REGIONAL STUDY OF THE PERMO - PENNSYLVANIAN STRATA OF SOUTH DAKOTA

Thesis for the Degree of M. S.

MICHIGAN STATE UNIVERSITY
MICHAEL WILLIAM BARRATT

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ABSTRACT

REGIONAL STUDY OF THE PERMO-PENNSYLVANIAN STRATA OF SOUTH DAKOTA

By

Michael William Barratt

The Permo-Pennsylvanian Minnelusa Formation in the state of South Dakota is represented by an accumulation of sandstones, dolomites, limestones, and some evaporites, resting unconformably on Mississippian rocks in the western part of the state. The Minnelusa rests on progressively older rocks eastwardly to finally rest on Precambrian rocks. Lying above the Minnelusa Formation unconformably is the Permian Opeche Shale.

Minnelusa sediments were laid down in a predominately marine environment and can be divided into three gross lithologic units. The lower unit consists of a basal sandstone (Bell), a middle cherty limestone, and an upper interbedded cherty carbonate and red shale. The middle unit is predominantly sandstone and carbonate with a few thin, black shales. The uppermost Minnelusa member is largely sandstone, dolomite and anhydrite.

The eastern limit of the Minnelusa Formation divides the state approximately in half with the zero line reflecting the basement structure of the Sioux Uplift.

The Minnelusa depositional conditions were controlled by two marine advances; one during Des Moines time and the other during lower Permian time.

Information was obtained chiefly from electric and lithologic logs for determining the thickness, lateral extent, lithology and distribution of the Minnelusa.

There are abundant petroleum occurrences in the Minnelusa sediments of the Powder River Basin of Wyoming. South Dakota has numerous oil shows in the Minnelusa and some production in the Barker Dome field south of the Black Hills. This makes South Dakota an interesting possibility for further oil production as more wells are drilled to the Minnelusa and more detailed sub-surface studies are made.

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By

Michael William Barratt

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INTRODUCTION

Purpose of the Investigation

South Dakota has never been a particularly active area for petroleum exploration. There are less than 600 test wells for petroleum in the entire state. This fact, coupled with the lack of exposure of the older rock section in areas outside the Black Hills, has made it difficult to unravel the stratigraphy and sedimentation of South Dakota. The Permo-Pennsylvanian Minnelusa Formation is a prolific producer of petroleum in the eastern portion of Wyoming. This study is an attempt to establish reliable correlations of the Minnelusa in South Dakota, to determine the environments of the various sedimentary units, and to relate these factors to the possible occurrence of petroleum in South Dakota.

Method of the Investigation

Electric logs from 109 oil and water wells were used to determine the extent, thickness and general character of the Minnelusa Formation. Lithologic logs from 46 oil tests were used to determine and verify the lithology and thickness of the Minnelusa. Several gamma ray-neutron logs were also available and proved valuable in picking and correlating formation tops. Accompanying the logs were approximately 200 commercial and company scout tickets. A total of 194 wells in South Dakota were found to be of value as control points. Control point density varied widely. Near the Black Hills and Buffalo Field, numerous wells within a township were available. In other areas south and north of the Black Hills, control proved adequate for the investigation being made. Eastward from the Black Hills, the number of test wells decreases rapidly. Control points were so widely spaced that one well per twenty townships was available in several areas of the south-central and northeastern part of the state.

With electric logs as the main source of information, a structure contour map was constructed. Lithologic logs provided information for the construction of the sandstone percentage, carbonate ratio, lithologic column maps and the graphical representation of lithology. It should be mentioned here that several companies publish and release electric logs and lithologic logs with the formational tops already picked. Although these logs are correlated and the tops picked by geologists, they lack the accuracy required in a detailed study of a region. The turnover in company personnel involved in picking these tops causes considerable confusion as to which criteria each particular geologist used to determine his pick. Because one man may not agree with another on the criteria used in choosing a formation top, a considerable number of wells in South Dakota were found to be in error. The South Dakota Geological Survey apparently accepts these commerical top picks as being valid, because their publications agreed essentially with the commercial tops. In this study it was soon learned that tops selected by commercial studies and South Dakota Geological Survey publications had to be re-evaluated.

A number of writers, using commercial top selections and state publications, presented papers involving areas surrounding and including South Dakota. It was evident that throughout the literature concerning South Dakota and areas around it, commercial top picks were accepted. The writer has re-evaluated these wells and has picked tops uniformly to construct the electric log cross-sections.

The distinctive pattern on the resistivity curve shown by the overlying Opeche and Minnekahta Formations was generally used as a reference point for preliminary correlations. A good example of this pattern can be seen on well number A-1 in the electric log cross-section (Plate VIII). After this pattern was recognized, it was relatively easy to find the top of the Minnelusa.

A problem developed with the determination of the thickness of the Minnelusa south and southwest of the

Black Hills area because most of the oil tests in this area penetrated the Minnelusa but did not go completely through it. Publications and company scout tickets were used in determining the thickness in these areas. During the course of well correlation, special care was necessary when correlating wells near the truncation on Precambrian rocks because the Opeche-Minnekahta resistivity pattern could become confused with that of the Minnelusa. Below the Minnelusa, Mississippian rocks which are unconformable at the Pennsylvanian-Mississippian contact, were readily determined on the basis of a characteristic resistivity high.

Webster (1963), in his paper, recommends an article by Stratton and Ford (1949) as a "primer" in log interpretation and this writer also agrees that the article "stands out in clarity and simplicity without sacrificing accuracy." It was used as a basis to interpret and correlate the well logs. Because the Minnelusa is composed of sandstones, dolomites, limestones, shales and evaporites, the above reference proved to be valuable since problems on lithic interpretations did arise.

Foster (1958) states that the most useful curves for correlation of the Minnelusa in the Powder River Basin are the gamma ray and resistivity curves.

Since several wells in the Powder River Basin were examined by the writer to facilitate correlation south and north of the Black Hills, Foster's recommendation was followed and proved true in South Dakota. Radioactivity logs were especially helpful in positive correlation of the Minnelusa where no electric logs were available. Electric and radioactive logs can be used to correlate wells adequately in the Pennsylvanian, provided the wells are not too far apart.

Using principles found in Stratton and Ford (1949), Foster (1958) and from personal communications, the writer was able to work out, to his own satisfaction, the well correlation phase of this investigation.

Previous Work

The literature dealing with the Minnelusa Formation in South Dakota has been concerned principally with the Black Hills area and the western bordering states of Wyoming and Montana.

Works of a regional nature, concerning the Minnelusa, including studies of larger areas than the state can be found in Darton (1901), Darton and Paige (1925), Brady (1931), Condra and Reed (1935, 1940), Ballard (1942), Baker (1951), Barnes (1952), Gries (1952), Noble (1952), Agatston (1954), Bates (1955), Foster (1958), Tranter and Petter (1963), and Tenny (1966).

Up to the present time, there has been no study of the Minnelusa published which is as detailed as the present study.

Location and Topography

The state of South Dakota, occupying an area of 77,615 square miles, lies in the northern Great Plains region. It can be divided into four main provinces.

The Black Hills are a mountainous, much eroded, dome shaped uplift, surrounded by nearly horizontal beds. They are situated along the west central border between South Dakota and Wyoming.

The Tertiary table lands are found west of the Missouri River. They are remnants of Tertiary beds differentially eroded by streams. Impermeable clay and shales, sparse vegetation, and sudden rainfall have all played a role in shaping these table lands and the badland topography along the White River in southwestern South Dakota.

The glacial province occupies the eastern half of the state. Here the typical features caused by glaciation such as moraines, kettle lakes, and till plains are found. The glacial terrain is interrupted on the border of Minnesota and South Dakota by the Sioux Uplift.

The Sioux Uplift is a quartzite remnant exposed in the southeastern corner of the state. The quartzite lies on a granitic basement complex.

Recent Petroleum Exploration

Webster (1963) adequately covers the period of petroleum exploration between initial discovery and 1960. Figure 1 shows the drilling activity since 1960 in the state. At the present time, the state of South Dakota has only one commercial oil field--the Buffalo Field located northwest of Buffalo in Harding County. This field produces oil from the Ordovician Red River Limestone at about 8000 feet. Several other non-commercial discoveries have been exploited, the most interesting of which is the Barker Dome Field in Custer County. Oil has been known to exist around the south end of the Black Hills since 1913. Many of the wells were oil tests, but there were also a number of dry holes too shallow to yield much geological data. During the period between 1929 and 1930, several good shows were obtained from the Minnelusa Formation. The First Leo Sand near the top of the formation yielded many of these shows. Non-commercial oil was found at Barker Dome (sec. 34, T. 6S., R. 2E., Custer County) in 1929. Several unsuccessful tests were drilled before L. A. Helms completed the Number 1 Coffing as a producing well in 1955. The production here was probably due to variations in permeability within the producing zone. Faulting also has been suggested as an explanation (Gries, 1964). Oil was obtained from a thin sand member (Leo) directly above a radioactive shale near

