GEOLOGICAL DEVELOPMENT, ORIGIN, AND ENERGY MINERAL RESOURCES OF THE WILLISTON BASIN, NORTH DAKOTA

by

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Geological Development, Origin, and Energy Mineral Resources of Williston Basin, North Dakota[1]

LEE C. GERHARD,[2] SIDNEY B. ANDERSON,[3] JULIE A. LEFEVER,[3] and CLARENCE G. CARLSON[4]

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 (Cambrian-Lower Ordovician), Tippecanoe (Ordovician-Silurian), and Kaskaskia (Devonian-Mississippian) sequence rocks are largely carbonate, as are the major oil- and gas-producing formations. Absaroka (Pennsylvanian-Triassic) and Zuni (Jurassic-Tertiary) rocks have more clastic content, but carbonates are locally important. Clastics of the Zuni sequence (Fort Union Group) contain abundant lignite. Tejas (Tertiary-Quaternary) sequence rocks are not significant in the production of minerals or energy, although glacial sediments cover much of the region.

Oil exploration and development in the United States portion of the Williston basin since 1972 have given impetus to restudy basin evolution and geologic controls for energy-resource locations. Consequently, oil production in North Dakota, for instance, has jumped from a nadir of 19 million bbl in 1974 (compared to a previous zenith of 27 million in 1966) to 32 million bbl in 1979 and 40 million bbl in 1980. Geologic knowledge of carbonate reservoirs has expanded accordingly.

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

Clastic sediments were transported into the southern part of the basin during Absaroka sequence deposition, a product of erosion of Ancestral Rocky Mountain orogenic structures. Continental and shallow marine clastic sediments were deposited during Zuni sedimentation until Cretaceous deeper 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 postorogenic regressive rock body.

Major structures in the basin, and the basin itself, may result from left-lateral shear along the Colorado-Wyoming and Fromberg zones during pre-Phanerozoic time. Deeper drilling in the basin has revealed several major structures and given indications of others. Most structures probably resulted from renewed movement or "tensing" of pre-Phanerozoic faults. Meteorite impact events have been suggested as the origin for one or more structures.

INTRODUCTION

Recent successful oil exploration and development in the Williston basin have 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 1970s that is remarkable in its definition of previously unrecognized structures, discovery of new producing zones, and high 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. The wildcat success rate in North Dakota has steadily increased from 25% in 1977; 28% in 1978; 33% in 1979; to 36% through the first 6 months of 1980, whereas the recent national average was 15 to 18% for a similar period (Johnston, 1980; Fig. 2). Although South Dakota and Montana also sustain active programs, their success rates are lower; Montana has the second most successful active drilling program in the basin.

Oil and gas are not the only mineral and energy resources

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Many of our colleagues, students, and cooperating scientists have spent extensive amounts of time discussing ideas, providing data, and redirecting our efforts. In particular, James H. Clement of Shell Oil Co.; Cooper Land, consultant; and Walter Moore of the University of North Dakota have been instrumental in construction of our ideas and approach. 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 original studies of depositional systems and reservoir geology came from the North Dakota Geological Survey, the Carbonate Studies Laboratory of the University of North Dakota, and from a grant by the U.S. Geological Survey (14-08-0001-G-591). All of the support is gratefully acknowledged.

of the basin. Lignite reserves are huge and are actively being explored and utilized. Rich potash resources are being mined in Saskatchewan and a mine has been announced for western Manitoba. In North Dakota and Montana, potash resources are potentially far more valuable than the lignite, but are not yet being mined. Halite is being mined near Williston, North Dakota, from depths of 8,000 ft (2,438 m) making it probably the world's deepest salt production. The halite deposits are vast, being approximately 1,700 mi^3 (7,086 km^3).

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

The Williston basin is a slightly irregular, round depression in the western distal Canadian shield. Structural trends within the basin reflect major directional changes in the structure of the Rocky Mountain belt (Fig. 2). Several writers have hypothesized a wrench-fault system for control of basin geometry and structure (Thomas, 1974; Brown, 1978), although those studies did not integrate sedimentary depositional facies and porosity development information.

Approximately 16,000 ft (4,875 m) of sedimentary rocks are present in the deepest part of the Williston basin, southeast of Watford City, North Dakota. The deepest well in the basin penetrated Precambrian rock at 15,340 ft (4,676 m); the deepest oil production is from 14,343 ft (4,372 m) in the Ordovician Red River Formation (Mesa 1-13 Brandvik, Dunn County, North Dakota).

