A MECHANICAL WELL LOG STUDY OF THE POPLAR INTERVAL OF THE MISSISSIPPIAN MADISON FORMATION IN NORTH DAKOTA

by

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ILLUSTRATIONS

ABSTRACT

The complex facies of the Madison Formation are subdivided into para-time rock units (intervals) on the basis of extensive thin anhydrite beds which are considered time-parallel units. The interbedded evaporites and carbonates of the Poplar Interval form the uppermost part of the Mississippian Madison Formation. Detailed mechanical well log study was used to differentiate the limestone, dolomite, anhydrite, and salt beds within the Poplar Interval. This analysis was used to interpret the Poplar's regional geology and to attempt to locate areas with potential for petroleum production.

The base of the Poplar Interval is a widespread anhydrite unit. The top of the Poplar on the basin flanks is a thin anhydrite, whereas in the basin interior a thick massive salt overlying the thin anhydrite is considered to be the top. Salt deposits formed during periodic increases in the rate of basin subsidence account for most of the increase in thickness (176 feet on the basin flanks, to 687 feet in the central basin area) of the Poplar Interval.

The anhydrites and salts of the Poplar Interval were deposited in a saline environment caused by the restriction of a regressing sea. Periodic transgressions caused near normal marine conditions that resulted in the deposition of carbonates. Some anhydrites that may have been deposited in sabkhas resulted in linear down-dip trends of thicks and thins in gross anhydrite in the basin and a general increase in anhydrite from the basin center to the basin margins.

Except where influenced by the Nesson anticline and other structures in Divide and Billings Counties, the Poplar Interval generally conforms to the Williston basin. The Nesson anticline and a small anticline named Divide high in Divide County were actively positive, although subdued in Poplar time. An anticline in Billings County appears to represent a post-Poplar event. Pre-Mesozoic erosion only affected a band along the northeast margins of the Poplar where this interval is not overlain by the Kibbey Formation.

Poplar exploration should be carried out primarily as a search for anticlines similar to that in the East Poplar Field in Montana that produces oil from the Poplar Interval. Stratigraphic traps should also be considered.

INTRODUCTION

Purpose

Since the discovery of petroleum in North Dakota in 1951, the most prolific producing horizons have proven to be those within the Mississippian Madison Formation. Carlson and Anderson (1965, p. 1841), in discussing Madison production, pointed out that the majority of this production is in northwestern North Dakota, primarily from structural traps along the Nesson anticline and secondly from stratigraphic traps in the form of porosity pinch-outs caused by updip facies changes and abutment against the pre-Mesozoic unconformity.

The interbedded carbonates and anhydrites of the Poplar Interval of the Madison produce oil in the East Poplar Field in Montana and have long been considered to have good potential for petroleum reserves in North Dakota.

On the recommendation of Dr. Walter L. Moore, Professor of Geology at the University of North Dakota, I undertook a mechanical well log study of the Poplar Interval in North Dakota. The result is a regional study of the Poplar in which the stratigraphy, structure, and lithology, along with the effects of erosional truncation, have been interpreted in an attempt to locate potential petroleum traps. A limited interpretation of the environments of deposition and its effect on petroleum accumulation has been made.

Location and Extent of Study Area

The Poplar Interval within North

Dakota is restricted to the Williston basin; and the study area, which is approximately 210 miles long and 195 miles wide, is delineated by the Canadian border to the north the Montana boundary to the west, the South Dakota boundary to the south, and the Ratcliffe Interval subcrop to the east (fig. 1). The Ratcliffe Interval lies conformably below the Poplar Interval. The eastern edges of the Poplar and the Ratcliffe subcrops were controlled by pre-Mesozoic erosional truncation. The Poplar subcrop below the unconformity occurs in Renville, McHenry, Sheridan, Wells, Kidder, Burleigh, Emmons, and Sioux Counties (pl. 1).

Methods of Study

Mechanical logs of 281 wells penetrating the Poplar Interval were examined. When available, electric, gamma ray, and sonic logs were used, supplemented by self-potential, micro, caliper, neutron, and formation density logs. Good log control permitted differentiation between limestone, dolomite, anhydrite, and salt. This interpretation of lithologies is made without the benefit of core or drill samples. It is based on the physical properties of the rocks, recorded in the mechanical logs.

I established mechanical well log parameters for differentiating the salts, anhydrites, limestones, and dolomites which had previously been established as the primary phases in the interval based on the literature. Dolomites could not easily be differentiated from silts and shales. Dolomites, as interpreted from the logs, were considered to range from very organic-rich dolomites to very argillaceous, silty dolomites.

Figure 2 shows a gamma ray log, sonic log (interval transit time), spontaneous potential log, and induction electrical log (resistivity–conductivity) along with the lithology of the Poplar Interval which was interpreted from them. Any phase with a resistivity greater than 75 ohms-m^2/m, an interval transit time less than 52 microseconds per foot and a gamma radiation of 16 API units or less was considered to be anhydrite. Phases with a gamma radiation in excess of 32 API units, which corresponded to a transit time of 61 microseconds per foot or greater and a resistivity of 8 ohms-m^2/m were considered to be dolomites. Phases with properties intermediate to those of anhydrite and dolomite as indicated by the logs were considered to be limestone.

Porous and clean limestone was interpreted from low resistivity, low gamma ray, and slow transit time readings on the logs, whereas argillaceous and dense limestone was interpreted from high gamma ray and fast transit time readings. Salt is not represented in figure 2, but where present it was easily recognized because salt has slow transit times (approximately 70 microseconds per foot) and the caliper log indicated washed-out intervals.

Five cross sections (pls. 5-9), using the top of the Poplar Interval as datum, were constructed to show the stratigraphy of the unit throughout the basin.

A structure contour map (pl. 1) was constructed on the top of the Poplar Interval to determine the strike and dip and general form of the interval within the basin. This map was also used to locate any anomalous features that may be potential structural traps for hydrocarbons. Two isochore maps were made, one of the total Poplar Interval (pl. 2) and one of the total salt in the interval (pl. 3). These maps were used to determine if there are any anomalously thick or thin parts of the interval which may suggest carbonate buildups, stratigraphic pinch-outs, or erosional truncations, which could result in hydrocarbon reservoirs. A map showing the ratio of anhydrite to carbonate in the interval (pl. 4) was made to show concentrations of anhydrite and carbonate. Because the carbonate is potentially porous and the anhydrite, nonporous, this map shows where areas of potentially high porosity are most likely to pinch-out in the zones of low porosity.

Previous Work

The Upper Mississippian intervals have received considerable attention in the past, but most of it has been applied to the more

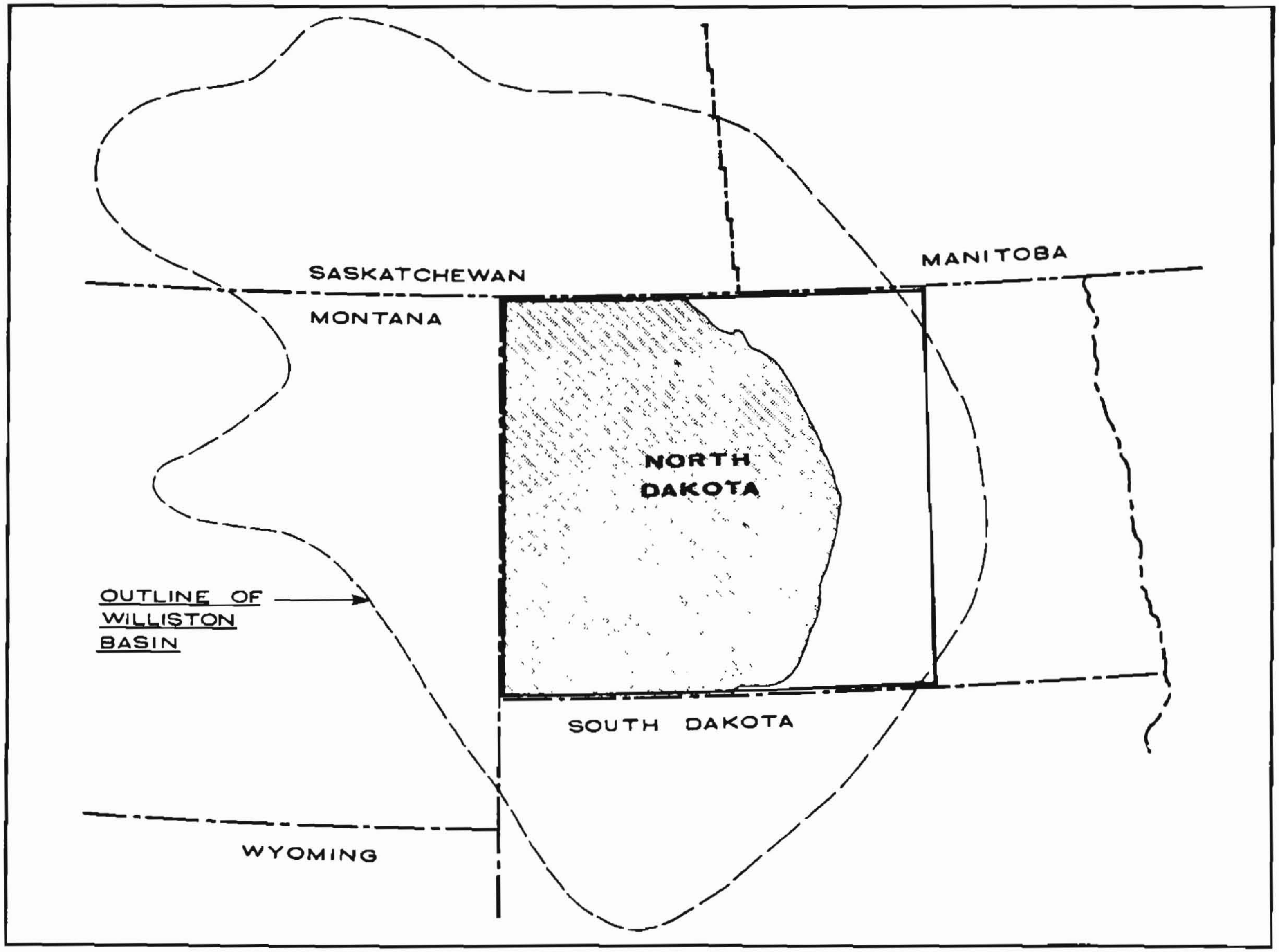

Figure 1. Map showing location of study area and occurrence of the Poplar Interval in North Dakota. (Modified after Carlson and Anderson, 1965, p. 1834.)

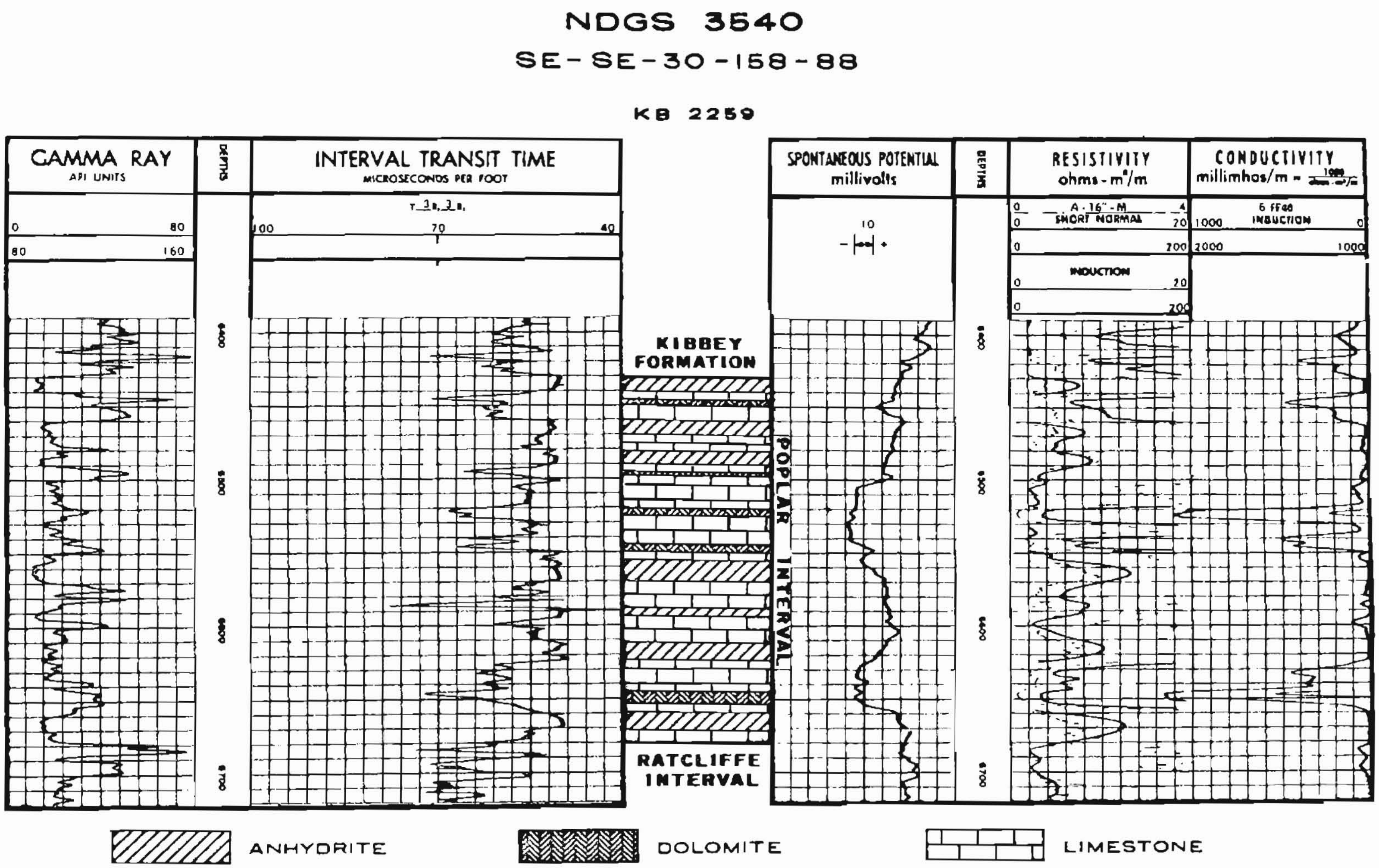

Figure 2. Diagram showing typical well logs of the Poplar Interval and the lithology which has been interpreted from them.

prolific producing zones such as Midale and Frobisher limestones.

