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Geological Evolution and Energy Resources of the Williston Basin

LEE C. GERHARD*

ABSTRACT

The Williston basin of North Dakota, Montana, South Dakota, and south-central Canada (Manitoba and Saskatchewan) is a major producer of oil and gas, lignite, and potash. Located on the western periphery of the Phanerozoic North American craton, the Williston basin has undergone only relatively mild tectonic distortion during Phanerozoic time. This distortion is largely related to movement of Precambrian basement blocks.

Sedimentary rocks of cratonic sequences Sauk through Tejas are present in the basin. Sauk, Tippecanoe, and Kaskaskia Sequence rocks are largely carbonate, as are the major oil and gas producing formations. Absaroka and Zuni rocks have more clastic content, but carbonates are locally important. Clastics of the Zuni Sequence (Fort Union Group) contain abundant lignite. Tejas Sequence rocks are not significant in the production of minerals and energy, although glacial sediments cover much of the region.

Oil exploration and development in the United States portion of the Williston basin in the time period 1972 to present has given impetus to restudy of basin evolution and geologic controls for energy resource locations. In consequence, oil production in North Dakota, for instance, has jumped from a nadir 19.5 million barrels in 1974 (compared to previous zenith of 27 million in 1966) to 32 million barrels in 1979 and 40 million barrels in 1980. Geologic knowledge of carbonate reservoirs has expanded accordingly.

Depositional environments throughout Sauk, Tippecanoe, and Kaskaskia time were largely shallow marine. Subtidal and even basinal environments were developed in the basin's center, but sebkha deposits were abundant near the basin's periphery. Evidence of subaerial weathering was commonly preserved in structurally high areas and on the basin's periphery, especially in late Kaskaskia rocks. Some pinnacle reefs were developed in Kaskaskia time, morphologically similar to the Silurian pinnacle reefs of the Michigan basin.

Clastic sediments were transported into the southern (U.S.) part of the basin during Absaroka time, a product of erosion of ancestral Rocky Mountain orogenic structures. Continental and shallow marine clastic sediments were deposited until deeper Cretaceous marine environments were established. Laramide orogenesis to the west provided detritus that was deposited in fluvial, deltaic, and marginal marine environments, regressing to the east. Major lignite deposits are part of this post-orogenic regressive rock body.

Major structures in the basin have ancient histories, many of them probably pre-Phanerozoic in origin. Reversals of structural movement on faults occur during Paleozoic events. Meteorite impact structures have been hypothesized in the basin, and some early Saukian structural complexity is seen.

A rapidly accumulating computerized data base in the North Dakota part of the basin is serving to establish the Williston basin as a model for study of cratonic basin structural grain and evolution.

INTRODUCTION

Recently successful oil exploration and development in the Williston basin has clearly demonstrated the inadequacy of previous tectonic and sedimentologic models of the basin to predict occurrences of mineral and fuel resources. The United States portion of the basin has sustained oil development during the last half of the 1970's that is remarkable in its definition of new structures, new producing horizons, and success rates. The largest single segment of the basin is the North Dakota portion (Fig. 1), which includes the deepest part of the basin and the thickest Phanerozoic section. In 1977, the wildcat success rate was 25 percent; in 1978, 28 percent; in 1979, 33 percent; and through the first six months of 1980, 36 percent, compared to a national 10 to 12.5 percent. Although South Dakota and Montana also sustain active programs, their success rates are lower. Montana has the second most active drilling program in the basin, and it has been successful.

Oil and gas are not the only mineral and energy resources of the basin. Williston basin lignite reserves are huge and are actively being explored and utilized. Potash resources are potentially far more valuable than the lignite but are not yet being mined.

Coincident with energy development, interest in water resources (for energy transportation) and overall economic significance of the basin has led to a serious study of basin geology with numerous programs of investigation underway. Programs of the North Dakota Geological Survey, the United States Geological Survey, the Department of Energy, and several oil companies deserve particular note; much of the information in this summary is derived from these sources.

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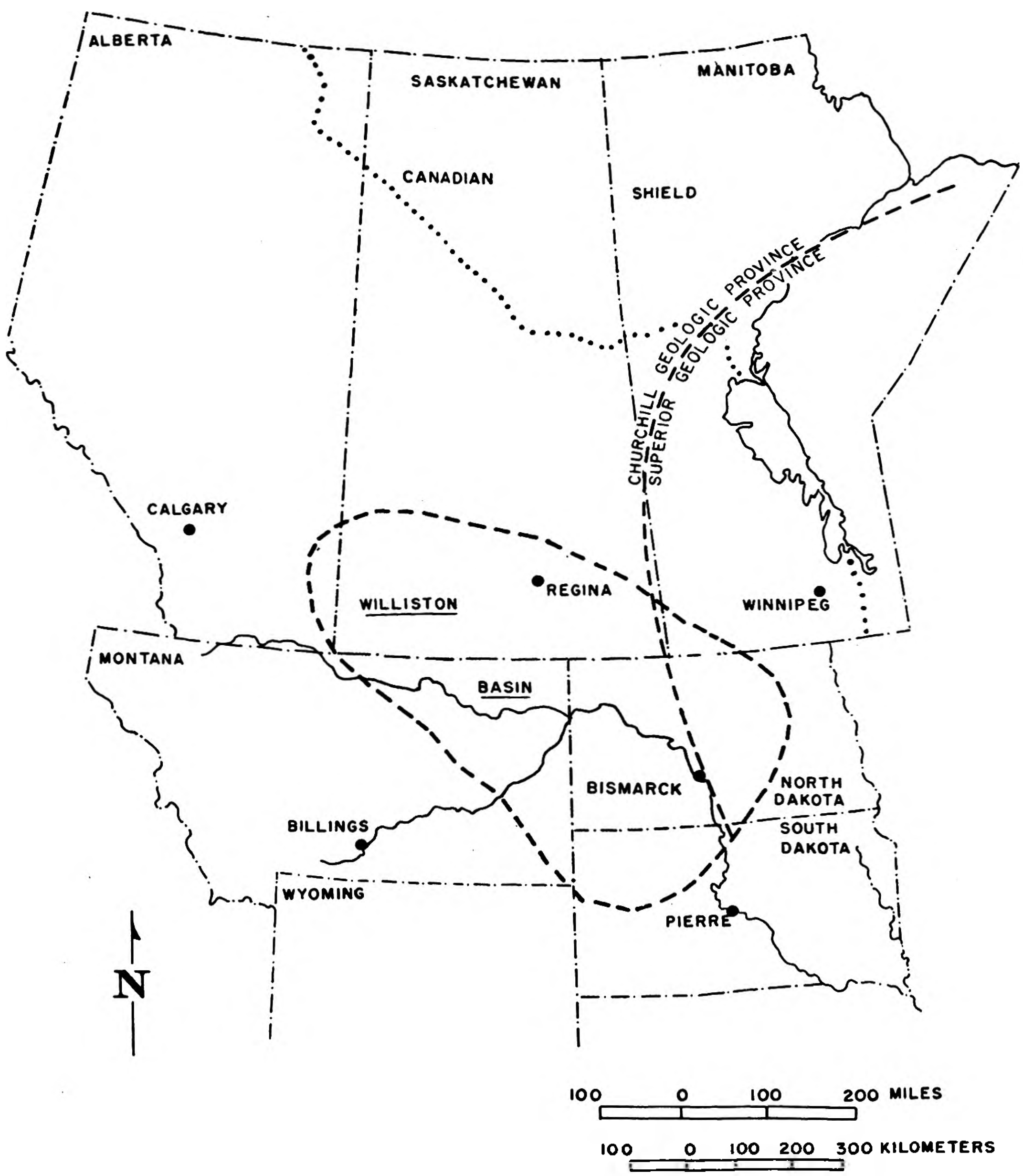


Fig. 1. Index map showing location of the Williston basin in the United States and Canada. Modified from Worsley and Fuzesy, 1978.

The Williston basin is a slightly irregular, round depression in the western distal Canadian Shield. It lies just north of the latitude of the Rocky Mountain structural grain directional change from north-south trends to northwest-southeast trends. Structural trends within the basin reflect both major structural directions (Fig. 2). Several writers have hypothesized a wrench fault system for control of the basin's geometry and structure (Thomas, 1971; Brown, 1978) but have not integrated this information on sedimentary depositional facies and porosity development. Approximately 16,000 feet of sedimentary rocks are present in the deepest part of the Williston basin near Watford City, North Dakota. The deepest well in the basin encountered Precambrian rock at 15,260 feet; the deepest oil production is from 14,343 feet in the Ordovician Red River Formation (Mesa #1-13 Brandvik, Dunn County, North Dakota).

Rocks deposited during all periods of Phanerozoic time are present in the basin (Fig. 3). Paleozoic rocks are mainly carbonates, followed by the more highly clastic Mesozoic rocks and nearly all clastic

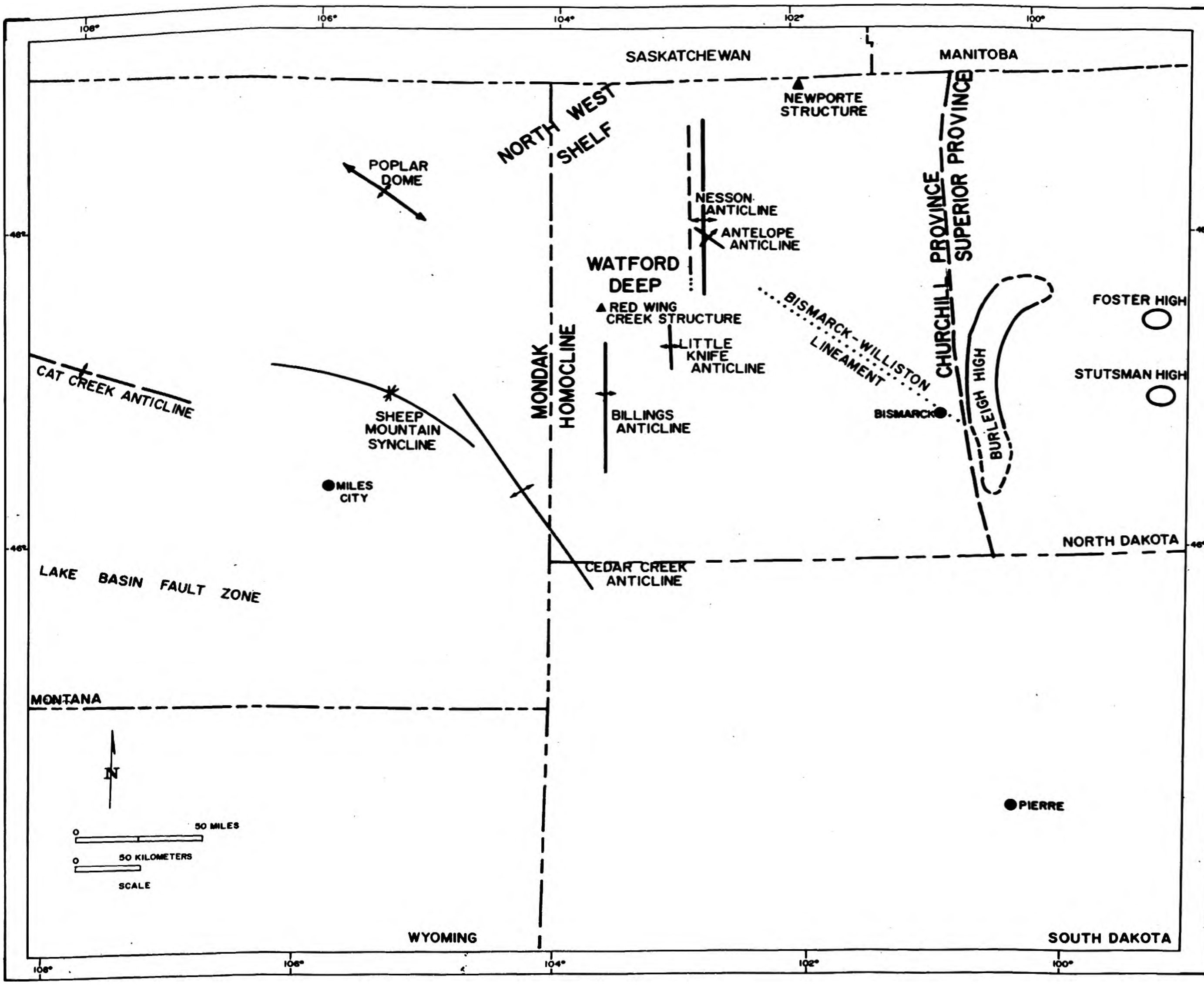


Fig. 2. Major structures of the Williston basin based on current subsurface structural mapping and geophysical interpretations.

Cenozoic rocks. Sloss's sequence concept (1963) is particularly useful in the study of these rocks, because it serves to "package" major transgressive cycles of continental scale with accompanying sediment deposition. For this reason, discussions of stratigraphic units and their significance in deciphering the structural evolution of the Williston basin is organized by sequences, following the practice of Carlson and Anderson (1966, 1970).

Regional studies of Williston basin rocks have been published infrequently. Several important contributions, which are used extensively in this paper, are the papers of Porter and Fuller (1959), Carlson and Anderson (1966), the various papers presented in the Geologic Atlas of the Rocky Mountains (Mallory, 1972), and McAuley (1964). Several unpublished works of oil company geologists are also used in this paper, especially those of James Clement (1975-1980, personal communication).

Several bursts of interpretive writing are evident in the literature about the Williston basin. Each proceeds from an equivalent burst of mineral or fuel development activity. This cycling of activities is common to most petroleum provinces. The Williston basin is in its third cycle of oil development and is rapidly increasing oil production, whereas most of the rest of the adjacent "48" has sustained declining production. North Dakota contains most of the United States portion of the Williston basin; its statistics are impressive. After

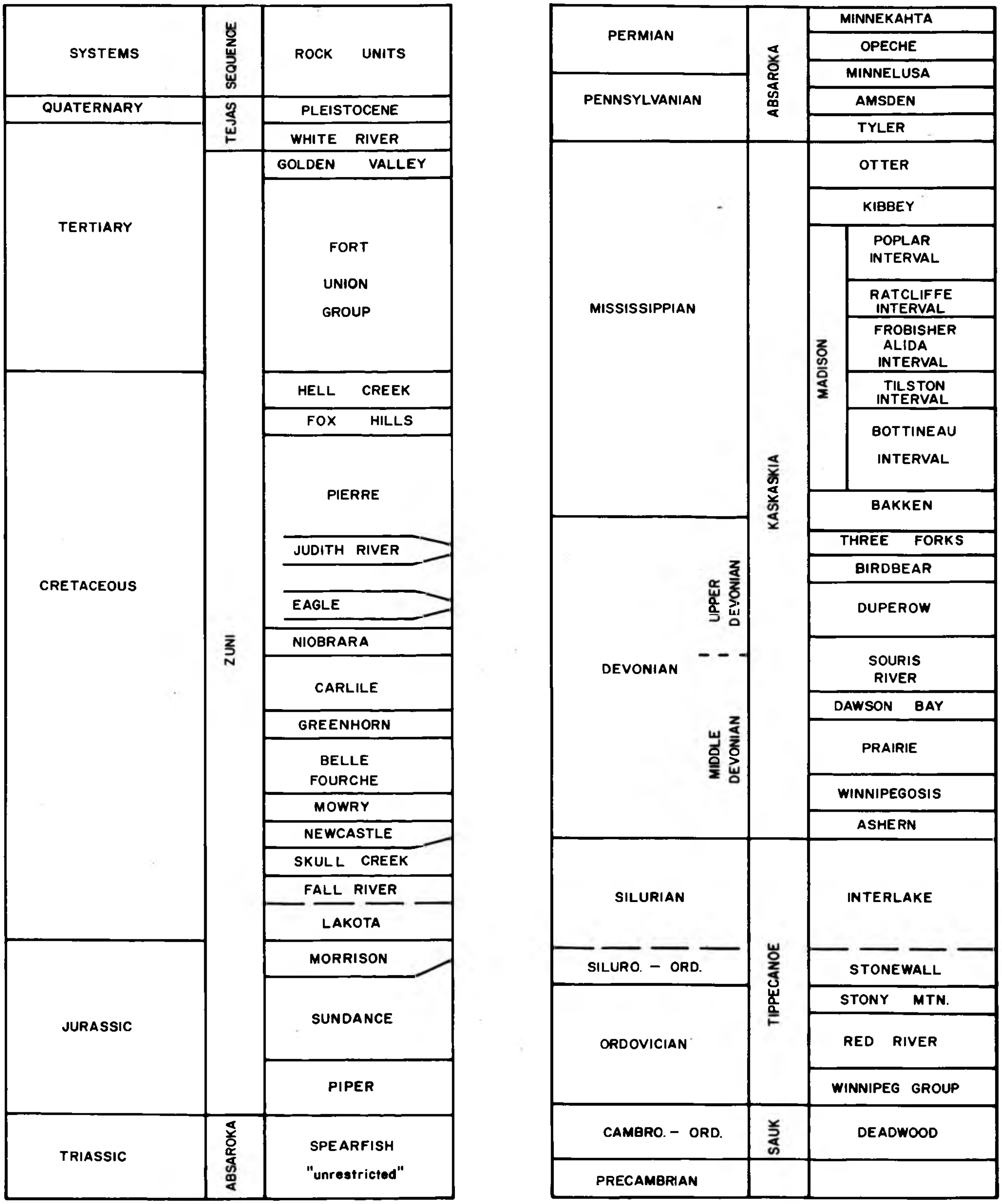


Fig. 3. Generalized stratigraphic column of the Williston basin.

reaching a high of 27 million barrels of oil produced in 1966, production declined to 19.5 million barrels in 1974. During the third cycle of development, production began to increase in 1975 and reached a new historical high of 32 million barrels in 1979 and 40 million barrels in 1980. Concurrent with this burst of development, research in oil and gas reservoir geology, regional depositional systems, and other aspects of basin analysis has been revived with applications of technolgy developed since the mid-sixties. Summary papers of this era are included in Estelle and Miller (1978) and in several publications of the North Dakota Geological Survey (Carroll, 1979; Bjorlie, 1979; Bluemle and others, 1980; Lerud, 1982; and Scott, 1981, among others). Various papers presented at national and regional society technical programs have also added ideas and data to the present research cycle.

Acknowledgments - My purpose in this paper is to summarize briefly the current knowledge of the geological evolution and energy resources of the basin. As in any summary paper, this effort is colored by my own geological philosophies and biases. Many of my colleagues, students and cooperating scientists have spent extensive amounts of time discussing ideas, providing data, and redirecting my efforts. In particular, Sidney Anderson of the North Dakota Geological Survey, James H. Clement of Shell Oil Company, Cooper Land, Consultant, and Walter Moore of the University of North Dakota have been instrumental in helping me to construct my ideas and approach. Julie LeFever has served ably as research assistant. Other colleagues and students, who have contributed to this summary, are Randolph Burke, Diane Catt, Tom Heck, John Himebaugh, Peter Loeffler, Tom Obelenus, and Nancy Perrin. Support for some of the studies of original depositional systems and reservoir geology has been provided by the North Dakota Geological Survey, the Carbonate Studies Laboratory of the University of North Dakota, and a grant from the U.S. Geological Survey (#14-08-0001-G-591). All of this support is gratefully acknowledged.

TECTONIC SETTING

The Canadian Shield extends under the Williston basin to the Cordilleran geosyncline. The Williston basin forms a large depression on the western edge of the shield and is located in much of North Dakota, northwestern South Dakota, and the eastern quarter of Montana. A significant portion is in southern Saskatchewan. This part of the craton is bordered on the south by the Sioux arch, on the southwest by the Black Hills uplift and Miles City arch, and on the west by the Bowdoin dome and Poplar anticline (Fig. 2).

The structural grain of the region appears to be controlled by the offset in the Rocky Mountain chain between the north-trending Southern Rocky Mountain Province and the north-trending Northern Rockies. The zone of offset in Wyoming and Montana (Central Rockies) is characterized by the northwest structural grain of basin and range configuration. Regional wrench faulting along the Cat Creek and Lake Basin zones suggests that structural control of the Williston basin is related to a large-scale "tear" in the edge of the craton.

Ballard (1963) outlined a hinge line for the eastern part of the Williston basin in central North Dakota (see also Laird, 1964) that is the provincial boundary between the Superior and Churchill Provinces of the Canadian Shield. Stratigraphic and gravity studies suggest that this boundary is an important factor in Phanerozoic basin development.

Structural trends within the Williston basin reflect both the north and northwest trending grain of the Rocky Mountain provinces. The Cedar Creek anticline and Antelope anticline are northwest trending structures. The Poplar anticline is slightly divergent from these but is also generally northwest trending. The Nesson, Billings, and Little Knife anticlines are north trending structures. An additional northwest trending structure, which is an extension of the Antelope anticline in the southwest part of the basin, has been mapped in the course of preparation of this paper (Bismarck-Williston zone).

Several smaller structures on the eastern shelf have been mapped by Ballard (1963). Of these, those in Foster and Stutsman Counties are probably important. His Cavalier high is apparently a paleotopographic afteraffect of pre-Mesozoic drainage (Anderson, 1974).

Two other structural elements are significant to basin interpretation, the Red Wing Creek structure and the Newporte structure (Fig. 2). Both of these structures are enigmatic, although the Red Wing Creek structure has been described as an astrobleme (Brennan and others, 1975; Parson and others, 1975). The Newporte structure is apparently a faulted block of early Paleozoic age in which oil has been trapped along unconformities within Cambrian and Ordovician sedimentary rocks. One well produces from Precambrian crystalline rocks (Clement and Mayhew, 1979).