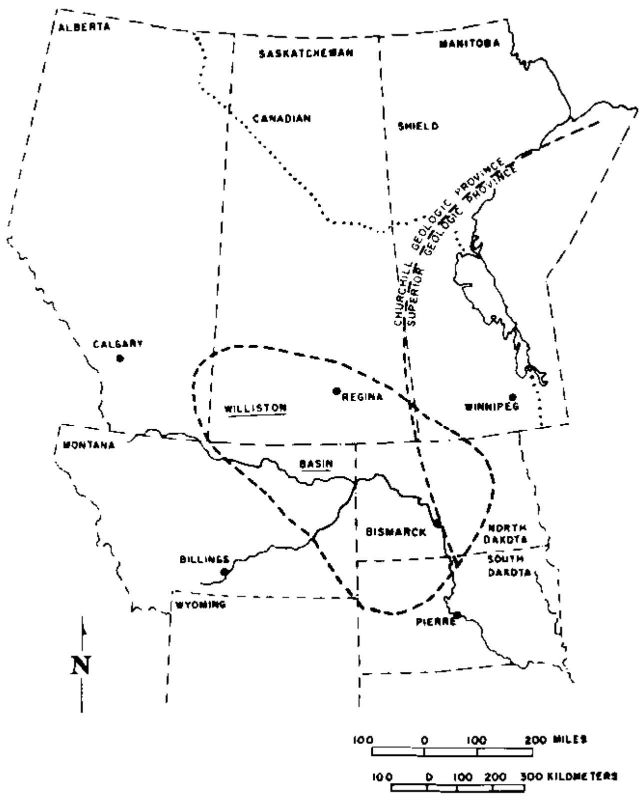


FIG. 1—Index map showing location of Williston basin in United States and Canada. Modified from Worsley and Fuzesy (1978).

Rocks deposited during all periods of Phanerozoic time are present in the basin (Fig. 3). Paleozoic rocks are mainly carbonates, followed by the dominantly clastic Mesozoic and Cenozoic rock sequence. Sloss's (1963) sequence concept is particularly useful in the study of these rocks, serving to "package" major transgressive cycles of continental scale with accompanying sediment deposition. For this reason, discussions of stratigraphic units and their significance to deciphering the structural evolution of the Williston basin are organized by sequences.

Few regional studies of Williston basin rocks have been published. Several important contributions 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 a, b), and Macauley et al (1964). Several unpublished works of oil company geologists are also used in this paper, especially those of James Clement (personal commun., oral discussions, 1975-80).

Several cycles of interpretive writing are evident in the literature about the Williston basin. Each proceeds from an equivalent cycle 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 now and is rapidly increasing oil production. Most of the United States part of the Williston basin is contained in North Dakota; its statistics are impressive. After reaching a high of 27 million bbl of oil produced in 1966, production declined to 19.5 million bbl in 1974. During the third cycle of development, production began to increase in 1975, reaching a new historic high of 32 million bbl in 1979, increasing to 40 million bbl for 1980. Concurrent with this cycle of development, research into oil and gas reservoir geology, regional depositional systems, and other aspects of basin analysis has been revived with applications of technology developed since the mid-1960s. Summary papers of this era are included in Estelle and Miller (1978) and in several publications of the North Dakota Geological Survey (Bjorlie, 1979; Carroll, 1979; Bluemle et al, 1980; Scott, 1981; Lerud, 1982). Various orally presented papers at national and regional society technical programs also added ideas and data to the present exploration cycle.

The purpose of this paper is to summarize briefly the current knowledge of the geologic evolution and energy resources of the North Dakota portion of the Williston basin. As in any summary paper, this effort is colored by the geological philosophies and biases of the writers.

TECTONIC SETTING

The Canadian shield extends under the Williston basin to the Cordilleran geosyncline. The Williston basin forms a large depression in the western edge of the shield, occupying much of North Dakota, northwestern South Dakota, the eastern quarter of Montana, a significant part of southern Saskatchewan, and a portion of southwestern Manitoba. 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 (Fig. 2).

Structural grain of the region appears to be related to the offset in the Rocky Mountain chain between the north-trending southern Rocky Mountain province and the northwest-trending northern Rockies indicated by proprietary seismic data. The zone of offset in Wyoming and Montana (central Rockies) is characterized by northwest structural grain of basin and range configuration. Regional wrench faulting along the Cat Creek and Lake Basin zones (Thomas, 1974) suggests to us that structural control of the Williston basin is related to large-scale "tears" 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), which is the 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 province. The Cedar Creek and Antelope anticlines 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 southeast 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); those in Foster and Stutsman Counties are probably important. The Cavalier high (Ander-

