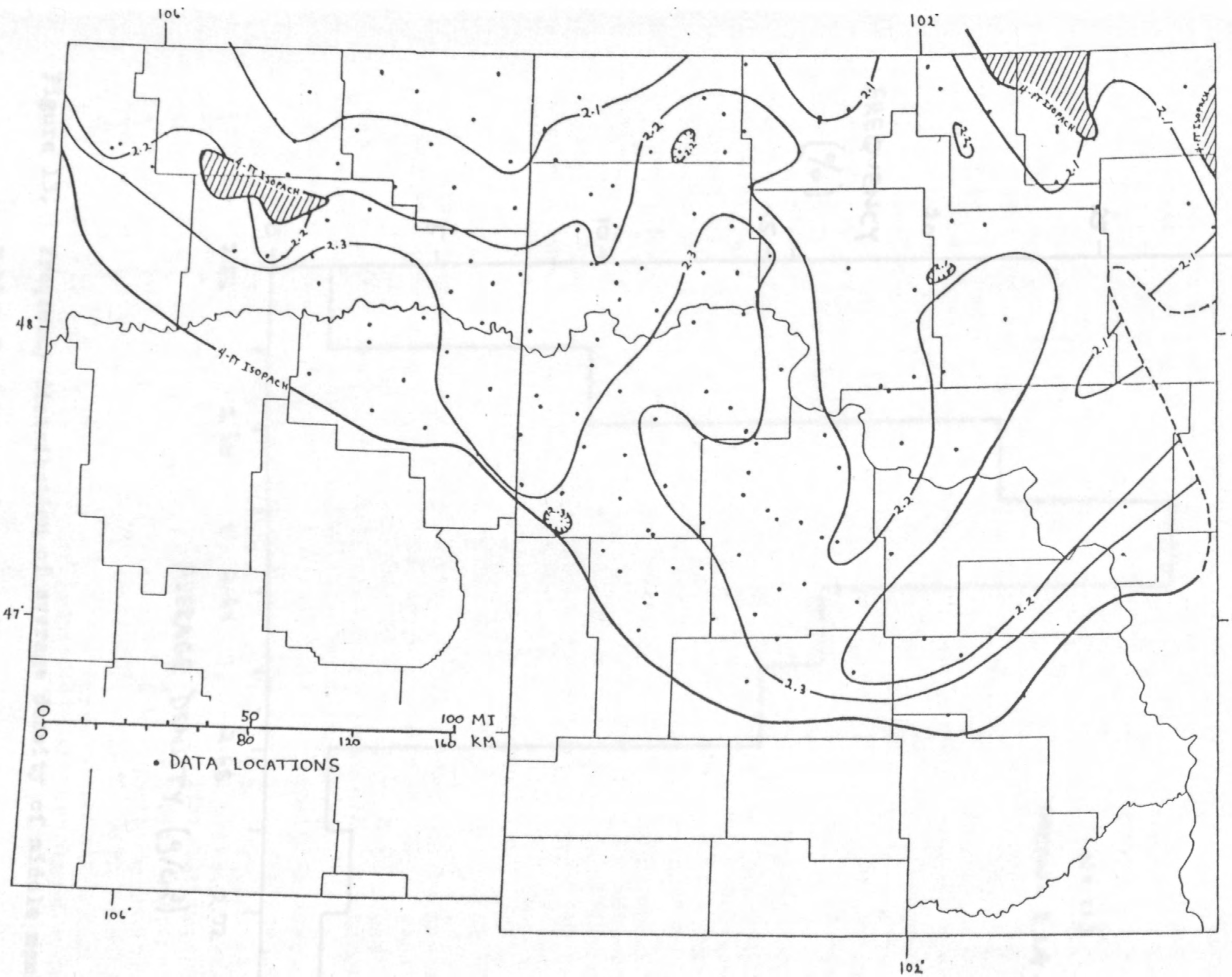


Figure 12. Average density of upper black-shale member of Bakken Formation. Contour interval = 0.10 g/cm$^3$. Four-ft (1.2-m) isopach marks minimum thickness for accurate density-log response.