Indications of other tectonic elements or theoretical projects of deformation have been published by several writers. Kearns and Trout (1979) illustrated satellite imagery surface lineations which are northwest and northeast trending. Although northwest trending structures are known to be of significance in the basin, this is one of the few illustrations of northeast trends that control much of the Mississippian structurally-assisted,

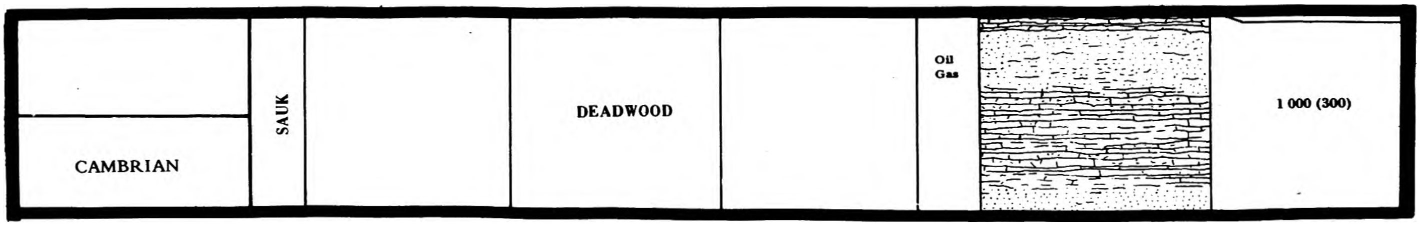


Fig. 4. Stratigraphic column of the Sauk Sequence. Modified from Bluemle and others, 1980.

stratigraphic oil traps in north-central North Dakota.

Several writers have attempted to establish a wrench faulted framework for the basin. Most recently, Brown (1978) has used isopach variations in individual stratigraphic units to build a wrench fault deformation fabric for the southern part of the basin. Earlier, Thomas (1971) built a regional theoretical model for wrench fault tectonics in the Montana and North Dakota parts of the basin.

There is little question in my mind that sedimentation and structure of the basin are controlled by movement of basement blocks, which were structurally defined in pre-Phanerozoic time. One of the earliest clear demonstrations of this was made by Carlson (1960), who drew attention to the Cambrian topographic relief on the Nesson anticline. Carroll (1979) illustrated the role of Precambrian topography in Red River porosity development.

The relative importance of wrench faulting, interprovince shearing, vertical-tensional deformation, and continental boundary compression or tensional stress has not been evaluated for the tectonic framework of the basin. Studies of depositional systems and mapping of structural changes through time are underway and should materially assist in the tectonic interpretation of the basin's history.

STRATIGRAPHY

Sauk Sequence

Phanerozoic sedimentation was initiated in the Williston basin during the latest Cambrian (Trempealeauean) time (Fig. 4) as the margin of the early craton was transgressed from the west by shallow marine water. In all probability, the entire basin sustained upper Sauk clastic sedimentation (Deadwood Formation); however, the eastern margin now retains only isolated remnants of the Deadwood. The total thickness of the Sauk sedimentary rocks in the basin probably does not exceed 1,000 feet. Isopachous mapping by Carlson (1960) and Lochman-Balk (1972) demonstrates that the present basin was simply a large embayment on the western shelf and was not structurally well defined. There apparently was a northwest slope into the western Canadian miogeosyncline (Porter and Fuller, 1959).

Transgression occurred over a highly irregular surface on Precambrian crystalline rocks (Carlson, 1960). Present data indicate a hilly terrain with a few large topographic prominences, such as the Nesson anticline. As with most basal Sauk units, the Deadwood is largely clastic and includes much reworked weathered Precambrian material. The middle of the Deadwood east of the Nesson anticline contains appreciable amounts of limestone and limestone conglomerate.

Carlson (1960) studied both the lithologic and faunal aspects of the Deadwood. He suggested that the conodonts are of Early Ordovician age and that the Deadwood is probably of Late Cambrian and Early Ordovician age. The only conspicuous break is between the Deadwood and the overlying Winnipeg Formation. A regional disconformity separates the Winnipeg from Deadwood rocks.

Tippecanoe Sequence

A second cycle of transgression, sedimentation, and regression comprises the Middle Ordovician through Silurian rock record of the Williston basin. This cycle, the Tippecanoe Sequence (Figs. 5, 6), marks the beginning of the Williston basin as a discrete structural depression with marine connections to the southwest (Foster, 1972). Although the transgressive phase (Winnipeg Formation) is clastic and includes a well developed basal sand, the sequence is largely carbonate. Isopachous studies of the sequence and its individual rock units suggest a southwesterly connection to the western geosyncline through the present Central Rockies. Whether or not this is a result of late erosional events is unknown. Similarly, it is possible that there was a marine connection across the Sioux arch to the eastern interior (Foster, 1972). Carroll (1979), in a study of the Red River Formation, clearly showed the influence of the Nesson anticline block, Billings anticline, the eastern North Dakota "highs", and several other structures. Isopachs of this formation are particularly

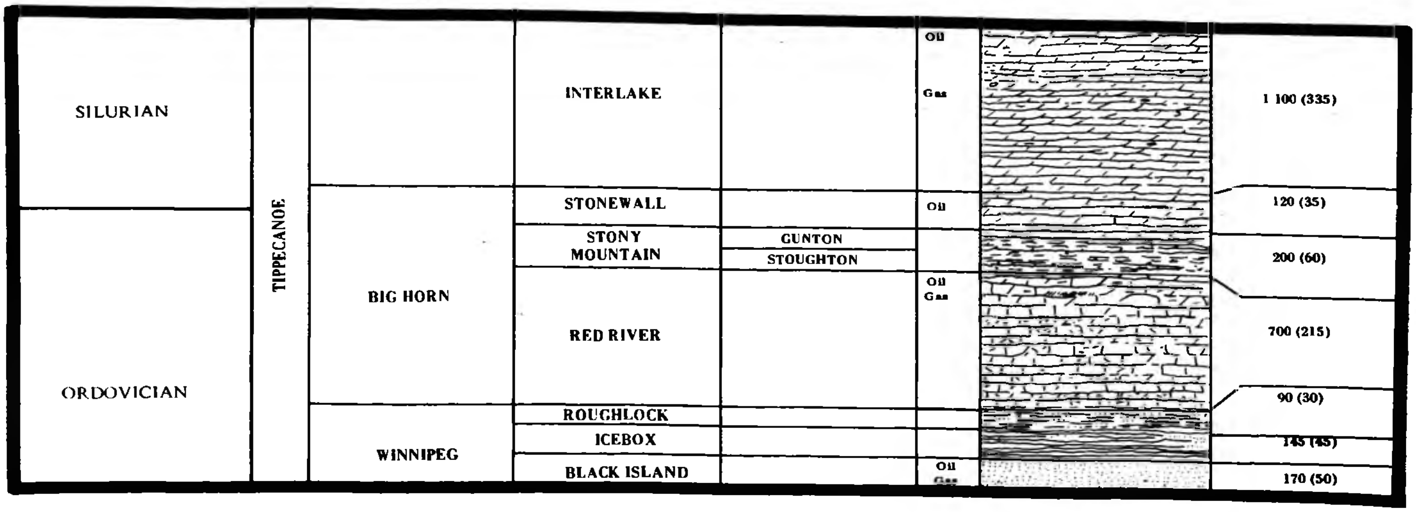


Fig. 5. Stratigraphic column of the Tippecanoe Sequence. Modified from Bluemle and others, 1980.

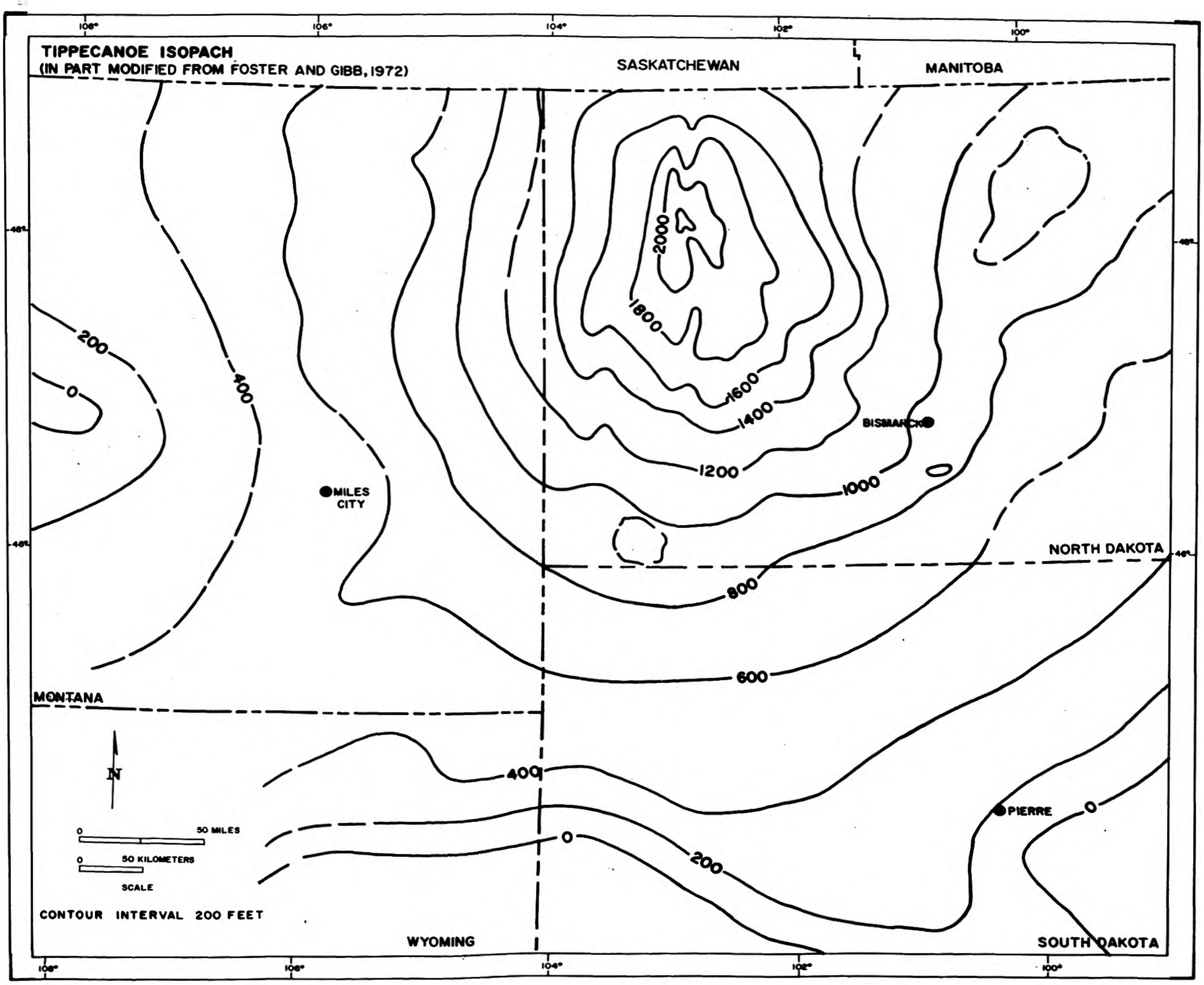


Fig. 6. Isopachous map of the Tippecanoe Sequence in the Williston basin.

important in the study of basin evolution, because they have been unaffected by later erosional events except along the basin's margin.

Carbonate rocks of the Red River and Interlake Formations (Carroll, 1979; Roehl, 1967) were deposited under shallow marine and evaporite sebkha environments. Although the basin was well defined, there is little evidence of any particularly deep basinal sedimentation. The Red River Formation contains shelf and lagoonal fabrics and biotas (Carroll, 1979) as well as sebkha evaporites and supratidal carbonates. Porosity development in the Red River is in part controlled by buried Precambrian hills or structures. (D zone selective dolomitization of burrowed wackestones occurs on the periphery of the buried "highs" because of the density of dolomitizing brines, whereas higher A, B, and C zone porosity is remnant after supratidal/sebkha dolomitization on the more crestal parts of the highs (Carroll, 1979; Carroll and Gerhard, 1979)(Fig. 7).)

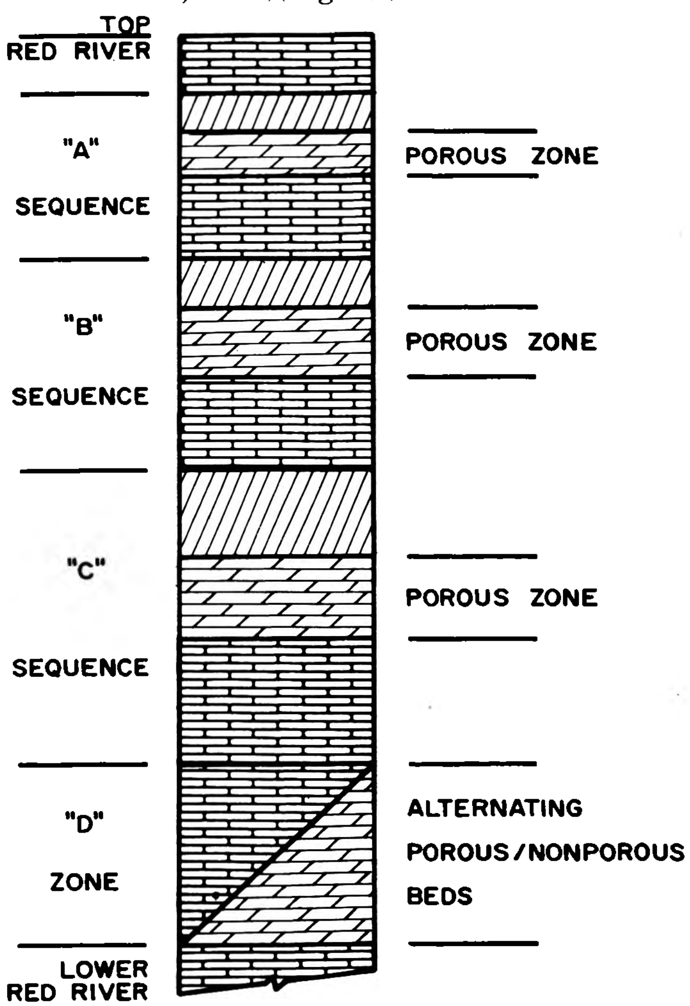
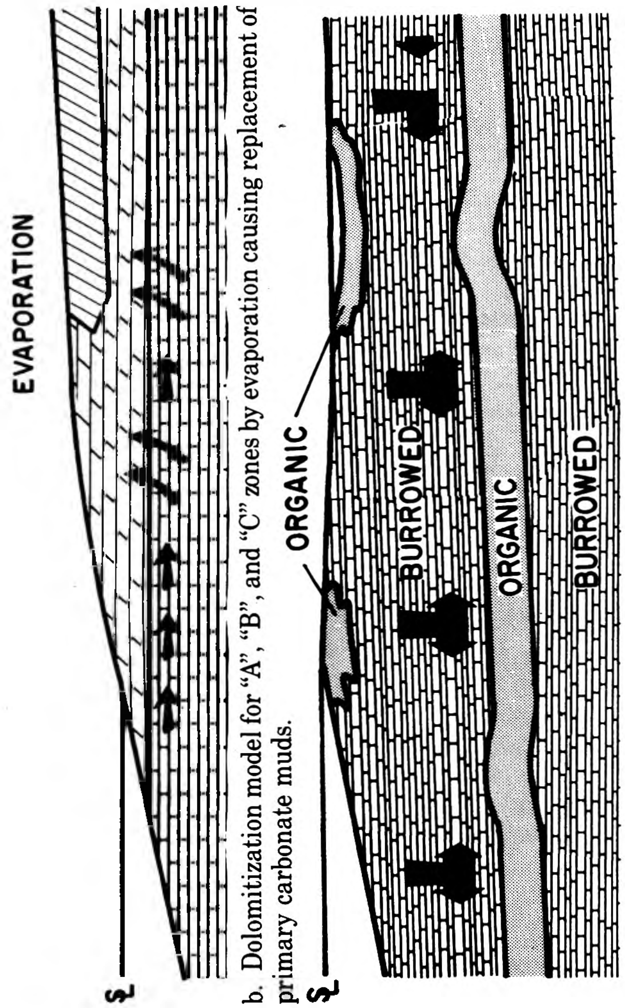
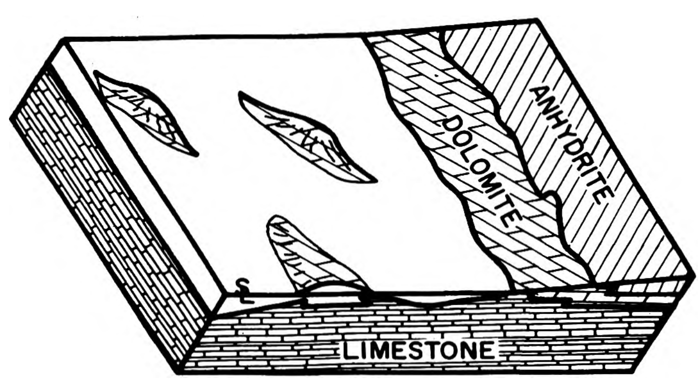


Fig. 7. a. Porosity zones in the Red River Formation. Note that "A", "B", and "C" zones have alternation of three lithologies: limestone, dolomite, and anhydrite in ascending order, whereas "D" zone porosity is alternating limestone and dolomite.

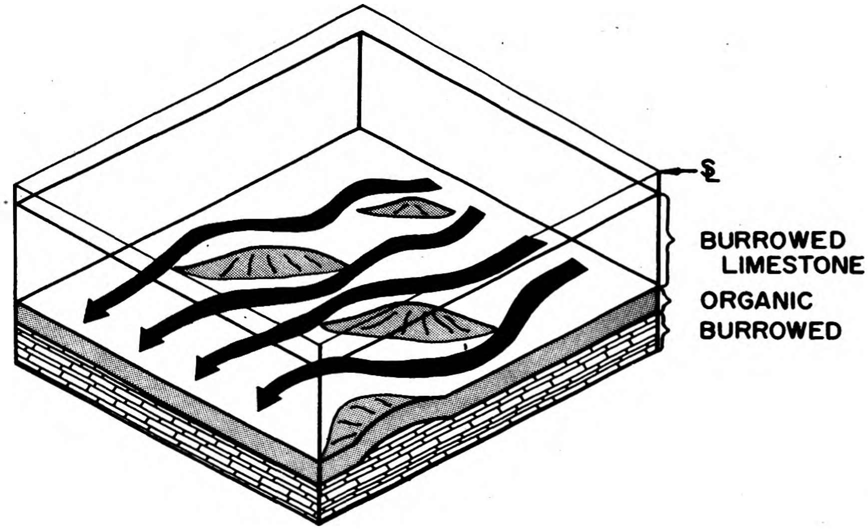


b. Dolomitization model for "A", "B", and "C" zones by evaporation causing replacement of primary carbonate muds.

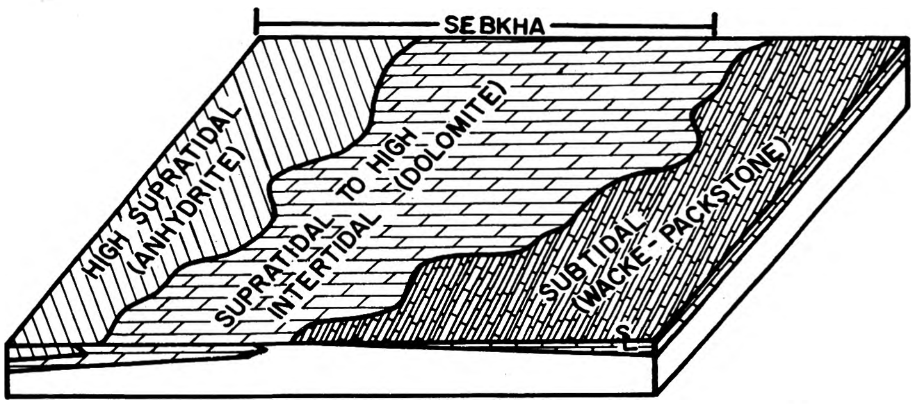
c. Dolomitization model "D" zone, showing brine that percolated down dip through primary burrowed carbonate muds but blocked by impervious organic carbonates from



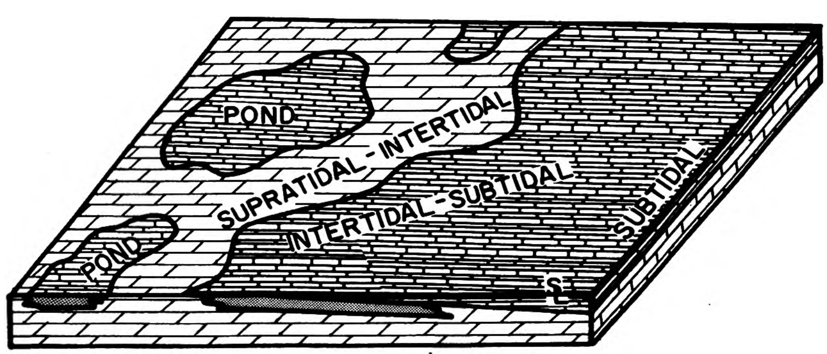
d. Diagram showing how "A", "B", and "C" zone dolomite porosity occurs on top of buried structures.



e. Diagram showing "D" zone dolomite porosity occurring on the flanks of buried structures.



f. Facies distribution during deposition of the "A", "B", and "C" zones, showing supratidal dolomitization belt.



g. Facies distribution during deposition of the "D" zone, showing pond and subtidal organic limestone deposited on top of lagoonal burrowed muds.