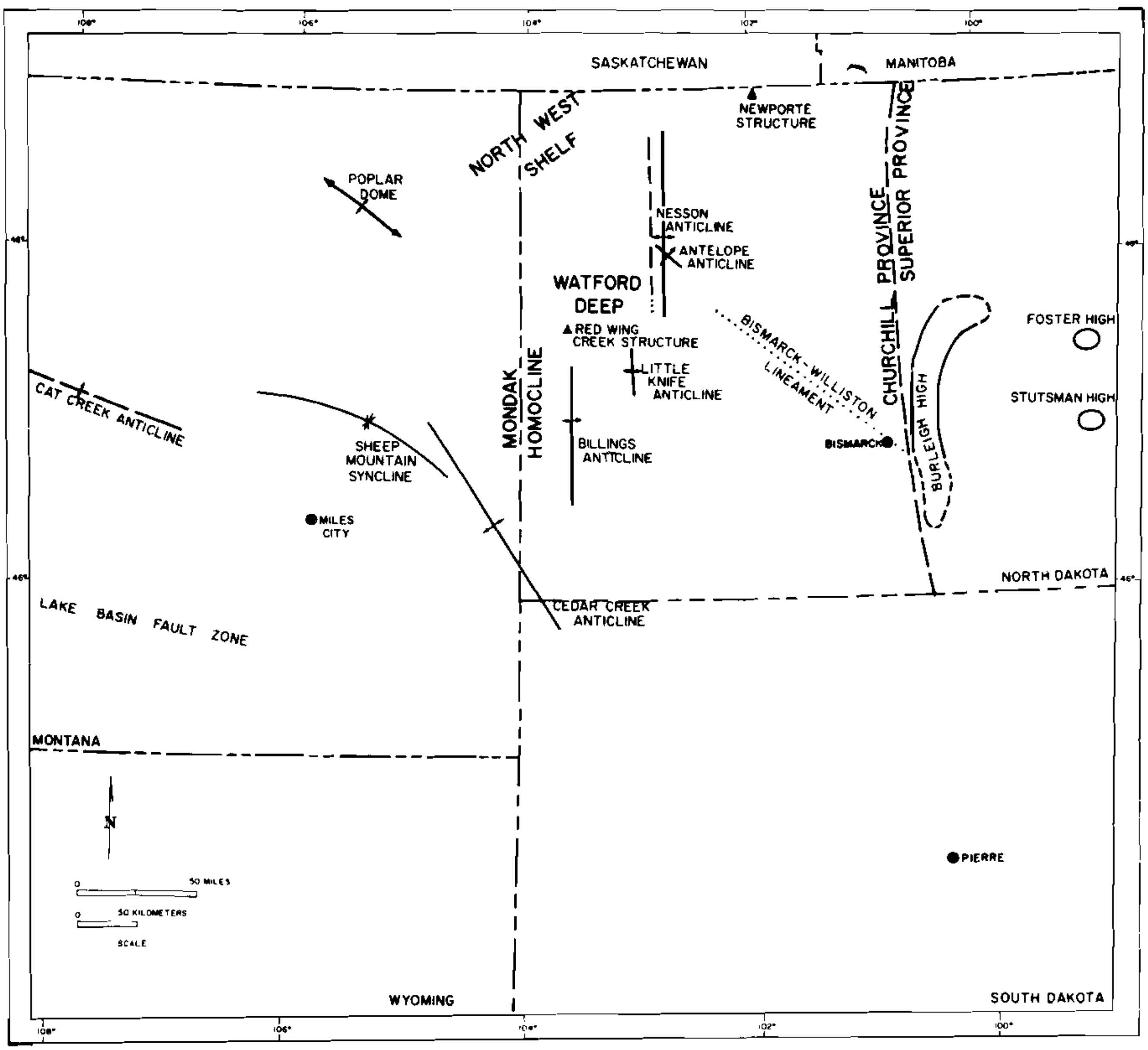


FIG. 2—Major structures of Williston basin based on current subsurface structural mapping and geophysical interpretations.