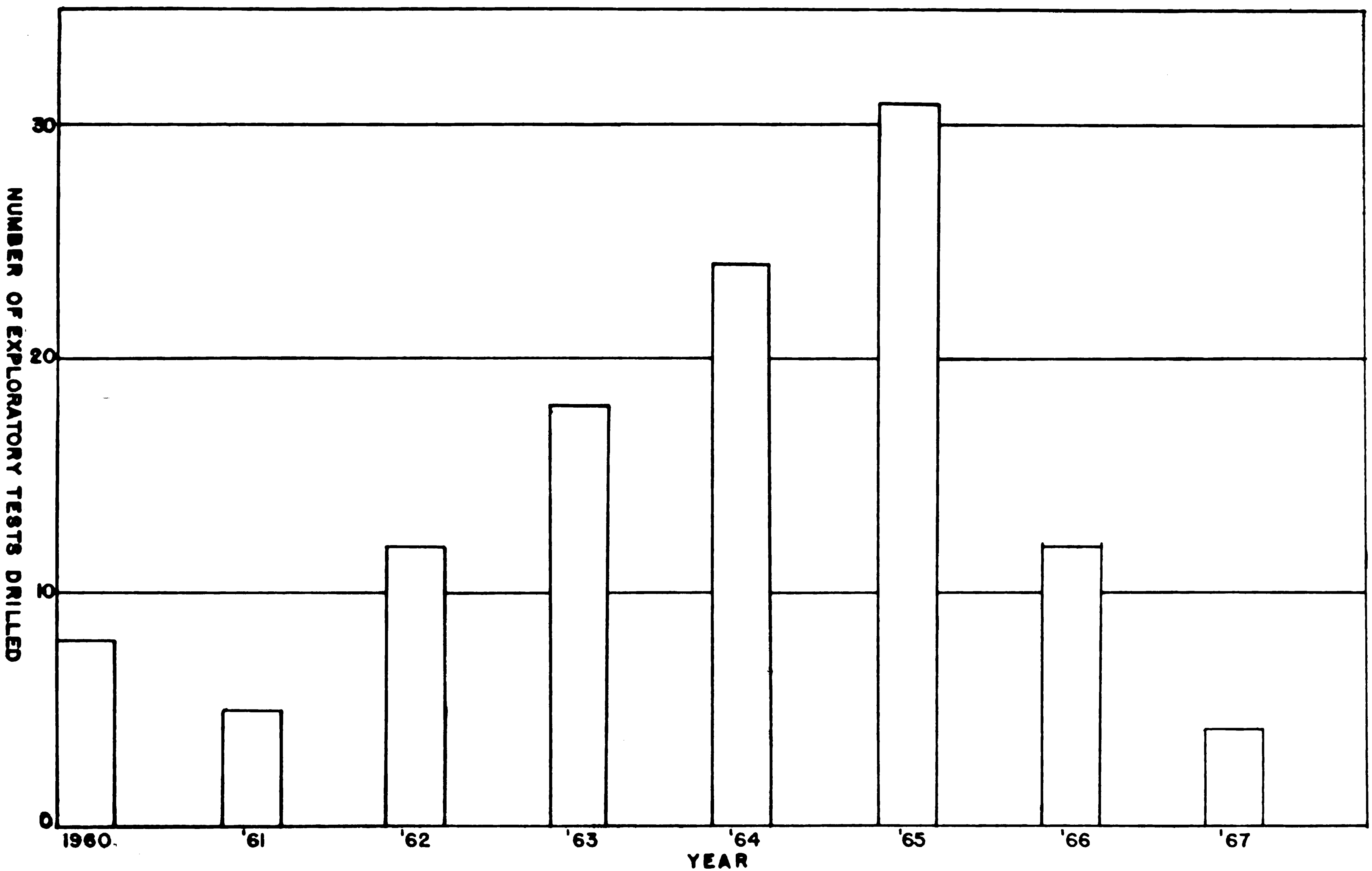


FIGURE I: PETROLEUM DRILLING ACTIVITY IN SOUTH DAKOTA SINCE 1960
DATA FROM A.A.P.G. BULL.

the top of the Minnelusa at depths between 1391 and 1392 1/2 feet (Gries, 1964). Oil recovered from this field shows an API gravity of 30 degrees and is black in color. Further tests have been discouraging.

Total oil production in the state averaged 650 barrels per day between 1963-1967. During this same period, 84 oil tests were drilled in South Dakota. All of them were unsuccessful. There remains approximately 25,000 square miles of undrilled, untested land that could prove favorable for oil accumulation within the Minnelusa Formation. Oil prospects in the state look dim, but because so much of the state remains untested, some pools could possibly be found. Preparation of detailed studies such as this could prove to be of some value. Numerous types of traps exist in the Minnelusa in Wyoming to the west. Looking for stratigraphic traps, porosity traps, and fault traps seems to be the best course when exploring for oil in the Minnelusa in South Dakota.

STRUCTURE

Figure 2 shows the major structural features in and around the state of South Dakota. The Black Hills, the Lemmon Syncline, the Sioux Uplift and the Chadron Dome are the most important ones.

Black Hills

The major structure in the southwest part of the state is the Black Hills. This can be seen as a domal shaped "island" rising out of the plain of western South Dakota and eastern Wyoming. The Black Hills, the easternmost part of the Rocky Mountains, have an elliptical shape, 120 miles by 60 miles. A Precambrian core of highly folded schists invaded by granite in the southern part of the Black Hills, trends nearly north-south and is flanked by upturned Paleozoic and Mesozoic strata. Laramide plutons intrude the core in the northern portion. The uplift trends and pitches northwest beyond the crystalline zone. The east flank is fairly steep, up to 45 degrees, the broad top is flat, and the west flank is gentle, less than 20 degrees. Adjacent to the central Precambrian core is a plateau area in the west central

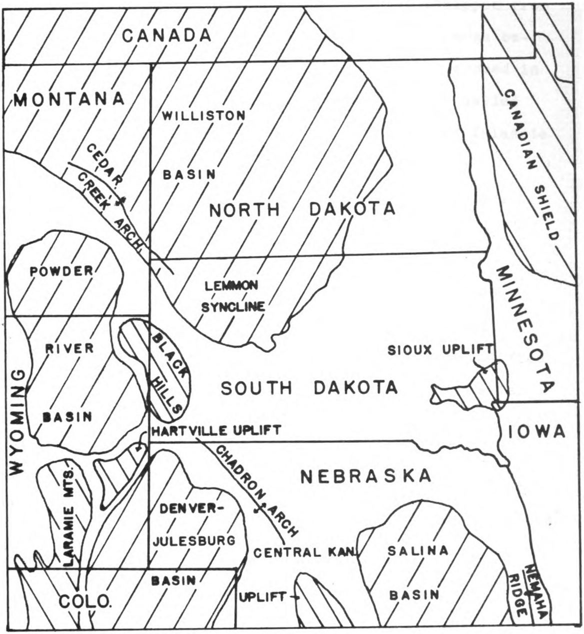
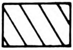


FIGURE 2: MAJOR STRUCTURAL FEATURE LOCATION MAP

MODIFIED FROM WEBSTER



part formed by Paleozoic limestones not yet stripped from the Precambrian rocks. Surrounding the uplift area beyond the plateau is a continuous strike-valley eroded in Jurassic and Triassic strata. This is commonly called the "Racetrack" or Red Valley because of the red Triassic Spearfish shales that principally underlie it.

Completing the structure of the Black Hills are inward facing hogbacks held up by the Fall River and Lakota sandstones of Cretaceous age.

To the west of the Black Hills lies the Powder River Basin which contains about 16,000 feet of sedimentary rocks. Darton estimates the strata were uplifted 9,000 feet in the Black Hills, so the structural relief between the bottom of the Powder River Basin and the top of the Black Hills is about 25,000 feet.

The age of the uplift can only be approximated because of the lack of Paleocene or Eocene overlaps in close proximity to the uplift. The Laramide age deposits that might have been derived from the Black Hills are now in surrounding areas and separated from the uplift by a Cretaceous belt of outcrops. The doming could have started in latest Cretaceous time with the deposition of the Fox Hills and Lance beds in the Powder River Basin.

The southern margin of the Black Hills contains two discernible anticlines. On the southeast, the Chilson Anticline and on the southwest the Cottonwood Creek

Anticline. These can be seen on the structure contour map (Plate I). Oil tests on these structures have so far yielded no commercial oil. Figure 3 shows a north-south cross-section of the Black Hills.

Lemmon Syncline

A basin extending into the north-central part of South Dakota is called the Lemmon Syncline. This is considered to be the South Dakota portion of the Williston Basin by most geologists. The Williston Basin is thought to have its origin in Precambrian time, existing through Paleozoic and Mesozoic time (Pye, 1953). The general shape of the Williston Basin with its southern extension give us some clue to the tectonics in the state. The Williston Basin is situated between the Cordilleran Geosyncline on the west and the Canadian Shield area on the east. During the Laramide Orogeny, between late Cretaceous and early Tertiary time, an eastward thrust was exerted on the beds in western United States. The thrust from the west, created the asymmetry of the Black Hills and the Williston Basin. The Lemmon Syncline is asymmetrical to the west as shown in the structure contour map (Plate I). The Williston Basin is an important producer of petroleum, with most of the oil coming from the Paleozoic section.

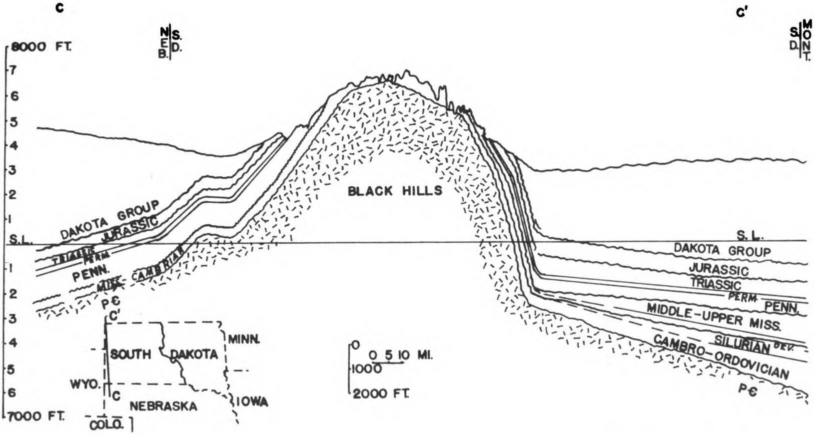


FIGURE 3: NORTH-SOUTH CROSS SECTION FROM NW. NEBRASKA TO SE. MONTANA

AFTER BALLARD (1942)

The Sioux Uplift

The Sioux Uplift occupies a portion of the southeastern part of the state as well as a small part of southwestern Minnesota. It is composed of a quartzite remnant overlying a granitic basement complex, both of which are Precambrian. The Sioux Uplift is a topographic as well as a structural feature. One may wonder why this particular remnant exists. The Sioux Quartzite was considerably more widespread in Precambrian time than it is now. Emerging about mid-Ordovician time (Baker, 1951), the quartzite was eroded down except for those areas with synclinal structure. In the subsurface, the Sioux Uplift extends westward in South Dakota to the vicinity of Pierre. It is thought to be a part of the old Transcontinental Arch which had its beginning in early Paleozoic time (Eardley, 1951).