All diagrams modified from Carroll, 1979, and Carroll and Gerhard, 1979.

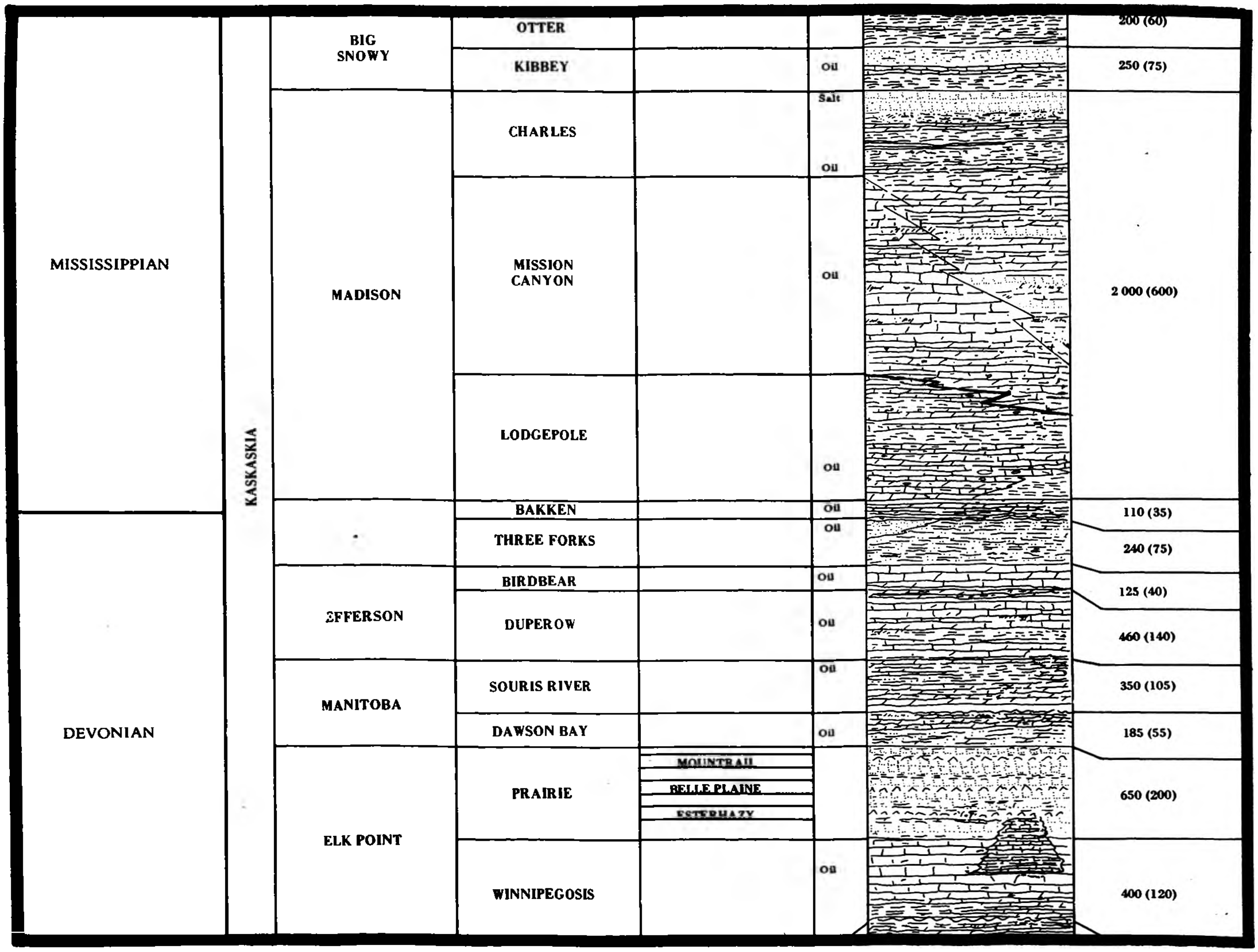


Fig. 8. Stratigraphic section of Kaskaskia rocks. Modified from Bluemle and others, 1980.

Sedimentation was continuous through the period of deposition of the Red River Formation and the Silurian. Roehl (1967) carefully documented the analogy between Silurian Interlake Formation fabrics, structures, and geometry and modern Bahamian tidal flat features. Regression after Silurian deposition resulted in at least a partial karst surface development.

Kaskaskia Sequence

Kaskaskia Sequence rocks are perhaps the best known of the sequences because of their economic importance and because there is more subsurface data available for them than other groups. Thirteen studies by North Dakota Geological Survey and University of North Dakota geologists of separate Kaskaskia rock units are either completed or in preparation for a volume, which will contain details of Kaskaskia sedimentation and porosity development.

Limestones are the most characteristic lithology of the sequence, but three episodes of evaporite deposition interrupt the carbonate pattern (Prairie, Three Forks, Charles)(Fig. 8). Winnipegosis carbonates transgressed an eroded surface of earlier Paleozoic rocks, represented by red and gray shaly beds and carbonate breccias (Ashern). Winnipegosis sedimentation culminated in the development of large stromatoporoid banks and pinnacle reefs before basin restriction increased salinity and induced Prairie evaporite deposition. Devonian seaways apparently opened northward and isopachs of the basin indicate a northward tilt for the structures (Fig. 9). The high point of the Nesson anticline shifted southward with the advent of Devonian sedimentation. The Dawson Bay

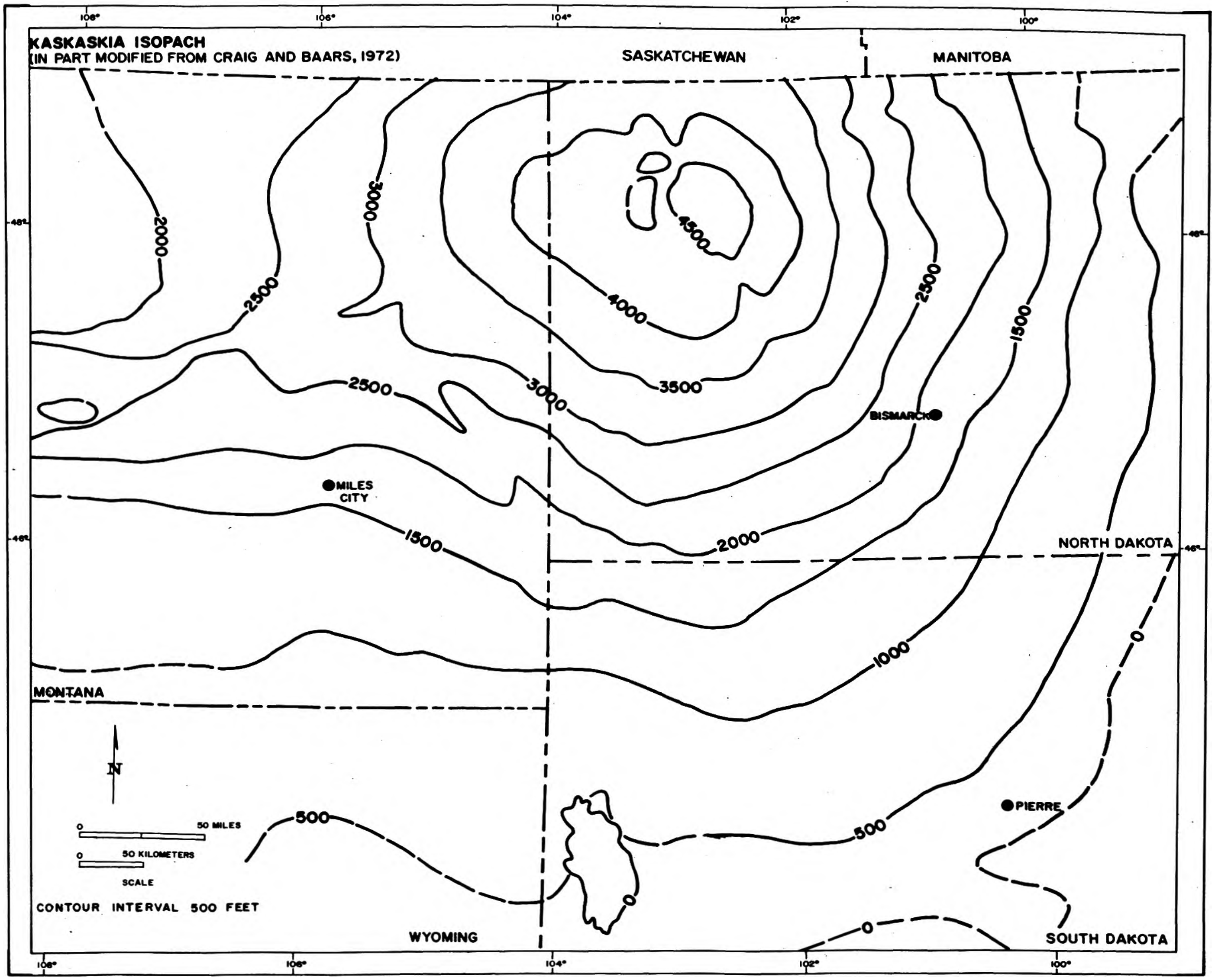


Fig. 9. Isopachous map of the Kaskaskia Sequence in the Williston basin.

and Souris River Formations are not as well known as other units but appear to mark an initial influx of clastics and supratidal carbonates over older deposits. Water deepened again during Dawson Bay time. Stromatoporoid reefs and banks flourished during Duperow sedimentation. The Birdbear (Nisku) rocks are shaly marine carbonates with shallow shelf faunas; farther north these rocks are reefal.

The red and green siltstone and shales that cover the Birdbear carbonates mark a hiatus in the middle of Kaskaskia time. These clastics are in turn overlain by initial transgressive deposits of upper Kaskaskia time, the Bakken Shale, a petroleum source rock and producer.

During the mid-Kaskaskia detrital interval, a reorientation of the seaways occurred so that during the Mississippian sedimentation, the Williston basin opened to the west through the central Montana trough (Bjorlie, 1979). Initial Mississippian sedimentation was a mixture of nearshore lagoonal clastics and apparent crinoidal mudmounds (Waulsortian mounds) in central North Dakota (Bjorlie, 1979).

Mississippian thicknesses as compared to Devonian in the basin reflect the change of seaways. Activity in the Transcontinental arch may have been responsible for the Devonian northward tilt; the Mississippian seaway may be related to development of shear systems in central Montana. Crustal instability is suggested by angularity between successive rock units of Upper Devonian

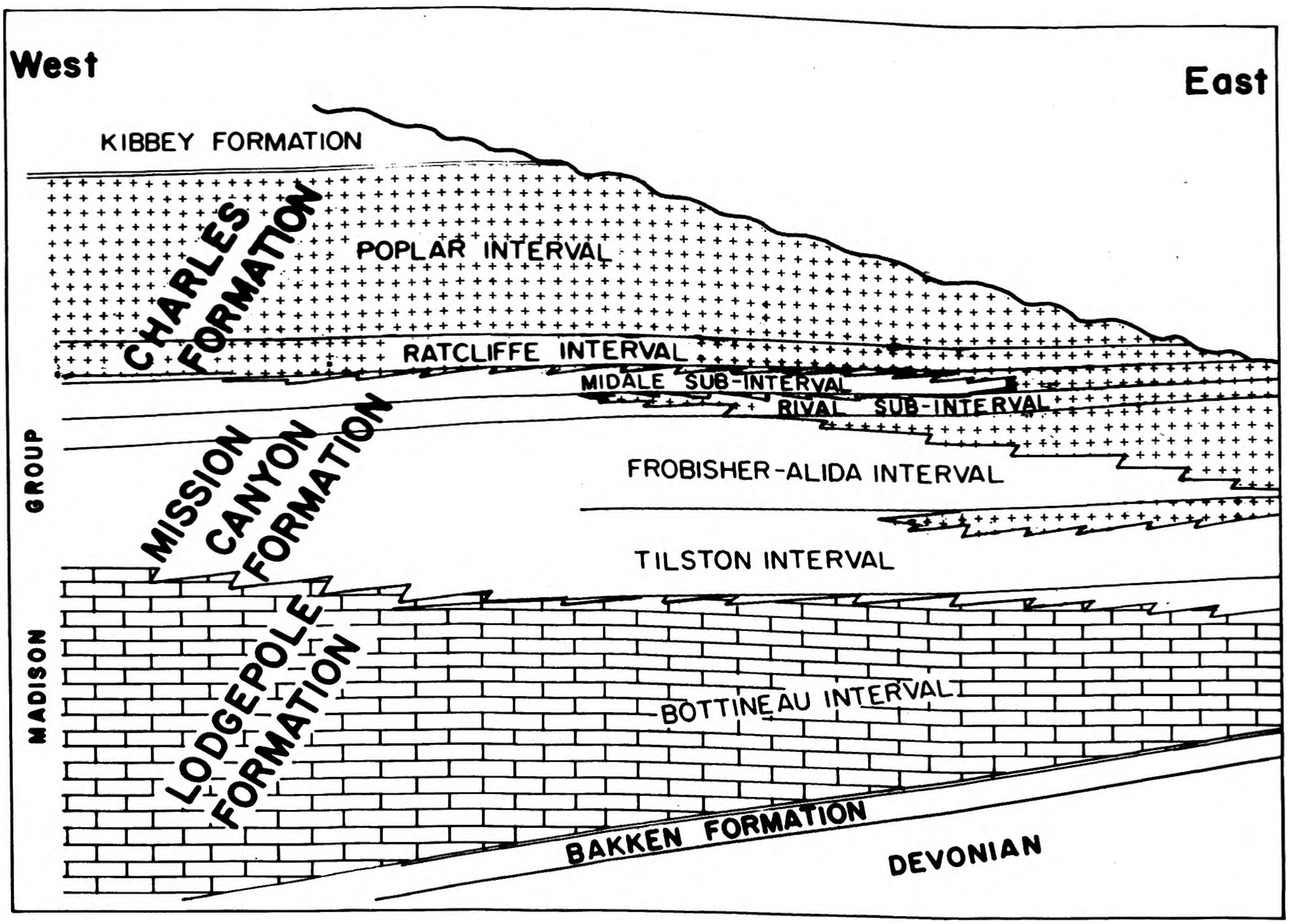


Fig. 10. Generalized cross section of Mississippian rocks in the Williston basin showing the relationship of facies to stratigraphic nomenclature. Modified from Carlson and Anderson, 1970.

and Lower Mississippian along the eastern margin of the basin.

Kinderhookian sedimentation in the Midcontinent is characterized by oolitic shelf carbonates. The Lodgepole Formation in the Williston basin is no exception (Heck, 1978). Upper Lodgepole rocks are concentric facies with peripheral lagoonal beds and oolite banks, basinward pelletal grainstones, and basinal flank and organic muds.

Maximum transgression occurred near the end of Lodgepole or early in Mission Canyon time. Mission Canyon rocks are typically skeletal wackestones with shoreward subaerial weathered fabrics and sebkha evaporites. Some marginal evaporites form coevals with the weathered fabrics and are important lateral seals for stratigraphic oil traps.

The carbonate-evaporite rocks are time regressive, with evaporites climbing westward in the section. Subaerial weathering of the skeletal wackestones has produced a variety of pisolitic and fenestrate fabrics, which form important oil reservoirs (Gerhard and others, 1978)(Fig. 10).

Continued evaporite deposition in the Charles Formation (salt) concluded Madison sedimentation. Red beds, sebkha carbonate, and sandstone sedimentation conclude Kaskaskia sedimentation. These extra basinal sediments mark the influence of the ancestral Rocky Mountains orogenic event west and south of the Williston basin.

Absaroka Sequence

Regression during latest Mississippian times marked the end of the last major Paleozoic marine sedimentation phase. Orogenic events including the Alleghenian, Ouachita, Arbuckle, and Ancestral Rocky Mountain events, resulted in cratonic uplift in the northern plains and Rocky Mountain region. Absaroka sedimentation is characterized generally by interfingering of terrestrial clastic sediments with marginal marine and evaporite sediments (Fig. 12). Basal Absaroka rocks in the

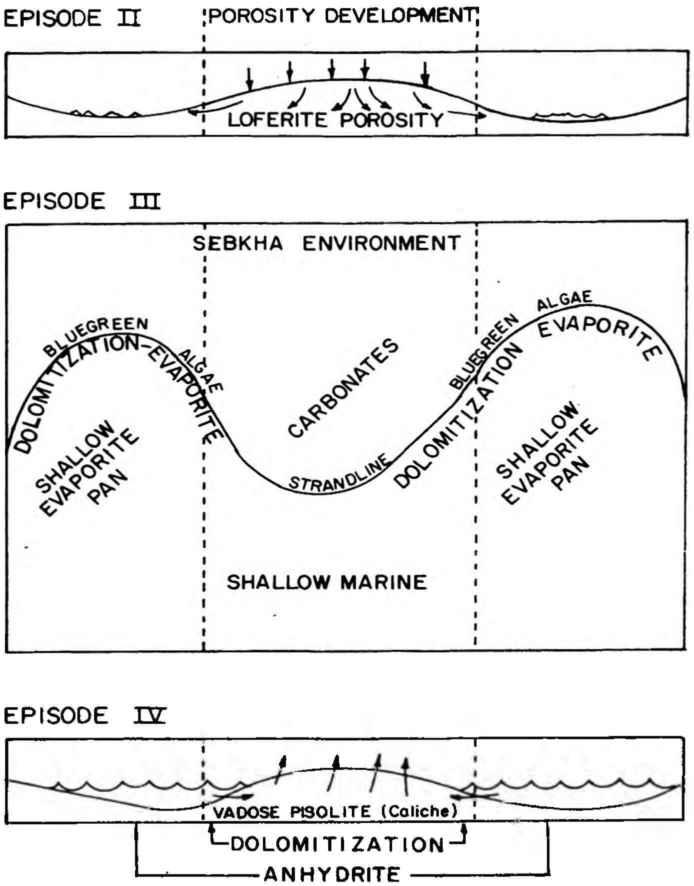


Fig. 11. a. Generalized sections of map showing porosity development in the Frobisher Alida zone, Glenburn Field, North Dakota. Episode 2 illustrates porosity development by fresh water weathering and desiccation. Episode 3 indicates the relative position of several strandlines and depositional/diagenetic lithologies. Episode 4 demonstrates the formation of porosity through generation of vadose pisolite or caliche.

b. Loferite shrinkage or desiccation voids overlain by subaerial laminated crust, in turn overlain by pisolitic loferites. Texota #1 Weber at 4600 feet. Scale on photo is 3 centimeters long.

Williston basin are the Tyler Formation estuarine, bar and marine sands and shales (Grenda, 1978; Ziebarth, 1964). Dense, microcrystalline carbonates and fine-grained red and brown clastics of the Amsden suggest more restricted depositional conditions. Broom Creek rocks are more sandy and contain dense carbonates. This suggests the prograding of sands into a hypersaline basin. An unconformity at the top of the Broom Creek records a period of subaerial exposure and weathering during the Permian. The remainder of Absaroka deposition includes hypersalinity in the center of the basin (Opeche Salt, Pine Salt) and fine-grained fluvial sediments deposited around the margins as well as across the rest of the basin.

Sources for Absaroka clastics are both southerly from the Ancestral Rocky Mountains and from the Canadian Shield and Sioux uplift. Tributary channels cut into the earlier Paleozoic rocks in the northwest part of the basin are filled with Triassic(?) and Jurassic rocks (Fig. 13). Some of these channels are several hundreds of feet deep. It is also possible that the Cedar Creek anticline directed sediment flow into the central part of the basin.

Zuni Sequence

Jurassic and Cretaceous sedimentary rocks in the Williston basin make up a single large cycle of sedimentation (Fig. 14). Although an unconformity exists between the Absaroka and Zuni Sequences, the lithologies on either side of the

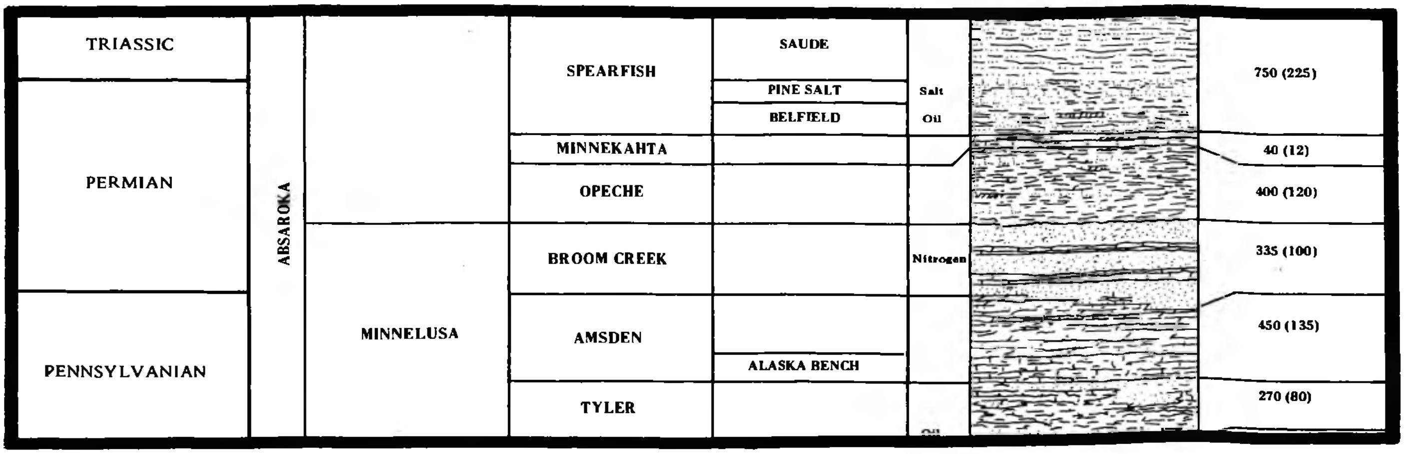


Fig. 12. Stratigraphic section of Absaroka Sequence rocks.