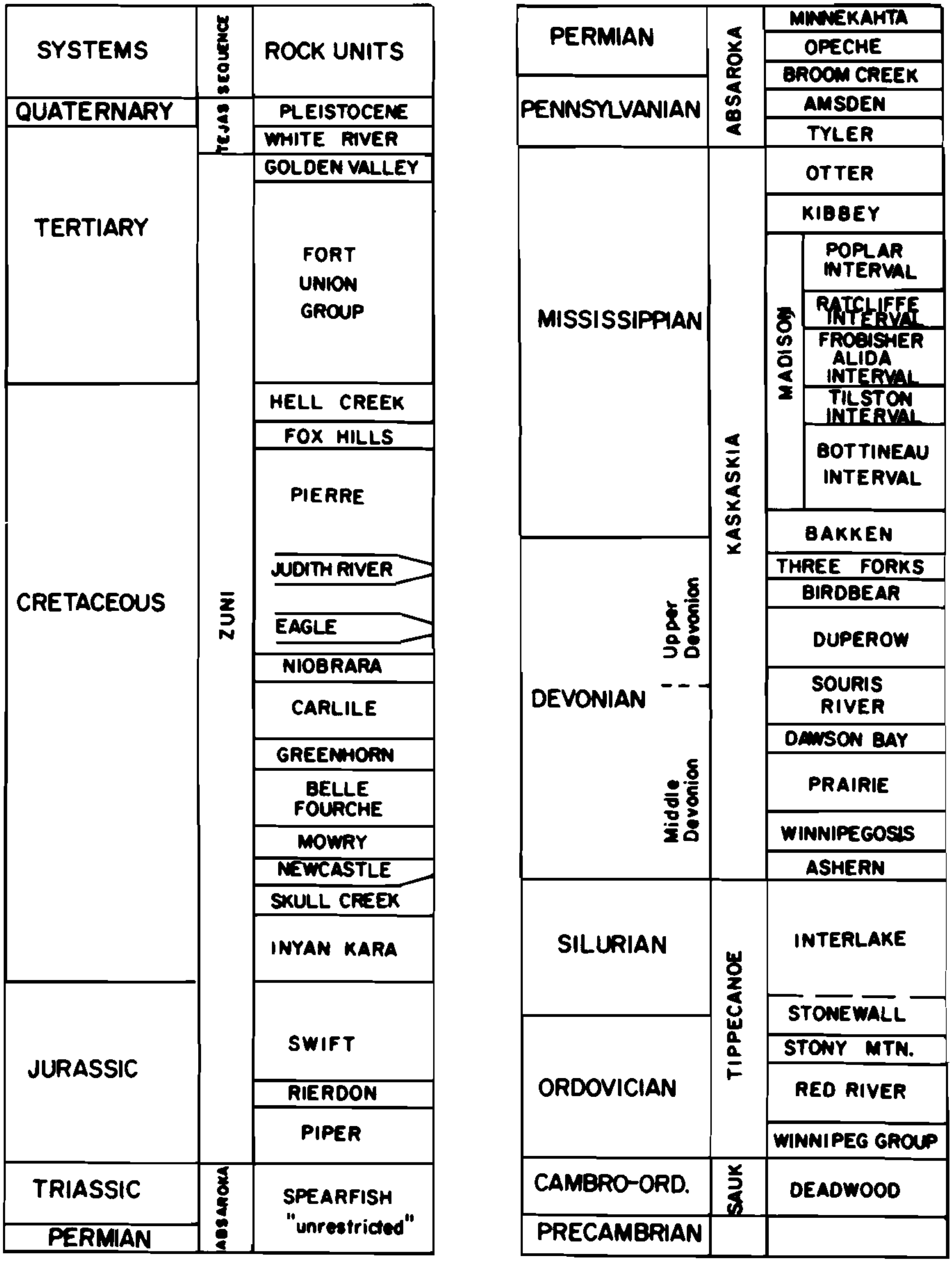


FIG. 3—Generalized stratigraphic column of Williston basin.

son, 1974) is apparently a paleotopographic artifact of pre-Mesozoic drainage (Fig. 4).

Two other structural elements may be 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 et al, 1975; Parson et al, 1975). The Newporte structure is interpreted to be a faulted block of early Paleozoic age in which oil has been trapped along unconformities within Cambrian and Ordovician sedimentary rocks; one well produced from Precambrian crystalline rocks (Clement and Mayhew, 1979). However, the structure may be of meteorite origin (Donofrio, 1981).

Indications of other tectonic elements or theoretical projects of deformation have been published by several writers. Kearns and Traut (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 the northeast trends that control much of the Mississippian structurally assisted stratigraphic oil traps in north-central North Dakota.

Several writers have attempted to establish a wrench-fault framework for the basin. 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 (1974) built a regional theoretical model for wrench-fault tectonics in the Montana and North Dakota parts of the basin.

There is little question in our minds that sedimentation and structure of the basin are controlled by movement of basement blocks that were structurally defined in pre-Phanerozoic time. One of the earliest clear demonstrations of this is the work of Carlson (1960) showing Cambrian topographic relief on the Nesson anticline. Carroll (1979) illustrates 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 have not been evaluated for the tectonic framework of the basin. Studies of

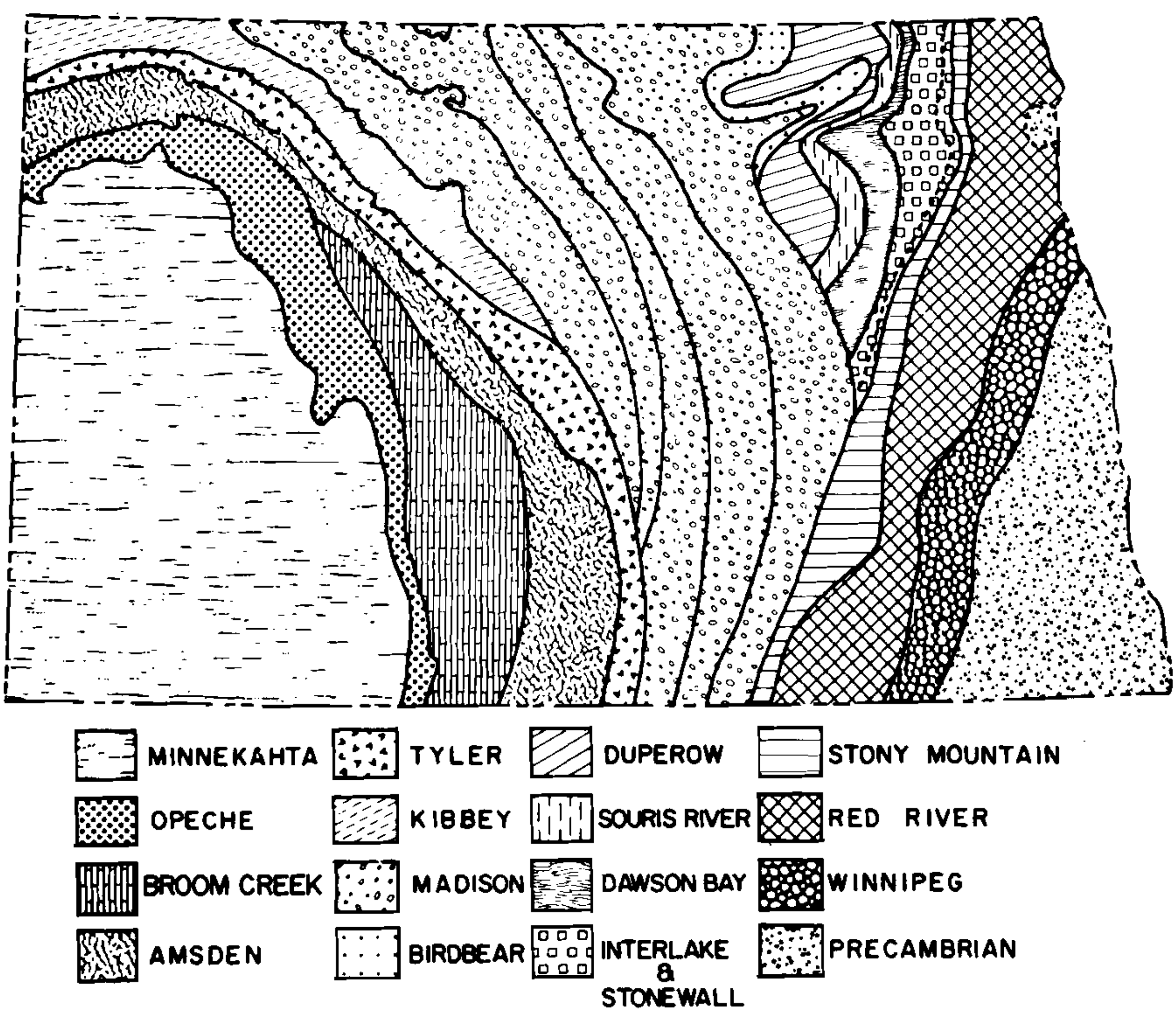


FIG. 4—Pre-Mesozoic paleogeologic map of North Dakota. Modified from Carlson and Anderson (1966).