Fuller (1956a, p. 32), in discussing the Charles facies, described the gross stratigraphy and lithology of the Poplar beds in Saskatchewan. Beekly (1956, p. 61-65) discussed the stratigraphy, structure, lithology, and type of porosity in the reservoir beds in the East Poplar Field in Montana. Anderson (1958) discussed the lithology and stratigraphy of the Charles Formation in northwestern North Dakota, and on several geologic cross sections of the Mississippian section in northwestern North Dakota, demonstrated the facies relationships and the stratigraphy of the Poplar Interval. The Special Studies Committee of the Billings Geological Society (1964, p. 105-108) has described lithology and depositional environments of the Charles Formation in northeastern Montana. Moore (1964, p. 263-265) discussed the limestone, dolomite, and anhydrite phases of the Mission Canyon facies and how they can be differentiated on mechanical well logs.

ACKNOWLEDGMENTS

I should like to thank my committee chairman, Dr. Walter L. Moore, for his guidance and counseling throughout this study. Drs. Frank Karner and Alan M. Cvancara, the other two members of my committee, are gratefully acknowledged for their suggestions and constructive criticism. The advice in log interpretation supplied by Sidney B. Anderson of the North Dakota Geological Survey was invaluable. Amerada Minerals Corporation of Canada Limited was most gracious in making their facilities available to me for the completion of this study.

STRATIGRAPHY

General Stratigraphic Correlations

The terminology for Mississippian rocks used in the Williston basin today is a combination of the original terminology applied to exposed strata in Montana and the terminology which has evolved as more and more information from the subsurface has been gathered from numerous wells drilled in the Williston basin. In North Dakota the Poplar Interval is considered to be the series of interbedded salts, anhydrites, carbonates, and occasional thin clastic tongues which make up the upper part of the Madison Formation (Carlson and Anderson, 1965, p. 1840-1841) (fig. 3).

Peale (1893, p. 33) applied the term "Madison limestone" to a series of Lower Carboniferous limestones exposed near Three Forks, Montana. The Madison was later elevated to the rank of group when it was subdivided by Collier and Cathcart (1922, p. 173) into two formations, the Lodgepole and Mission Canyon. The lower of the two, the Lodgepole, was named for 800 feet of thin-bedded limestone in Lodgepole Canyon. The upper formation consisted of 500 feet of thick-bedded limestone and was named for the Mission Canyon, where it is well exposed. Both of these type sections are located in the Little Rocky Mountains of Montana.

Subsurface terminology was first introduced by Seager (1942, p. 864) when he applied the term "Charles Formation" to some evaporites he logged in the California Company Charles No. 4 well in eastern Montana. Seager was uncertain whether the Charles should be included in the Madison Group below or the Big Snowy Group above. Ultimately he included it as the basal formation of the Big Snowy Group. This nomenclature was accepted until 1951 when the Charles was transferred to the Madison Group. The increased amount of subsurface information, combined with studies of exposures of the Madison in southwestern Montana, indicated that the Charles Formation was genetically related to the Madison (Sloss and Moritz, 1951, p. 2157).

With the added information from increased drilling throughout the Williston basin, geologists became aware of the complex facies relationships of the Madison. Porter (1955, p. 128) recognized that the Charles, Mission Canyon, and Lodgepole interfingered and exhibited both lateral and vertical facies relationships. In trying to correlate these subsurface facies, geologists found that the terminology as

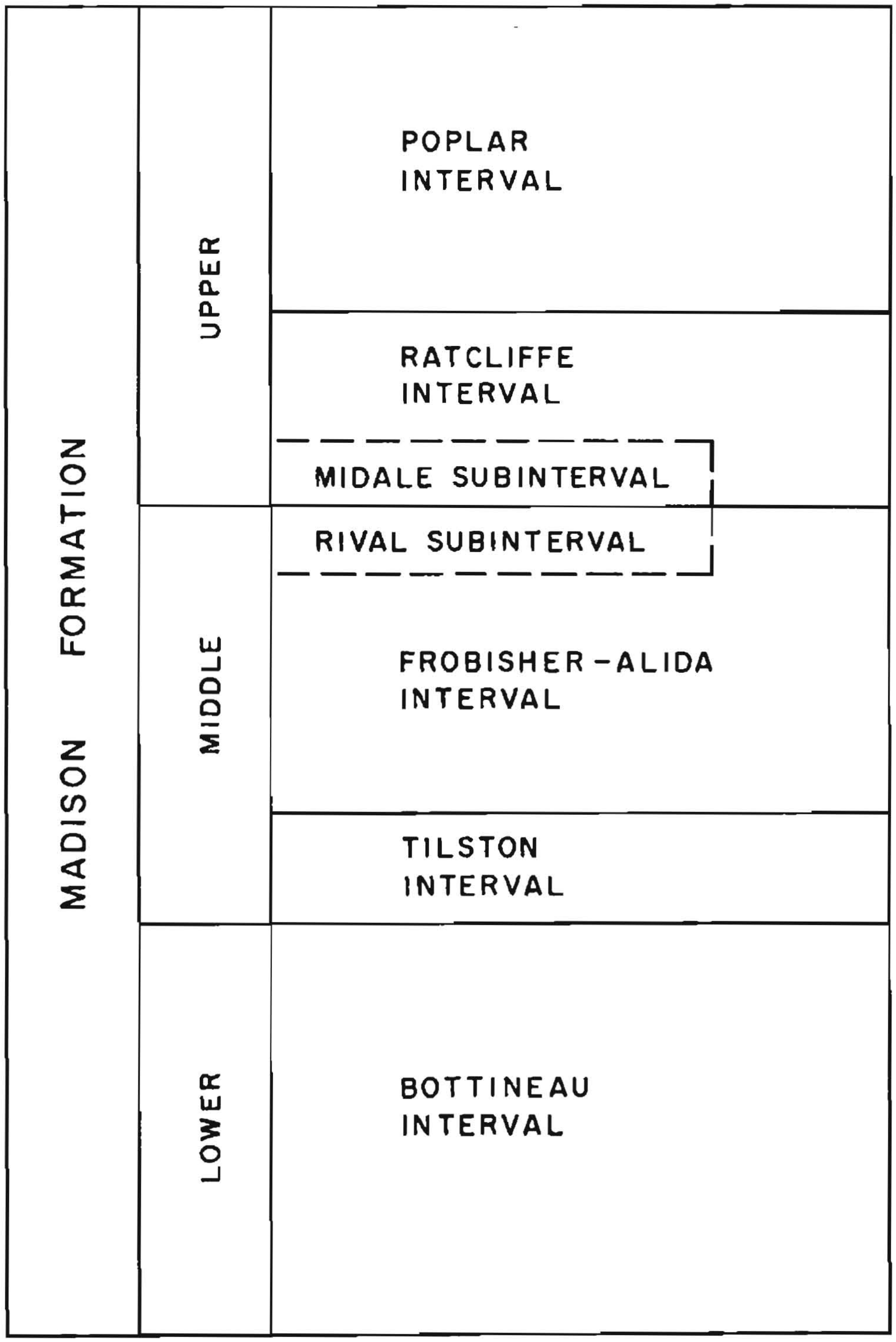

Figure 3. Chart showing subdivision of the Madison Formation into units, intervals, and subintervals. (Modified after Carlson and Anderson, 1966, p. 5).

applied at the surface was inadequate.

Fuller (1956a, p. 32), in discussing the Mississippian rocks in southeastern Saskatchewan, pointed out that the Charles Formation could be defined to include all the evaporite beds intertonguing with the Madison limestone along the margin of the basin as well as the beds overlying the continuous limestone within the central basin area, but he felt the result would lack utility. Fuller presented a second alternative which could be to pick some well defined, basin wide bed as the base or lower limit of the formation, but felt that this would leave the undesirable situation of massive evaporites on the basin flank within a sequence clearly defined as Madison or Mission Canyon limestone. Fuller (1956b, p. 26) overcame these problems by using mechanical log markers for subdividing the horizons of the Madison. He believed that the thin anhydrite beds, which were uniform over large areas, were time parallel units and, consequently, divided the Madison into para-time rock units (fig. 4).

This concept was accepted by both the Saskatchewan Geological Society and the North Dakota Geological Society and Survey. Since the marker horizons used in Saskatchewan were not suitable for basin wide correlations in North Dakota, a new definition of Madison stratigraphy was established by the North Dakota Geological Survey. Smith (1960, p. 959), who chaired the committee of the N.D. Geol. Society that redefined the Saskatchewan terminology, used two good basin wide marker horizons to subdivide the Madison in North Dakota. Of the changes Smith made, one was to redefine the Poplar, Ratcliffe, and Frobisher-Alida units. These terms in an abstract (Smith, 1960) were formally defined in oil fields of Burke County (Anderson, Hansen, and Eastwood, 1960). As the Stratigraphic Code does not recognize para-time rock units, a second change by the committee was to refer to the units as intervals (fig. 5).

Carlson and Anderson (1965, p. 1840) pointed out that, although the terms Charles, Mission Canyon, and Lodgepole are within the limits of the definition of formations, it is more convenient to refer to them as facies within the Madison, and the Madison should be considered a formation. In ascending order the intervals of the Madison Formation recognized in North Dakota are Bottineau, Tilston, Frobisher-Alida, Ratcliffe, and Poplar.

The North Dakota Geological Survey now recognizes the Poplar Interval as the sequence of rocks lying conformably between the Ratcliffe Interval beneath and the Kibbey Formation above, except where the Poplar has been truncated by Mississippian and pre-Mesozoic erosion. The Poplar subcrop is unconformably overlain by the Pennsylvanian Tyler Formation from the southwest half of Sheridan County to the South Dakota border, whereas from the northeast half of Sheridan County north to the Canadian border the Poplar subcrop is overlain by the Triassic Spearfish Formation (Anderson, 1974).

The Ratcliffe is an interval of interbedded carbonates and evaporites, similar to the Poplar Interval, except that there is little salt in the Ratcliffe.

The Kibbey, Otter, Heath, and Spearfish Formations for the most part consist of clastics that are predominantly shale with minor fractions of silts and sands.

Detailed Stratigraphy

Excluding the structurally deformed thick in south-central McKenzie County, and the thin, eroded subcrop area, the Poplar Interval is thinnest (176 feet) in northeast McLean County (pl. 2) and thickens toward the basin center, where it reaches 687 feet.

A series of stratigraphic cross sections, cross sections AA', BB', CC', DD', and EE' (pls. 5-9) show a varied and complex stratigraphy within the interval, but close examination of the sections reveals some consistency and rhythm in the strata.