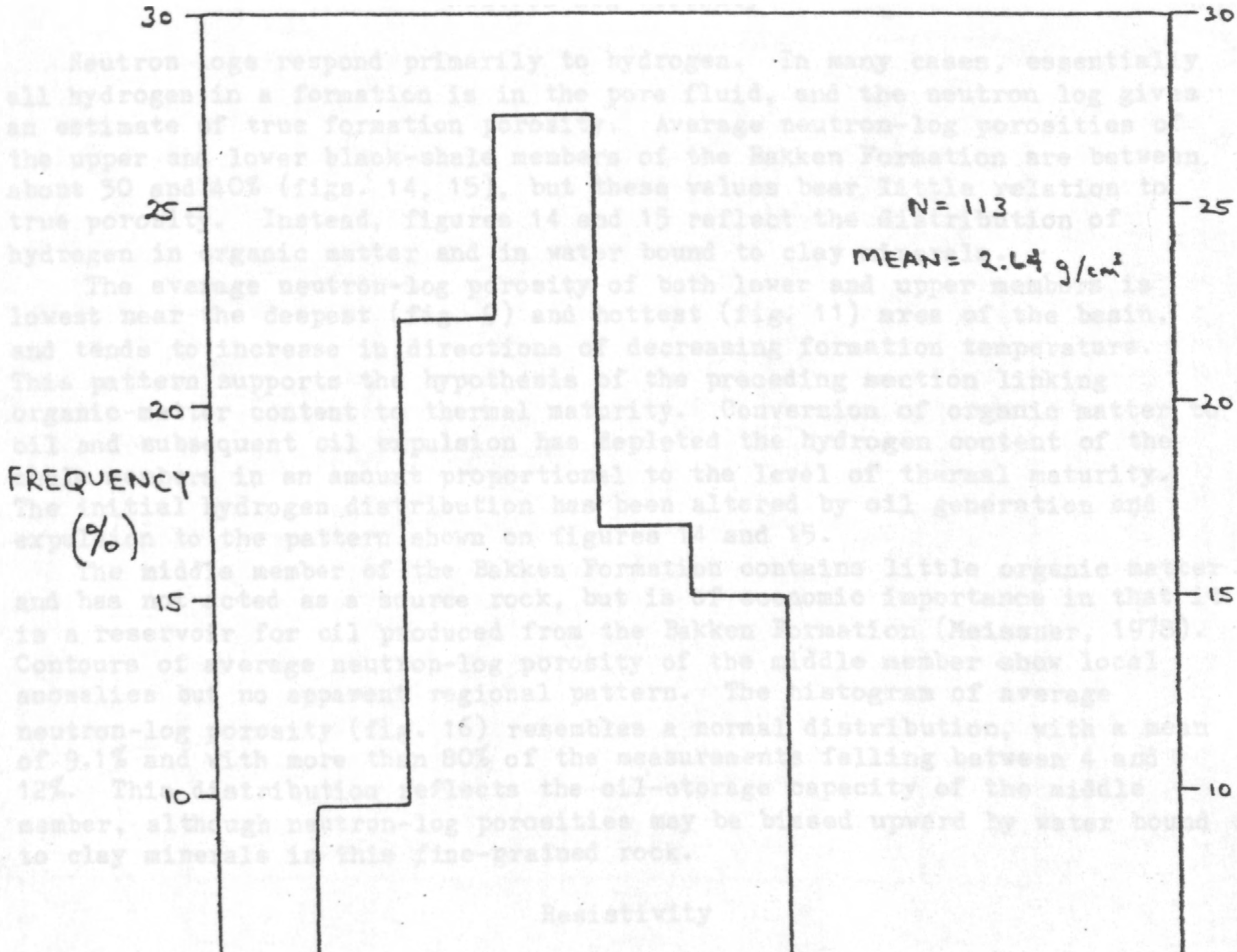


Figure 13. Frequency distribution of average density of middle member of Bakken Formation. Data are from well locations within middle-member boundary shown on Figure 2.

## 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% (figs. 14, 15), but these values bear little relation to true porosity. Instead, figures 14 and 15 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 (fig. 9) and hottest (fig. 11) 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 expulsion 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 figures 14 and 15.

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 is 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. 16) resembles a normal distribution, with a mean of 9.1% and with more than 80% of the measurements falling between 4 and 12%. 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 (figs. 17, 18) tend to be either very high (greater than 100 ohm $m^2/m$) or rather low (less than 25 ohm $m^2/m$). 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.

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 (figs. 17, 18).