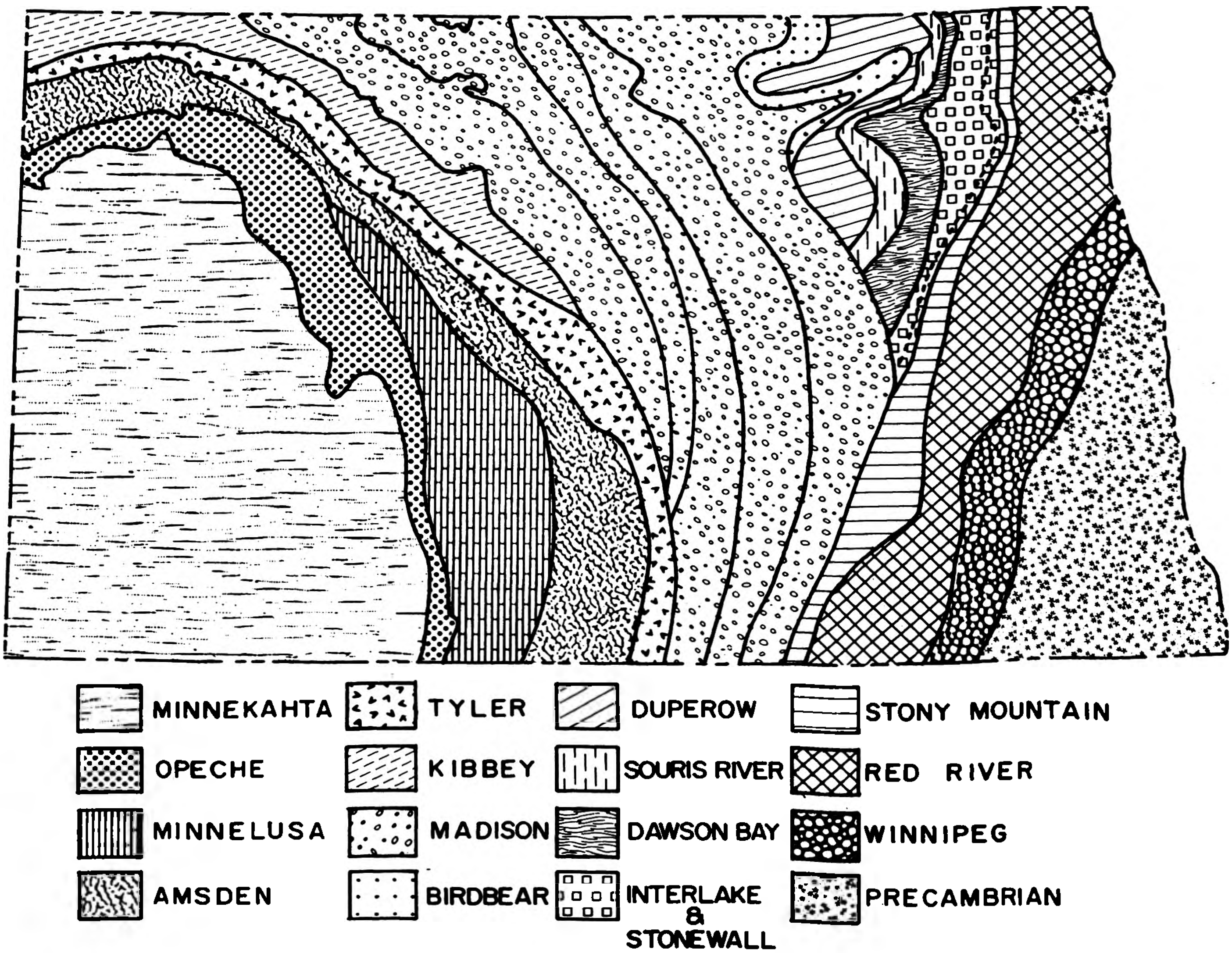


Fig. 13. Pre-Mesozoic paleogeologic map of North Dakota. Modified from Carlson and Anderson, 1970.

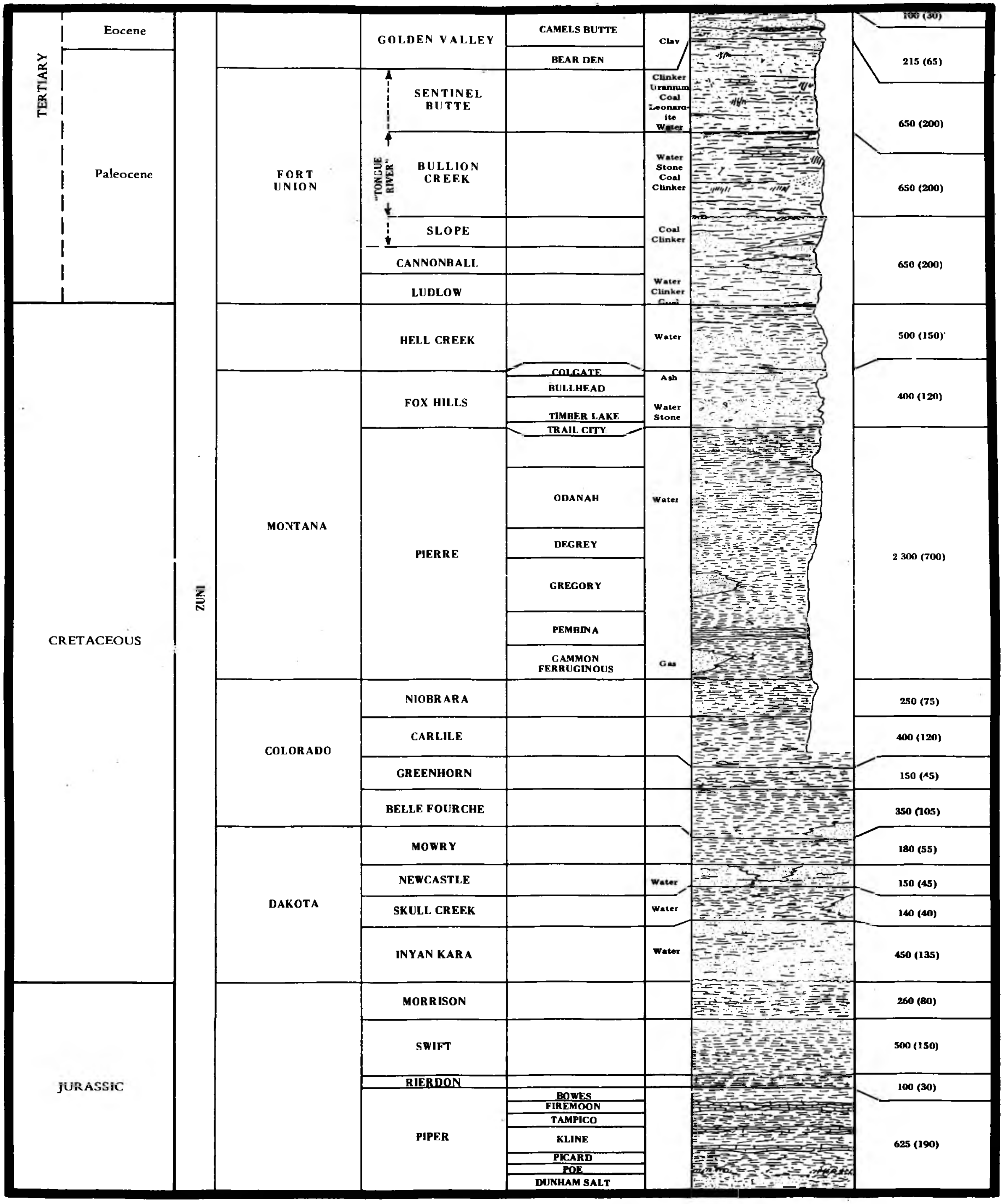


Fig. 14. Stratigraphic section of Zuni Sequence rocks.

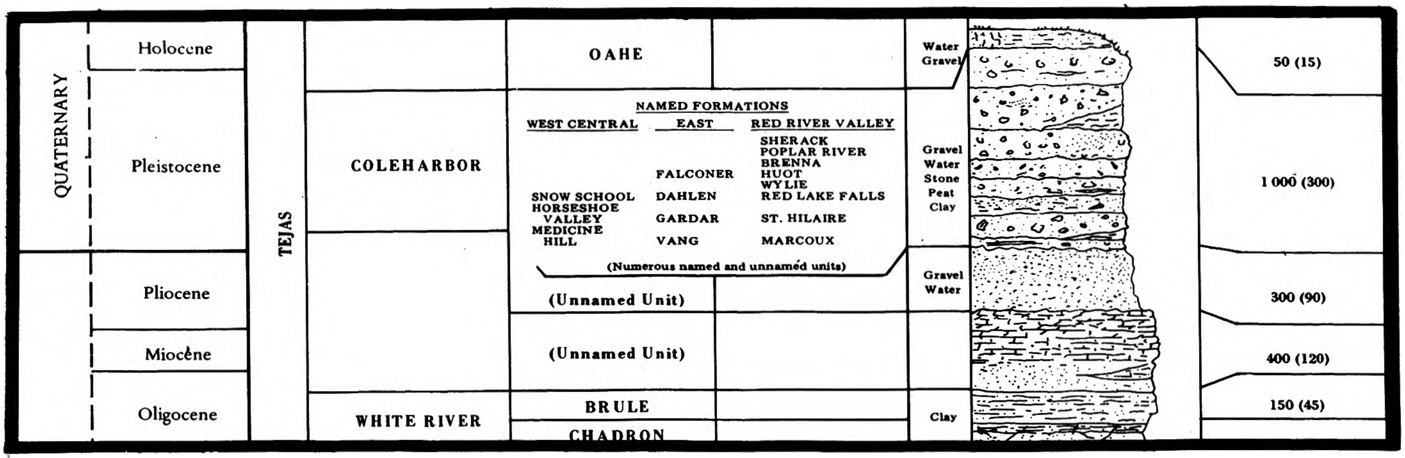


Fig. 15. Stratigraphic section of Tejas Sequence rocks and sediments.

unconformity are similar. Evaporites (including salt), fine-grained red and brown clastics, and a few dense microcrystalline carbonate beds compose the lowest part of each cycle. These rocks are overlain by more fluvial, humid-origin sedimentary rocks of the Swift and Morrison Formations, which also contain marine glauconitic sands and oolitic carbonate bars.

It is commonly thought that an unconformity truncates the top of the Morrison. Rather than a subaerial regressive exposure surface, it is suggested that this unconformity is simply the marine transgressive surface of the basal Cretaceous Inyan Kara Sandstone.

Progressive deepening of the Western Interior Cretaceous seaway provided for the deposition of the remainder of the Cretaceous marine section (Fig. 14). During deposition of the upper part of the Pierre Shale, increasing amounts of sand indicate regression of the Cretaceous sea strandline and the beginning of formation of the clastic wedge derived from erosion of the Laramide Rockies.

Further uplift, erosion, and volcanism in the Laramide Rockies provided extensive quantities of detritus to the Williston basin. In Lower Paleocene time, the last marine setting in North Dakota was the site of deposition of the Cannonball Formation; later Paleocene Ft. Union sediments covered and prograded over the Cannonball. Fluvial deltaic and paludal environments were characteristic of later Paleocene time during which extensive lignite deposits were formed. Cyclical or repetitive in nature, these deposits are one part of the combined Powder River and Williston basin detrital aprons from the Rockies.

Younger Sedimentary Deposits

During post-Zuni time (Tejas "Sequence"), few indurated stratigraphic units were formed. Scattered limestone and shaly sandstones with volcanic ash form the tops of the Killdeer Mountains and have been correlated with the White River (Oligocene) rocks of South Dakota (Fig. 15). Some indurated White River Formation is exposed in Bowman County, North Dakota, where a classical White River vertebrate fossil assemblage can be collected.

Pleistocene sediments cover over three-quarters of North Dakota and a considerable part of the Montana portion of the Williston basin. Although carefully mapped and studied by a number of writers, they have no major resource importance except for sand and gravel.

STRUCTURAL HISTORY

Until recent seismic and oil drilling exploration programs were initiated, the Williston basin was generally regarded as a simple depressed saucer with two positive structures, the Cedar Creek anticline and the Nesson anticline. This is obviously an oversimplified view of the basin based upon very limited data. The diagrammatic representation of current data and theory (Fig. 2) is also probably oversimplified. Before tracing the tectonic history of the basin by studying the two major anticlines, a brief survey of present structural elements and of depositional framework is necessary. Phanerozoic sedimentation transgressed from the west across a weathered crystalline terrain, mostly of Churchill Province rocks, but also across the Churchill-Superior provincial boundary. No basin was present in the early part of the Paleozoic; only an indentation was present in the north part of the western cratonic shelf, although Precambrian blocks were protruding from the shelf floor (Carlson, 1960). Basinal depression originated in the Ordovician (pre-

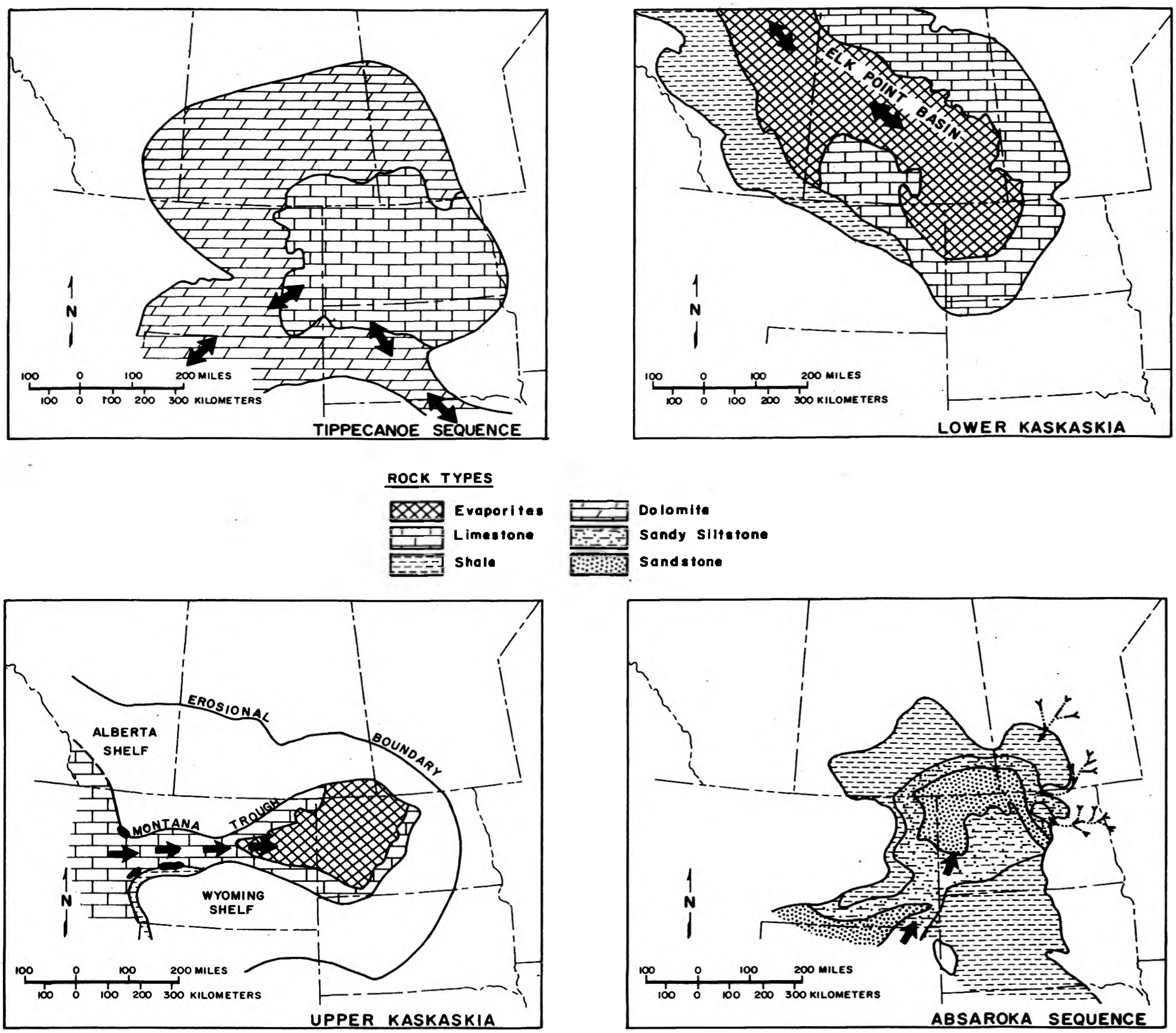


Fig. 16. Sequential maps showing marine communication directions of the Williston basin. a. Tippecanoe Sequence showing connection to the Cordilleran miogeosyncline to the southwest and to the eastern interior to the southeast across the Transcontinental arch. Modified from Foster, 1972. b. Lower Kaskaskia Sequence communication to the Elk Point basin in Canada. Modified from Clark and Stern, 1968. c. Upper Kaskaskia showing communication with the Cordilleran miogeosyncline to the Montana trough. Dark spots at the entrance and along the edges of the Montana trough represent bank development. Some bank development is also hypothesized within the basin. Modified from Bjorlie and Anderson, 1978. d. Absaroka Sequence showing a flood of clastics from the southwest as well as from drainages to the northeast and east. In all probability sediment flow from farther southeast also occurred. Modified from Mallory, 1972, and Rascoe and Baars, 1972.

Tippecanoe) with a seaway connection apparently to the southwest (Fig. 16a). This early connection to the Cordilleran geosyncline was broken during the Devonian by uplift on the Sioux arch and associated structures along the Transcontinental arch trend. Uplift tilted the Williston basin to the north, effectively moving the apex of the Nesson anticline southward and opening the Williston basin to the Elk Point basin sea to the north (Fig. 16b).

Mississippian transgression coupled with subsidence of the Transcontinental arch system

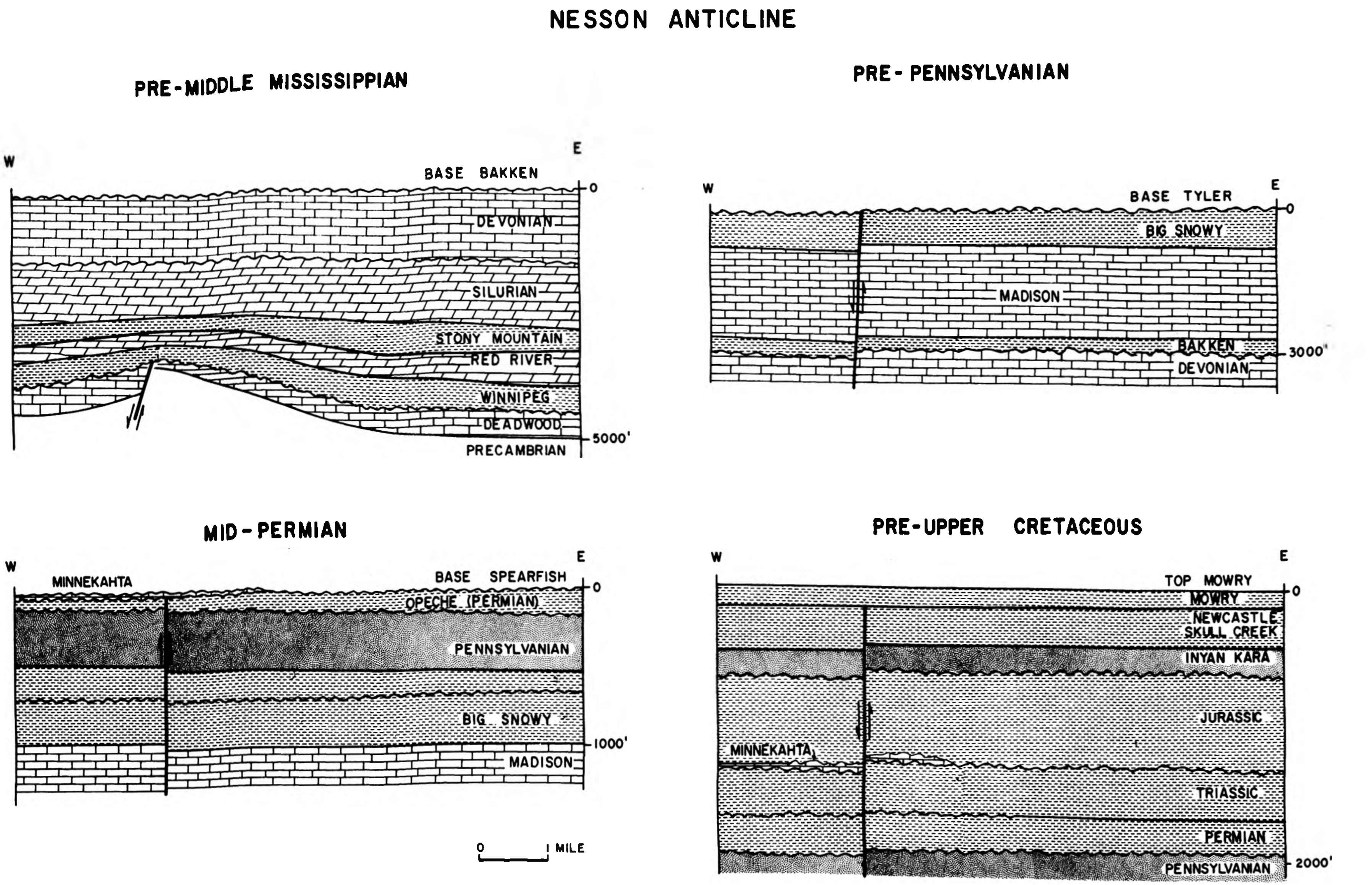


Fig. 17. Diagrammatic cross sections of Nesson anticline showing structural development. Note the apparent reversal of fault movement during the mid-Permian. Some of the pre-Upper Cretaceous movement may be related to salt solution.

changed the seaway connection to the Cordilleran again but due west through the Central Montana trough (Fig. 16c). This connection persisted into Absaroka time but with greatly reduced circulation. Clastics spread into the basin from the south (Tyler) and from the southeast and northeast. It is hypothesized that Sioux arch sediments entered from the southwest, whereas drainage from the Canadian shelf flowed in from the northeast (Fig. 16d).