A striking feature of the interval is the extent of some of the anhydrites which can be correlated great distances across the basin. There are two types of anhydrites, marginal anhydrites which occur on the basin flanks and wedge out toward the center of the basin, and basin anhydrites

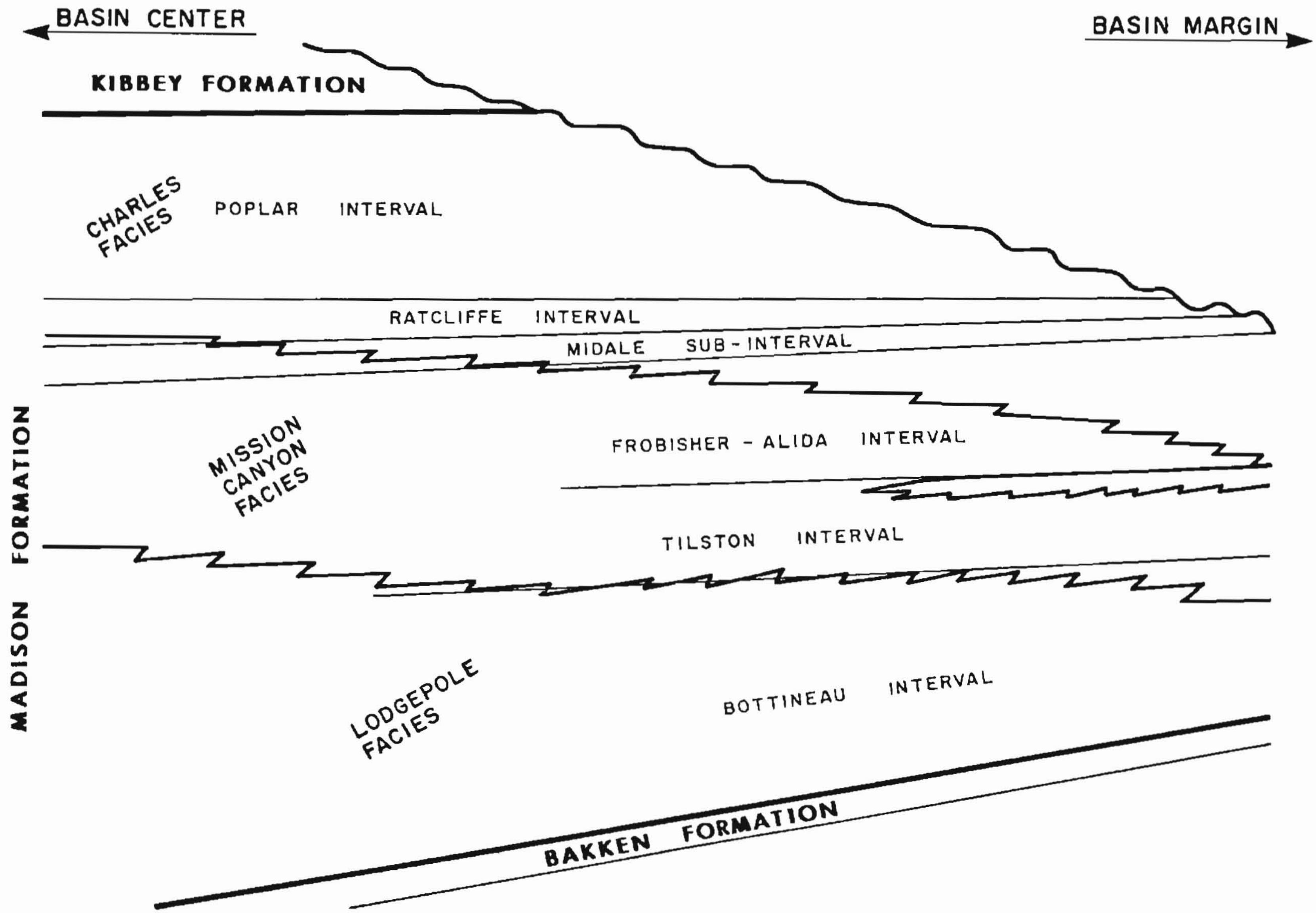

Figure 4. Diagram illustrating the relationship between para-time rock units and facies units of the Madison Formation. (Modified after Carlson and Anderson, 1965, p. 1842.)

STRATIGRAPHIC SECTION

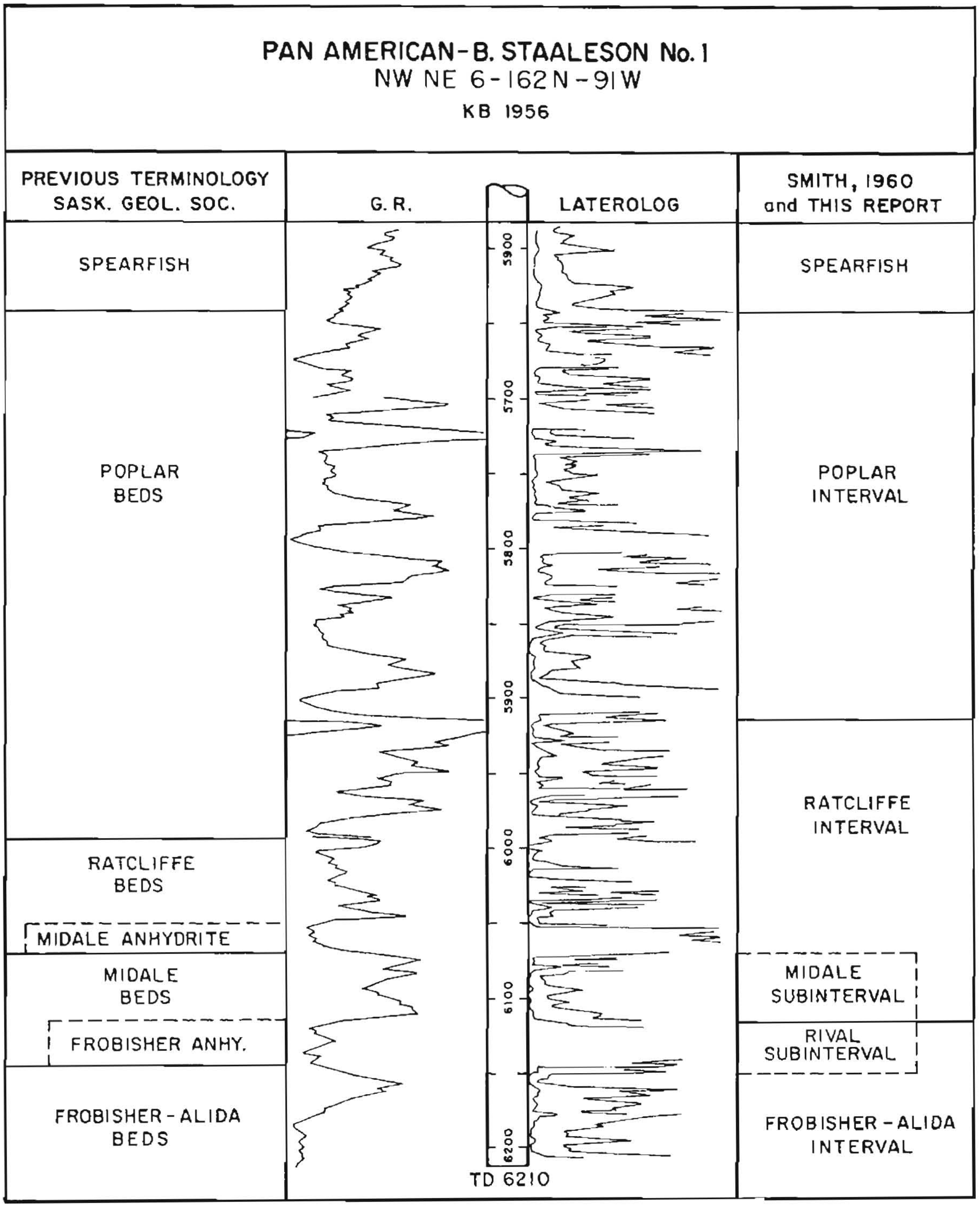

Figure 5. A well log showing the log characteristics of the two good marker horizons (base of the Poplar Interval and base of the Ratcliffe Interval) used for the subdivision of the Madison Formation in North Dakota as well as a comparison of the redefined intervals with the previously used Saskatchewan terminology. (With permission from Anderson and others, 1960, p. 4.)

which may but do not always extend across most or all of the entire study area. This distribution suggests that the former may have been deposited in sabkhas, whereas the latter probably were submarine deposits.

Two of the basin anhydrites which occur throughout the study area are labeled A-1 and A-2 on the cross sections. A-1, the lowermost anhydrite, is used to pick the base of the Poplar Interval, because it is easily recognized on logs throughout the basin. However, a thin limestone sometimes separates it from the Ratcliffe Interval below.

A-2, a thicker anhydrite unit, generally divides the Poplar Interval in half, except in the central basin area where the upper Poplar is much thicker due to the presence of thick salt at the top of the interval. A thick limestone unit overlies each of the anhydrites, and each limestone is overlain, in turn, by an apparently randomly interbedded sequence of limestones, anhydrites, and in the central basin area, also salts.

The beds of primary dolomite, scattered throughout the interval, are highly organic and argillaceous and, in some cases, may be predominantly silty shales. Unfortunately, it was not possible to differentiate between organic-rich dolomites and shales with mechanical logs.

The thin dolomites commonly overlie anhydrite beds, but this cannot be considered a rule. They occur with no obvious pattern throughout the limestone phase, and, consequently, are not differentiated from the limestone beds in the description of the stratigraphy which follows.

The lower sequence of limestones, anhydrites, and salts between A-1 and A-2 gradually thickens from an average of 90 feet on the basin margin to approximately 150 feet in the basin center. The first 50 feet of this unit is limestone, with the exception of the southwest part of the basin where the limestone is interbedded with thin, marginal anhydrites. As a rule, this limestone increases in porosity and to some extent shaliness from the central basin to the margins. The porosity tends to increase from the bottom of the bed upwards.

The second 50 to 100 feet of the unit consists of interbedded limestone, anhydrite, and salt, including two basin anhydrites. The first is limited to the central and northern portion of the basin and consequently is seen only on sections AA' and BB'. The second anhydrite was the last anhydrite deposited before A-2. It is more extensive, occurring throughout most of the study area with the exception of the extreme west-central area along the Montana border as shown on section BB'.

Several marginal anhydrites occur in the 50 feet below A-2. On cross sections paralleling strike such as CC' and the south portion of DD', marginal anhydrites commonly appear as individual lobes with little lateral extent. For example, marginal anhydrites in wells 1807 and 4400 have little lateral extent in cross section CC' (parallel to strike) yet extend for up to 10 miles down dip in cross section BB'.

Two salt beds occur in the sequence below A-2. The first lies within the limestone between the two anhydrites and is only 10 to 15 feet thick. It is restricted to the very central portion of the basin and consequently appears only on section BB'. The second salt, immediately above the second anhydrite on section BB', reaches a maximum thickness of approximately 30 feet in the central basin area. This salt extends much farther than the other to the north, south, and east, but, as with the anhydrite it overlies, it does not extend very far to the west as shown on sections AA', BB', and EE'.

Directly above A-2 another extensive unit consists of a thick limestone bed and a salt bed which are separated in places by a discontinuous anhydrite bed. The limestone gradually thins from approximately 75 feet in the central basin to approximately 60 feet on the north and northeast margins, and roughly 45 feet on the south and southeast margins. This limestone is similar to the one discussed in the sequence below A-2 in that porosity and shaliness appear to increase towards the margins with some pronounced exceptions as in well 2892 on section BB' in which the limestone appears quite tight. A few marginal anhydrites in this limestone can be seen on sections CC' and DD'.

The overlying salt in the sequence immediately above A-2 is the most extensive salt in the Poplar Interval. Its lateral extent can be seen on the Total Salt Isochore Map (pl. 3). It has a maximum thickness of approximately 60 feet in the central basin and thins gradually to 0 feet in the marginal area on sections BB' and EE'. Where the extensive salt bed thins to zero feet the underlying limestone merges with the limestones and anhydrites above, and the unit can no longer be distinguished (for example, see sec. BB').

In the central basin area, immediately above the extensive salt bed, a 135-foot sequence of thinly interbedded limestones, anhydrites, and salts occurs (secs. AA', BB', and EE'). It is also evident from these three sections that the top of this sequence correlates with the top of the Poplar on the basin flanks.

On the basin flanks the extensive salt bed described earlier is overlain by a limestone unit which thins from a maximum of 60 feet at the edge of central basin to roughly 40 feet on the eastern margin (sec. BB') and down to 10 feet on the southeast and southern margins (secs. EE' and DD'). This limestone is overlain by a 10-foot anhydrite bed which is the top of the Poplar Interval on the basin flanks.

Near the edge of the central basin the upper limestone and anhydrite cap changes facies into the previously discussed, thinly-bedded sequence of limestone, anhydrite, and salt (secs. BB' and EE'). Where the facies change occurs, the dip of all the beds discussed in the Poplar Interval so far increases into the basin center (secs. AA', BB', and EE'). The dip seen on the cross sections is apparent. The structure contour map (pl. 1) shows that the top of the Poplar actually has a substantial dip into the basin center, and hence the dip of the beds is actually greater than is apparent in the cross sections. The hinge line where the thinly-bedded sequence increases in dip into the basin center coincides with the zero edge of an overlying massive salt bed which thickens to over 170 feet in the central basin area. This salt is capped in places by a minor limestone bed (secs. AA' and BB'). Although this salt is the uppermost unit of the Poplar Interval in the central area, it is younger than the anhydrite at the top of the Poplar Interval on the basin flanks, because it overlies the anhydrite's equivalent in the basin center.