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

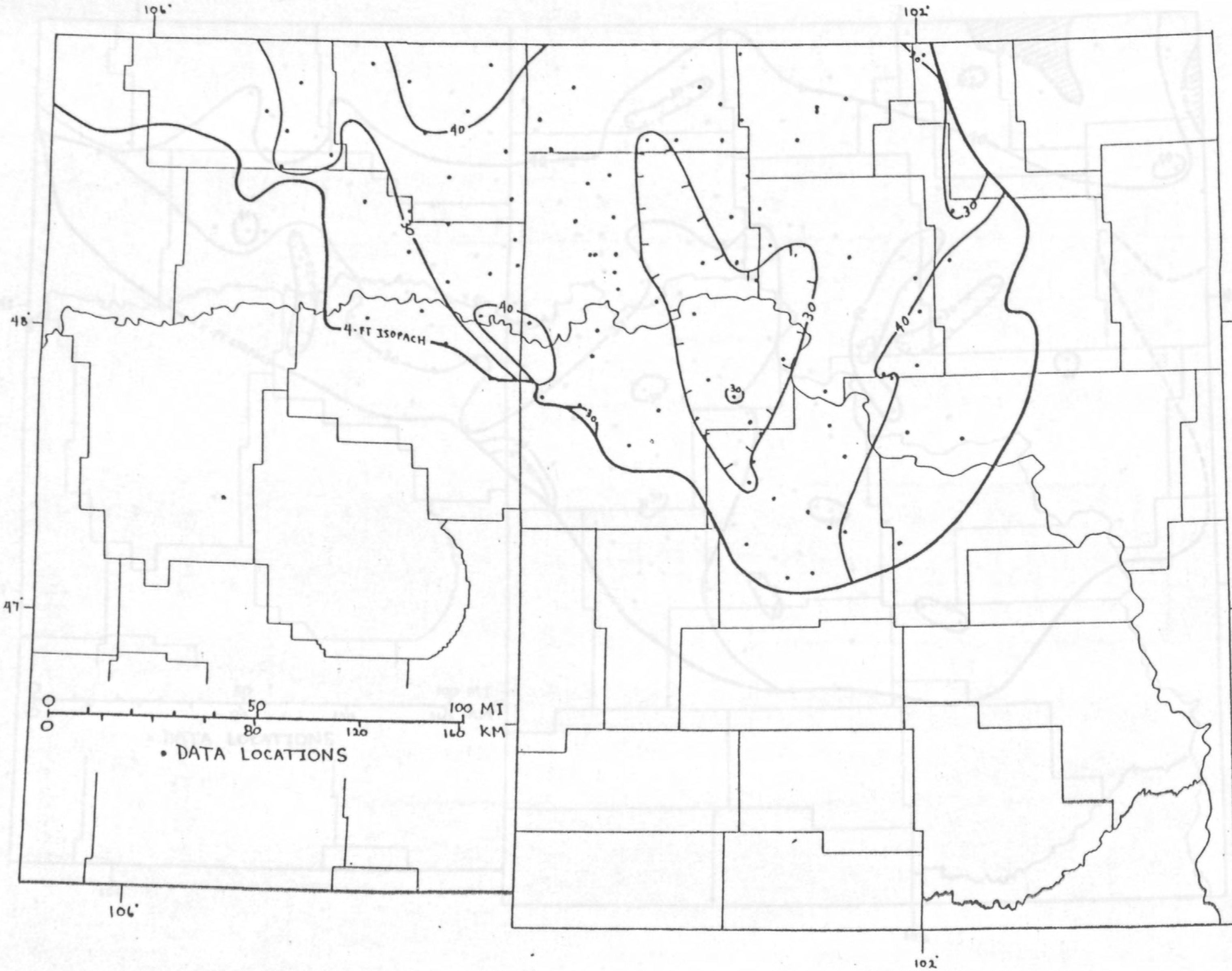


Figure 14. Average neutron-log porosity of lower black-shale member of Bakken Formation. Contour interval = 10 porosity units. Four-ft (1.2-m) isopach marks minimum thickness for accurate neutron-log response.