Cedar Creek and Nesson Anticlines

The two major structures, the Cedar Creek and Nesson anticlines, in the Williston basin are both oil productive and surface mappable, although the Nesson is largely obscured by glacial cover. Because of the large amounts of subsurface data available on these structures, their structural development can be documented (Figs. 17, 18).

Nesson anticline history was initiated in the Precambrian. Lower Deadwood sediments were deposited around, but not over, the crystalline core of the present anticline. Upper Deadwood sediments are present on the top of the structure. Abrupt changes in thickness across the structure indicate fault movement on the west flank of the Nesson. Renewed activity along the fault also affected Winnipeg deposition. Erosion between Deadwood and Winnipeg rocks formed the Sauk-Tippecanoe disconformity. Thinning of the post-Winnipeg-pre-Devonian section is due to renewed uplift without faulting.

A second period of normal fault movement occurred in the pre-Pennsylvanian, post-Mississippian Big Snowy interval. This is evidence of Ancestral Rocky Mountain orogenic movement in the Williston basin. A mid-Permian event changed the stress regime. The former normal fault changed direction of motion, up on the west, rather than down on the west.

Laramide-related strain is evident during the Cretaceous, with a reversal of movement along the Nesson fault in the pre-Upper Cretaceous. Since that time, there is little evidence of major fault movement, although minor seismic activity continues along the Nesson trend. Cretaceous rocks are folded across the structure and may also be faulted.

A comparison of structure in the basin contoured on the top of the Silurian Interlake Formation (post-Tippecanoe) (Fig. 18) and on the Cretaceous Mowry Formation (Fig. 19) shows asymmetry

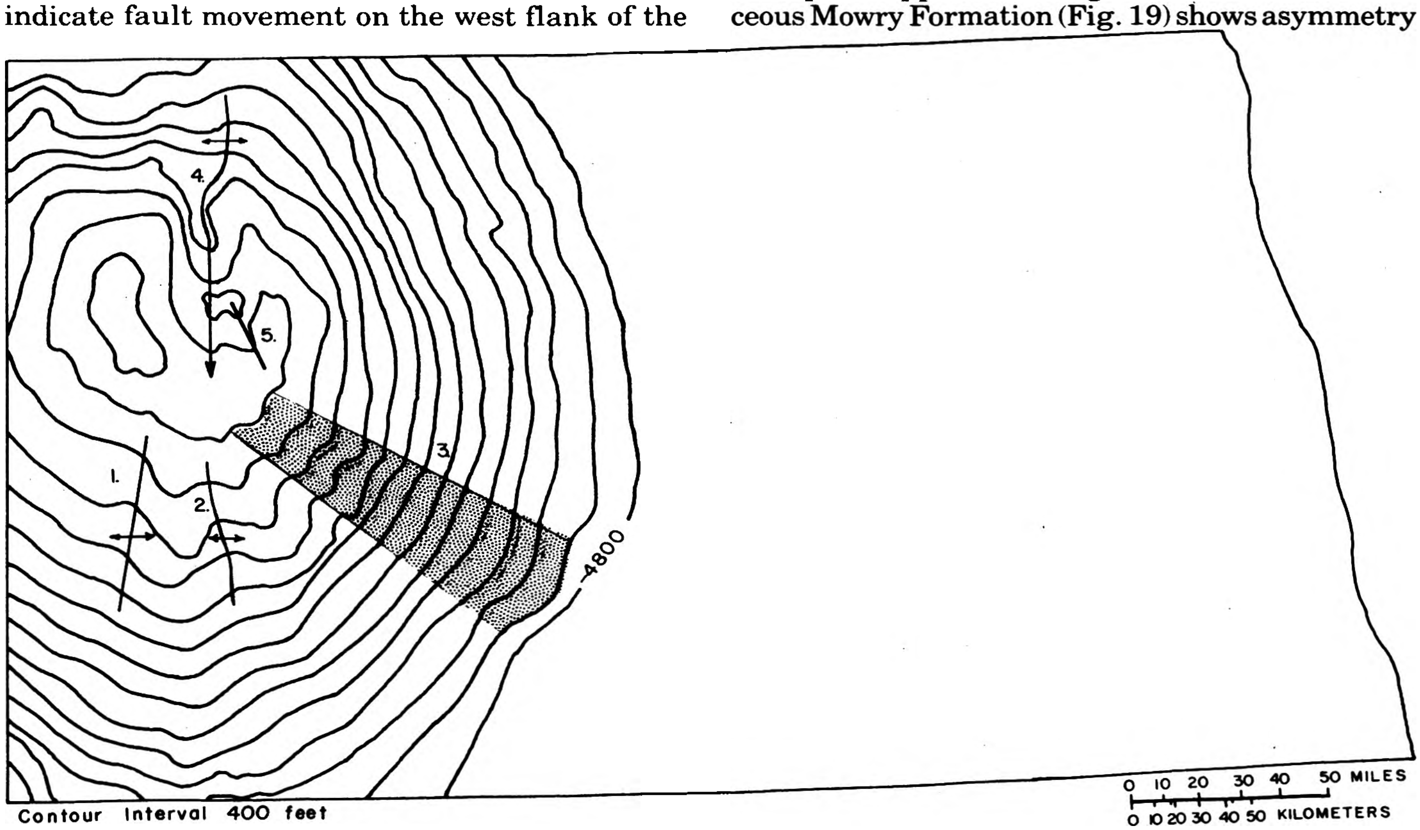


Fig. 18. Isostructural map on top of the Silurian Interlake Formation showing geometry of the Williston basin in North Dakota. 1 is Billings anticline; 2, Little Knife anticline; 3, Bismarck-Williston trend; 4, Nesson anticline; 5, Antelope anticline.

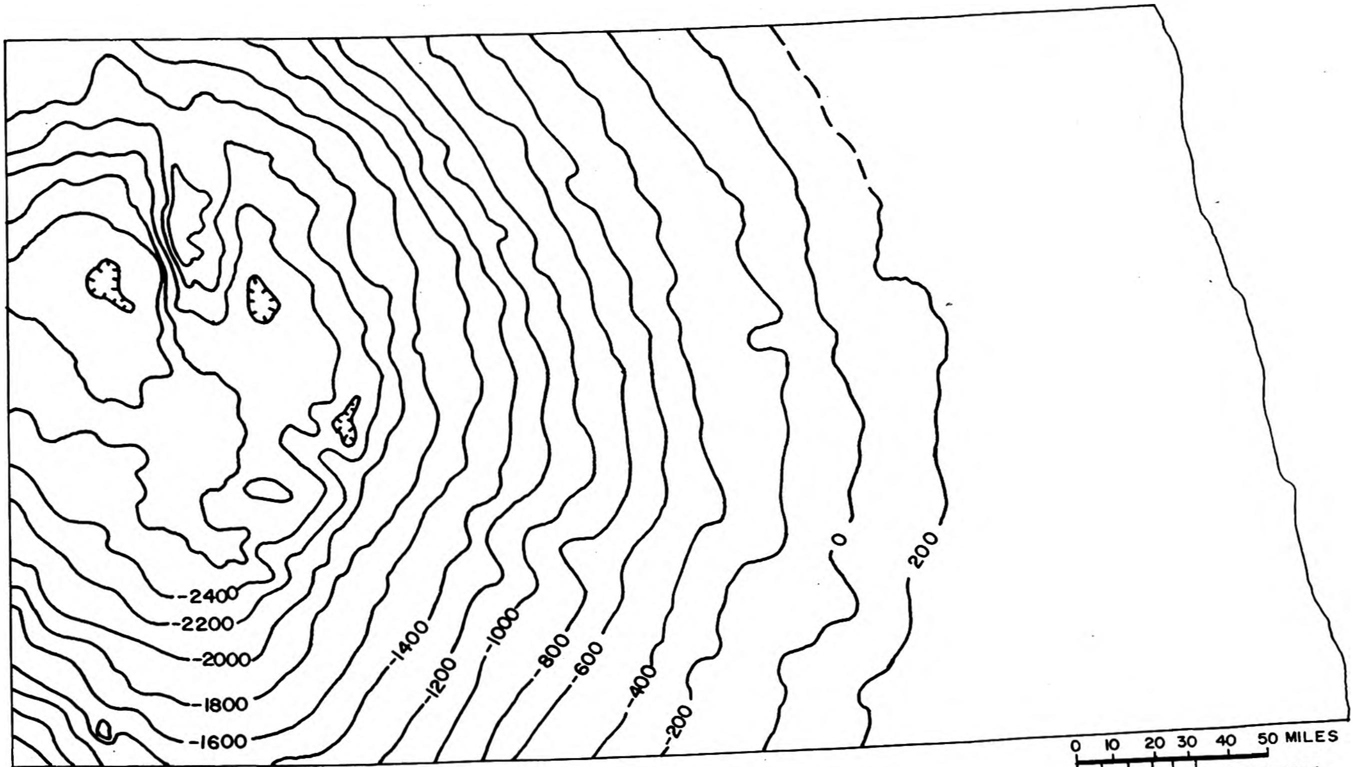


Fig. 19. Isostructural map on top of the Mowry Formation (Cretaceous). Compare to Figure 18. Closely spaced contours on the west side of the Nesson anticline suggest post-Mowry faulting on that structure. Bismarck-Williston trend appears to be well developed as well as is evidence for the Billings anticline. Little Knife anticline does not appear to be as well defined at its horizon.

and steep dip on the west flank of the Nesson anticline as well as indications of the other major structures in the basin. Comparison with a map of structural elements (Fig. 2) shows that the Little Knife and Billings anticlines, Antelope anticline, and the Bismarck-Williston trend can be seen in Silurian rocks better than in Cretaceous rocks. There are also suggestions of northeast-trending anticlinal structures.

The asymmetry and steep dip on the west flank of the Nesson probably reflects Laramide fault movement on that structure. Northwest-trending structures in Cretaceous rocks underscore the importance of this relatively unexplored structural trend.

The Cedar Creek anticline has a somewhat familiar history (Fig. 20) (Clement, 1975-80, personal communication). Two periods of fault movement on a western border fault zone occurred in the pre-Middle Devonian and pre-Mississippian intervals, although no data are available to establish a pre-Winnipeg or pre-Red River history.

A second fault zone east of the original zone was created at the same time that the original fault reversed direction to upward motion on the western block. This created a crestal graben on the Cedar Creek anticline during ancestral Rocky Mountain strain.

Pennsylvanian rocks were broken by continued motion on the graben border faults. Unlike the Nesson, fault motion apparently did not reverse during the Cretaceous, although Cretaceous and Paleocene rocks were deformed across the anticline.

Newporte Structure

In north-central North Dakota, the Shell 27X-9 Larson discovered oil in Deadwood Sandstone (Fig. 21) (Clement and Mayhew, 1979). Continued development of this field demonstrated the complexity of early Paleozoic structural history of the Williston basin as well as one of the rare oil wells producing from Precambrian crystalline rocks (Shell 14-34 Mott). Interpretative cross sections (Fig. 22) suggest that Deadwood Sandstone was deposited between Precambrian hills in part and that pre-Winnipeg (post-Sauk, pre-Tippecanoe interval) erosion accompanied by pre-Winnipeg faulting created a small basin of detritus from Deadwood and Precambrian rocks. Winnipeg sedi-

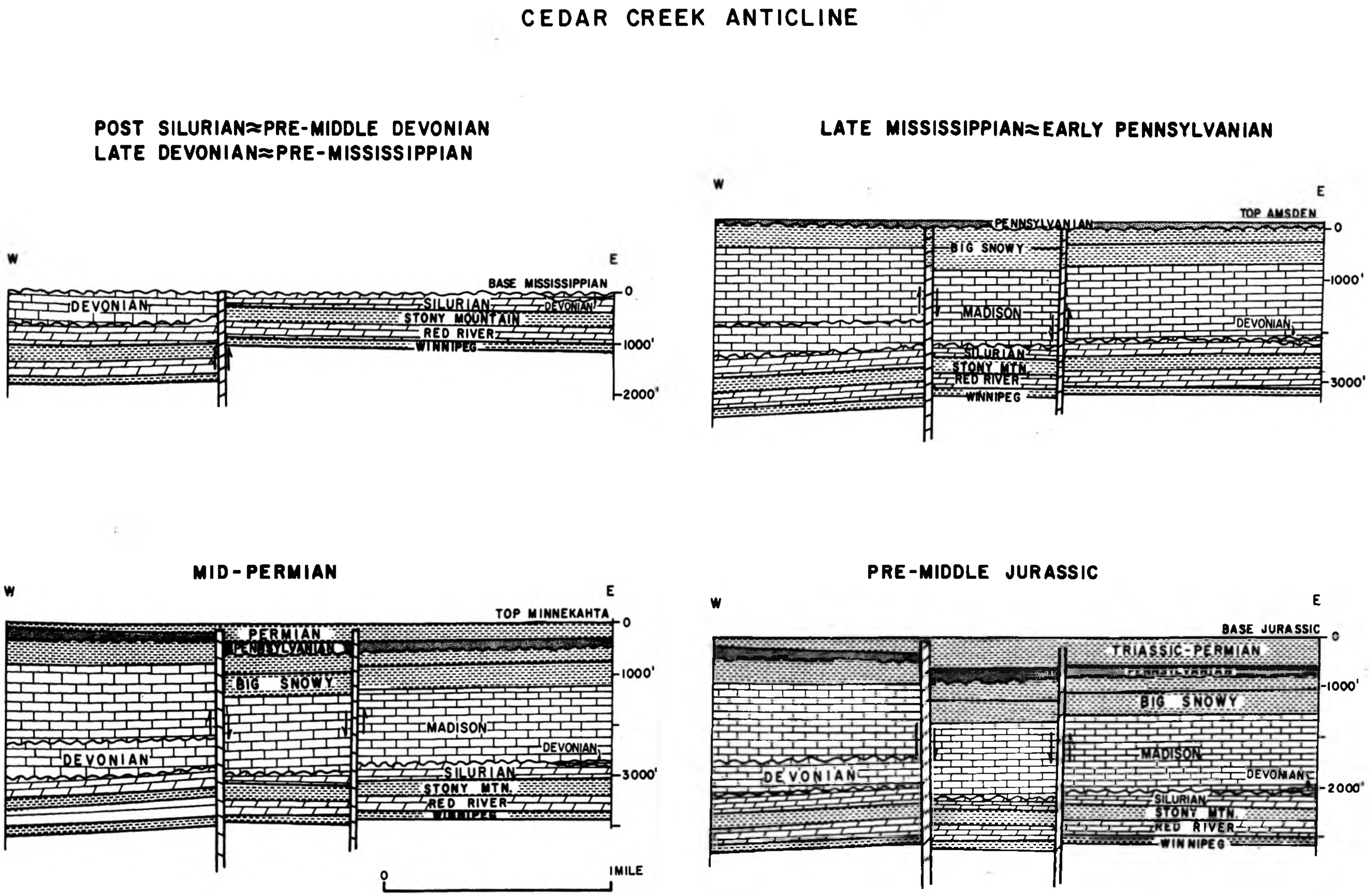
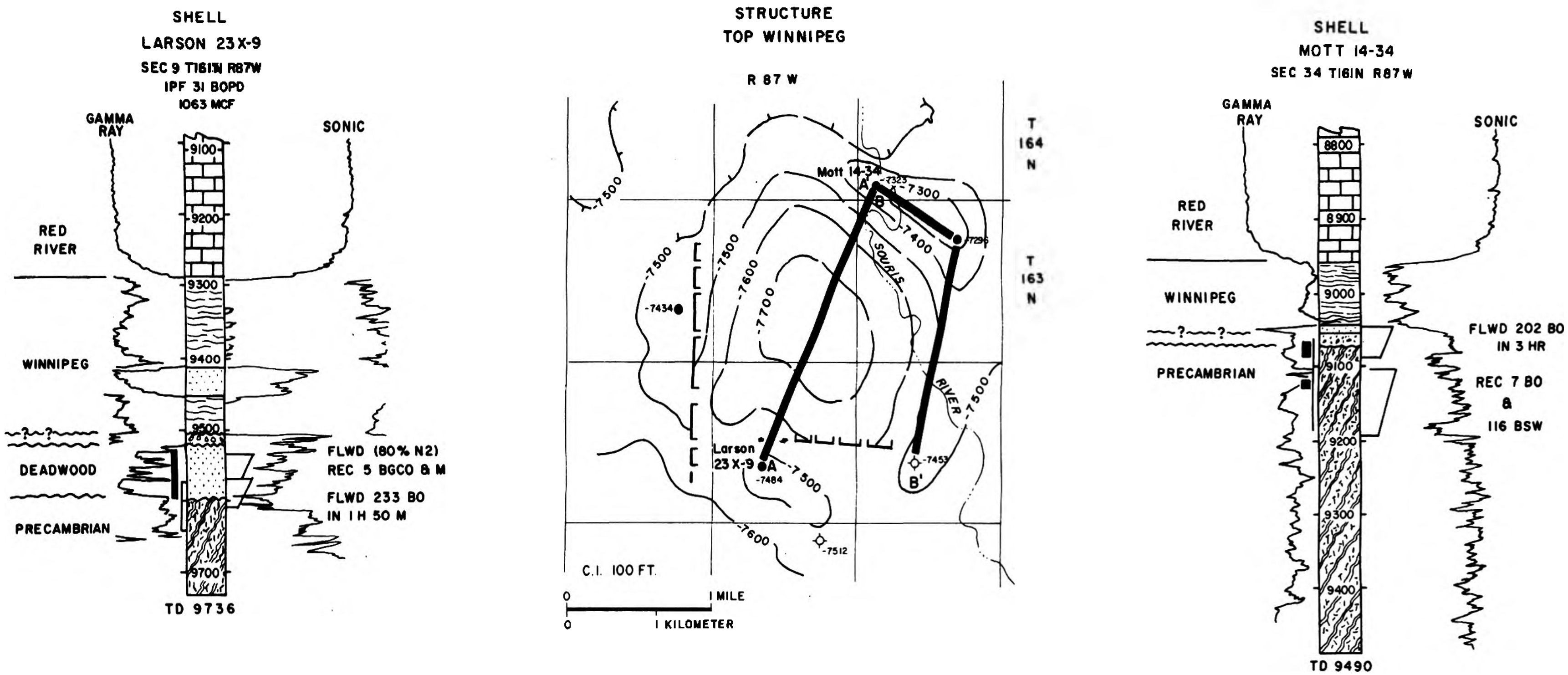


Fig. 20. Diagrammatic cross sections across the Cedar Creek anticline. Modified from Clement, 1976. Note the second fault generated during the Late Mississippian-Early Pennsylvanian episode, with concurrent reversal of movement on the original (westerly) fault.



a. Shell Larson 23 X-9 showing producing interval in the Deadwood Formation.

b. Structure on top of the Winnipeg Formation in the Newporte Field.

c. Shell Mott 14-34 showing producing intervals in the Precambrian and at the Winnipeg Precambrian contact. Modified from Clement and Mayhew, 1979, and Carlson, personal communication.

Fig. 21. Newporte Field structure map and lithologic sections.