depositional systems and mapping of structural changes through time are under way and should materially assist a tectonic interpretation of basin history.

STRATIGRAPHY

Sauk Sequence (Cambrian-Lower Ordovician)

Phanerozoic sedimentation was initiated in the Williston basin during latest Cambrian (Croixian) time (Fig. 5), when 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). The total thickness of Sauk sedimentary rocks in the basin probably does not exceed 1,000 ft (305 m). Isopach maps by Carlson (1960) and Lochman-Balk (1972) demonstrate that the present basin was simply a large embayment on the western Cordilleran shelf and was not structurally well defined. Apparently, there 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. Like most basal Sauk units, the Deadwood is largely clastic, including much reworked, weathered Precambrian material. The middle of the Deadwood in western North Dakota contains appreciable limestone and limestone conglomerate, becoming more clastic as it thins eastward.

The only faunal studies of the Deadwood in North Dakota are studies (Carlson, 1960) of conodonts from the upper part of the Deadwood in the Nesson anticline area. The conodonts are probably of Early Ordovician age. Ross (1957) also noted Early Ordovician fossils in cores from eastern Montana confirming that the Deadwood is of Late Cambrian through Early Ordovician age where the thicker sections are preserved. A regional disconformity separates Winnipeg and Deadwood rocks.

Tippecanoe Sequence (Ordovician-Silurian)

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. 6, 7), 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, including a well-developed basal sand, the sequence is largely carbonate. Isopach studies of the sequence and its individual rock units suggest a southwesterly connection to the western geosyncline through the present central Rockies. Whether this is an artifact of late erosional events or not is unknown. Similarly, a marine connection existed across the Sioux arch to the eastern interior (Fuller, 1961, Fig. 21). 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 struc-

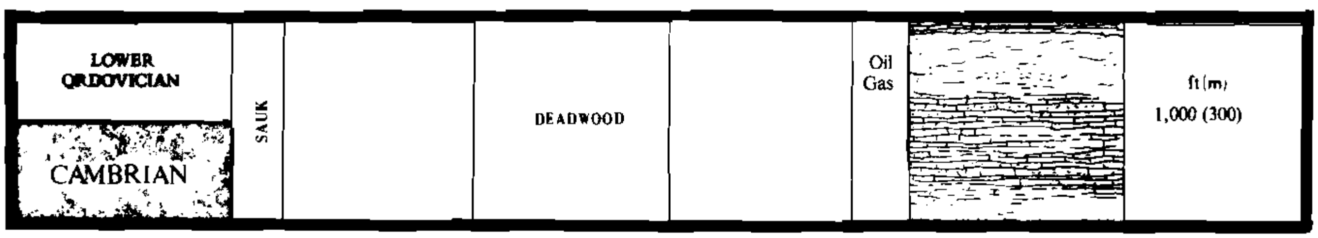


FIG. 5—Stratigraphic column of Sauk sequence. Modified from Bluemle et al (1980).

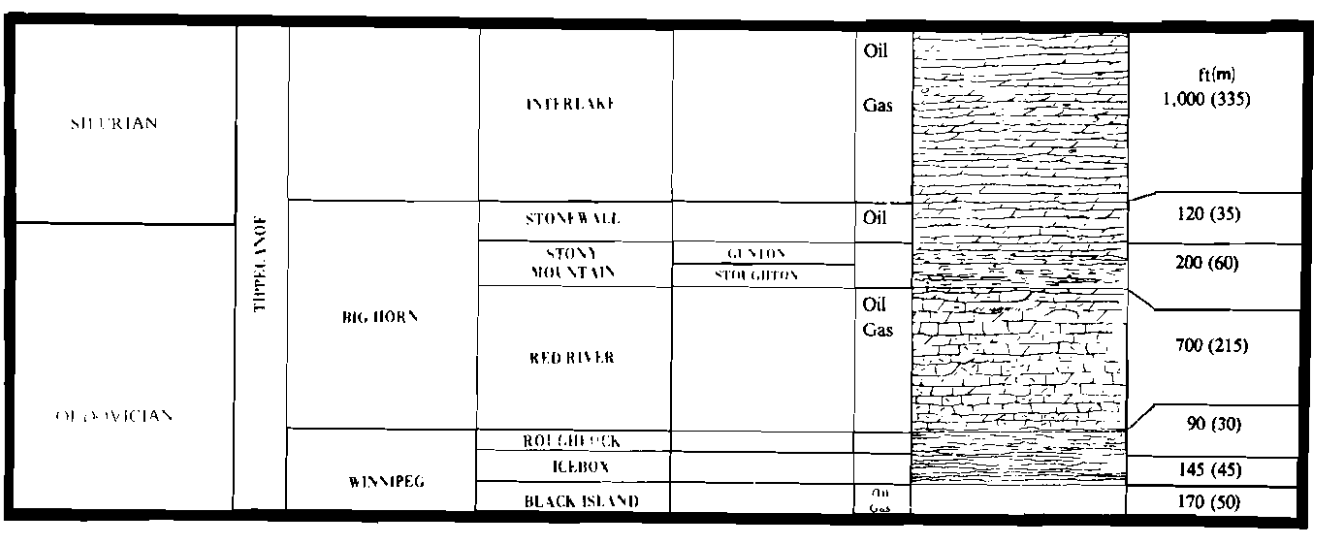


FIG. 6—Stratigraphic column of Tippecanoe sequence. Modified from Bluemle et al (1980).