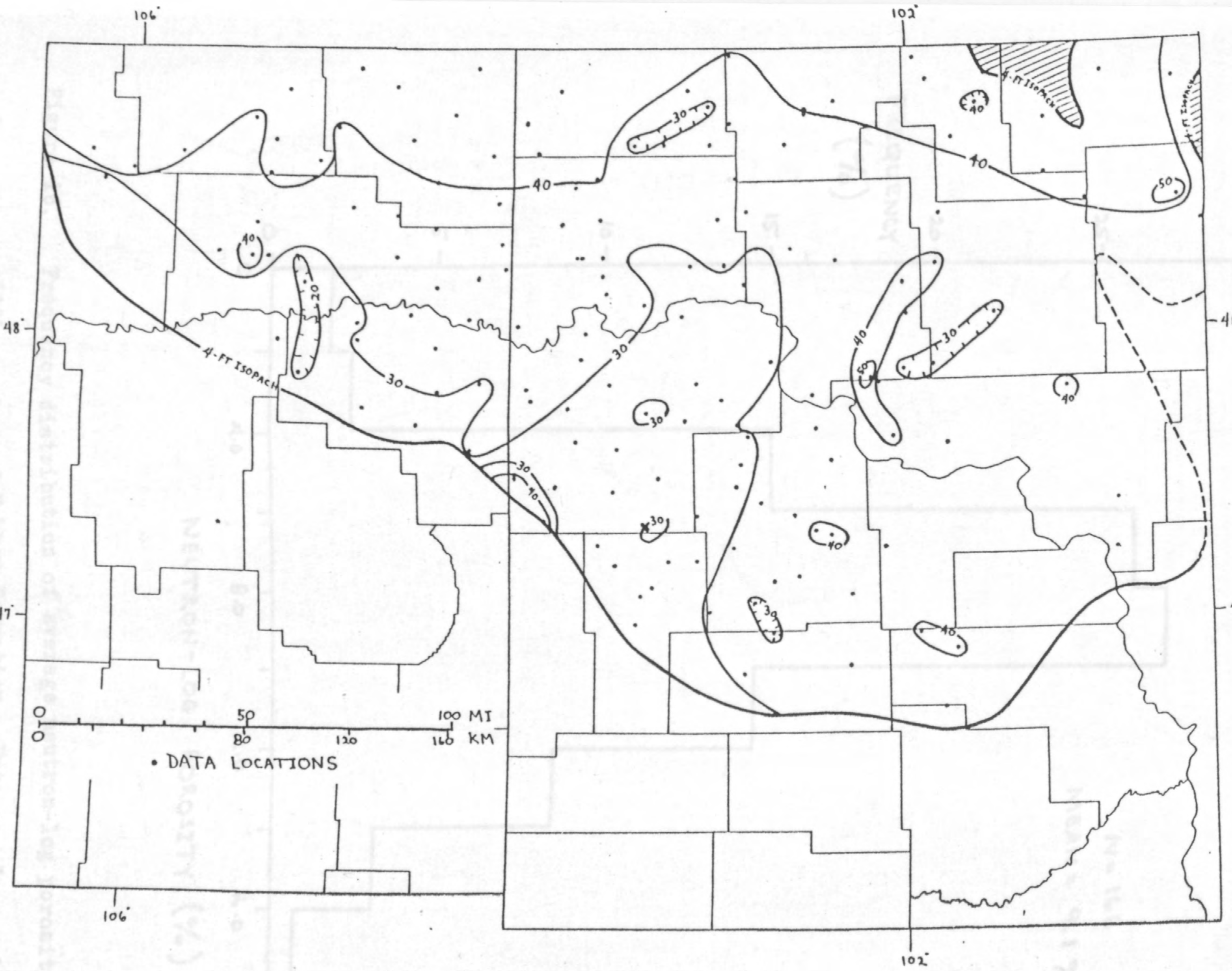


Figure 15. Average neutron-log porosity of upper black-shale member of Bakken Formation. Contour interval = 10 porosity units. Four-ft (1.2-m) isopach marks minimum thickness for accurate neutron-log response.