It is noteworthy that the change in dip of the beds corresponds to an abrupt increase in total Poplar thickness towards the center of the basin (pl. 2).

This change also corresponds to an abrupt increase in salt thickness (pl. 3) towards the basin center. On the basin flank the beds below the extensive salt have an increased dip to accomodate the salt as it thickens towards the basin (sec. BB', pl. 6). The same is true of the beds beneath the salts in the sequence below A-2.

All the salt beds thicken towards the basin center, whereas there is little variation in the total carbonate and anhydrite thickness throughout the basin. This is borne out by the two isochore maps (pls. 2 and 3). The Poplar Interval can be seen to thicken gradually from roughly 200 feet at the subcrop to approximately 275 feet where the first salt occurs, and then it thickens abruptly to 687 feet in the basin center, an increase of 412 feet (pl. 2). On the Total Salt Isochore (pl. 3) the salt increases from 0 feet to 367 feet in the same distance. The salt was responsible for all but 45 feet of the total increase.

Apparently the central basin periodically subsided more rapidly than the basin flanks, and, when it did, salt was deposited. Generally the deposition of salt kept pace with subsidence as the tops of the salt beds in each case are flat relative to their bases. This is most evident with the last thick salt where the top of the salt is level with the top anhydrite bed on the basin flank.

LITHOLOGY

General Lithology

In order to interpret lithologies from mechanical logs some prior knowledge must be gained of the range of lithologies to be expected. A search of the literature produced no descriptions specifically of the Poplar, probably because the Poplar does not outcrop, and very few cores have been cut during drilling operations. However, a number of authors described the general lithology of Mississippian rocks of the Williston basin; and the Charles facies, which generally includes the Poplar Interval, has been described in general. Descriptions of the Charles facies can be applied with discretion to the Poplar.

Fuller (1956a, p. 32) described the Charles Formation of southern Saskatchewan as consisting of iron oxide-rich silty anhydritic mudstones, dolomitized limestones, argillaceous and organic dolomites, and massive anhydrite. He thought the mudstones were equivalents of the massive salts in North Dakota and Montana, suggesting the salts had been removed by groundwater solution.

Beekly (1956, p. 62) described the Charles Formation in the East Poplar Field of Montana as consisting of 41 percent limestone, 27 percent anhydrite, 27 percent dolomite, 3 percent salt, and 2 percent shale. He indicated that the low percentage of salt was a local anomalous condition unique to the East Poplar Field. In the general area of the field normally over 100 feet of salt and occasionally up to 280 feet are present.

The Special Studies Committee of the Billings Geological Society (1964, p. 105-107) discussed the Charles rocks in eastern Montana in more detail, discriminating between argillaceous limestones deposited in deep water which may be dolomitized, and reefoid limestones deposited in patch reefs in shallow water. The Committee indicated that the upper Charles facies were deposited in a more restricted environment and described the limestones of this type as dense and argillaceous with few fossils. The dolomites are of two types, primary dolomites which are argillaceous and in part silty, and secondary dolomites, which result from the dolomitization of limestone. The anhydrites range from pure to very argillaceous. The Committee described the formation as having salt deposits, which may be interbedded with shales and siltstones.

Moore (1964, p. 263-264) described limestone, dolomite, and anhydrite phases of the Ratcliffe and Frobisher-Alida Intervals. Although the strata he described are below the Poplar Interval, the general sequence of interbedded carbonates and anhydrites is similar to that on the margins of the Poplar Interval. The environments of deposition of the Ratcliffe were probably similar to those of the Poplar at times, and, consequently, similar lithologies probably exist in both intervals.

Moore (1964) described the limestones as being highly variable, highly indurated, fossilized, and, at times, secondarily dolomitized. The dolomite phase he described as consisting of subhedral grains of dolomite in a finer-grained dolomite matrix. It is generally weakly indurated, soft, and friable. Significantly, he described it as having minor amounts of organic material as opposed to the highly organic dolomite described by Fuller (1956a) in Saskatchewan.

Moore described a bimodal anhydrite phase. One mode is a mixture of fine anhydrite and dolomite grains and the other a contorted, interlaminated sequence of thin, fine-grained dolomite stringers and relatively coarser-grained anhydrite stringers.

For the purpose of interpreting lithologies from the mechanical logs, it is assumed, on the basis of the above references, that the Poplar Interval consists primarily of limestone, dolomite, anhydrite, and salt. The criteria for differentiating these lithologies using the mechanical logs is discussed under Methods of Study.

Lithologic Variations

The ratio of total anhydrite to total carbonate in the Poplar Interval was determined for all wells in which the Poplar lithology was interpreted, and an anhydrite/carbonate ratio map (pl. 4) was constructed. The map shows linear trends of anhydrite-rich areas and anhydrite-poor areas. The areas of high anhydrite/carbonate ratios generally correspond to the presence of marginal anhydrites. This variation in lithology will be further discussed in the following chapter on depositional environments.

Salt is the dominant lithology in the central basin area but is minor in the basin flanks and absent in the basin margins.

There is a general increase in anhydrite from the central basin area towards the basin margins that corresponds to a decrease in carbonates towards the margins.

DEPOSITIONAL ENVIRONMENTS

To fully understand the depositional environments one should have a detailed knowledge of the lithology and paleontology of the area he is dealing with. As my understanding of the Poplar lithology is gathered from a gross application of general rock types to mechanical well logs, my interpretation of environments must be grossly generalized. As the Poplar Interval consists of interbedded carbonates and anhydrites capped with a thick salt in the central basin area, it is assumed to have been deposited in a sea which was generally regressing. The cyclical deposits of carbonate and evaporites indicate that regression was interrupted with many transgressive surges.

The Poplar Interval is the final stage of a normal marine carbonate and evaporite cycle deposited in the Williston basin during Madison time.

Sandberg (1964, p. 38) suggested that the Williston basin of Mississippian time was flooded from the west by a sea that transgressed from the Cordilleran Geosyncline eastward through a trough in the position of the eroded Central Montana Uplift. According to the Special Studies Committee (1964, p. 105) the first shallow waters of the transgression deposited argillaceous and sparsely fossiliferous limestone of the Lodgepole facies, which was followed by a deeper, normal marine sea that deposited the fossiliferous limestones of the Mission Canyon facies.

The Committee stated that a progressive restriction of the sea over wide areas during Charles time was caused by shallow tectonic and/or organic topography such as reefs. The organic deposits of the initial Charles facies were interrupted by saline cycles that the Committee believed were created by distant sills.

The saline cycles resulted in the deposition of the anhydrite and salts of the Poplar Interval. The carbonates of the Poplar were deposited during interruptions of the saline cycles by marine transgressions that resulted in nearly normal marine environments.

The basin anhydrites described in the section on stratigraphy are no doubt evaporites that resulted from restrictive conditions imposed by barriers. Because these anhydrites are so widespread and uniform, the Special Studies Committee believed the restrictive barriers were remote from a local area. The Committee also referred to some localized evaporites that were thought to have developed on the sill area. These are the marginal anhydrites, discussed under stratigraphy, which I suspect were deposited in sabkhas.

Sloss (1966, p. 30) used the Briggs model (fig. 6) as one explanation for the deposition of thick basin evaporites. In that model, normal sea water fed into a shallow basin isolated from the open sea by a sill or bar, undergoes intense evaporation. The concentrated brines that result around the basin margins become more dense and sink to the basin floor. If the concentration reaches 3 1/3 times normal sea water, gypsum will precipitate. The gypsum commonly inverts to anhydrite when buried to a depth of 500-3000 feet, depending on whether water can escape. The important feature of this model is that the dense concentrated brine solution liberated of gypsum flows back to the open sea either by refluxing through the barrier or through stratified flow across the barrier (dense brine flows out below normal sea water flowing in). By removing the gypsum-depleted brine more normal marine water is allowed into the basin, and a current is set up that allows continuous deposition of anhydrite on the basin floor. If the brine solution cannot flow or reflux back to the open sea the brine concentration increases and salt is precipitated.

Sloss (1966, p. 24) also related the deposition of different facies to the rate of subsidence of the basin; and he believed that salt is deposited during a high rate of subsidence but did not indicate why. As

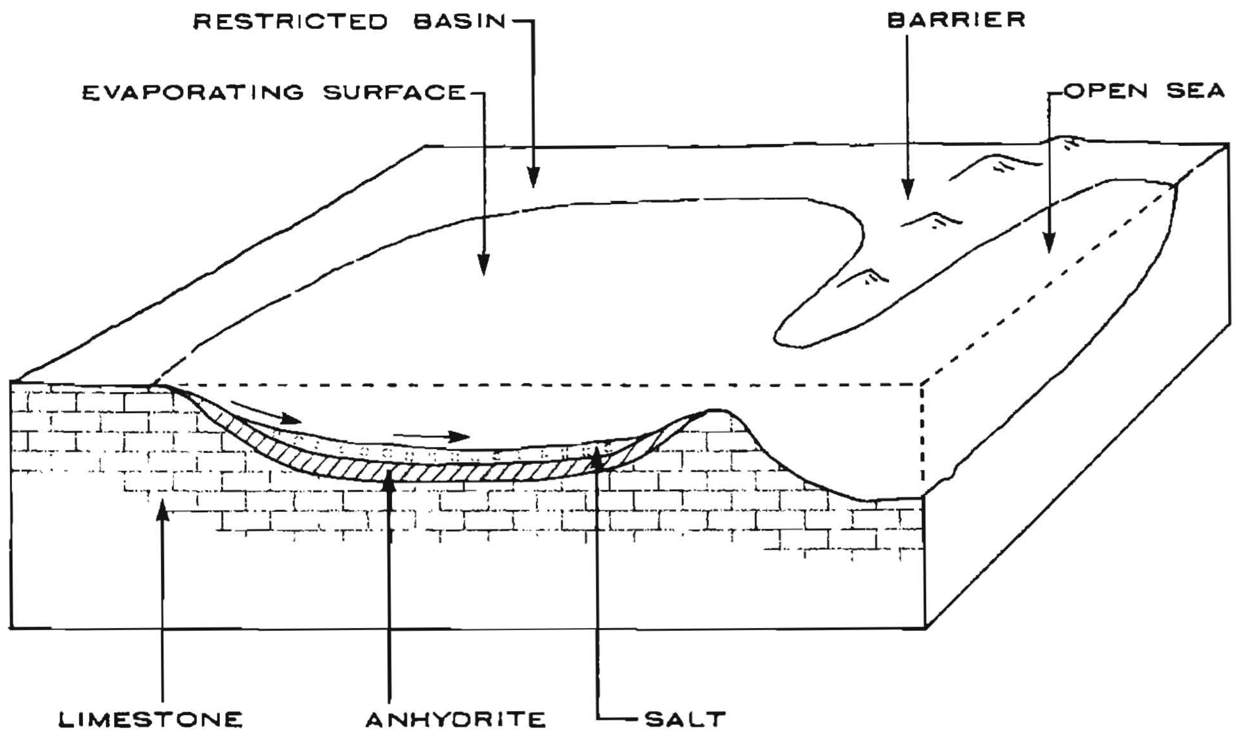

Figure 6. Diagram showing a restricted basin that could precipitate thick evaporite sequences. (Modified after Sloss, 1966, p. 30.)

noted in the discussion on stratigraphy, this idea appears to comply with the deposition of the Poplar salts. Perhaps periodic, rapid subsidence in the basin center in Poplar time elevated the barrier to the point that concentrated brines could no longer flow back to the open sea. However, if the barrier were still in the same position relative to the open sea, normal sea water could still flow into the basin to replace water losses resulting from constant evaporation. The process, if prolonged, would result in thick salt deposits.

Sloss (1966, p. 31) differentiated between basin interior anhydrites (dark and micro- to crypto-crystalline) and basin margin anhydrites, light colored, dolomitic, nodular, and granular or bladed. He pointed out that marginal anhydrites can originate in a sabkha.

In this study sabkhas represent wide, flat, coastal areas, such as those along the Persian Gulf described by Illing (1966, p. 11-17), where high evaporation rates can result in the precipitation of evaporites. When referring to the genesis of anhydrites, I refer to those deposited in sabkhas as sabkha anhydrites. Those deposited in submarine conditions, I refer to as basin anhydrites.

As noted in the discussion on stratigraphy, marginal anhydrites are extensive down dip (pls. 5, 6, and 9) but discontinuous along strike (pls. 7 and 8). This results in linear, down-dip trends of thicks and thins in gross anhydrite in the interval, which are shown on the Anhydrite/Carbonate Ratio Map (pl. 4). Assuming the marginal anhydrites were deposited in sabkha, it is possible to explain the variations in the anhydrite/carbonate ratio in the Poplar Interval.