tures. Isopachs of this formation are particularly important in studying basin evolution because they have been unaffected by later erosional events except along the basin margin.

Carbonate rocks of the Red River and Interlake Formations (Carroll, 1979; Roehl, 1967) were deposited under shallow marine and evaporite sabkha environments. Although the basin was well defined, there is little evidence of any particularly deep basal sedimentation. The Red River Formation contains shelf and lagoonal fabrics and biotas (Carroll, 1979), as well as sabkha evaporites and supratidal carbonates. Porosity development in the Red River is partly controlled by buried Precambrian hills or structures. D zone selective dolomitization of burrowed wackestones occurs on the periphery of a buried "high" owing to density of dolomitizing brines. Higher A, B, and C zone porosities are remnant after supratidal and/or sabkha dolomitization on the more crestal parts of highs (Table 1, Fig. 8; Carroll, 1979; Carroll and Gerhard, 1979).

Sedimentation was continuous from the beginning of Red River deposition through 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 partial karst surface development.

Kaskaskia Sequence
(Devonian-Mississippian)

Kaskaskia sequence rocks are perhaps the best known of the sequences because of their economic importance and because more subsurface data are available than for other groups. Thirteen studies of separate Kaskaskia rock units are either completed or in progress by North Dakota Geological Survey and University of North Dakota geologists.

Limestones are the most characteristic lithology of the sequence, but two episodes of evaporite deposition inter-