Chadron Dome

The bulbous extension of the northwestern end of the Chadron Arch is called the Chadron Dome. The northern portion of the dome can be seen on the structure contour map (Plate I), in the southwestern part of the state. The Chadron Dome was uplifted during Early Pennsylvanian time (Atoka) along with the Central Kansas Arch. The Laramide Revolution subjected it to further uplift.

Another structure which should be mentioned is the northwest-southeast trending fault northeast of the

Black Hills. It was based upon the information obtained from the two wells drilled by Mobil. They are the Sipila Number F11-14P located in NW 1/4, NW 1/4 of section 14, T. 9N., R. 8E. and the Mickelson Number 1 located in NE 1/4, NE 1/4 of section 7, T. 9N., R. 9E. as shown on Plate I. Because of the proximity and general trend of this fault to the fault zone lying on the southeastern side of the Cedar Creek Anticline, it is possible that a fault zone trending from the Cedar Creek Anticline, through South Dakota could exist. Pye (1953) believes that the deformation of the Cedar Creek Anticline occurred in late Devonian or pre-Mississippian time.

STRATIGRAPHY

Nomenclature

The history of nomenclature of Permo-Pennsylvanian rocks in South Dakota and the surrounding regions is a very complex problem because of the fact that three main sets of names exist in Wyoming and South Dakota. Darton, working in the Bighorn Mountains in north-central Wyoming during the early 1900's postulated a twofold division within the Pennsylvanian beds. The lower beds were referred to as Amsden and the upper ones were called Tensleep. Later, Darton and Paige (1925) formulated a nomenclature system within the Black Hills area. Here, the name Minnelusa, as applied by Winchell (1875), was accepted as the Pennsylvanian system. A correlation was attempted between the Bighorn classification and the Hartville Uplift area when Condra and Reed (1935) described the Hartville Formation and then sub-divided it into divisions. This classification was then correlated with the Black Hills area by Condra and Scherey (1940) and Condra and Reed (1940). A rough correlation was attained but the Hartville classification never became popular.

This paper uses the classification system proposed by Darton in the Black Hills area; the writer has extended it eastward through the state.

The name Minnelusa, (Sioux for rapid water), was applied by N. H. Winchell in 1875 to a series of white crystalline sandstones, anhydrites, shales and limestones in the Black Hills area. The section is well exposed west of Rapid City. Darton and Paige (1925) reported that G. H. Girty had identified fusulinids from the medial beds of Minnelusa in the Black Hills. Later investigations of the Minnelusa near the Black Hills and surrounding areas, especially the Hartville Uplift area, disclosed that accurate correlation could be obtained with the use of fusulinids.

Dille (1930), in his work in the southern part of the state, concluded that the base of the Minnelusa beds were equivalent to the "Des Moines stage of the Carboniferous." He based this on "<u>Fusulina</u> cf. <u>cylindirica</u>" which he found in the basal red shales of the Minnelusa in Custer County.

Roth (1930), working in the same region as Dille, identified <u>Fusulinella</u> <u>euthusepta</u>? from approximately 100 feet above the base of the formation, which places it in the Cherokee (Upper Atoka-Lower Des Moines). He divided the Minnelusa into two units: the lower, correlating with the Amsden and the upper, correlating with the

Tensleep. He considered the upper Minnelusa to be Missourian and upper Des Moines in age on the basis of Tensleep correlations in the Bighorn Basin. The Tensleep-Amsden contact problem in Wyoming bears directly on the correlation of the upper and lower Minnelusa near the Black Hills area. This contact, discussed by Fisher (1963), is still sometimes difficult to establish, but it is generally agreed that the contact is between Atoka and Des Moines strata. Figure 4 shows the correlation chart (Bates, 1955; Tranter and Petter, 1963; and Tenny, 1966).

Age and General Correlation

The Minnelusa Formation was once thought to be Pennsylvanian in age, but is now considered to be Permo-Pennsylvanian. However, determining and correlating the upper and lower boundaries has remained a problem. The name Minnelusa is now generally applied throughout the entire state of South Dakota, north to the Nesson Anticline and westward through the eastern half of the Powder River Basin. The term "Minnelusa sandstone" is erroneously used because the formation contains numerous carbonates and evaporites as well as sandstone.

Primary age correlations have been made from the Eastern Powder River Basin in Wyoming to the Black Hills area. On the basis of fusulinids, the lower and middle

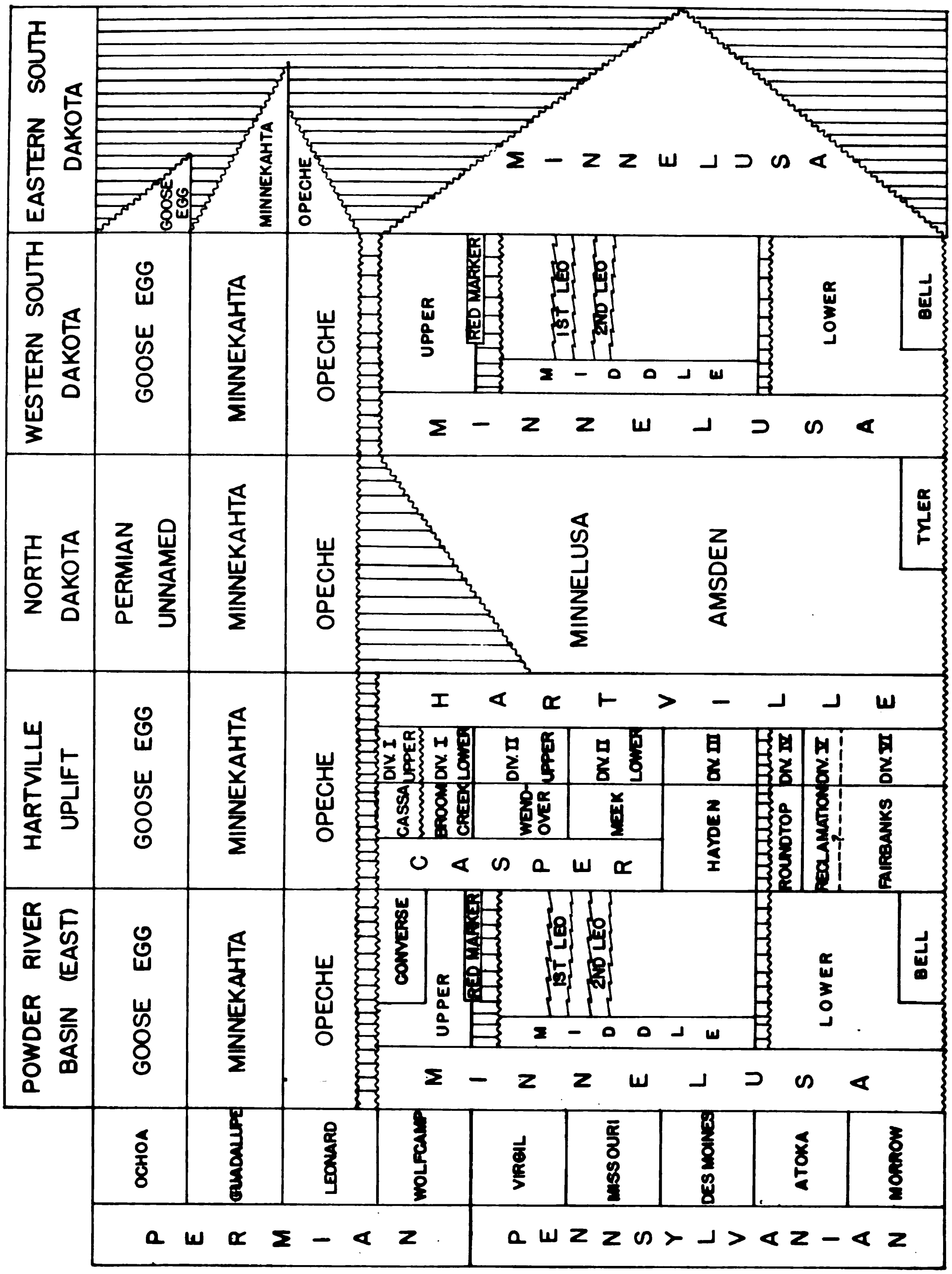


FIGURE 4: CORRELATION CHART

Minnelusa in the Black Hills is Pennsylvanian in age with the upper member being placed in the Wolfcampian. Very good correlations between the eastern Powder River Basin and areas north and south of the Black Hills can be obtained. The western portion of the Powder River Basin, however, correlates best with the Bighorn Mountains section.

The correlation between the Minnelusa and the Hartville Formation is acceptable in the Black Hills region, but it has not been possible to trace all the divisions of the Hartville Formation throughout the Black Hills area and farther east.

One of the problems in correlation, in this study, was the division of the Minnelusa east of the Black Hills. A good correlation was obtained from the eastern portion of the Powder River Basin to the area south of the Black Hills. As more electric logs were correlated to the north and east, the divisions became less conspicuous until they were lost a short distance east of the Black Hills.