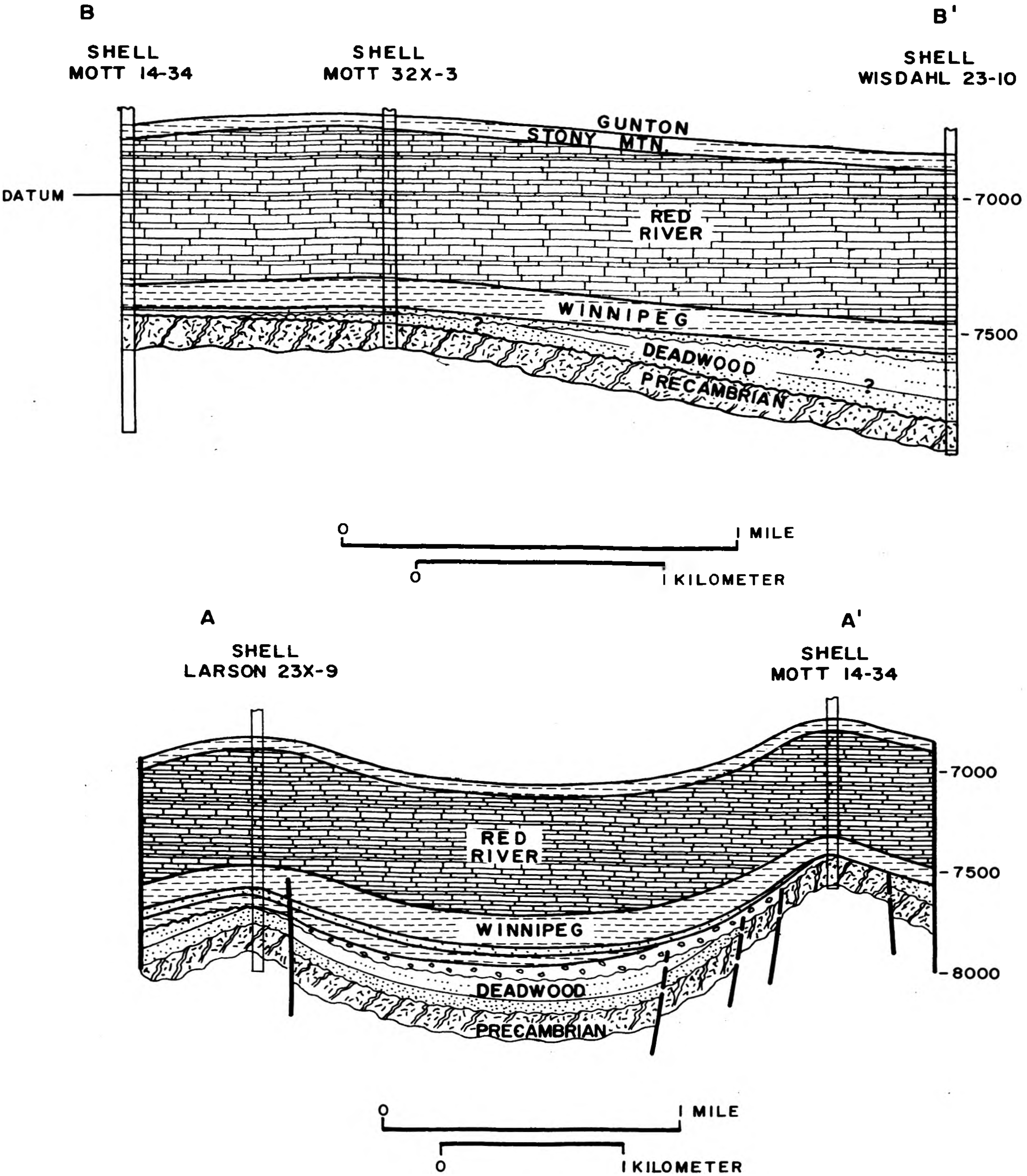


Fig. 22. Cross sections across the Newporte Field. See Figure 21 for lines of section. Modified from Clement and Mayhew, 1979, and Carlson, personal communication.

mentation covered the structure but was in part cut by at least one growth fault.

Red Wing Creek Structure

One of the most controversial and interesting structures in the Williston basin is the Red Wing Creek structure, which produces oil from a greatly exaggerated thickness of Mississippian rocks. At the time of its discovery in 1972, this structure was a seismic anomaly which fit no pattern for Williston basin structures. Exhibits presented to the North Dakota Industrial Commission during the spacing hearing for the Red Wing Creek Field interpreted this structure as an astrobleme. Succeeding publications by Brennen and others (1975) and Parson and others (1975) presented additional data supporting this hypothesis.

Generally, it appears that sedimentation across the structure followed normal patterns for the Williston basin through Triassic (Spearfish) time. In the Jurassic, a major structural disruption of a very small area occurred (Fig. 23), which has been interpreted by the previously cited writers as a meteorite impact. This event was apparently pre-Piper Formation, because real sandstones and siltstones fill a ring depression on Spearfish and below Piper, although in samples it is difficult to distinguish true "crater fill" from Spearfish Formation clastics. The discovery well (True Oil 22-27 Burlington Northern) cut a very thick pay section in disturbed Mississippian rocks. Much of the picture of the Red Wing Creek structure is apparently based on seismic information as well as interpretation of complex well logs and samples. Renewed movement on bounding faults is seen as high in this section as the Dakota Sandstone.

The central part of the structure is an elevated block, surrounded by a ring depression. The geometry of the structure is clearly cryptovolcanic, and it is difficult to argue against a meteorite impact origin of this complex structure. Bridges (1978) suggested a section of several faults, which change orientation through time as an alternate hypothesis (concentricline). Others, precluding myself, suggested that this structure could also result from deep seated igneous activity (diatreme). Detailed geochemical analysis of samples may determine the validity of the meteorite impact hypothesis.

OIL AND GAS RESOURCES

Oil and gas are the primary energy resources of the Williston basin, despite its large resource of lignite. It is difficult to separate the Montana Williston basin production from other Montana production so that North Dakota production and development figures are used to demonstrate the significance of oil and gas from the U.S. part of the Williston basin. North Dakota has approximately 70% of the U.S. Williston basin production and drilling activity.

Oil was discovered in the Williston basin in Montana on the Cedar Creek anticline (1936) and in North Dakota on the Nesson anticline (1951). Since that time, several significant cycles of exploration success have been completed, mostly in North Dakota, and another is in progress (Gerhard and Anderson, 1979).

Dramatic expansion of producing area has occurred during the present cycle, including new producing counties, new pay horizons, and new producing depths. Maps of North Dakota producing fields in 1970 and 1980 illustrate the resurgence of the Williston basin as a major oil province (Figs. 24, 25). In 1970, there were about 20 active locations in the entire basin; in 1980 there were about 150 locations active on the average.

During the early development of the basin, Mississippian (Madison Group), Devonian (Duperow Formation), Silurian (Interlake Formation), and Ordovician (Red River Formation) were mainstays of production in the Cedar Creek and Nesson anticlines. After flank development of the Nesson anticline, discoveries of Mission Canyon Formation oil off the anticline in stratigraphic traps along the northeast flank of the basin kept exploration programs active and added significant daily production during the last part of the 1950's. Decreased drilling success caused a decline in activity but Red River exploration revived the success in the early 1960's. By 1965, though, oil production peaked, and only independent operators were active in the basin.

In 1972, after successive dry holes by a major oil company, the True, Burlington Northern 22-27 (SE NW 27-148-101), brought in the Red Wing Creek Field, McKenzie County, North Dakota (Fig. 23). Typical basin net pays were 10 feet thick or less; initial potentials were 100 barrels per day. Red Wing Creek opened a major lease play. Increasing oil prices and five-year-term lease expirations fueled a drilling boom, which in turn gave North Dakota a billion barrel reserve. Total oil resources of the U.S. Williston basin may be as much as five billion barrels.

Oil source rocks are commonly regarded to be the Winnipeg Formation, Bakken Shale, and Tyler Formation dark shales and silts. Oils from these rocks have been categorized into three types relative to their presumed sources (Williams, 1974).

I and others, who have studied the rock sections in the basin, believe that many producing horizons self-sourced, that is, sufficient organic material is

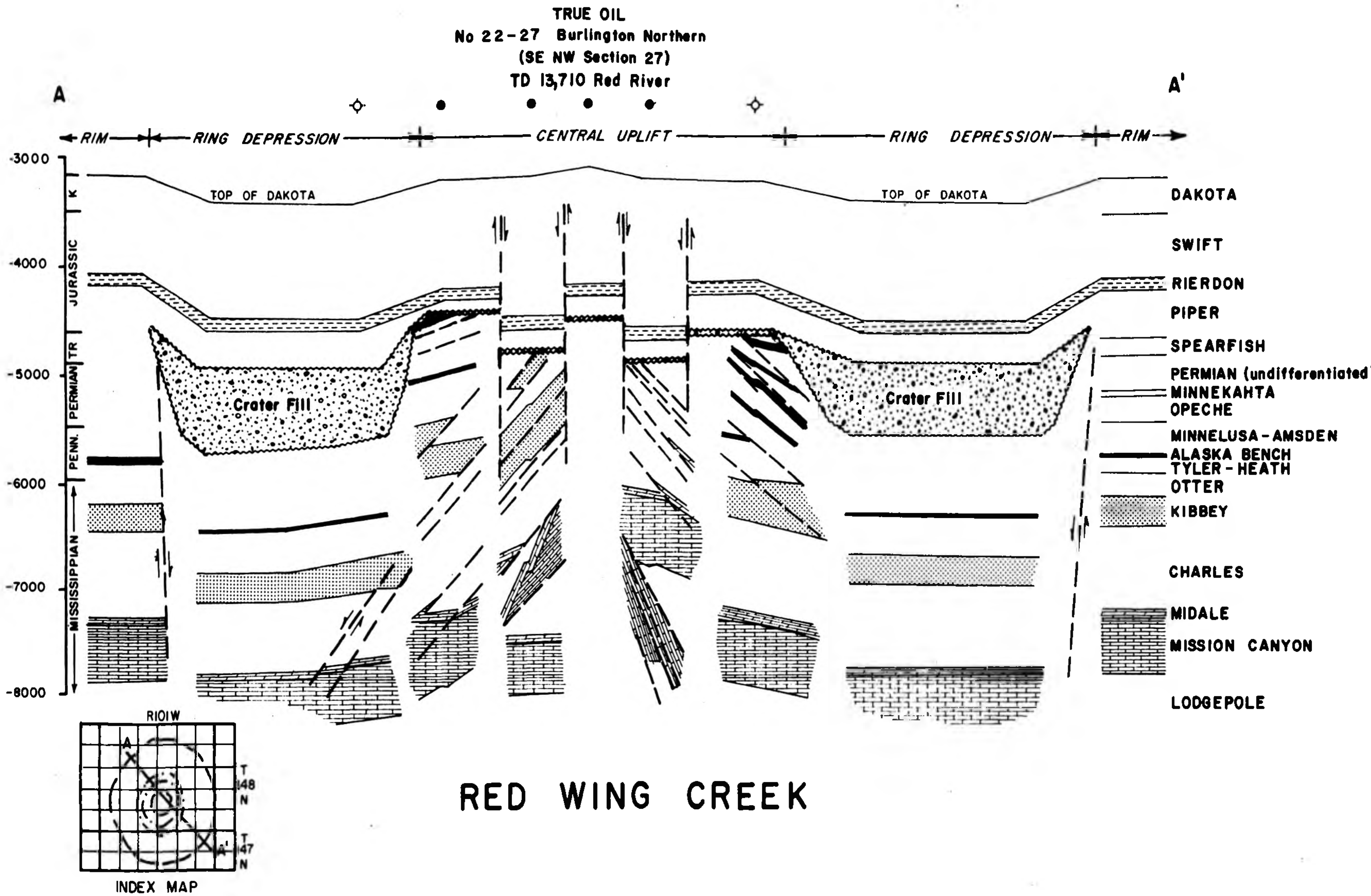


Fig. 23. Cross sections through the Red Wing Creek structure, McKenzie County, North Dakota, demonstrating the meteorite impact hypothesis for origin of this structure. The True Oil #22-27 Burlington Northern discovery well was drilled on the top of the central uplift. Modified from Exhibit #6, case #1152, North Dakota Industrial Commission, submitted by Union Oil Company of California.

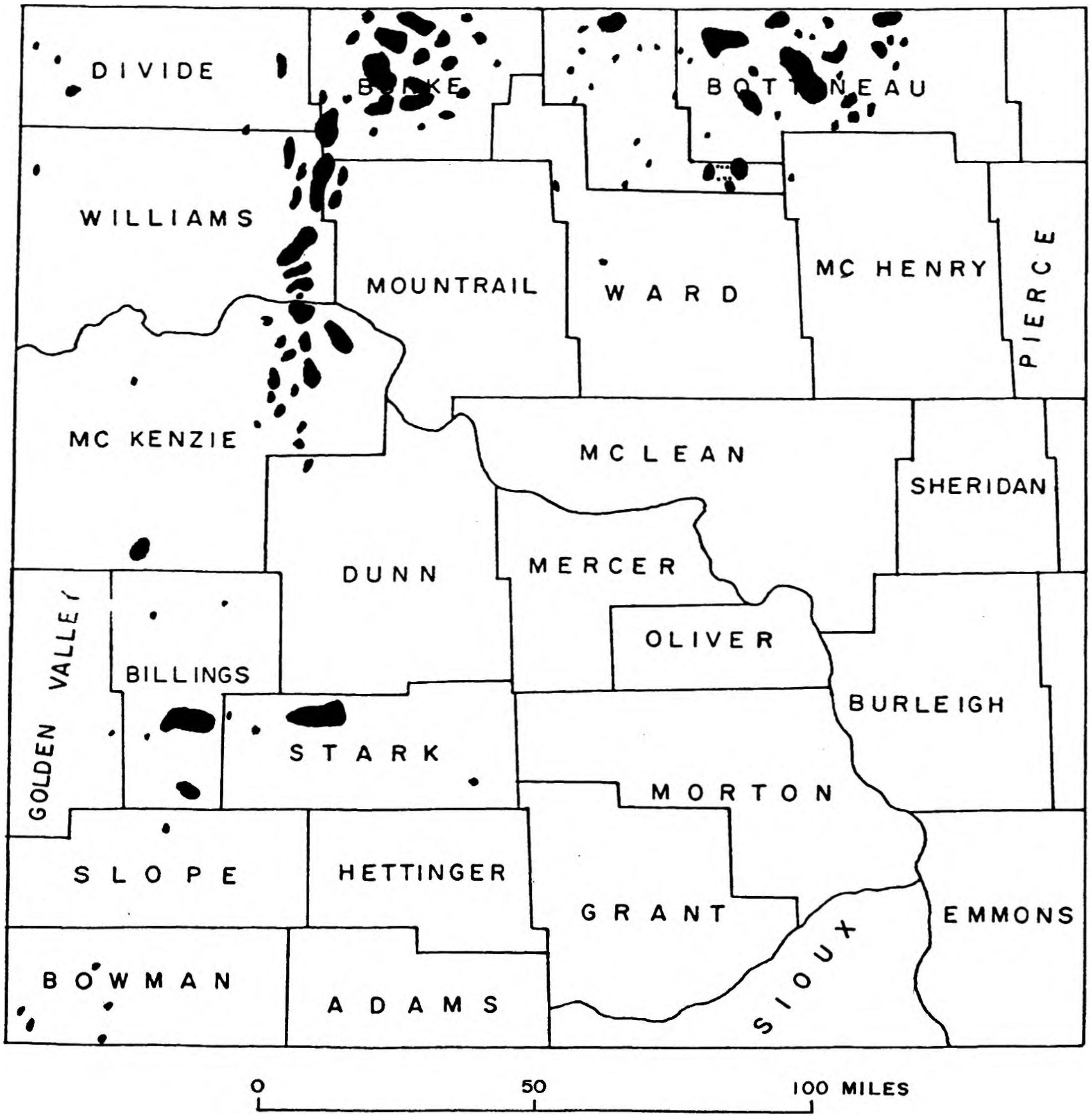


Fig. 24. Producing fields in North Dakota 1952-1970.

present in the producing units to generate the oil produced. Certainly, the Red River, Birdbear, Duperow, Winnipegosis, and Madison, among others, have sufficient indigenous organics to provide large quantities of liquid hydrocarbons.

It is of interest that exploration and production have followed technology. Initial production was from Nesson anticline seismic-origin prospects; Amerada Petroleum Corporation drilled a string of successes 70 miles long without a dry hole. An interpretation of basin geometry progressed, stratigraphic/structural traps were defined. Later, in Bowman County, North Dakota, structural seismic results successfully defined Red River "bumps". Stratigraphic plays and long-shot deeper drilling sporadically generated interest until the well-known unusual seismic configuration at Red Wing Creek became productive.

At the present time, the basin has been sustaining ever increasing wildcat success ratios, as earlier listed. This increase in success is attributed first, to the use of the CDP seismic method second, to better reservoir geology, and third, to completely revised testing and completion techniques.

Activity now is centered in western North Dakota and the bordering Montana counties. Tax differentials between the two states keep a higher number operating on the North Dakota side than might otherwise be the case. Significant new discoveries have been Little Knife Madison (109 wells, 125 million barrel reserve, 1977), Mondak Madison (112 wells, unknown reserves, 1977), and the Billings anticline area Duperow, which con-

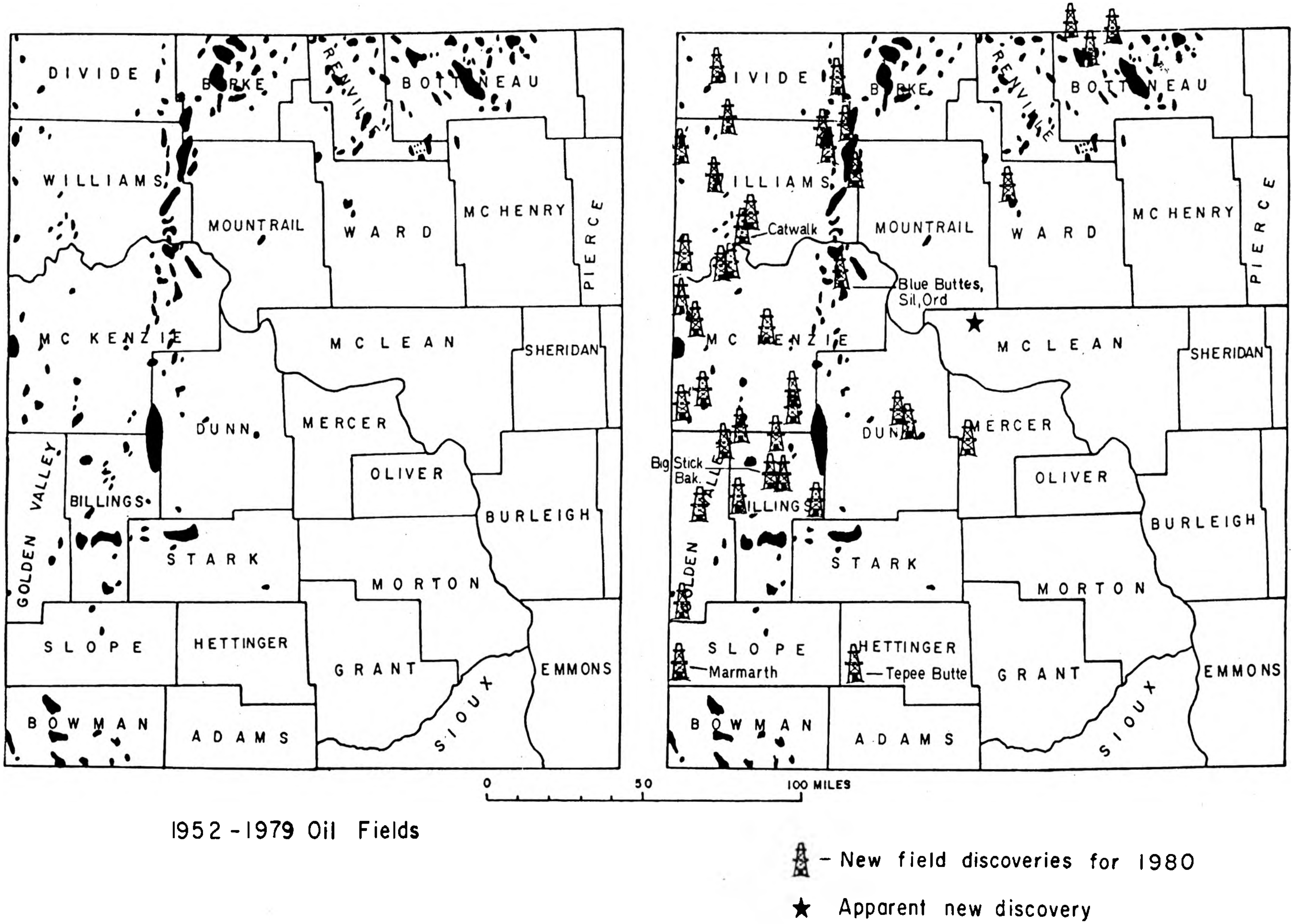


Fig. 25. Producing fields in North Dakota 1980. Note the large expansion of the number of fields in western North Dakota south of the Nesson anticline.