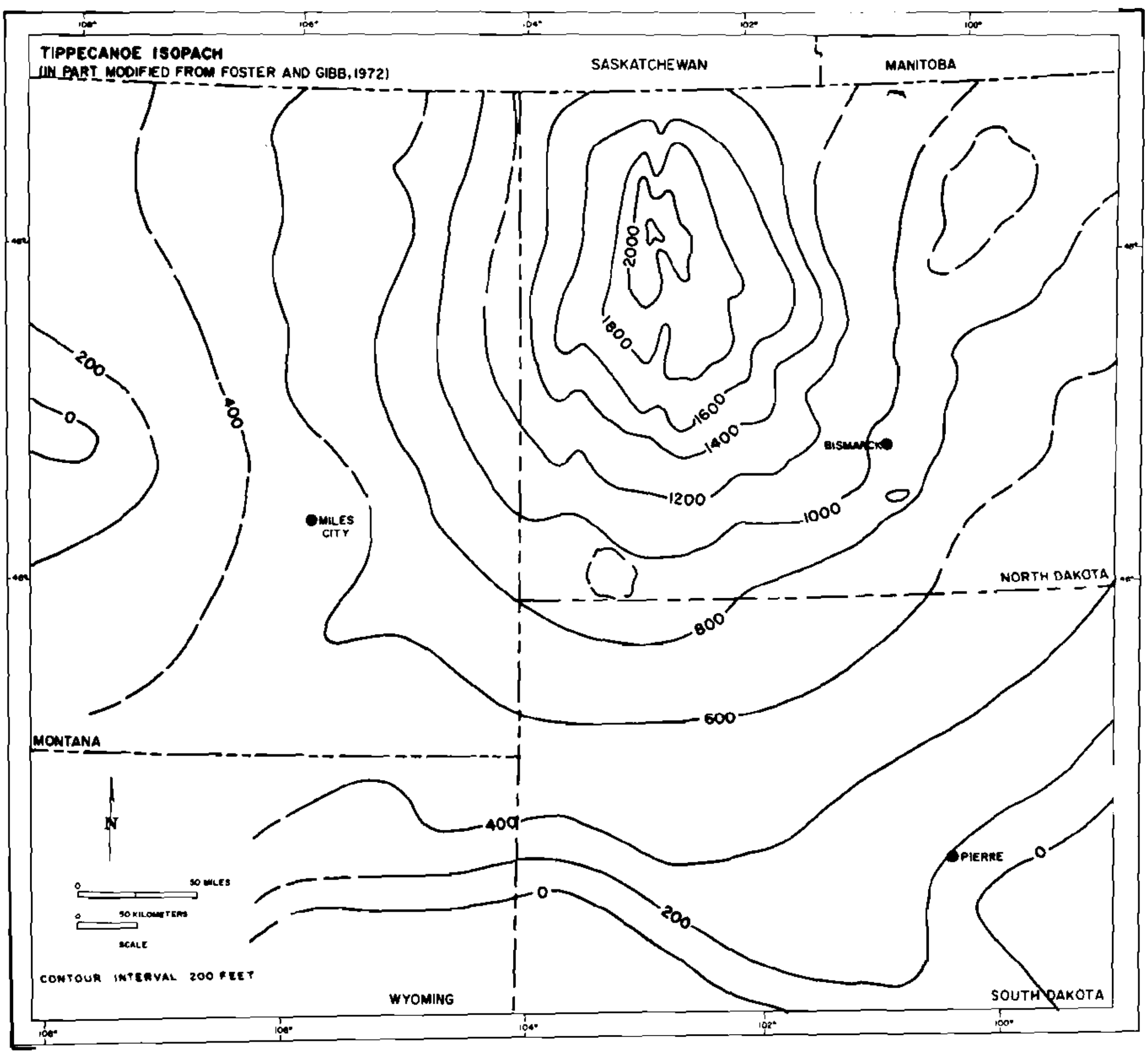
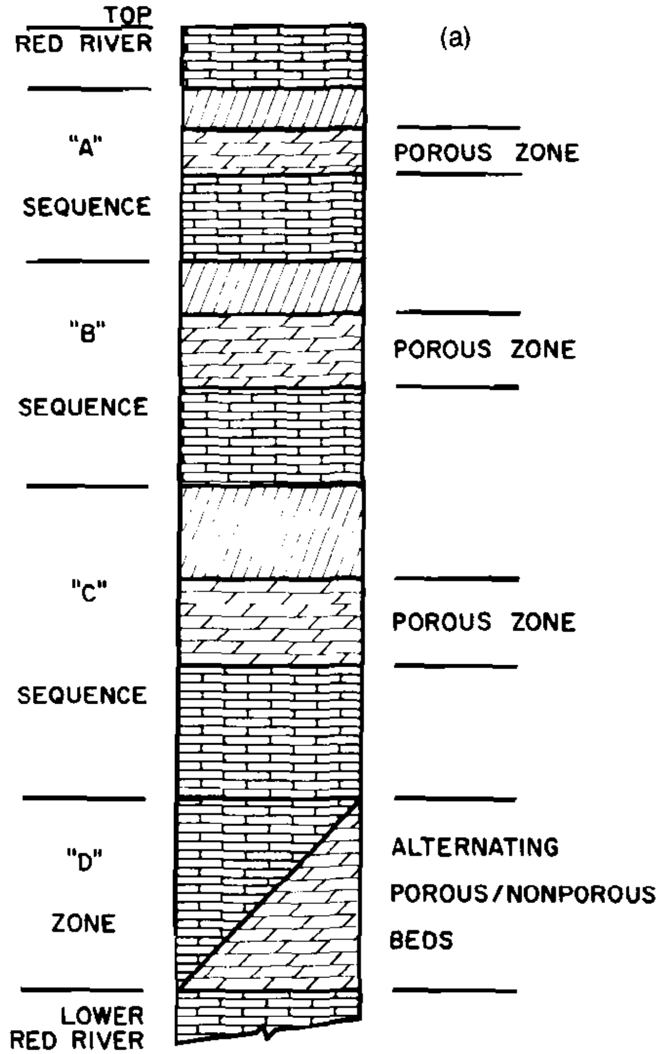
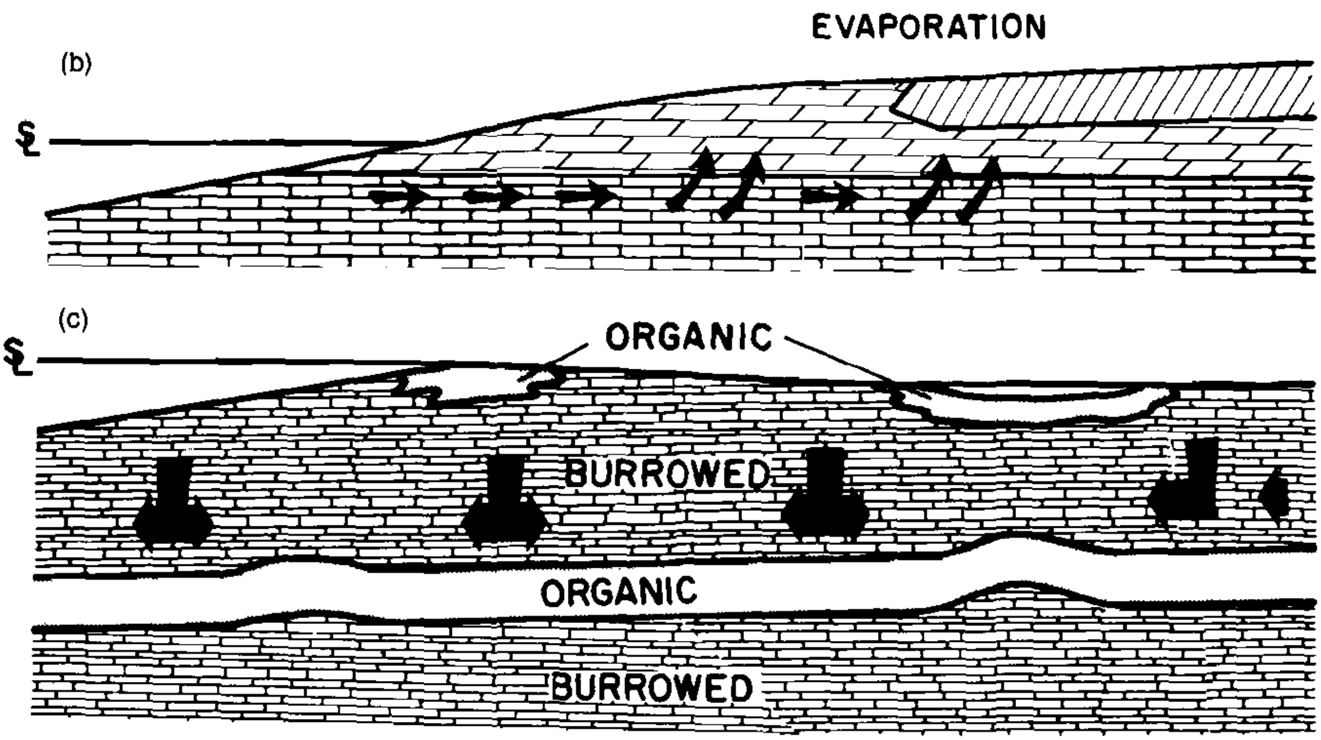