Foster (1958) suggested that a threefold division within the Minnelusa-Lower, Middle, and Upper, each with regional unconformities above and below, be used in correlations within the Powder River Basin. The threefold division holds in the Powder River Basin, but is not applicable east of the Black Hills. Figure 5 shows the graphic columnar section of the Minnelusa in the state.

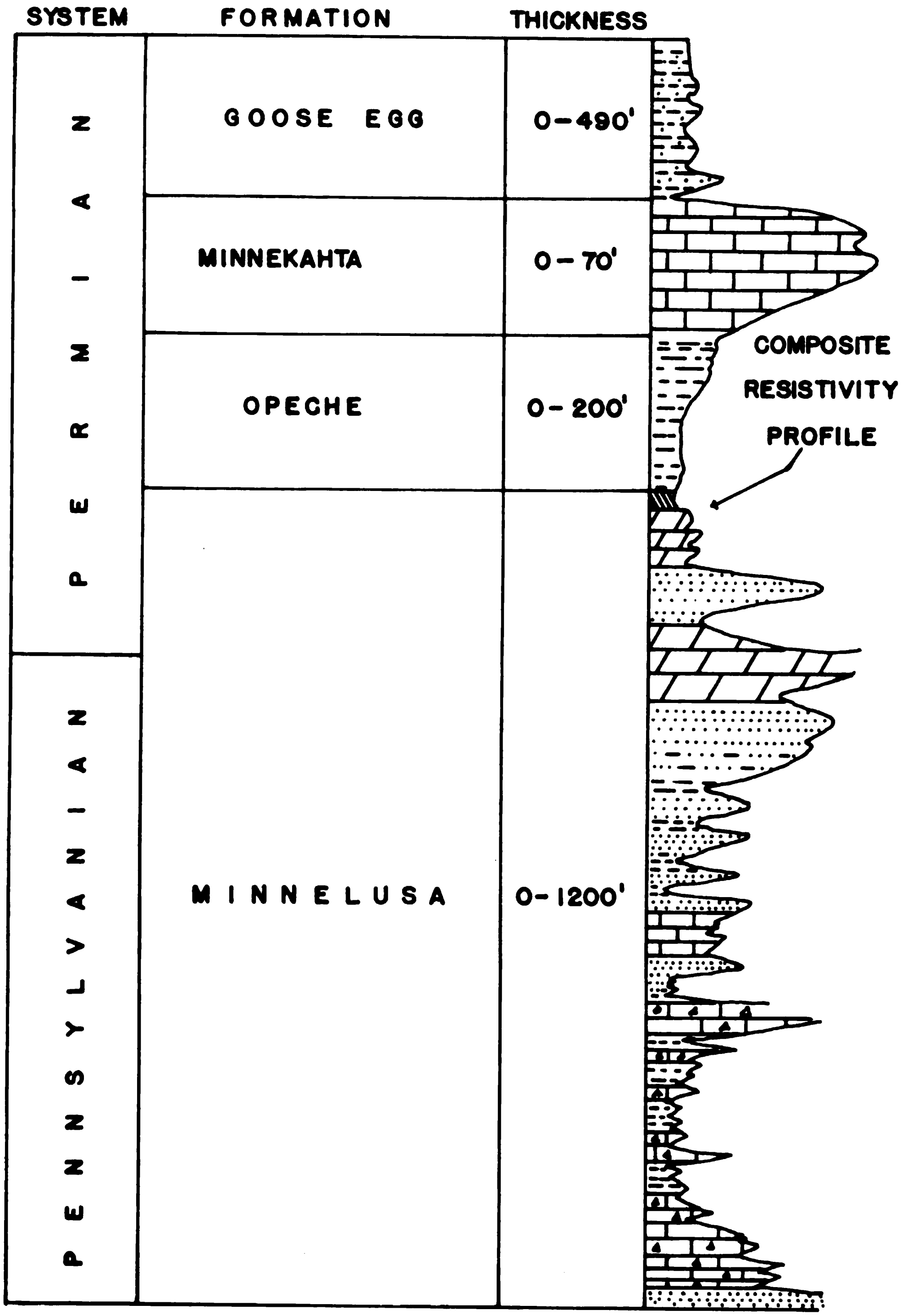


FIGURE 5: GRAPHIC COLUMNAR SECTION OF THE MINNELUSA FORMATION OF SOUTH DAKOTA

MODIFIED FROM WEBSTER (1963)

Figure 6 shows a panel diagram correlating the Black Hills and Laramie Mountains.

Description and Correlation of Mississippian Sediments

Mississippian rocks in the state of South Dakota unconformably underlie the Minnelusa Formation because of post-Chesterian--pre-Pennsylvanian erosion. They consist of a lower Madison Group, and an upper Big Snowy Group. The term Madison is used to include the Lodgepole, Mission Canyon and Charles Formations. Laudon and Severson (1953) concluded, on crinoid fossil data that the Lodgepole and Mission Canyon Formations represent continuous uninterrupted marine deposition during Kinderhookian and early Osagian time. The Charles Formation was named by Seager (1942) and has the type section in Garfield County, Montana. The formation is composed of dense dolomites, limestones and some evaporites. It is considered to be Meramecan in age. The Mississippian outcrop of the Black Hills is known as the Pahasapa Formation and was named by Jagger in 1901. This formation consists of a carbonate series up to 630 feet in thickness. It overlies the Englewood unconformably and is well exposed in the Black Hills area. The formational name is usually confined to the Black Hills area. The term Mission Canyon is usually considered correlative with the Pahasapa, and is used in the subsurface in the Williston Basin-Lemmon Syncline areas.

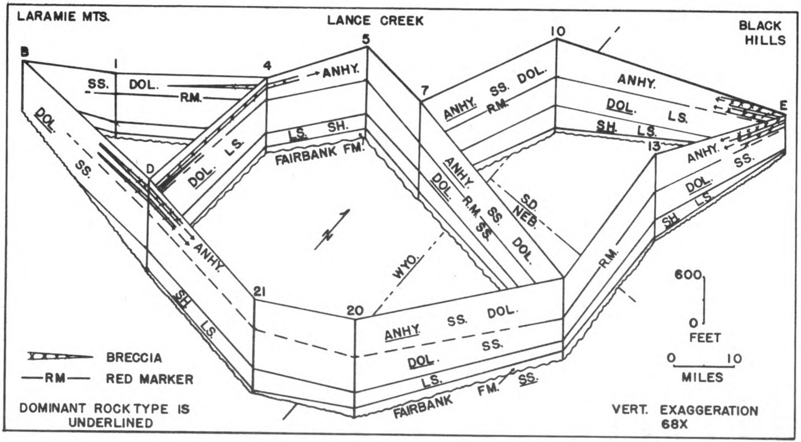


FIGURE 6: PANEL DIAGRAM OF THE MINNELUSA FORMATION FROM LARAMIE MOUNTAINS TO BLACK HILLS

FROM BATES (1955)

The Big Snowy Group of Chesterian age overlies the Madison Group in northwestern South Dakota. It consists of, in ascending order, the Kibbey, Otter and Heath Formations, a series of clastics and non-clastics lying in central Montana and the Williston Basin. The Kibbey Formation is the only one that extends far enough south into South Dakota to unconformably underlie the Minnelusa there.

Agaston (1954), reporting the effects of pre-Pennsylvanian erosion on the Mississippian surface in northern and eastern Wyoming, stated that channel fills, 5-35 feet thick, commonly contain blocks of limestone and chert in a quartz sand.

Overlying the Mississippian carbonates in other areas of Wyoming and South Dakota are the Amsden, Minnelusa and Hartville Formations. These three are generally correlative, but in Montana lowermost Amsden is thought to be of Mississippian age.

The thickness of the Madison Group in eastern Wyoming and South Dakota shows great variations mostly due to pre-Pennsylvanian truncation. The lithology of the Madison in this area is mostly dolomitic limestone grading westward into a rather pure limestone. The sedimentation pattern of the Madison consists of carbonate sequences with interbedded evaporite cycles. The Mission Canyon Formation along with an overlying evaporite unit of the basal Charles Formation form the medial beds of the Madison Group. The

Mission Canyon Formation exhibits two evaporite cycles. The lower one, at the base of the formation is represented by a minor evaporite development. The upper evaporite unit of the Mission Canyon is overlain by the basal Charles evaporites. A Mississippian exposure in Spearfish Canyon (T. 6N., R. 2E.) is the same lithologically as the subsurface with the exception of the development of minor limestones in the lower evaporite cycle.

Late Madison sedimentation is represented by the Charles Formation. The formation consists of a lower evaporite cycle overlain by marine carbonates. The evaporite cycle is not as pronounced as that in the Mission Canyon. Primary carbonates represent intense saline conditions in southeastern Wyoming and solution-breccias are developed in outcrops of the evaporite zone. The upper contact of the Charles is easily recognizable where it is overlain by Big Snowy and Pennsylvanian Amsden or Minnelusa sediments because they are composed mostly of sand and shales, in marked contrast to the Madison Group carbonates. The lithology of the Charles Formation in northeastern Wyoming is dominantly dolomite with interbedded limestones and evaporites. North of the Black Hills the limestone and dolomite proportions show wide variations.

The Madison Group in South Dakota shows a variety of lithologies, but consists chiefly of carbonates. Figure 7 shows the eastern limits of Mississippian units.