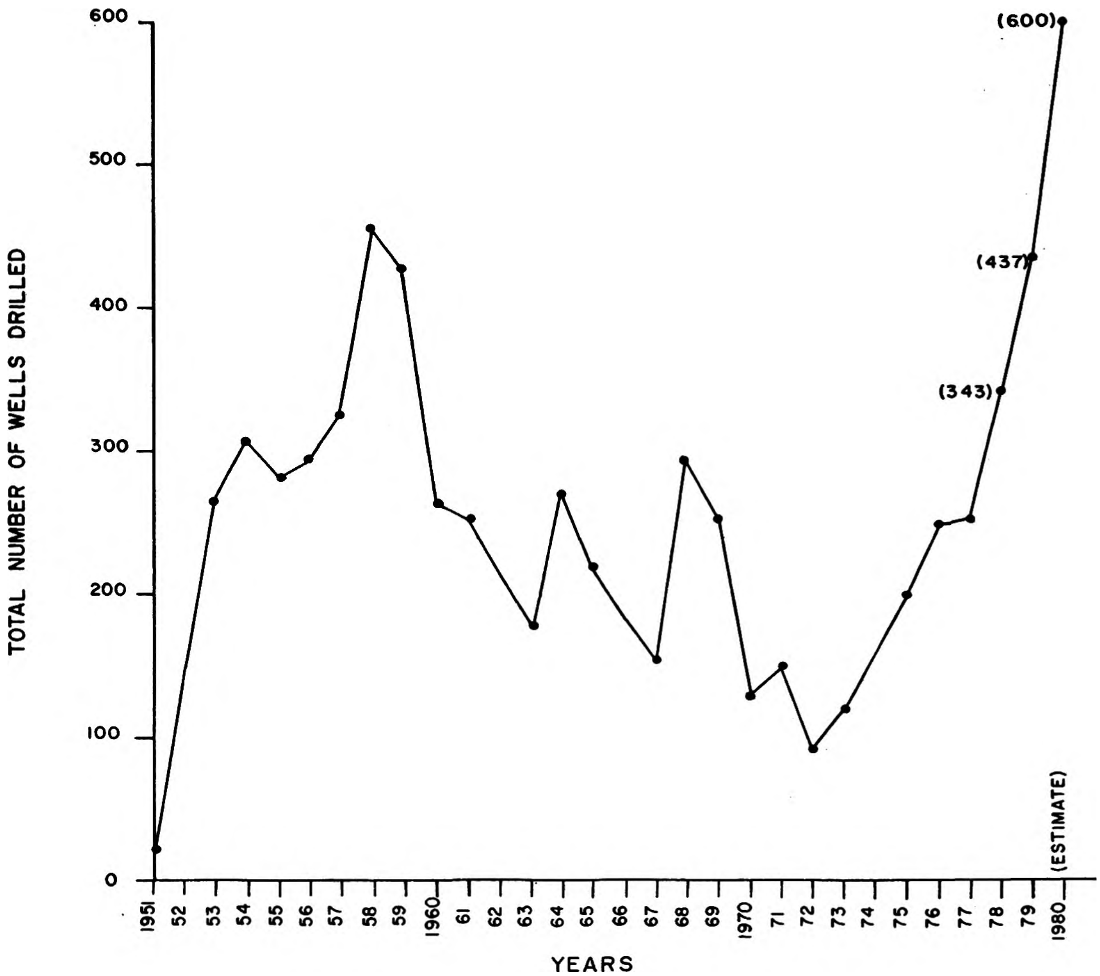


Fig. 26. Graph showing total number of wells drilled in North Dakota in 1951 through 1980. Last three years' numbers are shown.

tains many wells with initial potentials of over 2,000 barrels a day and a few with potentials of over 3,000 barrels.

Shallow gas plays are in their infancy in the basin but are in process. Air drilling is necessary for adequate testing of Pierre (Judith River and Eagle Sands) and Niobrara rocks, but the rigs that use this technique are uncommon in the basin, and surface holes can be a problem with air drilling. Little testing has been done on the southeast extension of the Antelope anticline, an area that has only recently been staked out as a major potential hydrocarbon area. Stratigraphic traps around the Cedar Creek, Nesson, and Poplar anticlines are untested in the east as is much of the eastern and western basin flanks. The northwest shelf, west of the Nesson anticline, holds promise and has been tested mostly on the Montana side of the basin. Many prospects remain to be drilled.

Financial impacts on the state of North Dakota brought about by the oil business are very significant. For the 1980's, oil and gas-generated revenues will be the most significant single source of income to the State government.

Oil development can be tracked by studying graphs of the activities and events. Total wells drilled since the 1951-52 initial discovery period (Fig. 26) rose from 1951 to 1958, sliding off rapidly to 1963 and then more erratically to 1977. From 1977 to date, increases have occurred, with an extremely rapid increase from 1977 through 1980. The number of wildcat wells (Fig. 27) is more stable. Initial discovery period wildcats form a peak in 1954, the stratigraphic Mississippian play peaked in 1958, Bowman County Red River play wildcats peaked in 1964, and the shallow Dakota Sandstone play had the highest number of wildcats until 1980 (1968), although no discoveries were made. Since 1972, although a minor 1977

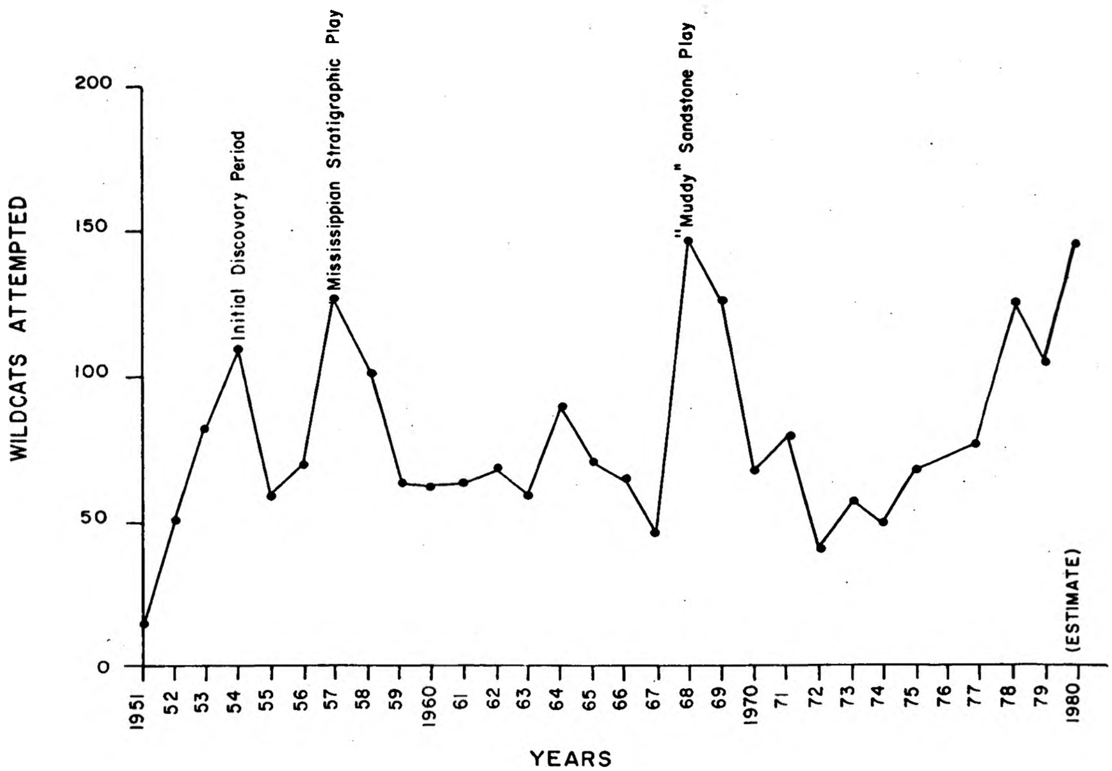


Fig. 27. Graph showing number of wildcats wells, 1941 through 1980.

peak occurs, wildcat activity has steadily been up.

If new pool discoveries are compared to the preceding curves, the significance of the present development boom becomes obvious (Fig. 28). Except for the Dakota Sandstone wildcat program, high levels of wildcat activity have a corresponding peak of new pool discoveries. However, the number of new pool discoveries per wildcats drilled has risen dramatically in the last four years, reflecting the very high wildcat success ratios that have been enjoyed.

Annual production levels reflect drilling activity as well as other factors (Fig. 29). Original oil production from the Nesson anticline discoveries had already begun to level off when the Madison Formation stratigraphic traps north and northeast of the Nesson began to produce in 1955. This production, coupled with the Nesson anticline fields, increased production until 1962. A slight production decrease in 1963 was to be expected because of the total wells drilled and lack of wildcats (Figs. 24, 25). However, discovery of the Red River Formation production in southwestern North Dakota (Bowman County) gave a boost to production from 1964 to 1966, when penultimate production was reached. The curve probably would have peaked much earlier except for prorationing. Production in North Dakota followed national trends from 1966 to 1974. Continual decline of production here and elsewhere, coupled with increased consumption, meant increased imports.

However, two events occurred close together to change Williston basin production history significantly. First, the Organization of Petroleum Exporting Countries (OPEC) was formed and emplaced production controls and price increases on its members' production (first embargo). Second, Red Wing Creek Field was discovered in McKenzie County, North Dakota.

OPEC created the first substantial increase in the volume of oil so that exploration could be deemed a profitable venture. (Prior to this, many companies found that exploration risk money had a better return in regular bank savings accounts than in actual wildcat drilling.) The price increases created risk capital, and, thus, exploratory drilling was enhanced.

The Red Wing Creek discovery at the same time excited basin oil operators because of the relatively high productivity of the wells and because of the anomalously high pay section thickness. Because no one really understood the nature of the Red Wing Creek structure at the time, industry's only possible response was to gain lease foothold in the area. The lease play set off by the Red Wing Creek discovery set the stage for much further

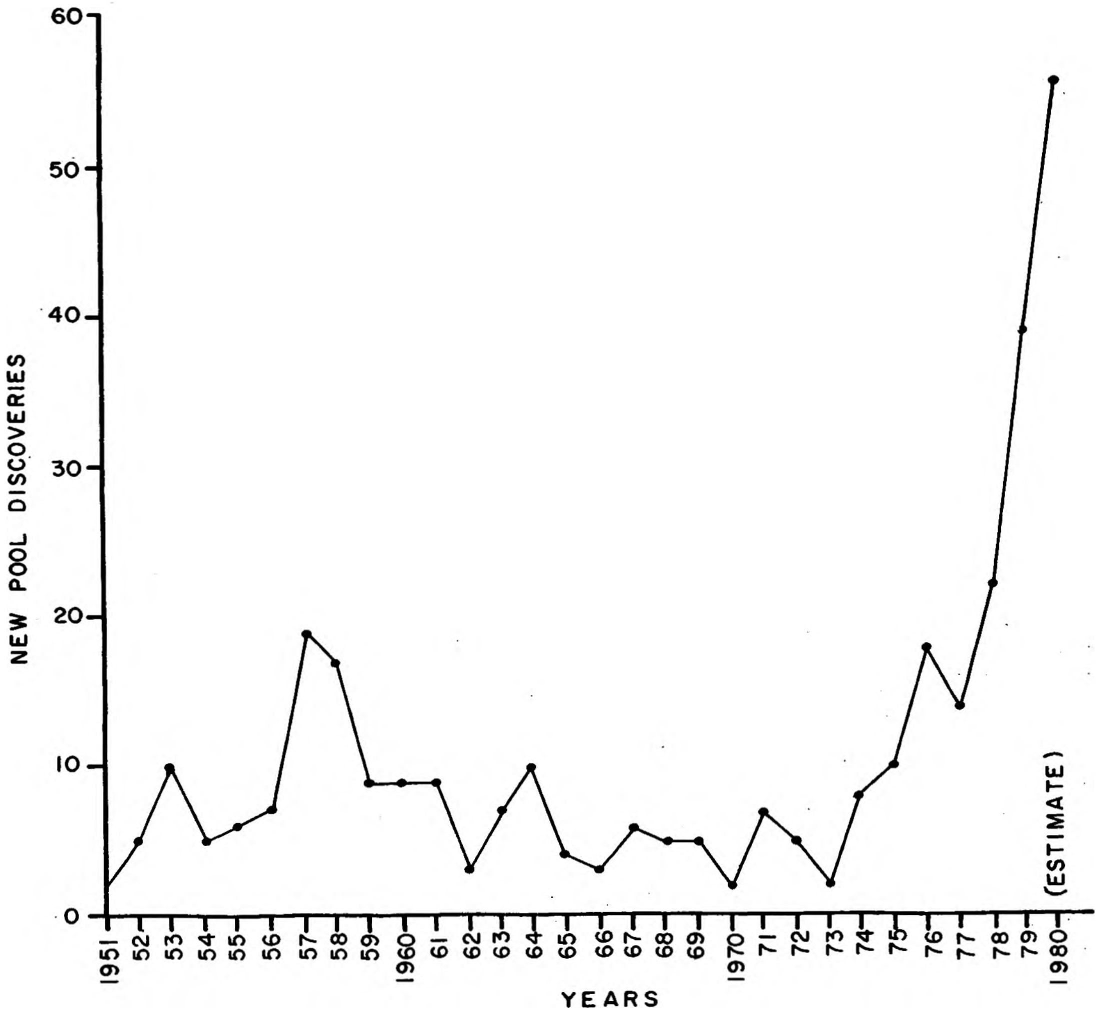


Fig. 28. Graph showing number of new pool discoveries, 1951 to 1980. The 1980 number appears to be approximately 57 discoveries.

development. The five-year-term leases of western North Dakota tend to increase exploratory activity as compared to ten-year leases. The lease play, coupled with the sudden availability of venture capital, caused exploratory drilling to begin to increase in 1974 and 1975, in part in response to the lease expiration dates.

Best prospects are drilled first, naturally, and the results for North Dakota are history, as recorded in the production curve. Two major fields were discovered in 1976—Mondak Mississippian and Little Knife Mississippian. It was quickly apparent that these fields, especially Little Knife, were prolific, large fields in Williston basin vernacular, and a lease rush occurred, which is still active today. The independents who kept the basin oil industry going in the sixties are largely frozen out of the main activity now by high lease prices.

One example of this is in state land sale values. In 1970, the total bonuses paid for the year for state leases was $294,000. In 1978, the annual total neared $20,000,000. In 1980, for the *last quarter* sale only, over $30,000,000 was paid.

The future for oil and gas production in the Williston basin looks bright for the next few years. New rigs moving in, major exploratory programs underway, and high lease prices all support a continuation of the present exploratory boom, with yet several years of development drilling needed after decreased exploratory drilling occurs.

OTHER MINERAL AND ENERGY RESOURCES

The Williston basin contains two major resources besides hydrocarbons, although present production of either does not begin to compare to the value of the hydrocarbon resource. Lignite is actively mined and is a significant energy and revenue producer in North Dakota. Potash resources are not yet being mined but serve as a

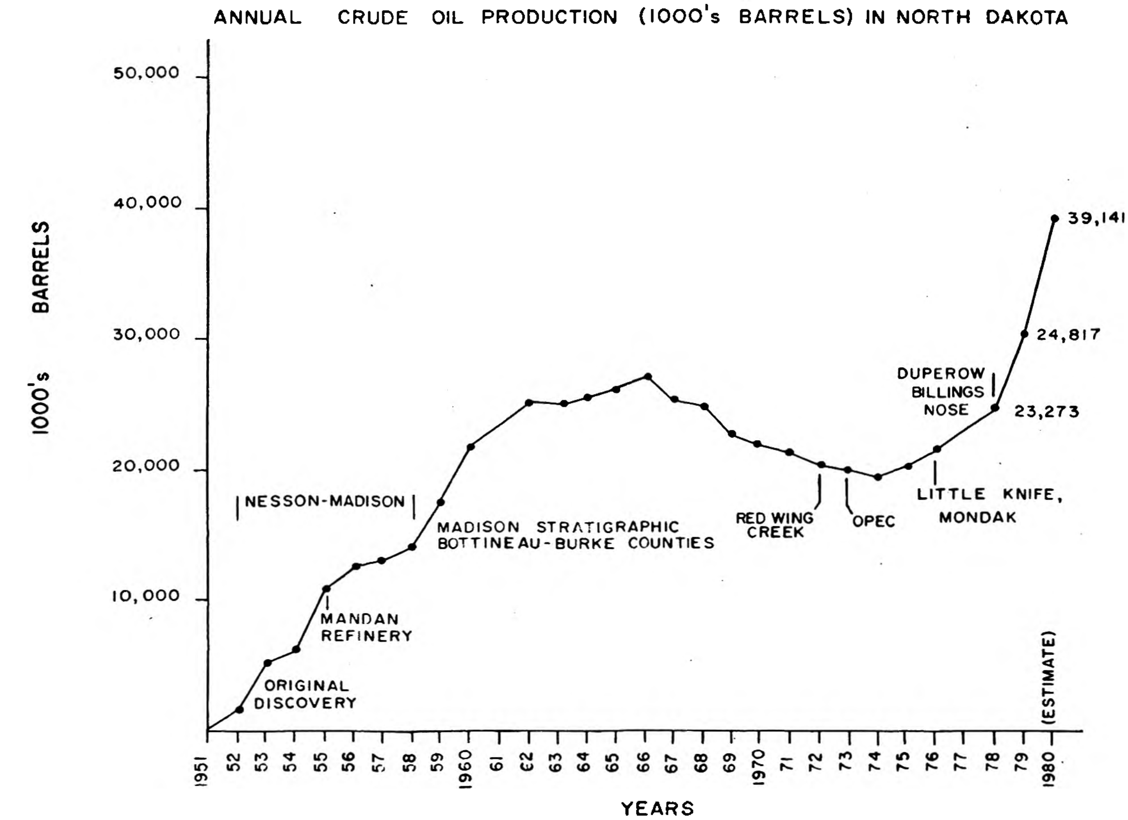


Fig. 29. Annual oil production in North Dakota, 1951 through 1980. See text for discussion of events on graph.

damper on potash prices in the world market, especially on Canadian resources.

Deposition of Prairie Formation evaporites, after restriction of circulation in the Elk Point basin of Devonian time, has created a very large resource of salt and potash in the Williston basin (Figs. 8, 16, 30). Within the Prairie Salt section, three potash units occur, the Esterhazy, Belle Plaine, and Mountrail Members (Anderson and Swinehart, 1979) (Fig. 31). At the present time, potash is being mined by both conventional underground and solution methods in southern Canada. Approximately 50 billion tons of potash lie south of the international border in North Dakota, with additional resources in Montana.

During the mid-1970's, increasing world market prices coupled with both export taxes on Canadian potash and action by the Canadian government to take control of the Canadian potash mines created a flurry of leasing and pre-mining activity in North Dakota and Montana. Because the depth to minable potash in the United States portion of the basin precludes conventional mining techniques, solution mining was planned for North Dakota. A drop in the world price of potash ended the development of pilot plant mining installations, but the resources are under secure lease. As production from the New Mexico deposits wanes, the Williston basin deposits serve to prevent any world potash cartel from major price increases. The 50 billion tons of resources insures the domestic supply of this critical mineral.

Lignite is a major energy resource in the North Dakota portion of the basin (Fig. 32). Lignite occurs as part of the Cenozoic rock suite deriving from erosion of the Laramide Rocky Mountains. These rocks, generally called the Ft. Union Group, are mostly of terrestrial origin, although the Cannonball Formation below the Ft. Union is the youngest marine stratigraphic unit in this area (Fig. 33). Mining is now exclusively by surface techniques, but earlier in the history of North Dakota, underground workings were common but are now a source of major environmental concern as they collapse.

Because this is a low sulfur but high water content fuel, waste of the lignite is utilized close to the mining site for electrical generation (Fig. 34). Despite national need for additional energy re-

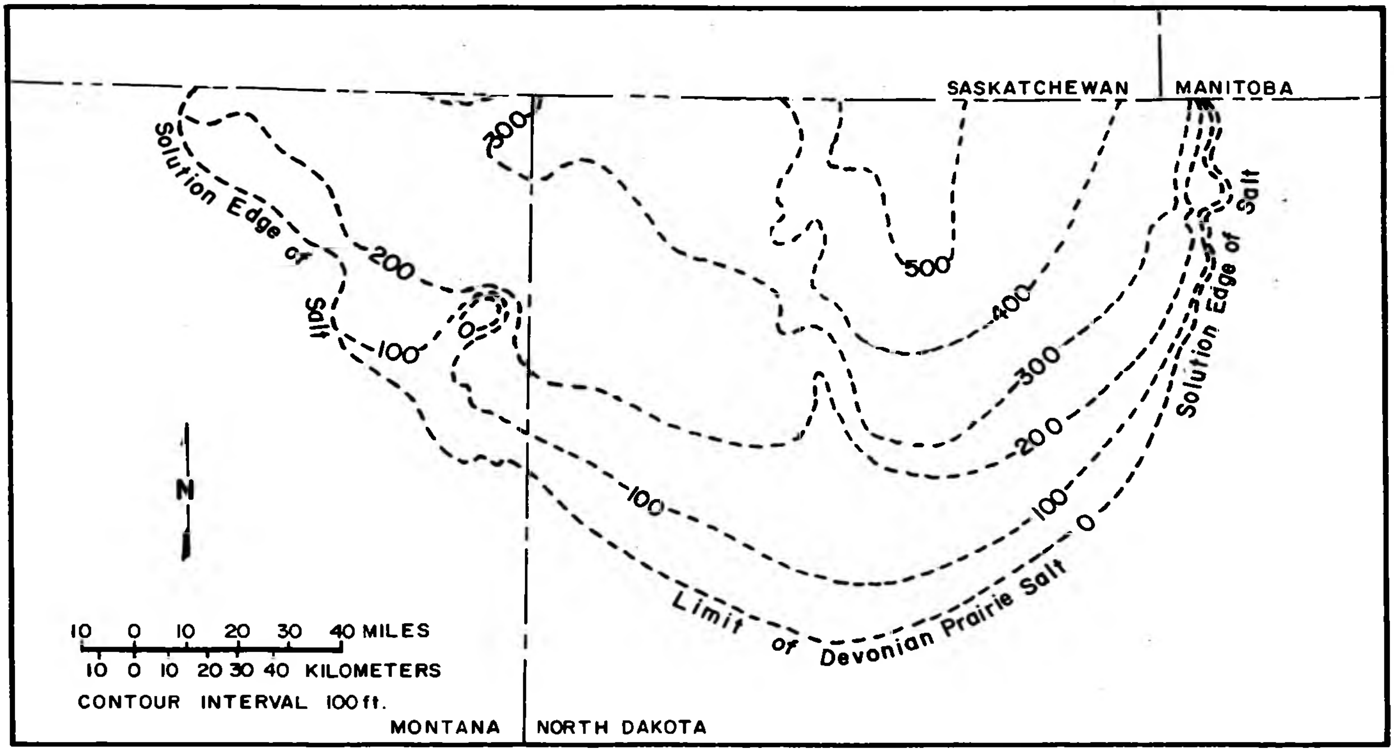


Fig. 30. Isopach map of the Prairie Salt in Montana and North Dakota showing the limit of the Prairie Salt. Modification from Anderson and Swinehart, 1979.

sources, severe restriction on leasing of reserved Federal coal and State reclamation policies have held down production increases. Still, production in North Dakota has doubled in the last five years as new electrical generation plants have gone on stream (Fig. 35). The 20-billion ton reserves and 350-billion ton resources specify that the lignites will be major energy sources for decades.