Assuming there were minor topographic highs and lows on the supratidal flats of the basin margins and conditions were right for the development of sabkhas, anhydrites would have been precipitated on the highs, in the capillary zone above the water table (Illing, 1966). Drainage present, either from storm waves or continental drainage, would have followed the lows (fig. 7A).

A drainage pattern would have been established that would have maintained the low areas. When the area was flooded by marine transgression, and limestones and basin anhydrites were deposited, they would have draped over the highs and sagged into the lows preserving the previously established topography (fig. 7B). When the sea regressed and conditions were reestablished which were favorable for the development of sabkhas, deposition and drainage would have been on and in the preserved highs and lows (fig. 7C). In this way the sabkha anhydrites were successively deposited in the same geographic locations causing anhydrite-rich and anhydrite-poor areas (fig. 7D and pl. 4).

STRUCTURE

Configuration of the Top of the Poplar Interval

The structure of the Poplar Interval in North Dakota generally reflects the shape of the Williston basin, except where it has been influenced by the Nesson and lesser anticlines (pl. 1).

The center of the Poplar basin is in central McKenzie County. Excluding an impact crater feature (Red Wing Creek Field), about 12 miles west of the basin axis, the lowest recorded Poplar top in the study area is 6,589 feet below sea level (well 2849, T152N, R99W, pl. 1). This general area apparently was the basin center during Poplar time, as the Poplar reaches its maximum thickness there (687 feet in well 2828, T154N, R98W, pl. 2), if a structurally deformed thickness in T148N, R101W is excluded.

The highest recorded Poplar in the North Dakota portion of the basin, excluding the subcrop area, is 2,411 feet below sea level in northeast McLean County (well 3076, T150N, R79W, pl. 1). The maximum relief in the study area, discounting the structurally anomalous well 4062, is 4,178 feet.

The north-south trending axis of the basin extends from north-central Divide County southward to the eastern part of Bowman County (pl. 1).

The northern, eastern, and southern

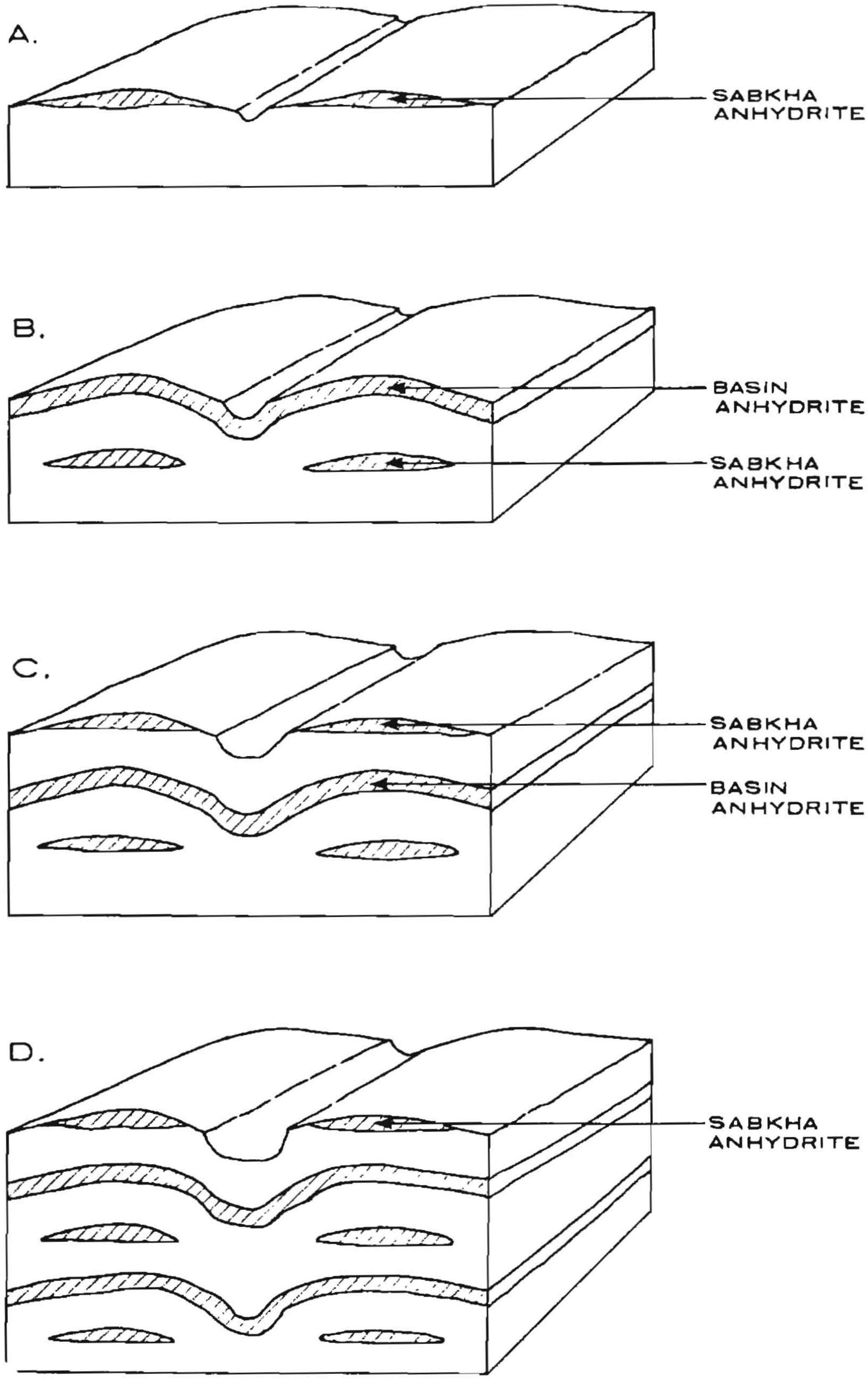

Figure 7. Diagrams illustrating anhydrite deposition which would lead to the variations in the ratio of anhydrite to carbonates in the Poplar Interval.

flanks of the Poplar basin occur largely within the study area, whereas the western flank lies essentially beyond the study area. The flanks studied dip fairly uniformly toward the basin center. The dip that is 40 feet per mile on the south flank changes gradually to 47 feet per mile on the east flank, and to 56 feet per mile on the northeast. The north flank, which is interrupted by the Nesson anticline, dips about 47 feet per mile. In all cases the dip flattens fairly abruptly to about 13 feet per mile in the central part of the basin. The change to flatter dips occurs between the elevation of -6000 feet and -7000 feet.

Influence of Individual Structures

Nesson Anticline

The Nesson anticline, the dominant structure in the basin, is a north-south trending feature approximately 90 miles long by 25 miles wide that plunges an average of 22 feet per mile from the southeast corner of Divide County southward into west-central Dunn County. Relief on the structure is a maximum of 900 feet near the border between Williams and McKenzie Counties and decreases uniformly north and south from that area.

The Poplar Interval thins slightly across the axis of the anticline (pl. 2), as is seen in the three wells 1765, 3843, and 2969 in T151N, R97W, R96W, and R95W. In well 1765 the Poplar is 592 feet thick. It thins to 562 feet in well 3843 and thickens again to 583 feet in well 2969. Because the Poplar thins over the Nesson anticline the structure was actively positive during the deposition of the Poplar Interval. However, considering that the structure's effect on the thickness of the Poplar was limited to a decrease of 10 to 30 feet, in striking contrast to the present relief of 900 feet, the anticline clearly was a more subtle feature during Poplar deposition than it is at present. Most of the relief on the structure today must be a result of post-Madison activity.

Surprisingly, although the anticline was positive during deposition of the Poplar Interval, it has not affected the pattern of deposition of the Poplar, as there are no significant facies changes related to the anticline. This supports the suggestion that relief was low during deposition of the Poplar Interval.

Billings High

A structural high almost wholly within Billings County (pl. 1) is referred to in this paper as the Billings high. The high is approximately 60 miles long by 12 miles wide, strikes north-south and plunges gently north at 15 feet per mile. It extends from northern Slope County to southern McKenzie County. Relief across the structure is interpreted to be 50 to 100 feet on the west flank. The east flank dips into the basin center, and therefore, most of the relief on that flank, up to 300 feet, is a regional effect. Because there is no evidence of this structure in the Poplar isochore map (pl. 2), it must represent a post-Poplar event.

Divide High

In the northwest corner of the study area, a structural high plunges out of Saskatchewan into Divide County and is referred to here as the Divide high. The North Dakota portion of this high is approximately 21 miles long by 10 miles wide, strikes northwest-southeast and plunges to the southeast at 50 feet per mile. The structural relief across the Divide high is greater than 100 feet and locally greater than 200 feet. A slight thin on the isochore map (pl. 2) corresponds to the high, suggesting that the Divide high was present and active during the deposition of the Poplar Interval.

Cedar Creek Anticline

The Cedar Creek anticline lies to the south, outside of the study area. It trends northwest-southeast and intersects the South Dakota-Montana boundary just south of the southwest corner of North Dakota. The effect of the Cedar Creek anticline on the Poplar structure in North Dakota can be seen as a slightly steeper northeast dip (pl. 1) in the southwest corner of Bowman County. There is no evidence that the anticline influenced the Poplar's thickness in North Dakota (pl. 2). Because it lies outside of the study area, no conclusions are drawn as to its effect on the Poplar Interval in general.

Effects of Pre-Mesozoic Erosional Truncation

Pre-Mesozoic erosional truncation had little effect on the structure of the Poplar. A subtle change in slope from that on the eroded surface of the Poplar to that on the uneroded top of the Poplar can be detected on plate 1. The break in slope is most apparent in the northeast where it steepens from approximately 41 feet per mile southwest on the subcrop to approximately 56 feet per mile southwest on the basin flank. In the southeast where the dip of the Poplar is less steep, the break in slope is more difficult to detect. There it changes from about 35 feet per mile on the subcrop to about 40 feet per mile on the basin flank.

ECONOMIC GEOLOGY

Present

To date the only economic production from the Poplar Interval has been the oil produced from the East Poplar Field in Montana, midway between the Bowdoin dome and the Nesson anticline. Production is from what Beekly (1956, p. 61-65) referred to as the "A," "B," and "C" zones. I believe the "A" and "B" zones correlate respectively with the limestones immediately overlying the A-2 and A-1 anhydrites discussed in this study. The "C" zone appears to lie within the Ratcliffe Interval. According to Beekly, the average porosity in the limestones is 11 percent and consists of fractures, intercrystalline porosity, and occasionally larger vugs.

The oil in the East Poplar Field is in a structural trap, an anticline 10 miles long by 6 miles wide. With an average net pay of 35 feet, an average porosity of 11 percent, and a productive area of approximately 17,000 acres, Beekly estimated in 1956 that the recoverable reserves for the field were greater than 60 million barrels of oil.

Future

Perhaps the first step in the exploration for other petroleum reservoirs in the Poplar Interval should be to determine anomalous conditions associated with the East Poplar Field which are directly responsible for entrapment of hydrocarbons. Similar conditions should then be looked for throughout the basin. As previously noted, the East Poplar Field occurs on an anticline, and porosity is intercrystalline, fracture, and in part vuggy. One anomalous situation in the East Poplar Field that does not appear directly related to entrapment is the lack of thick salt directly over the anticline. The Special Studies Committee (1964, p. 107) pointed out that the carbonate rocks often have a salt matrix, and if this salt is removed by secondary processes, porosity is enhanced. Perhaps the lack of salt and the intercrystalline porosity in the East Poplar Field is a result of groundwater solution.

Plate 1 shows structure contours drawn on the top of the thick salt present in the central part of the Poplar basin. Across two prominent structures, the Divide high and the Nesson anticline, the total salt interval (pl. 3) thins, and it can be concluded that the structural relief on subsalt stratigraphic units is even greater than that shown on the top of the interval. The Billings high, on the other hand, corresponds more or less with an area of thicker salt; and subsalt structural relief there will be subdued relative to that on the top of the interval. The structure contour map, used in conjunction with the salt isochore map, is thus a good indicator of structures to be expected at deeper levels. Nonetheless, some structures at depth could be masked by the thick salt deposits, and for a full understanding of any specific interval a separate structure map should be constructed.

Structure maps made on the A-1 and A-2 anhydrites would be more suitable for showing the structure of limestones above them. Similarly, the Total Salt Isopach map (pl. 3) does not show the variation in thickness of the individual salt beds, and isochores made on the salts immediately overlying the limestones would be more likely to show any anomalous thins within the salts.

In general, the area bounded by the

Nesson anticline on the east, the Billings high to the south, and the Canadian border to the north has been the most unstable during and since Madison time and is, therefore, the most logical area to explore for structures. Mechanical logs indicate that the Poplar limestones generally are tighter towards the central basin area, but they are also cleaner; and porosity could be enhanced by fracturing and/or by salt solution, as in the East Poplar Field.