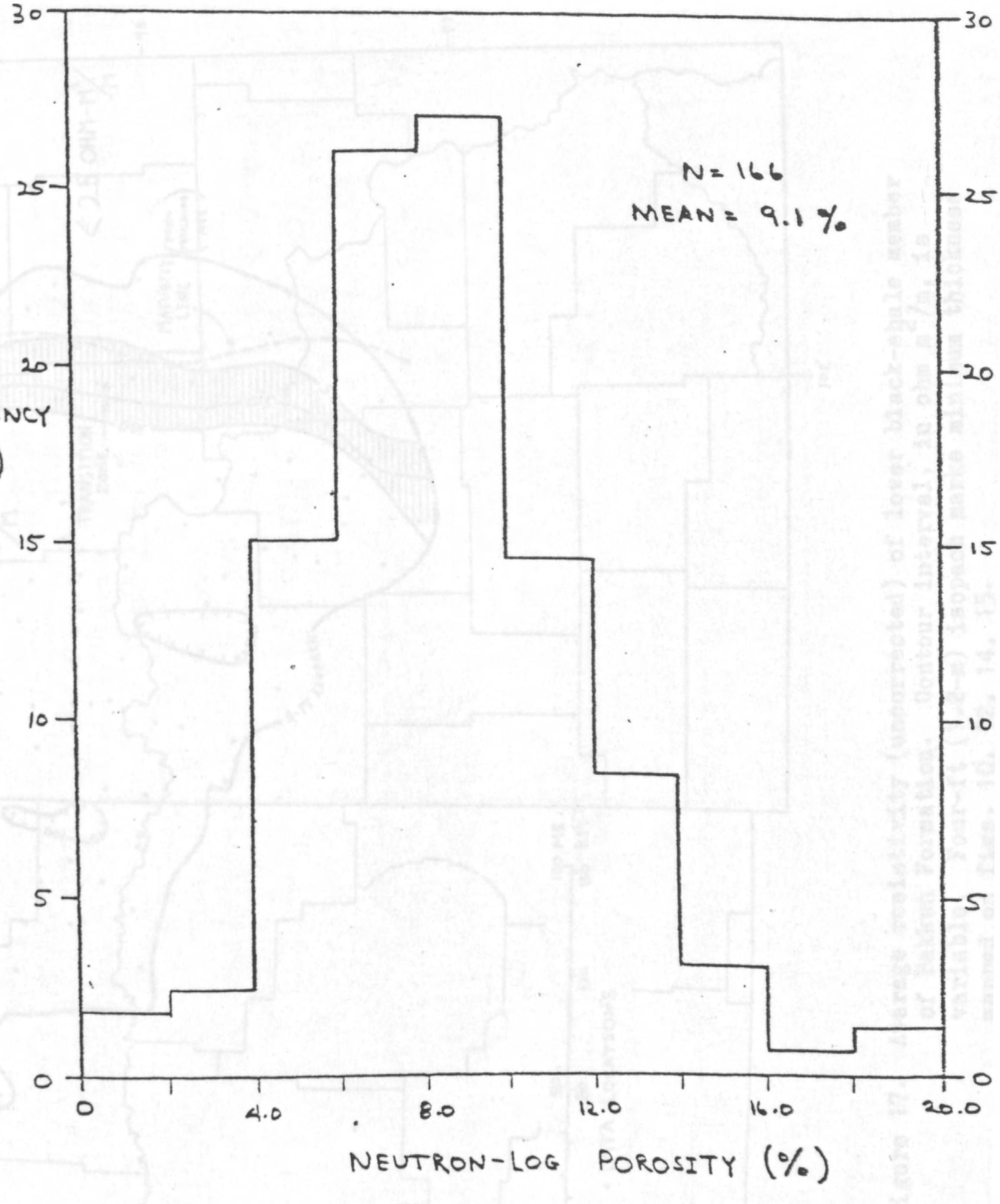


Figure 16. Frequency distribution of average neutron-log porosity of middle member of Bakken Formation. Data are from well locations within middle-member boundary shown on Figure 2.