SUMMARY

Geological analysis of the Williston basin has benefited from expansion of the subsurface data base through renewed oil exploration, application of computer techniques to data handling, and detailed environmental and diagenetic analyses of cores and cuttings. Results of the study of these new data indicate a much more structurally complex basin than heretofore realized.

Basin evolution in Phanerozoic time begins with Sauk transgression across a rough Precambrian topographic surface but without definition of a basin. Tippecanoe Sequence rocks result from initial depression of the Williston basin with seaway connections west and southwest to the Cordilleran miogeosyncline.

During Kaskaskia time, movement along the Transcontinental arch trend tilted the Williston basin northward, creating a marine connection to the north into the Elk Point basin during the Devonian, while shutting off the Tippecanoe Cordilleran marine connection. During the upper part of Kaskaskia time (Mississippian), the northern connection was cut off, and the Williston basin reconnected to the Cordilleran sea through the Central Montana trough.

Post-Kaskaskian (ancestral Rocky Mountain) structural disturbance in the southern Rockies disrupted sedimentation patterns and primary carbonate-dominant lithologies in the basin. From this time forward, clastic sedimentary facies predominated in the Williston basin with interspersed evaporites and a few carbonates.

A full marine setting was established during the Cretaceous as part of the Western Interior seaway. Regression accompanying uplift of the Laramide Rockies provided paludal and fluvial environments, which trapped much sediment moving eastward from the Rockies in Paleocene times and assisted in the formation of extensive lignite deposits.

Substantial quantities of lignite, potash, and petroleum are present in the Williston basin. Lignite mining for electrical generation is a major industry, but potash resources are not yet being mined.

Oil and gas production is rapidly expanding in the basin. Very high rates of success in exploration drilling have doubled oil production in the last four years. Continued increases in oil production are forecast for the next few years.

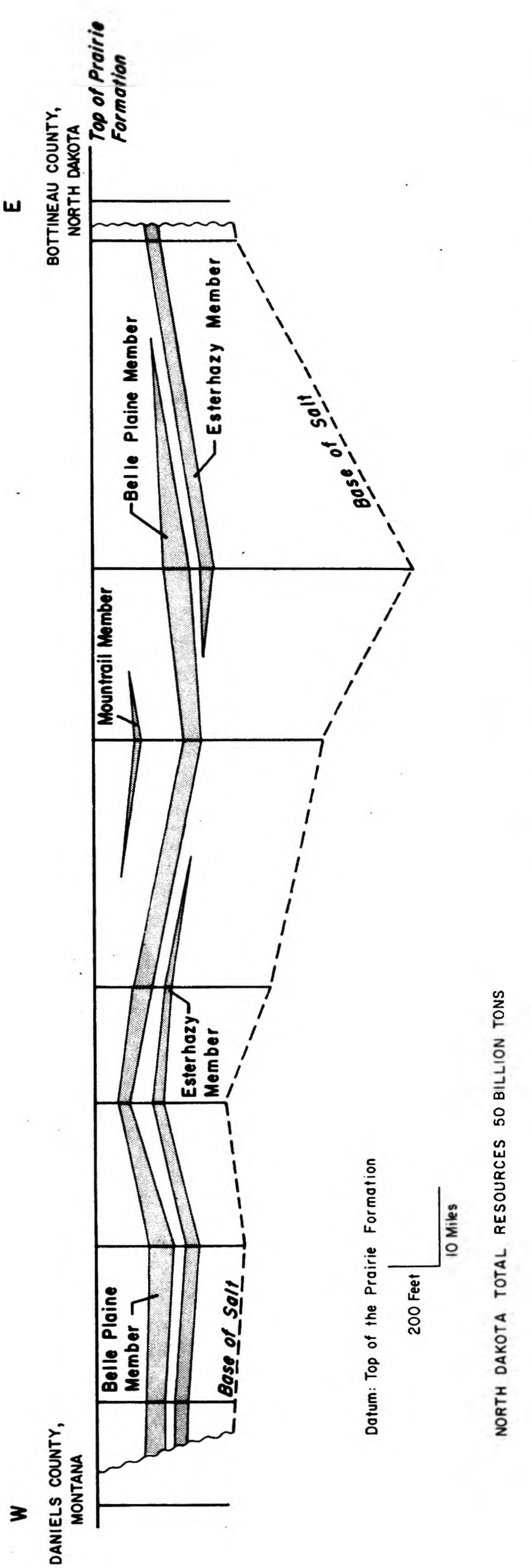


Fig. 31. Cross section from Daniels County, Montana, through Bottineau County, North Dakota, showing the potash beds within the Prairie Formation. Shaded zones are potash bearing. Modified from Anderson and Swinehart, 1979.

Several new structural trends have been mapped in recent years and are the basis for the increases in oil production. Several of the structural trends now being mapped have not been substantially explored.

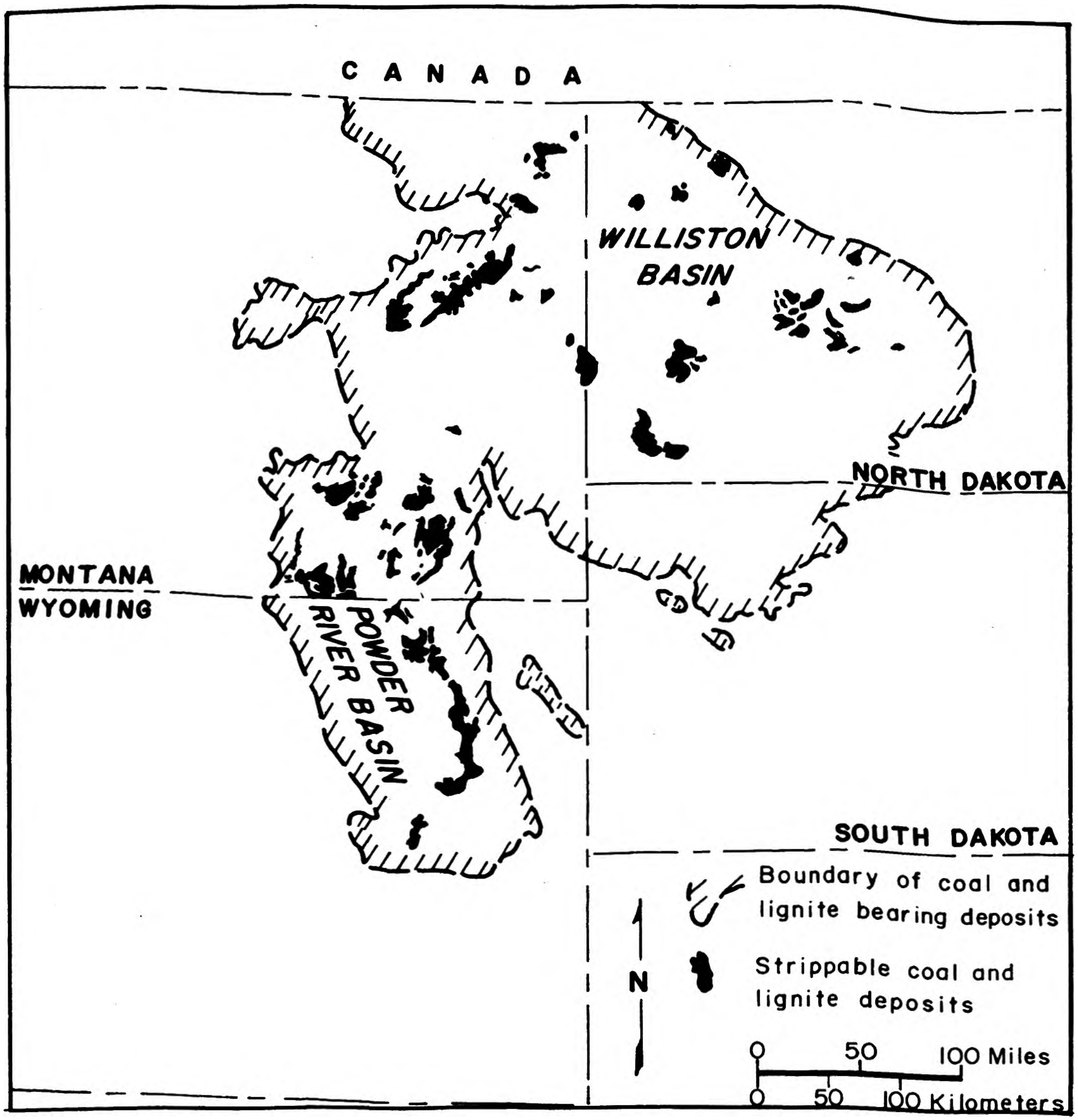


Fig. 32. Map showing distribution of strippable coal deposits in the Williston and Powder River basins of North Dakota, Montana, and Wyoming. Modified from U.S. Geol. Survey Misc. Map MF-540.

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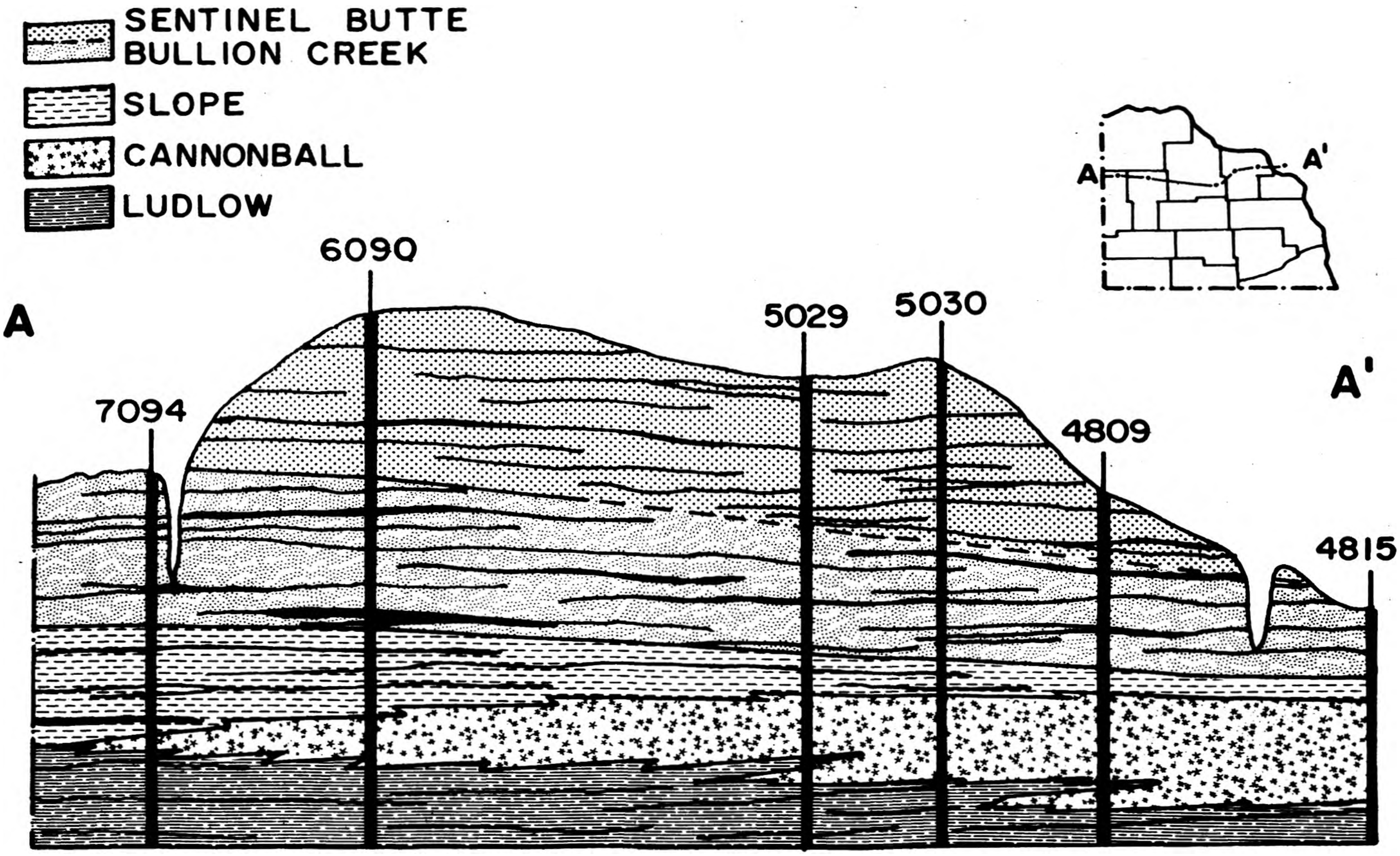

Fig. 33. Diagrammatic cross section of Paleocene rocks in western North Dakota showing relationship of lignite beds to stratigraphic units. Numbers at vertical dark lines refer to North Dakota Geological Survey drillhole control.

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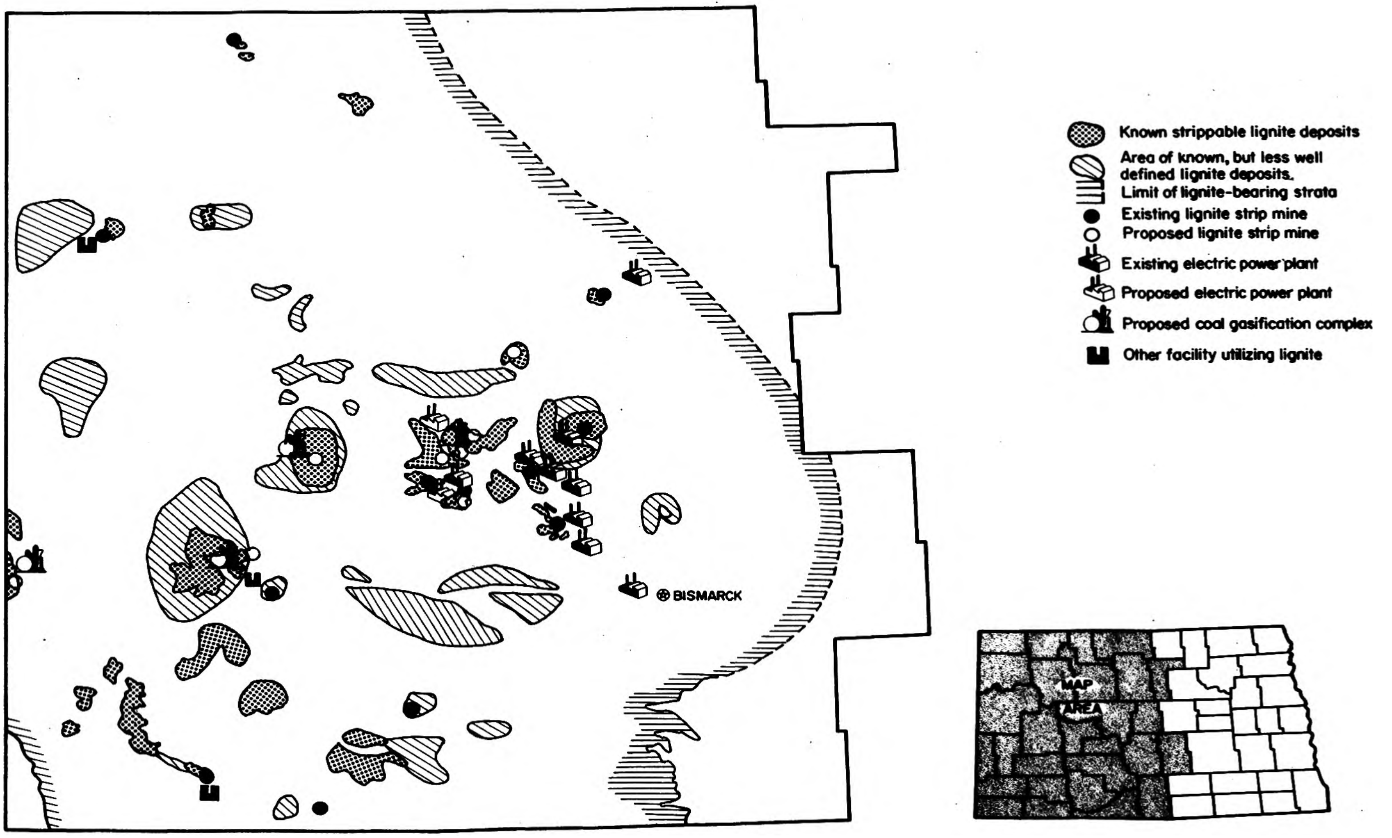

Fig. 34. Map showing strippable lignite deposits and development areas of lignite in North Dakota. Note the heavy concentration of active or proposed usage of lignite northwest of Bismarck. Modified and redrawn from Lerud 1982.

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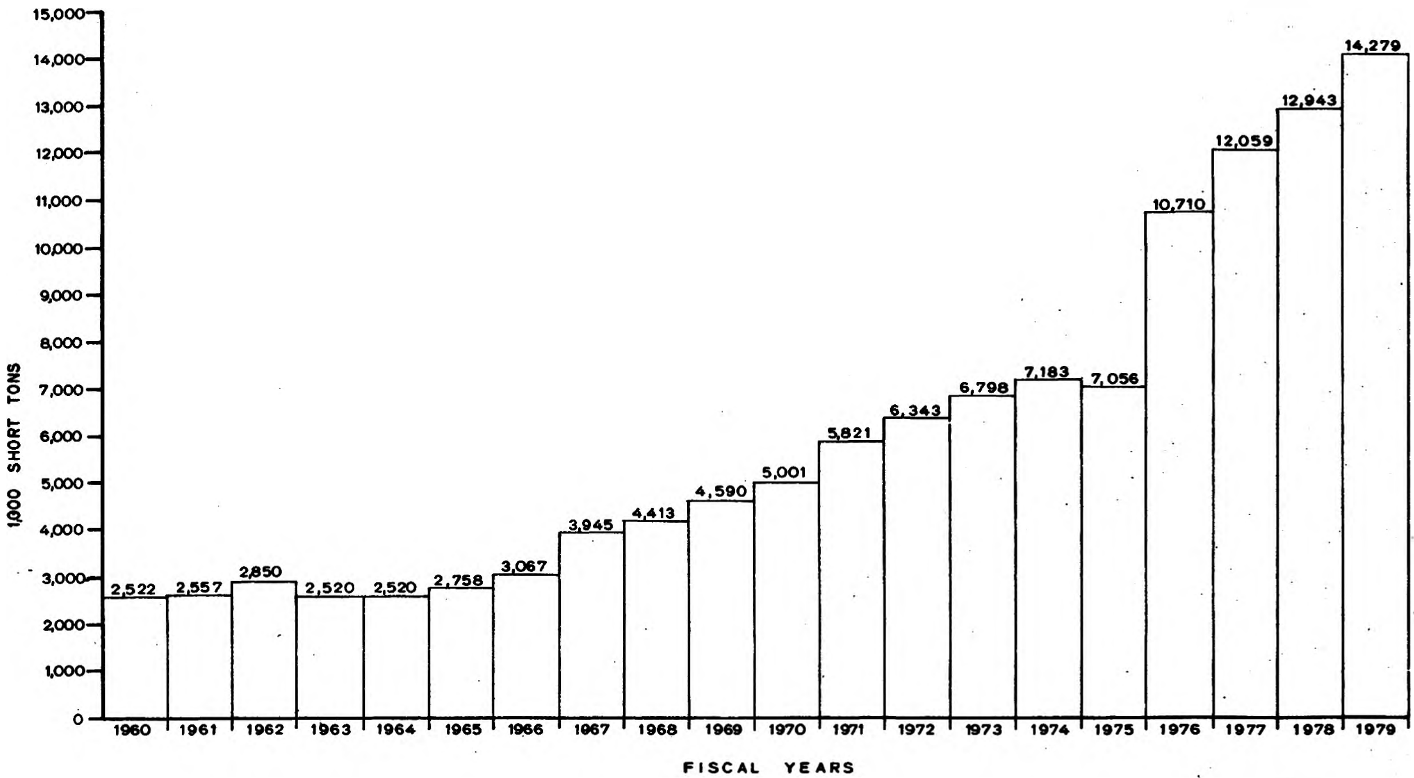

Fig. 35. Graph showing production of coal (lignite) in North Dakota 1960-1979. Note steady increase in production from 1966 to 1974 with a jump in 1976 and additional increases. These increases in 1976-79 apparently reflect increasing demand for electrical generation replacing other sources of energy.

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