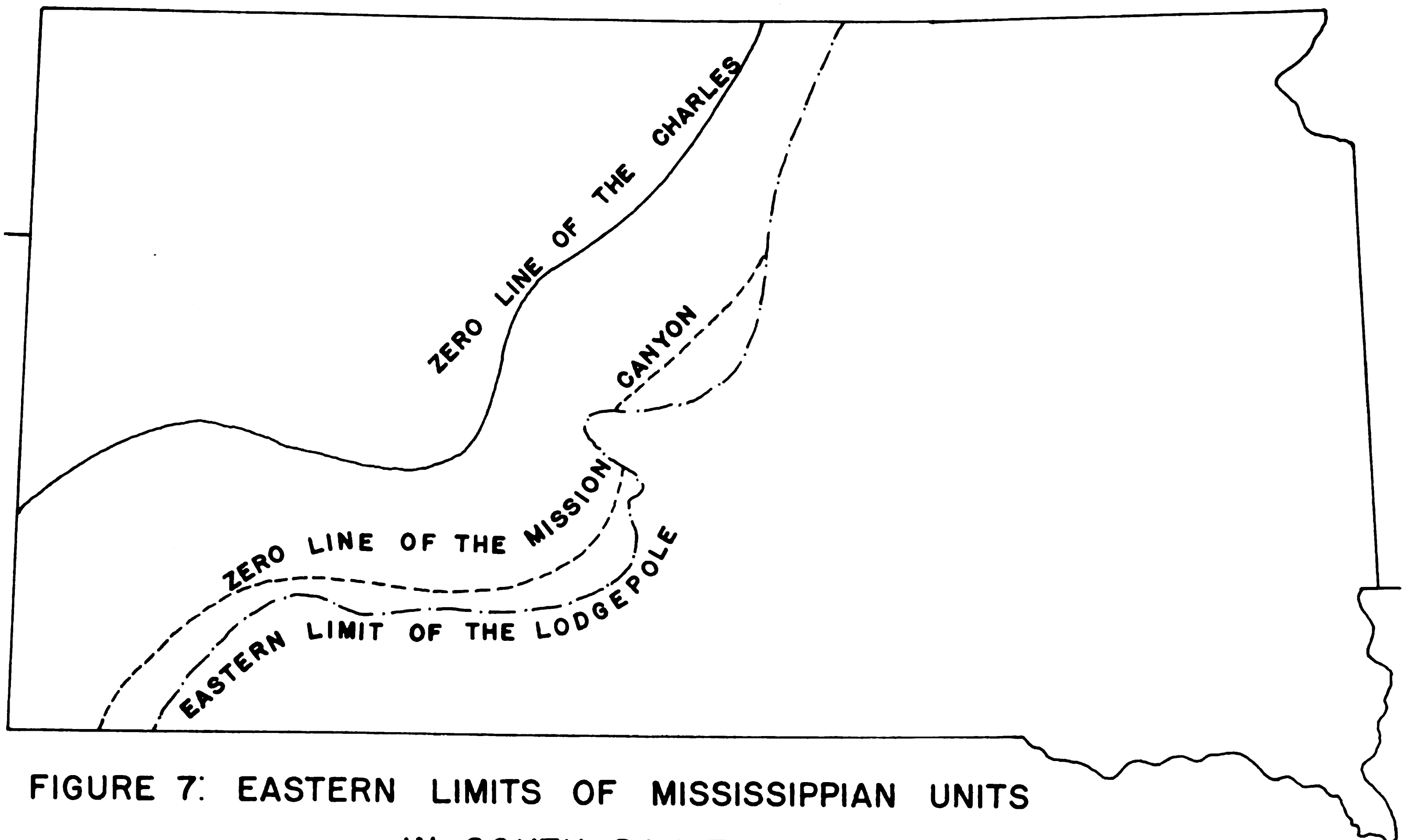


FIGURE 7: EASTERN LIMITS OF MISSISSIPPIAN UNITS IN SOUTH DAKOTA

MODIFIED FROM GRIES & MICKELSON (1964)

DESCRIPTION AND ORIGIN OF PERMO-PENNSYLVANIAN SEDIMENTS

Minnelusa Formation

A general lithologic description of the Minnelusa shows that in surface outcrops around the Black Hills, it contains numerous beds of breccia, although the number and thickness of these beds vary locally. Gypsum beds sometimes appear in surface outcrops, but these are relatively uncommon due to solution and leaching of these beds. The Minnelusa thickens rapidly toward the southwest because the Lusk Embayment was being filled with increasing thicknesses of limestone-shale sequences during lower Minnelusa time. Another factor accounting for marked thickening in the subsurface is the appearance of thick anhydrite beds which are represented on the outcrop by thin collapse breccias in the southwestern Black Hills. We can see then that the Black Hills lithology represents a leached and thinned formation which is more fully developed to the southwest.

The question of age correlation of the Minnelusa Formation in South Dakota is a problem. The lower limit of the formation is not a major problem because of the marked unconformity between Mississippian and lower

Pennsylvanian sediments. The contact generally was easy to pick. The problem of calling Minnelusa only Pennsylvanian in age existed before Bates (1955) suggested that surface upper Minnelusa was, in general, correlative to a subsurface upper evaporite zone. This was thought to correlate with Upper Hartville in Wyoming which Love, Henbest and Denson (1953) consider to be Wolfcampian in age. It is now generally agreed that upper Minnelusa is Wolfcampian in age based on fusulinid evidence and lithic correlations.

Fossils in the Minnelusa Formation are somewhat rare, but fusulinids in the Black Hills area have been found and dated generally as Desmoinesian. The upper limey beds near Hot Springs have shown a few *Composita* sp. and *Spirifer* sp. found by G. H. Girty (Darton and Paige, 1925). Sedimentary structures within the Minnelusa show cross-bedding (Darton and Paige, 1925) in upper and middle members. The type section of the Minnelusa as measured and described by Brady (1958), is given in the Appendix.

The thickness of the Minnelusa Formation in South Dakota ranges from zero to 1200 feet as shown in Plate II, the isopach map. The formation is absent in the eastern half of the state. It thickens toward the northwest but then thins to 400 feet in the northwestern part of the state. The Minnelusa thickens also to the southwest where, just southwest of the Black Hills, it reaches its maximum thickness. A very interesting ridge and valley effect is exhibited south of the Black Hills. A significant pattern also is developed in the northwestern part of the state. Where the Opeche was laid down on top of a post-Wolfcampian erosional surface and because the Opeche-Minnekahta contact is conformable, thickness variations within the Opeche are due to the erosional surface. As can be seen on a comparison of Plate II and Plate VII, the Opeche is thin where the Minnelusa is thicker. This can be seen particularly well in the northwestern portion of the state.

Plate III, a carbonate-evaporite ratio map, was included in the study to ascertain the location and relative position of carbonates, chiefly dolomites and limestone, within the Minnelusa Formation. This map, used in conjunction with the isopach map, demonstrates that the Minnelusa Formation had considerable thicknesses of carbonates located in the west-central portion of the state. Another relatively high carbonate-evaporite concentration is shown in the north-central part of the state.

In order to determine the location of principle source areas of coarse clastics, a sandstone percentage map was constructed (Plate IV). An accumulation of sands in the northwestern and southwestern portions of the state suggest proximity to source areas. The pattern of sand accumulation shows that the initial source areas probably were separate as opposed to one great source. The southern accumulation was probably due to activity in the Chadron Arch area. This area was tectonically active throughout Pennsylvanian time. The northern accumulation was caused by an uplifting of the Central Montana Uplift during late Pennsylvanian time. This furnished coarse clastics to the south and southeast.

For the purpose of completeness, an isopach map of the Opeche Formation was drawn (Plate VII). A problem has existed as to whether the Opeche was conformable where it overlies the Minnelusa. Darton (1901) suggested that an uplift occurred after Minnelusa time, but did not imply any significant erosion. He concluded that the Minnelusa-Opeche contact is conformable. Brady (1931) also concluded the same thing in the Beulah, Wyoming district. Later, as more drilling was done in Wyoming and South Dakota, the contact was interpreted as unconformable.

Post-Wolfcamp time in the Black Hills was a time of erosion. To show that the Opeche-Minnelusa contact is unconformable is somewhat difficult because of lack of exposures. The outcrop thickness of the Opeche ranges from 52 to 109 feet and the subsurface thickness increases in the southwestern part of the state to over 300 feet. Three possibilities for an explanation of the surface and subsurface thickness differences in the Opeche exist. The first explanation postulates that a flat base but an irregular top exists in the Opeche. This can be ruled out because of the regular contact between the Opeche and the overlying Minnekahta. The possibility of the Opeche having both an irregular top and base can be dismissed for the same reason. This leaves the possible explanation of the Opeche having an irregular base and a flat top. According to Stone (1966), the irregularity of the Minnelusa top suggests an area of topographic relief chiefly southwest and northwest of the Black Hills showing the Opeche as a broad channel fill on the Minnelusa. He states further than channel filling east of the Black Hills is limited because two main channel areas seem to present themselves, the most predominate being from the northwestern portion of the state. This interpretation is quite unlikely because it is generally thought that the Opeche is a tongue of the Phosphoria sea.

The electric log cross-sections (Plate VIII), are possibly the most valuable tools in this study. They show the general distribution pattern, the thickness and interval of the Minnelusa in the state.

Since the Minnekahta-Opeche interval can be readily determined, this was used as a "control point." Where this was non-existent or where the interval thinned out so much that the pattern was lost, a typical lower Minnelusa pattern could be used. This lower Minnelusa resistivity pattern could be confused with the Mississippian Kibbey limestone, but careful correlation proved it to be lower Minnelusa.

The problem of the depositional environment and source areas of the Minnelusa Formation in South Dakota is still debatable. Because so much work has been done in eastern Wyoming, a number of theories attempting to solve this problem have been postulated. However, east of the Black Hills area, relatively little work has been done to solve the questions of where and how the Minnelusa sediments were deposited.