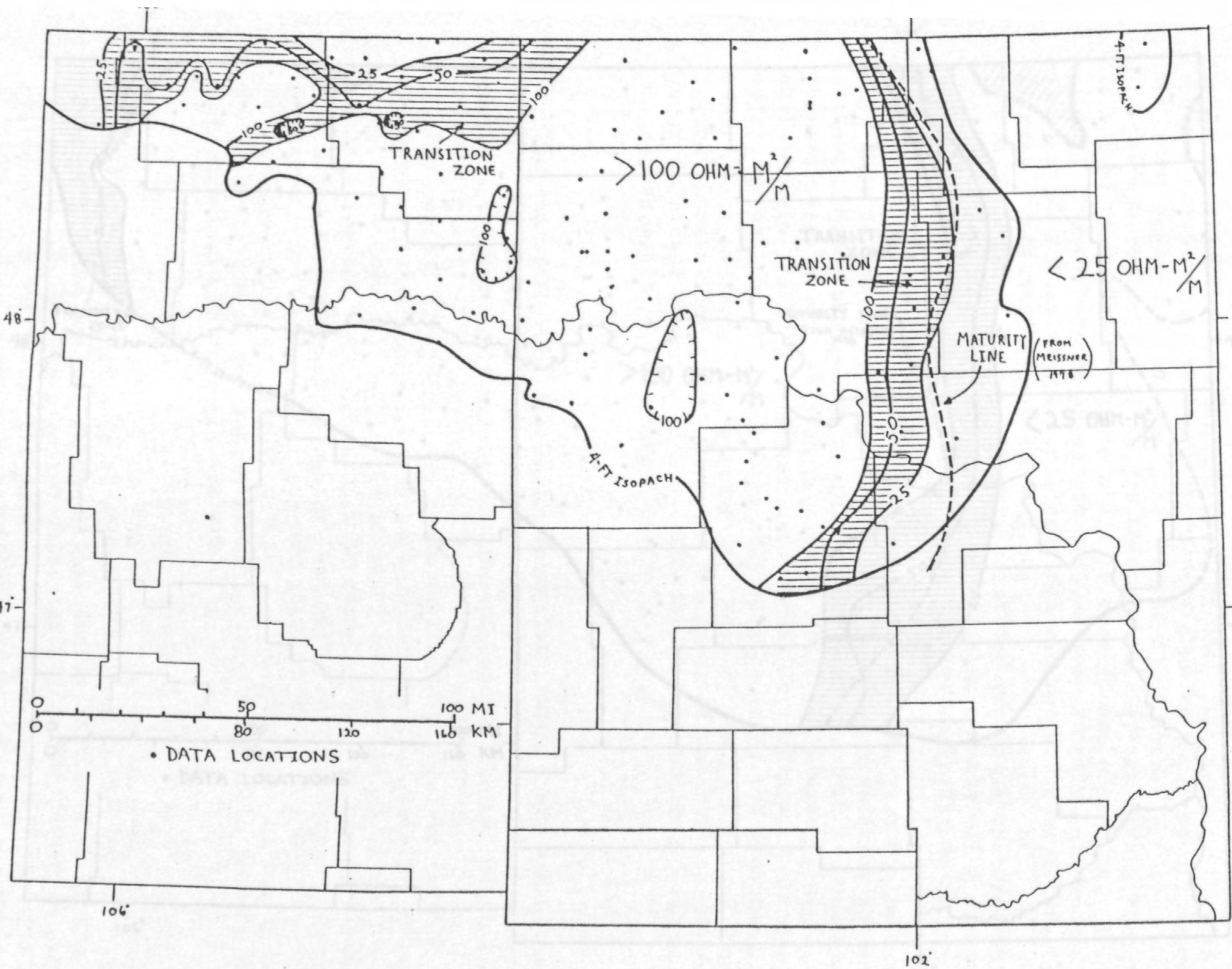


Figure 17. Average resistivity (uncorrected) of lower black-shale member of Bakken Formation. Contour interval, in ohm $m^2/m$, is variable. Four-ft (1.2-m) isopach marks minimum thickness mapped on figs. 10, 12, 14, 15.