Fuller (1956, p. 48) pointed out that as the sea levels gradually regressed during deposition of the Madison "Group" (Mission Canyon and Charles facies), each marine limestone facies which resulted from periodic retransgressions was deposited farther basinward. This is reflected in the positions of oil pools in stratigraphically lower reservoirs towards the edge of the basin and higher horizons towards the basin center.

In North Dakota production in the northeast part of the basin is established from horizons stratigraphically below the Poplar. For example, the Midale subinterval is productive in the northeast half of Burke County. Consequently, production from the Poplar might be expected in the northeast and southeast of Williams and Divide Counties.

Fuller indicated oil pools that are similar to these in southeastern Saskatchewan are structural stratigraphic traps in which the escape of oil is prevented in part by the impermeable rock at the pre-Mesozoic erosion surface that forms a continuation of overlying bedded anhydrites. In addition, there is a loss of permeability due to metasomatic replacement of reservoir limestone by anhydrite.

If similar conditions prevail in the Poplar Interval the Anhydrite/Carbonate Ratio map (pl. 4) can be used to locate areas of low anhydrite concentrations that trend into areas of high anhydrite concentration. In the areas of higher anhydrite percentages there is a greater possibility of limestone replacement by anhydrite. One such area is in Mountrail County where the ratio of anhydrite to carbonate is 0.2 in central Mountrail County and 0.7 updip in northeast Mountrail County. A stratigraphic trap resulting from loss of porosity and permeability due to replacement of limestone by anhydrite could exist in this area, assuming the necessary overlying anhydrite bed is present to act as a cap rock.

Although mechanical log interpretations indicate that porosity increases towards the margins, the increase in porosity is often accompanied by an increase in shaliness which reduces the effectiveness of the porosity. In spite of the increased shaliness the subcrop has potential for petroleum entrapment, because any porosity in limestones sloping up to the eroded subcrop area should be effectively sealed above and below by anhydrites, and should be capped on the updip eroded surface through induration of the erosion surface and by silts and shales of the Spearfish Formation. Examples of this type of trap are seen in Bottineau County in the Starbuck and Kuroki fields in which the truncated Midale subinterval is sealed by the overlying Spearfish Formation.

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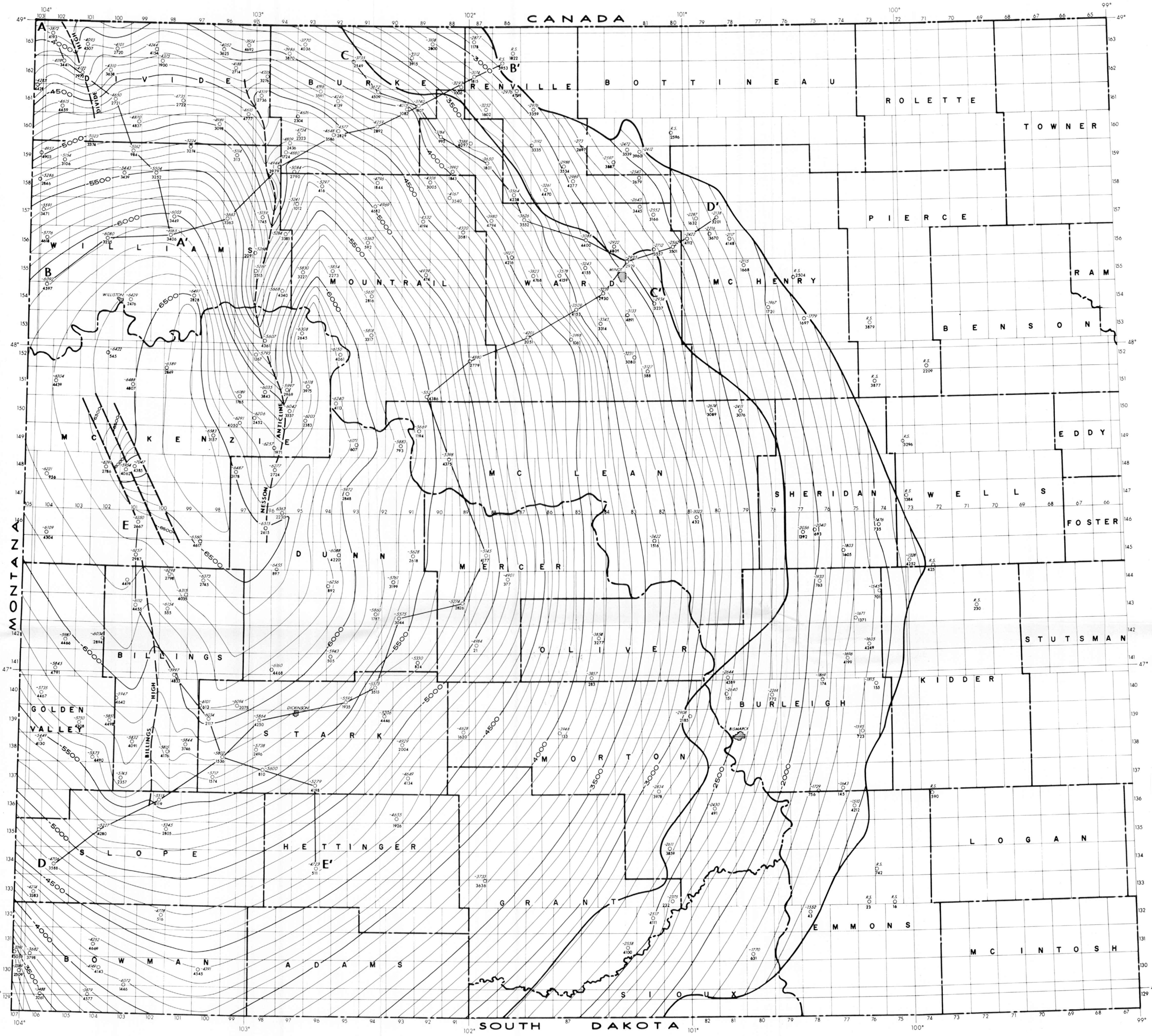


NORTH DAKOTA

PLATE # 1

STRUCTURE CONTOUR MAP
TOP OF POPLAR INTERVAL
SHOWING POPLAR SUBCROP

CONTOUR INTERVAL = 100 FEET

SCALE 0 6 12 18 24 30 MILES

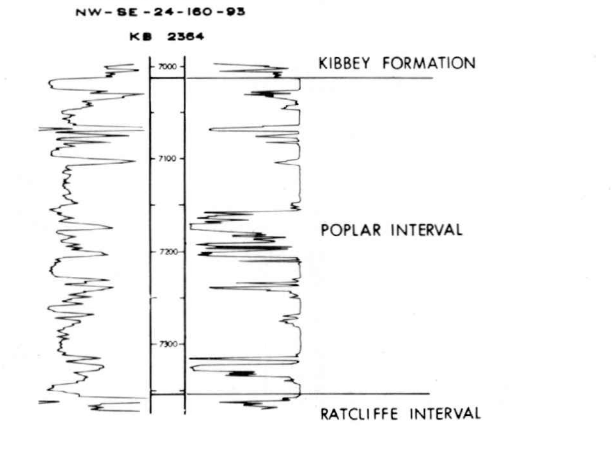
C.W. COOK 1976

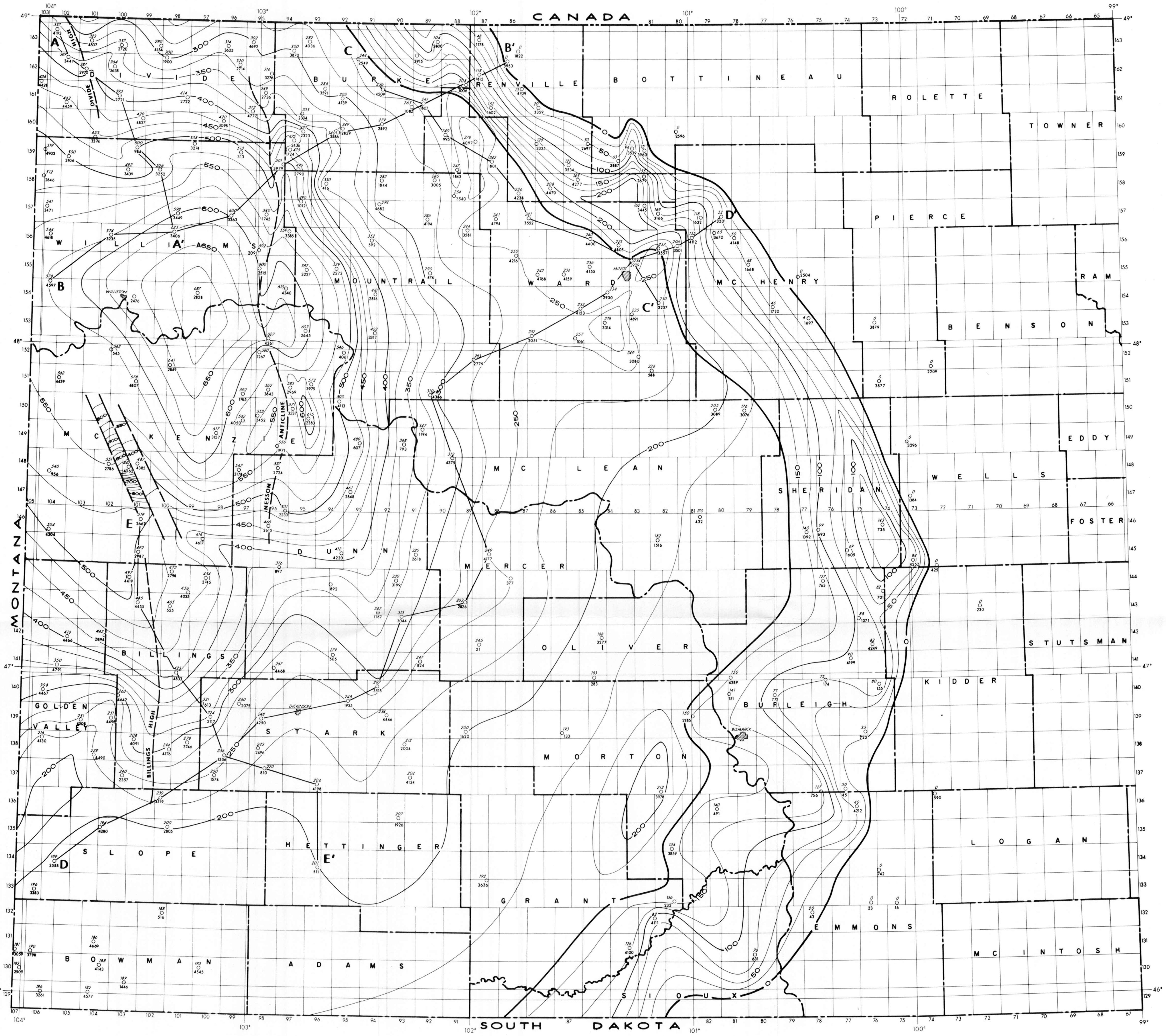
LEGEND

-4648 ..... SUBSEA ELEVATION. (R.S. ..... RATCLIFFE SUBCROP.)
o ..... CONTROL WELL.
3586 ..... N.D.G.S. NUMBER.