Figure 8, a pre-Pennsylvanian paleogeologic map shows the state at the end of post-Mississippian erosion. Ballard (1942), believes that the Pennsylvanian was laid down on an eroded Mississippian carbonate sequence with a Precambrian high, extending northeast from the Cambridge Arch to the Sioux Uplift, serving as a source area. Tranter and Petter (1963), approaching the problem from a regional point of view, believed that recurrent uplifts in central Wyoming created cyclic deposition of shale, dolomite and sandstones on the Wyoming shelf area in eastern Wyoming and western South Dakota. Tenny (1966), also working on a regional basis, conceived of a positive area, the Pathfinder Uplift, in southeastern Wyoming furnishing sediments to the west, north, and east along with the ancestral Front Range Uplift to the south. The

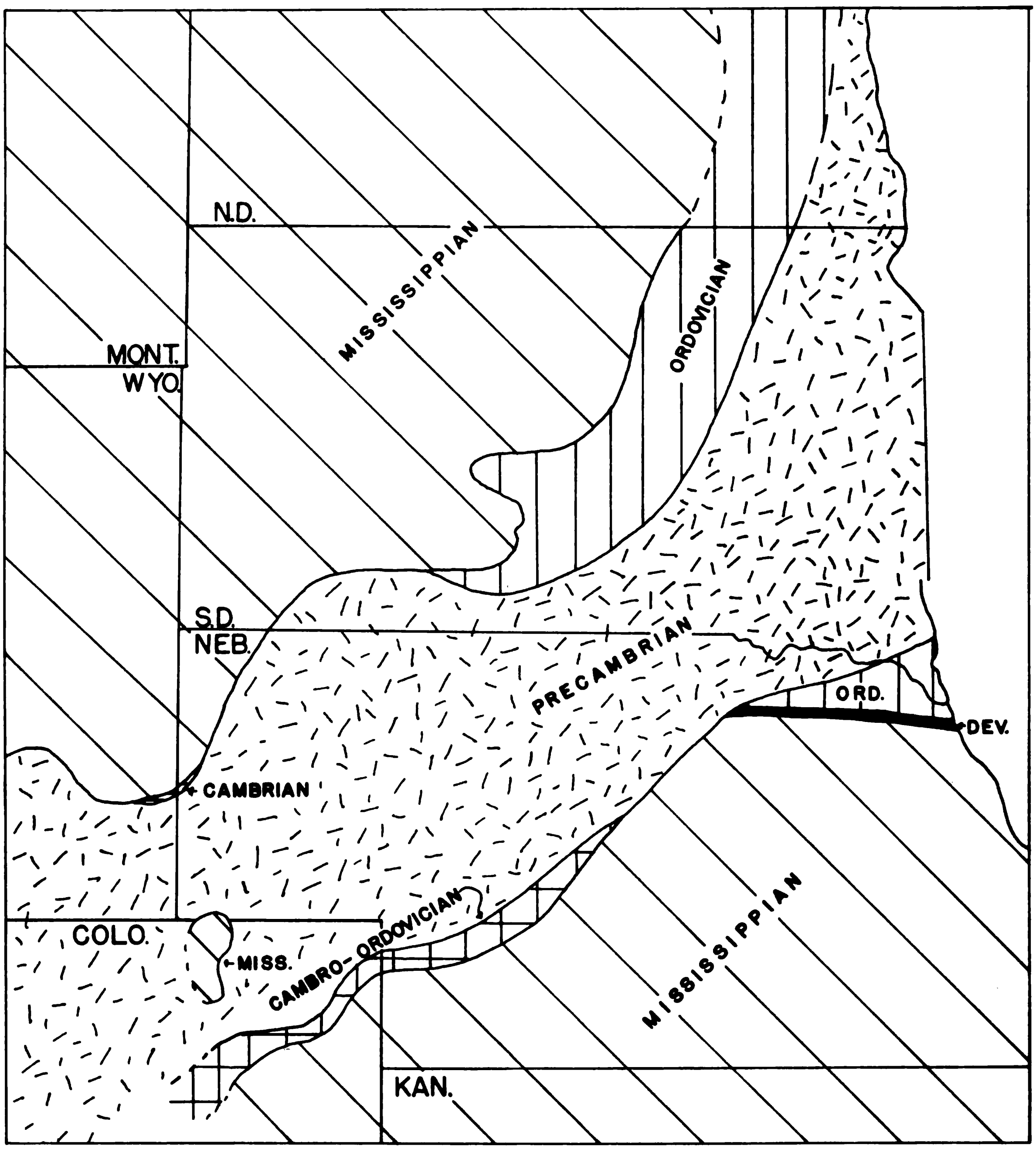


FIGURE 8: PRE-PENNSYLVANIAN PALEOGEOLOGIC MAP

(AFTER ANDRICHUK, 1955 & MACAULEY, 1964)

Black Hills area and Chadron Arch area, he thought, were also positive but did not contribute significant sediments in South Dakota. Allen (1966), believes that the Minnelusa sandstones are southeast trending shore line sand dunes with an almost cyclical rise in sea level at the same time that the dunes were being blown onto tidal flats. He also postulated an uplift after Wolfcampian time with subsequent drainage incisions allowing the Opeche Formation to fill in the valleys which were related to the original Minnelusa sandstone build-ups.

On the basis of the literature and on the maps and cross-sections which were constructed, the writer believes the following events transpired during the Permo-Pennsylvanian time.

Following the termination of Mississippian time a general southward tilting of eastern Wyoming and western South Dakota took place.

Two seas developed during Morrowan time, one moving northeastward from the Denver-Julesburg Basin, the other transgressing eastward out of the Cordilleran Geosyncline. The series of paleogeographic maps modified from Tranter and Petter (1963) (Figures 9 through 13) show this diagramatically. The sea transgressing from the Denver-Julesburg Basin was restricted by the Colorado Mountains, Sioux Uplift and the Cambridge Arch. By the end of Morrowan time, the western half of the state was covered.

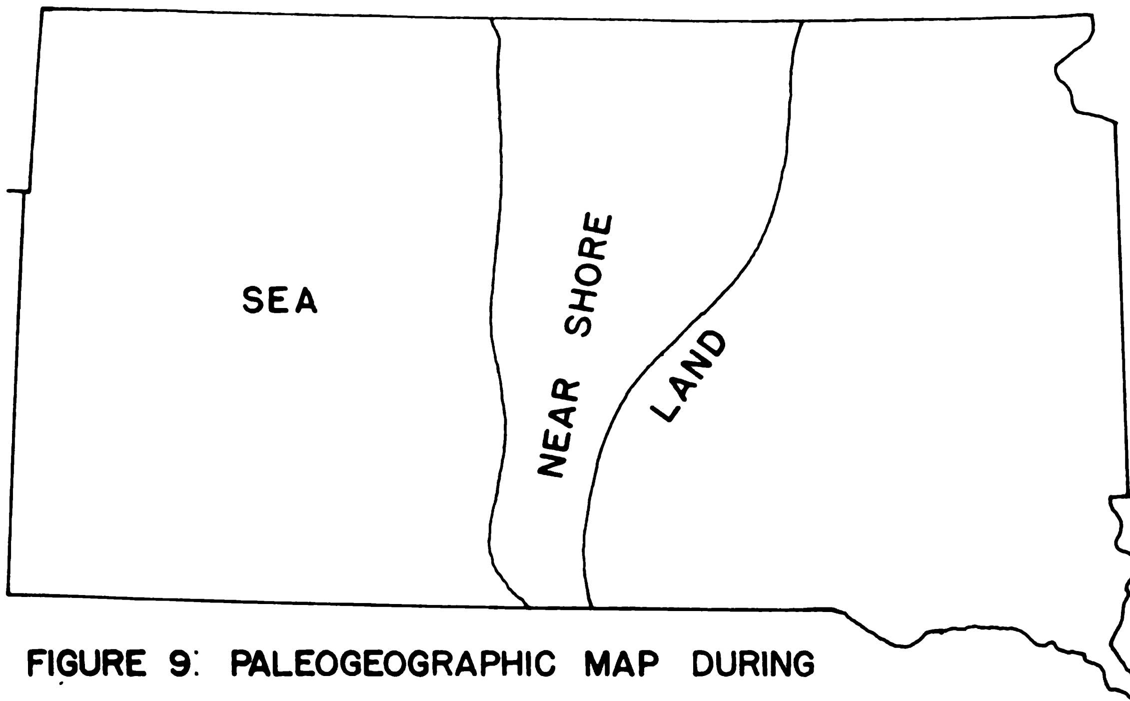


FIGURE 9: PALEOGEOGRAPHIC MAP DURING EARLY DES MOINESIAN TIME

MODIFIED FROM TRANTER & PETTER (1963)