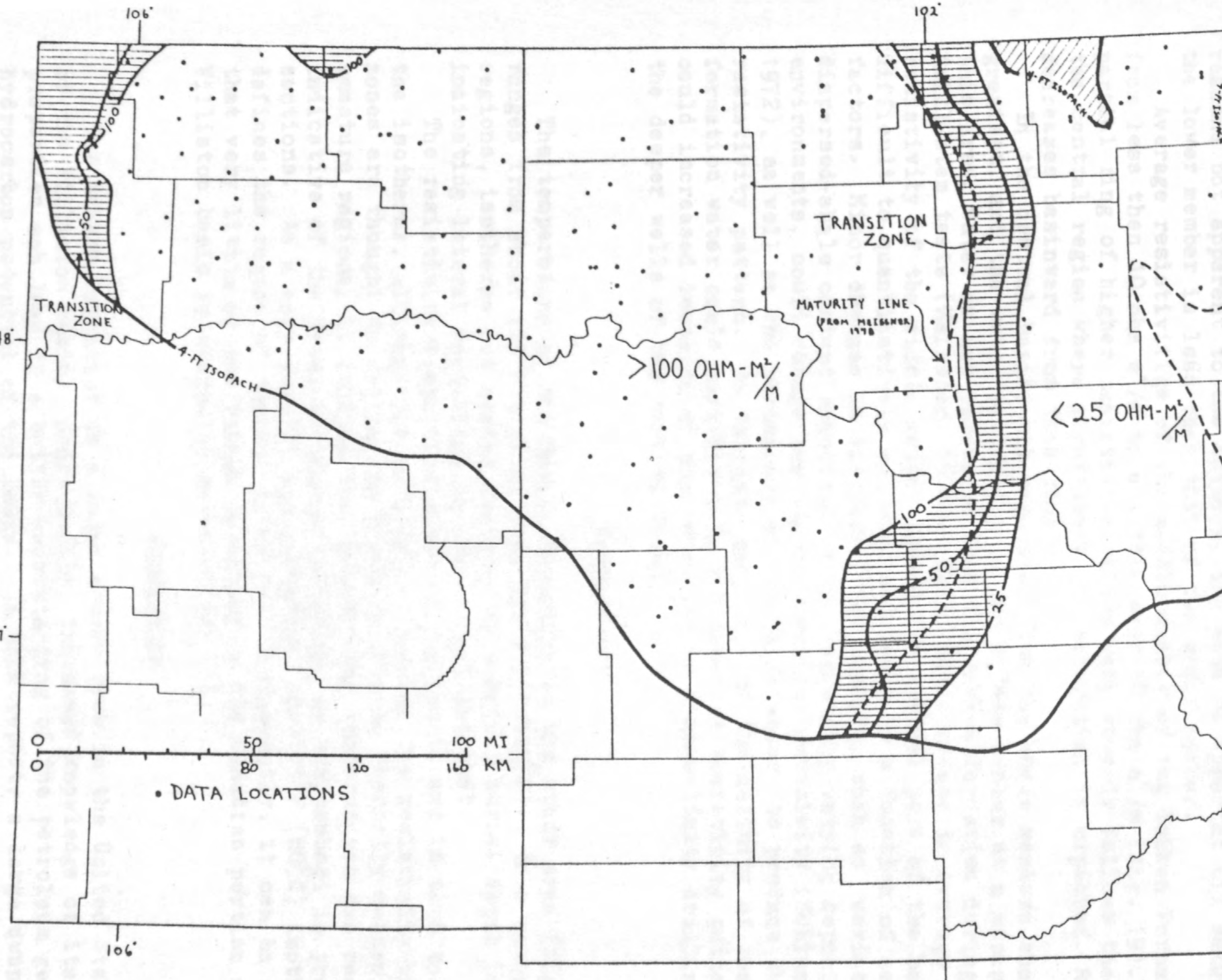


Figure 18. Average resistivity (uncorrected) of upper black-shale member of Bakken Formation. Contour interval, in ohm $m^2$/m, is variable. Four-ft (1.2-m) isopach marks minimum thickness mapped on figs. 10, 12, 14, 15.

maturity boundary in Montana, in addition to the eastern boundary described by Meissner (1978). In Montana, the transition zone of the lower member (fig. 17) also lies basinward of that of the upper member (fig. 18). 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 $m^2/m$ to a little over 30 ohm $m^2/m$ (fig. 19). A partial ring of higher resistivity values very 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, for example, 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. An increase basinward of the salinity of residual formation water 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 (fig. 11) 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 (fig. 9), indicating lateral variations in the thermal gradient.

The resistivity-transition zones of figures 17 and 18 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 very general approximation, the 175°F (80°C) isotherm defines the region of thermal maturity. Consequently, it can be assumed that very little of the Bakken Formation in the Canadian portion of the Williston basin is thermally mature (fig. 11).

## CONCLUSION

The Bakken Formation is a major source rock in the United States portion of the Williston basin. Consequently, increased knowledge of its physical properties can lead to a better understanding of the petroleum geology and hydrocarbon potential of the basin. In this report, a large quantity of wire-line measurements is consolidated into a series of physical-property maps, with the intention of facilitating the regional study of the Bakken Formation and associated problems of hydrocarbon generation and migration.