POPLAR SUBCROP.
(PRE-MESOZOIC TRUNCATION)

NDGS 3586
NW-SE-24-160-93
KB 2364





NORTH DAKOTA

PLATE #2

ISOCHORE MAP

POPLAR INTERVAL

SHOWING POPLAR SUBCROP

CONTOUR INTERVAL = 25 FEET

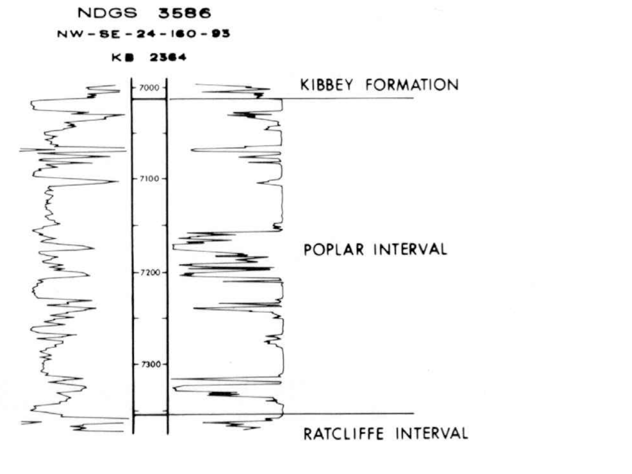
SCALE 0 6 12 18 24 30 MILES

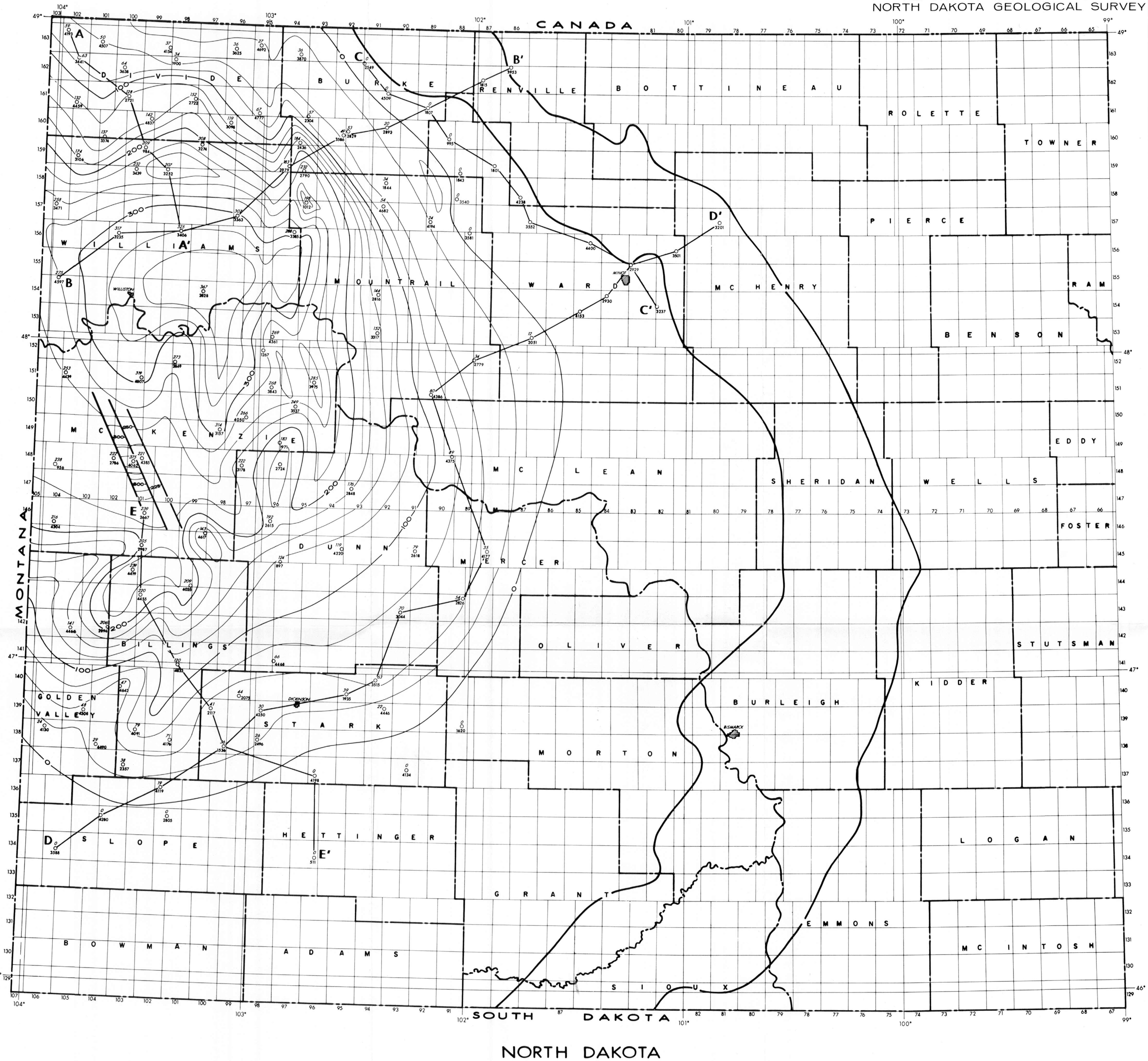
C.W. COOK 1976

LEGEND

340 — APPARENT THICKNESS.
o — CONTROL WELL.
3586 — N.D.G.S. NUMBER.

( ) POPLAR SUBCROP. (PRE MESOZOIC TRUNCATION)





NORTH DAKOTA

PLATE # 3

TOTAL SALT ISOCHORE

POPLAR INTERVAL

SHOWING POPLAR SUBCROP

CONTOUR INTERVAL = 25 FEET

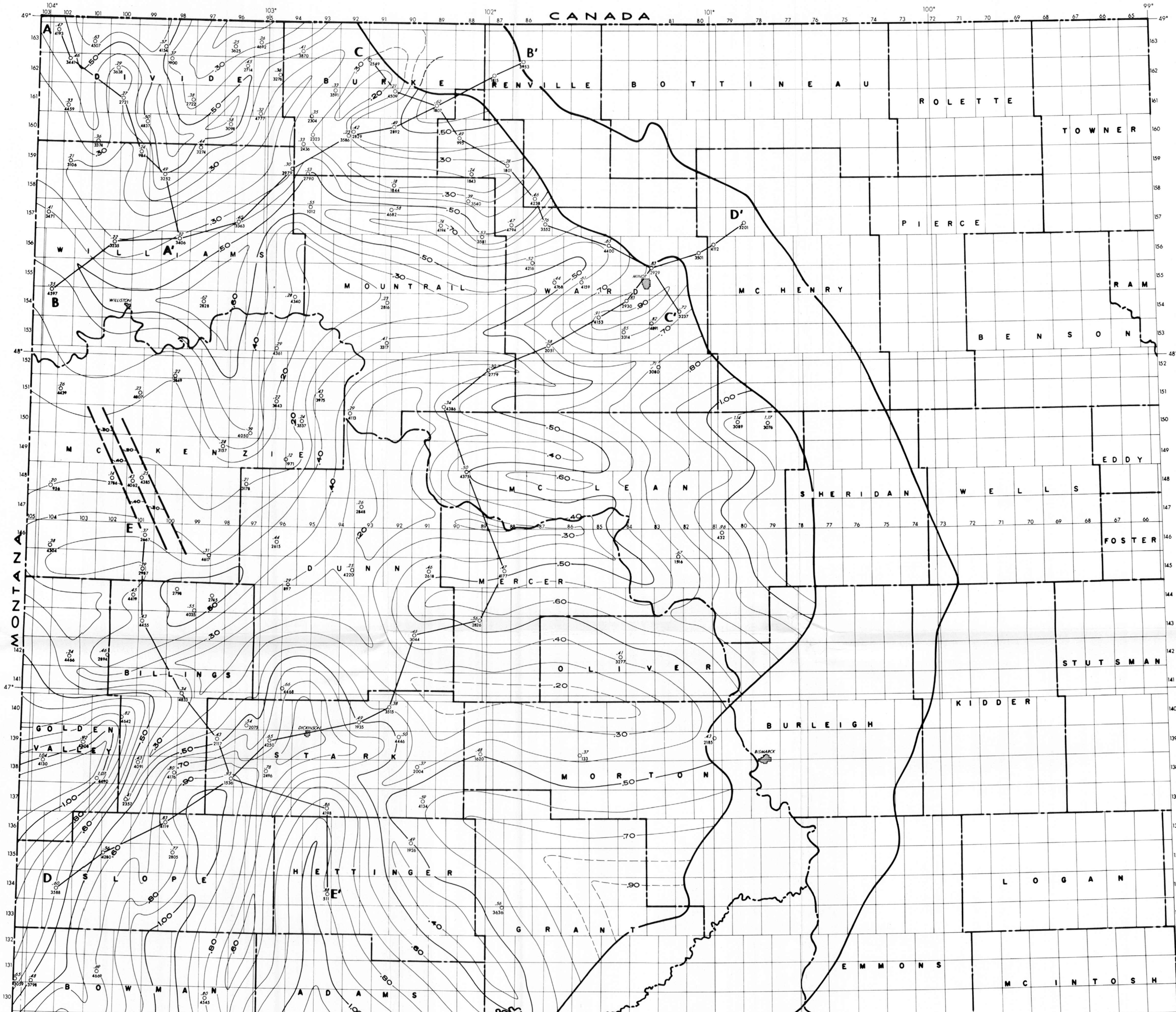
SCALE 0 6 12 18 24 30 MILES

C.W. COOK 1976

LEGEND

49 — APPARENT THICKNESS.
○ — CONTROL WELL.
3586 — N.D.G.S. NUMBER.

POPLAR SUBCROP.
(PRE-MESOZOIC TRUNCATION)



NORTH DAKOTA

PLATE #4

ANHYDRITE/ CARBONATE RATIO MAP

POPLAR INTERVAL

SHOWING POPLAR SUBCROP

CONTOUR INTERVAL = 0.10 FT. ANHYDRITE TO 1.00 FT. CARBONATE

SCALE 0 6 12 18 24 30 MILES

C.W. COOK 1978

LEGEND

.28 ANHYDRITE / CARBONATE RATIO.
O CONTROL WELL.
3586 N.D.G.S. NUMBER.

POPLAR SUBCROP.
(PRE-MESOZOIC TRUNCATION)

A

A′

REPORT OF INVESTIGATION 52
NORTH DAKOTA GEOLOGICAL SURVEY

PLATE #5

STRATIGRAPHIC CROSS SECTION A-A′

POPLAR INTERVAL

DATUM: TOP OF POPLAR INTERVAL

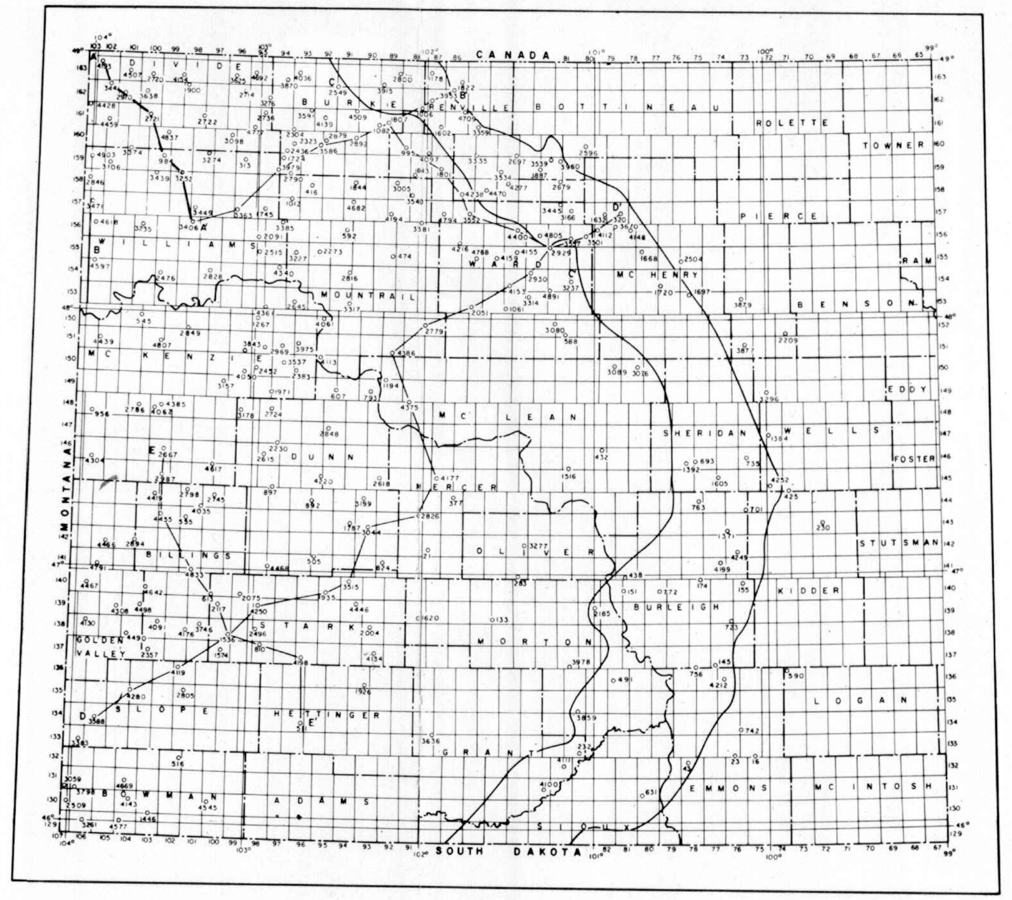
RES — RESISTIVITY.
GR — GAMMA RAY.
SP — SPONTANEOUS POTENTIAL.

ANHYDRITE.
DOLOMITE.
LIMESTONE.
SALT.