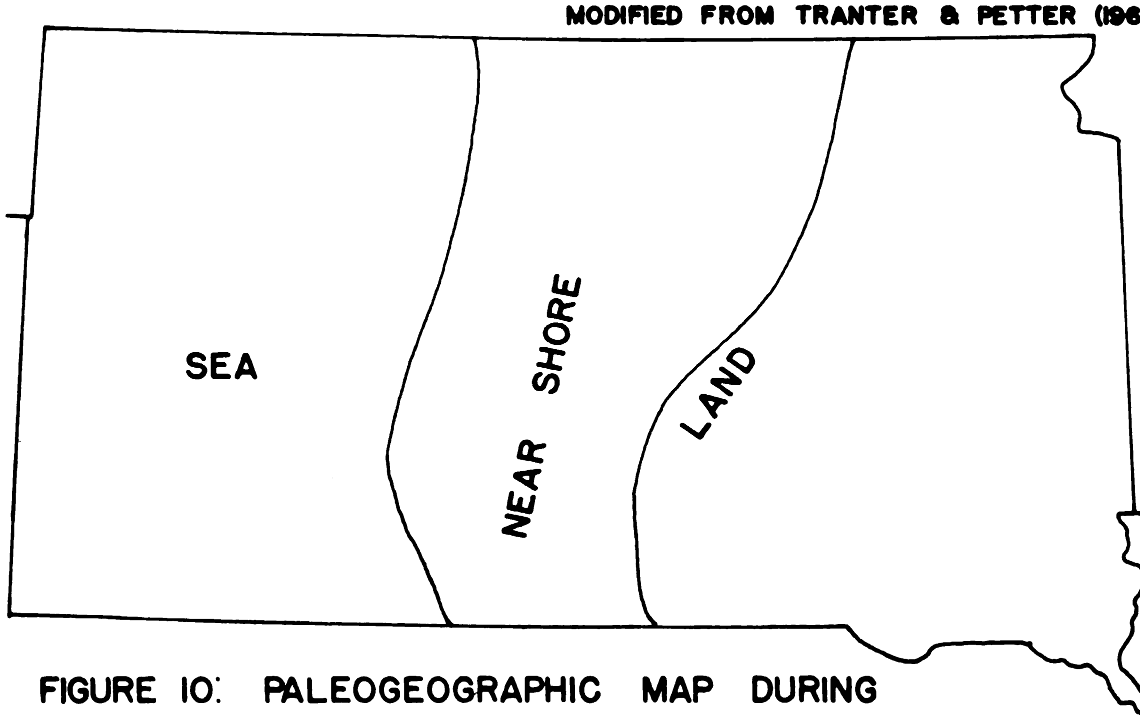


FIGURE 10: PALEOGEOGRAPHIC MAP DURING LATE DES MOINESIAN TIME

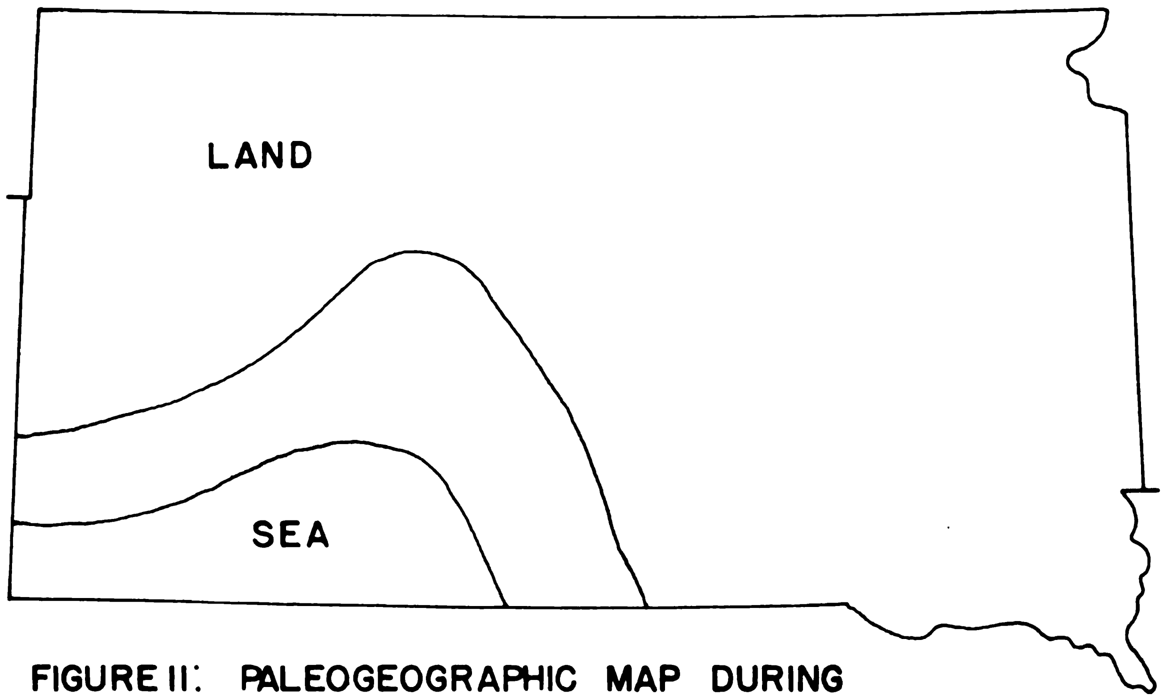


FIGURE 11: PALEOGEOGRAPHIC MAP DURING MISSOURIAN TIME

MODIFIED FROM TRANTER & PETTER (1963)

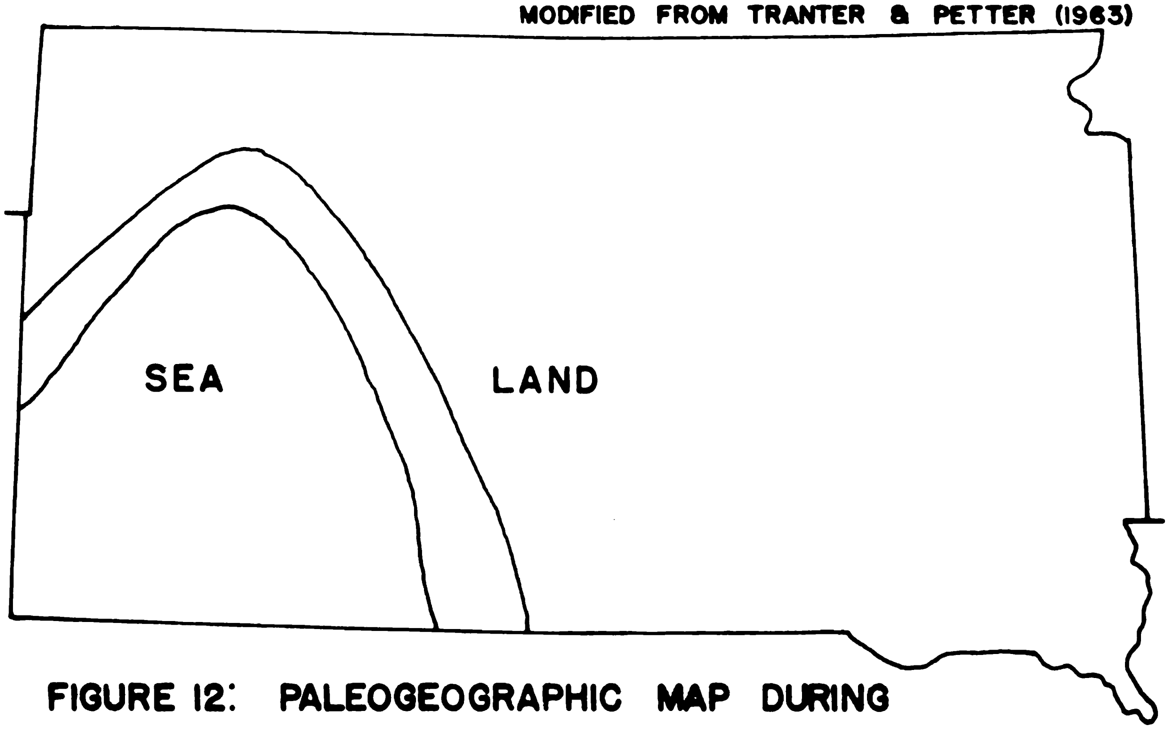


FIGURE 12: PALEOGEOGRAPHIC MAP DURING VIRGILIAN TIME

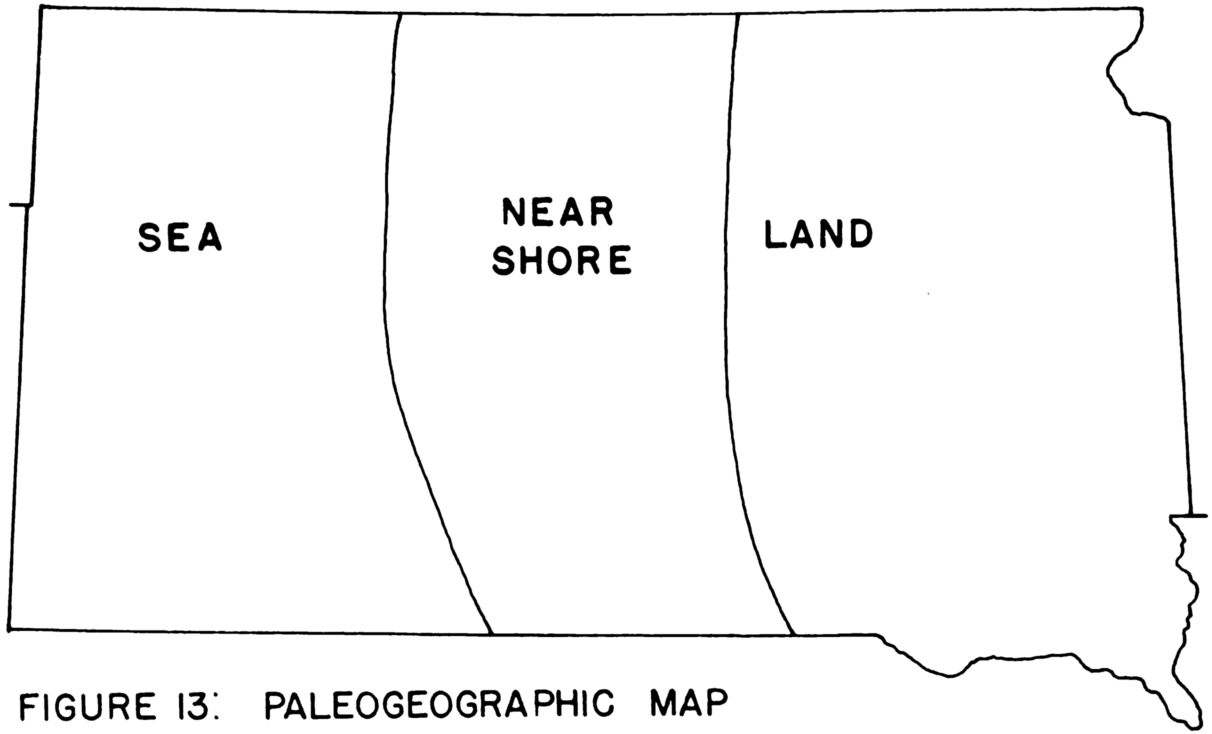


FIGURE 13: PALEOGEOGRAPHIC MAP DURING WOLFCAMPIAN TIME

MODIFIED FROM TRANTER & PETTER (1963)

The sediments deposited were of a normal marine sequence thickening toward the southeastern part of the state into the Lusk Embayment.