Collectively, the maps depict and partially quantify the increasing thermal maturity of the Bakken Formation as it dips basinward. The resulting picture of hydrocarbon generation and expulsion is largely consistent with the original ideas of Meissner (1978). Present formation

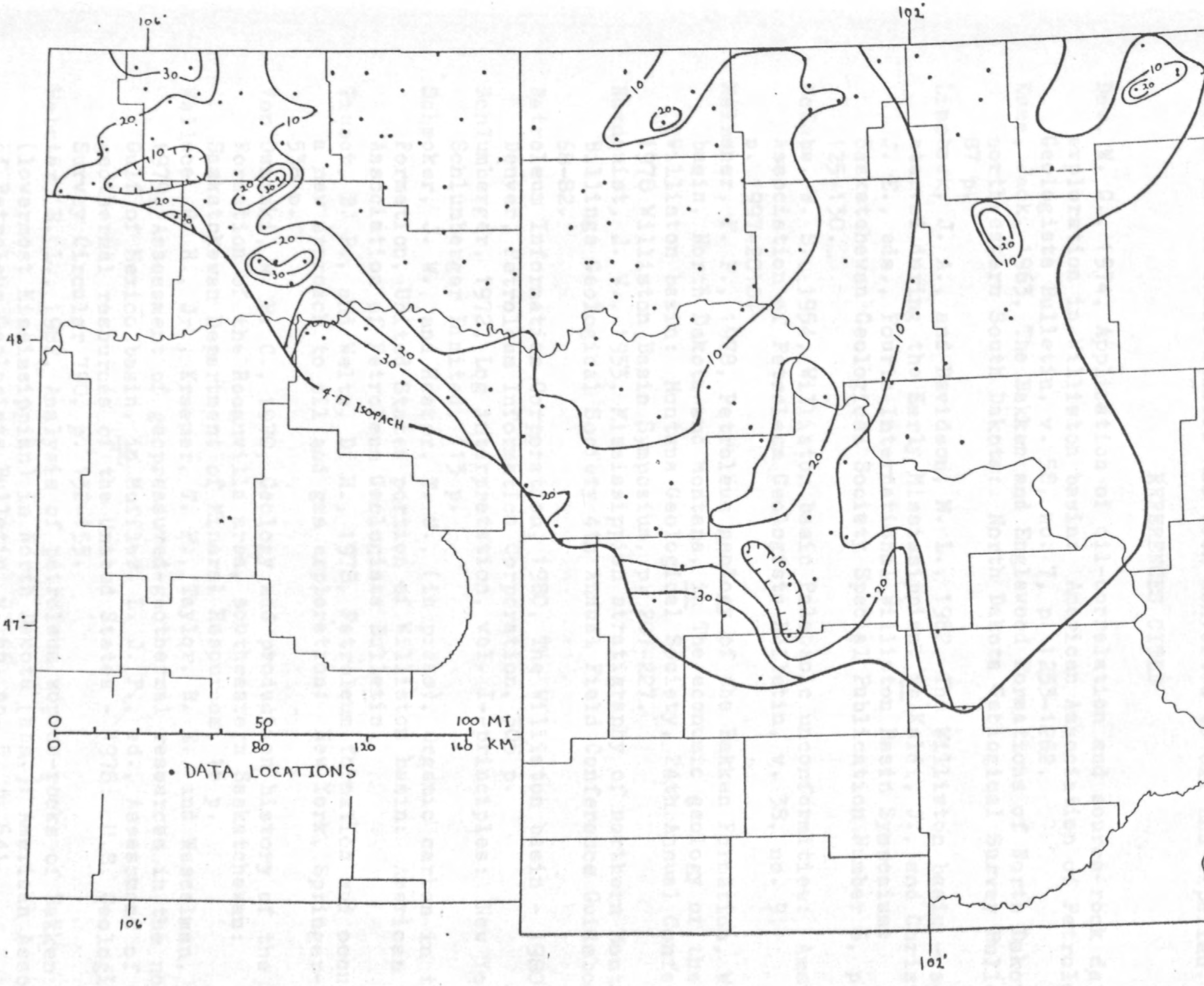


Figure 19. Average resistivity (uncorrected) of middle member of Bakken Formation. Contour interval = 10 ohm $m^2$/m. Four-ft (1.2-m) isopach marks minimum thickness mapped on figs. 10, 12, 14, 15.

temperatures are roughly proportional to the level of thermal maturity, resistivity values define the region where oil saturations are high, and density and neutron-log data show that a significant amount of organic matter in the shale members has been converted to oil and expelled.

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