100 FEET
50
0

AS NOTED

C. W. COOK 1976



REPORT OF INVESTIGATION 52
NORTH DAKOTA GEOLOGICAL SURVEY

PLATE # 6

STRATIGRAPHIC CROSS SECTION B-B′

POPLAR INTERVAL

DATUM: TOP OF POPLAR INTERVAL

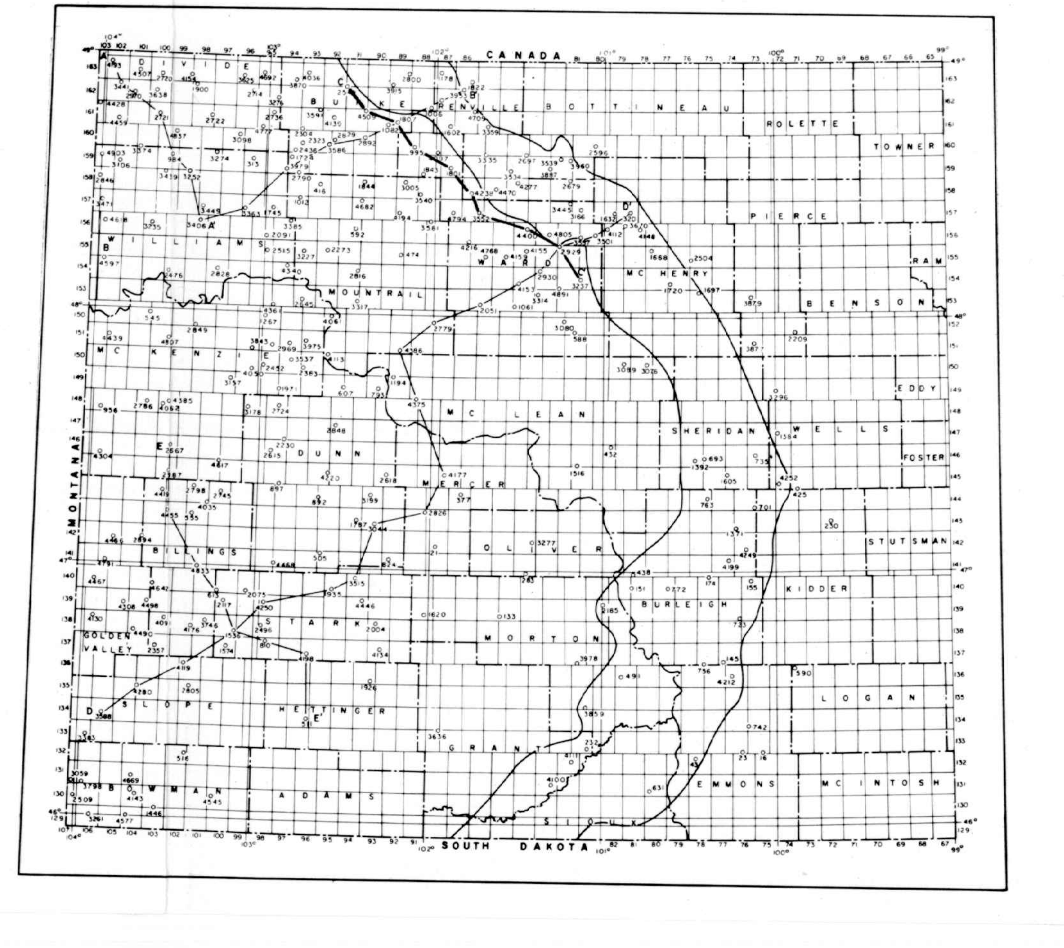
RES — RESISTIVITY.
GR — GAMMA RAY.
SP — SPONTANEOUS POTENTIAL.

ANHYDRITE.
DOLOMITE.
LIMESTONE.
SALT.

100 FEET
50
0
AS NOTED

C. W. COOK

1976



REPORT OF INVESTIGATION 52
NORTH DAKOTA GEOLOGICAL SURVEY

PLATE #7

STRATIGRAPHIC CROSS SECTION C-C'

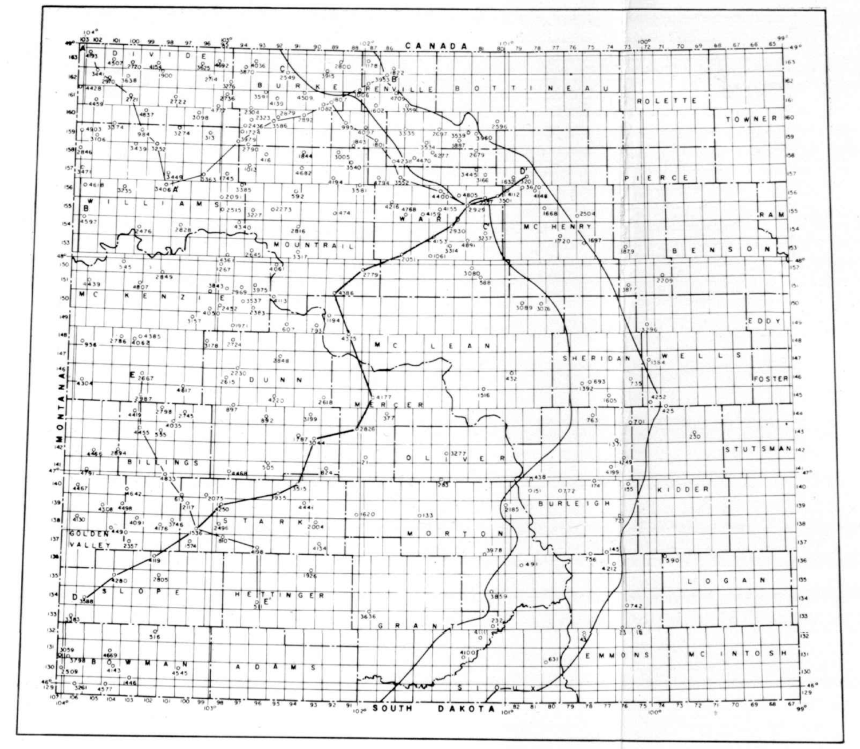
POPLAR INTERVAL

DATUM: TOP OF POPLAR INTERVAL

RES — RESISTIVITY.
GR — GAMMA RAY.
SP — SPONTANEOUS POTENTIAL.
ANHYDRITE.
DOLOMITE.
LIMESTONE.
SALT.

100 FEET
50
0
AS NOTED

C.W. COOK 1976



REPORT OF INVESTIGATION 52
NORTH DAKOTA GEOLOGICAL SURVEY

PLATE #8

STRATIGRAPHIC CROSS SECTION D-D′

POPLAR INTERVAL

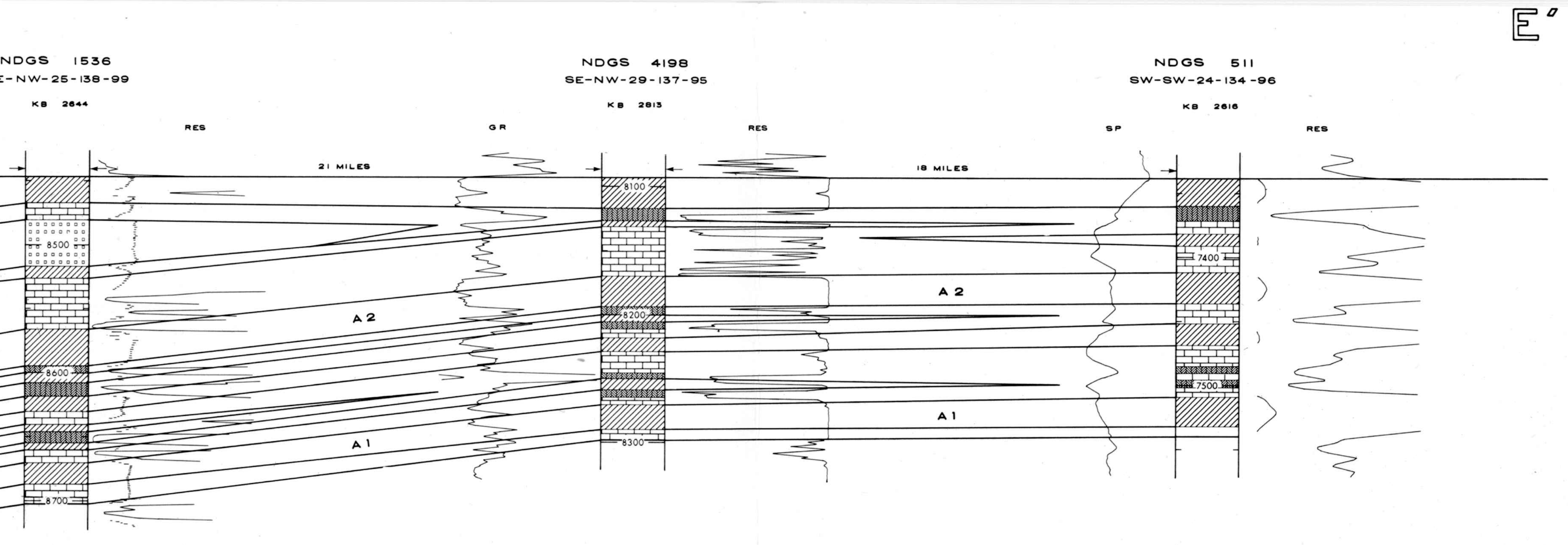
DATUM: TOP OF POPLAR INTERVAL

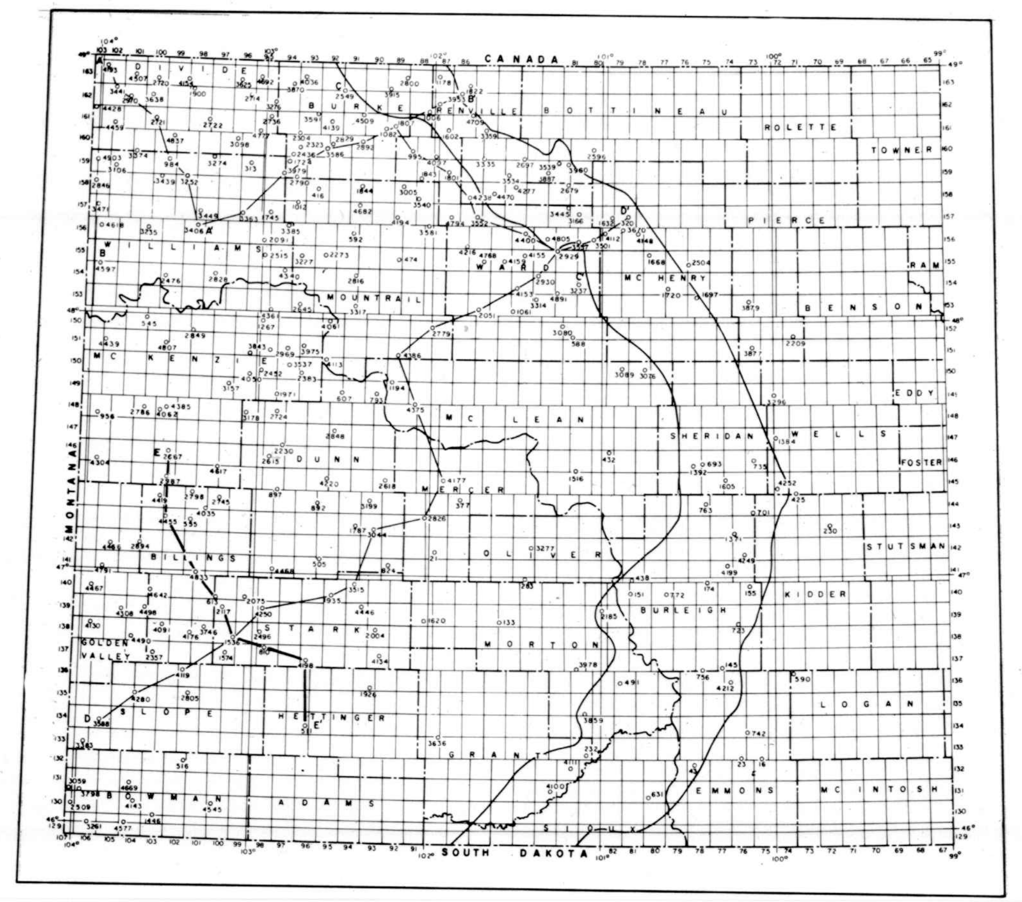
RES — RESISTIVITY.
GR — GAMMA RAY.
SP — SPONTANEOUS POTENTIAL.

ANHYDRITE.
DOLOMITE.
LIMESTONE.
SALT.

100 FEET
50
0
AS NOTED

C.W. COOK 1976





REPORT OF INVESTIGATION 52
NORTH DAKOTA GEOLOGICAL SURVEY

PLATE #9

STRATIGRAPHIC CROSS SECTION E-E'

POPLAR INTERVAL

DATUM: TOP OF POPLAR INTERVAL

RES — RESISTIVITY.
GR — GAMMA RAY.
SP — SPONTANEOUS POTENTIAL.

ANHYDRITE.
DOLOMITE.
LIMESTONE.
SALT.

100 FEET
50
0
AS NOTED

C. W. COOK 1976