Early Desmoinesian time saw an uplift of the Colorado Mountains to the southwest. These furnished great quantities of arkose in southeastern Wyoming but quartz sands comprised most of the sediments in South Dakota. The sea was regressing at this time and was relatively shallow. The most likely source area was the Colorado Mountains. A thickening toward this structure along with an increase in sandstone is shown on the lithologic column map (Plate V). An interfingering relationship exists between the sand and a dolomite, shale lithology. This possibly represents a near shore environment. We also see an interbedding of thin limestones with sandstone beds. This points to periods of marine transgression followed by longer periods of regression during late Pennsylvanian time.

During these regression periods, tidal flats and beaches were exposed to erosion giving rise to cross-bedded eolian deposits better sorted than the marine sediments.

Opeche Formation

The Opeche Formation, named by Darton in 1901 is composed of maroon, red, purple and ochre shales and siltstones with thin beds of brown and white dolomite. Inclusions of anhydrite and gypsum are found in some locations. It lies conformably below the Minnekahta limestone and unconformably above the Minnelusa Formation as discussed earlier. No fossils have been found in the Opeche so its placement in middle Permian is dependent on stratigraphic position. The Opeche is widespread throughout the western half of South Dakota. The thickness varies from a feather edge in the middle of the state to over 300 feet in the southwest. The great changes in thickness are due to its unconformable relationships with the Minnelusa.

The depositional environment of the Opeche shale was that of a transgressing sea. The Wyoming shelf area, at the beginning of Opeche time was tilted to the west and the Phosphoria sea to the west transgressed to the west depositing tongues of limestone and shales. The Opeche and Minnekahta Formations are eastward tongues of the Phosphoria sea.

Minnekahta Formation

The Minnekahta limestone, which lies conformably above the Opeche and below the Goose Egg is the most extensive deposit of the Phosphoria sea. Lithologically, it can range from a dense, hard limestone to a fine, crystalline dolomite but it generally consists of a very uniform, thin bedded, light pinkish-gray limestone. Some pinpoint porosity does exist in wells near the Black Hills. It is also somewhat anhydritic throughout the state. The Minnekahta averages 40 feet thick in the Black Hills area. It is also easily recognized in this area as the predominant cliff-former.

As a result of the westward tilting of eastern Wyoming, a restricted sea in eastern Wyoming receded towards the west. Coupled with this, a climatic change to a more arid environment allowed the deposition of the Minnekahta to take place along near-shore flood plains, bars and tidal flats. Weller (1956) believes that the Minnekahta was deposited as an inorganic, fine-grained, chemical precipitate. Oolites found in the Minnekahta and the fact that it was deposited along with red beds led him to the above conclusion. However, the writer disagrees with Weller because the Minnekahta shows algal structures in many areas (Fisher, personal communication).

Goose Egg Formation

The boundaries and naming of the Goose Egg Formation have been a problem since the early 1900's. In 1901, Darton, working in eastern Wyoming, described a series of redbeds between the Minnekahta limestone and the Jurassic Sundance which he referred to as the Spearfish Formation. The lower portion of these beds was later described by Burk and Thomas in 1956. They proposed the name Goose Egg Formation to include rocks between the Casper Formation of Pennsylvanian age and the Chugwater Formation of Triassic age. Burk and Thomas included the Minnekahta and Opeche beds within the Goose Egg. This relegated them to members, which they are not. It is common practice among writers to refer to the Goose Egg as a formation and the Opeche and Minnekahta as members of that formation.

If we look at the definition of a member, we can see the problem. According to Weller, members are "comparatively unimportant and more or less local rock units included within formations." We can see that the Opeche and Minnekahta are certainly not local beds, because they cover most of western South Dakota and portions of three surrounding states. The Minnekahta and Opeche beds were called formations before the name Goose Egg was proposed, so they have priority. The type section of the Goose Egg Formation as described by Burk and Thomas (1956), is located near the Goose Egg Post Office in central Wyoming. This section contains approximately 10 feet of Minnekahta limestone and 70 feet of Opeche shale which they identify. This writer proposes that the Goose Egg Formation name should be retained but that it should have its lower limit at the top of the Minnekahta.

The Goose Egg contains sandy dolomites in the east-central Wyoming area, but because it grades laterally into a gypsum anhydrite sequence near the Black Hills, it makes it difficult to determine the upper boundary in surface exposures.

Petroleum Possibilities in the Minnelusa

The Minnelusa Formation in South Dakota offers a number of possibilities for finding petroleum. Because the state of South Dakota lies in the Mid-Continent region, structural patterns that are developed in the Rocky Mountains are much more subdued in the state. During the Laramide Orogeny, the compressive force diminished to the east and thus produced very little in the way of folding, east of the Black Hills. Some anticlines do exist in the Lemmon Syncline, but their closure is so small that economic accumulations are not present. This does not preclude larger anticlines being present. Some fault traps could be productive along the western portion of the Lemmon Syncline. One fault is known to exist there and others probably exist between the Cedar Creek Anticline and the above mentioned fault. Stratigraphic traps offer the most promising traps in South Dakota. The Minnelusa contains a number of sandstone beds, among them, the Leo sands of the Middle Minnelusa capable of producing petroleum. The impervious Opeche shale overlying the Minnelusa acts as a good seal where it is present. Along the zero line of the Minnelusa near the middle of the state, the formation thins on the underlying granite and quartzite. Where the formation feathers out and where overlying shales, either within the Minnelusa or the overlying Jurassic, could be found, wedge out traps are possible. Most of the exploration to date has been around the Black Hills. Near the zero line of the Minnelusa, very little drilling has been done. Another possibility for petroleum accumulation would be unconformities. The Opeche lies unconformably on the Minnelusa so traps such as buried topography, or a regional truncation along with buried topography present good possibilities. Again, the area near the middle of the state, where the Minnelusa thins would be worth testing. Other traps one could look for here would be local updip porosity pinchouts, facies changes from sandstone to dolomite or anhydrite and local porosity developments in dolomite units.

CONCLUSIONS

The Minnelusa Formation in South Dakota has been shown to be a predominately marine sediment that has the possibility of producing petroleum. The Minnelusa Formation in South Dakota has been shown to be a predominately marine sediment. During early Pennsylvanian time, South Dakota was inundated by seas transgressing from the west and southwest. During middle and late Pennsylvanian time the seas regressed in a sporadic manner creating shallow water deposits and some eolian sediments. Post-Wolfcampian erosion and a climatic change to more arid conditions accompanied Opeche and Minnekahta deposition which are tongues of the Phosphoria sea. With a number of places showing favorable conditions for oil accumulation, especially near the edge of the Minnelusa, the writer believes that it will only take a matter of time to test these areas and find commercial oil.

Surface work has helped in determining the gross lithology of the Minnelusa in the Black Hills region, but it is now the responsibility of the subsurface geologist to determine the specific aspects of the Minnelusa in the rest of the state for petroleum production. Prolific production from the Minnelusa of the Powder River Basin has encouraged the industry to explore the possibilities of the Minnelusa Formation in South Dakota containing the elusive "Leo sands" which the writer believes to exhibit good possibilities for petroleum.

Since seismic exploration techniques can be of little use in most areas of South Dakota because of the fact that the Opeche is underlain by porous sandstone and the matrix velocities of the two units are nearly identical, intense and detailed subsurface geology will eventually be the best method for exploiting petroleum possibilities in South Dakota.

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APPENDIX

TYPE SECTION OF THE MINNELUSA FORMATION

TYPE SECTION OF THE MINNELUSA FORMATION

SW, 1/4, Sec. 10, T. 52 N., R. 61 W., exposed in Sundance Canyon, Crook Co., Wyo. (After Brady, 1958)

		Thickness (Feet)
	Opeche Red Shale	
	Opeche Gypsum	12
Unconformable contact with Opeche Formation		
21.	Buff, dense, arenaceous limestone; fossiliferous; regional member	10
20.	Light brown, fine grained, well rounded, friable, gypsiferous sandstone; regional member	10
19.	Soft, white, friable gypsum	22
18.	Thinly bedded, pink to purple striped limestone; fossiliferous	2
17.	White, massive gypsum	10
16.	Soft, red, gypsiferous shale	4
15.	White, massive gypsum	30
14.	Yellow to buff, massive, medium grained sandstone, regional member	30
13.	White, massive, dense anhydrite	8
12.	Interbedded gray limestones, red shales, and buff siltstones; purple siltstone and gypsiferous conglomerate near the top; fossiliferous; regional member	11

		Thickness (Feet)
11.	Red, brown, and pink, fine-grained, evenly bedded sandstone; <u>regional member</u>	30
10.	Gray, dense, arenaceous limestone; interbedded with brown, gray, and purple shales and siltstones; fossiliferous; <u>regional member</u>	7
9.	White, massive, dense gypsum and anhydrite	15
8.	Gray, dense limestone; fossiliferous	5
7.	White, dense, massive gypsum and anhydrite	8
6.	Interbedded gray limestone and purple shale	5
5.	Soft, white, friable gypsum	27
4.	Gray, very dense, dolomite, lithographic, well-bedded limestone; fossiliferous	4
3.	White anhydrite	6
2.	Yellow to buff, calcareous, ferruginous, medium to coarse grained sandstone; <u>regional member</u>	10
1.	Dense, yellowish to lavender, crystalline limestone; brown spots; <u>regional member</u>; not fully exposed	3
		257

Creek bed