FIG. 7—Isopach map of Tippecanoe sequence in Williston basin.

FIG. 8—(a) Porosity zones in Red River Formation. A, B, and C zones have alternation of three lithologies: limestone, dolomite, and anhydrite in ascending order. 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 percolating down dip through primary burrowed carbonate muds, but blocked by impervious organic carbonates from vertical movement. (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 flanks of buried structures. (f) Facies distribution during deposition of A, B, and C zones, showing supratidal dolomitization belt. (g) Facies distribution during deposition of 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).

(Figure continued on next page).





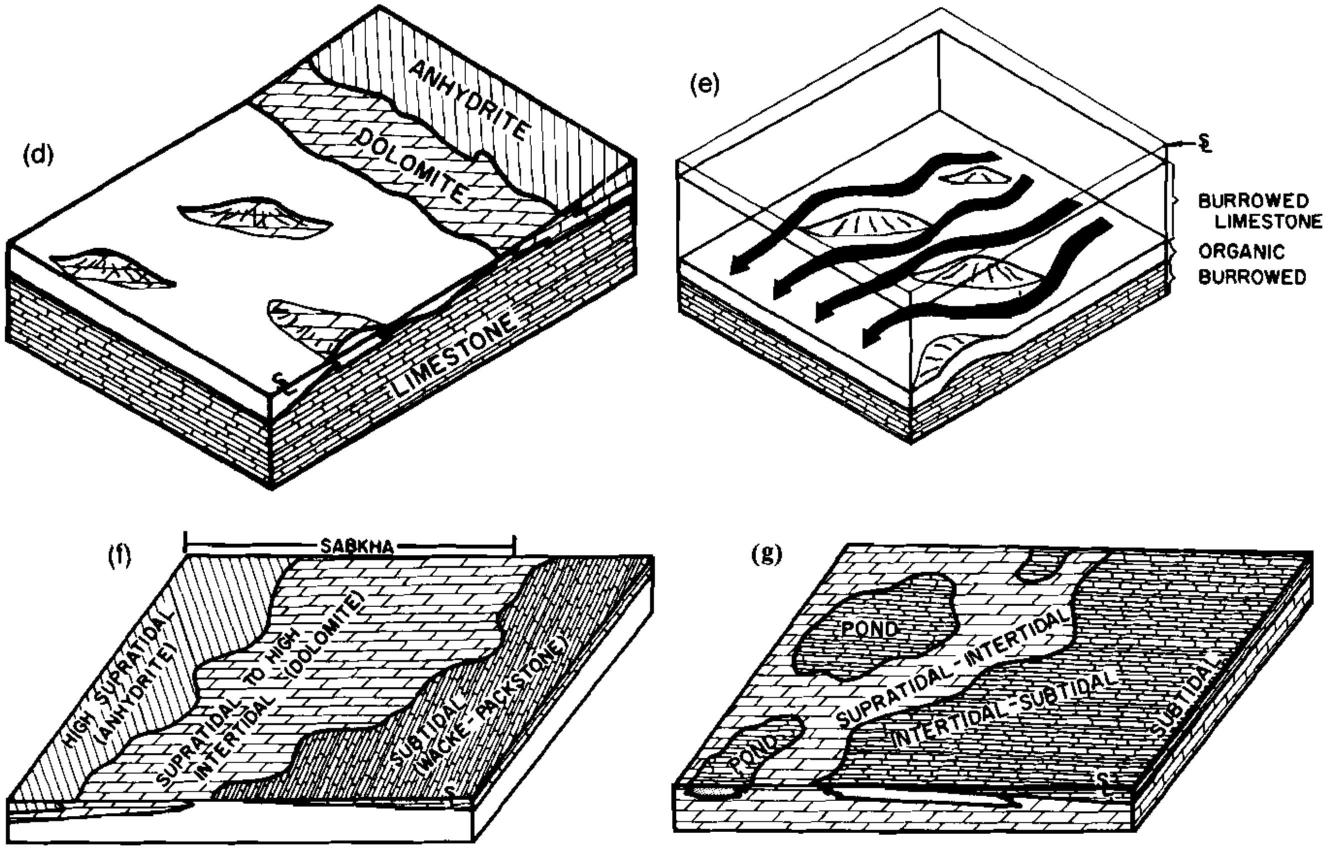


FIG. 8 (Continued).

rupted the carbonate deposition (Devonian Prairie and Mississippian Charles; Fig. 9). 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 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 to structures (Fig. 10); the high point of the Nesson anticline shifts southward with the advent of Devonian sedimentation. The Dawson Bay and Souris River 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 the time of Dawson Bay deposition. Carbonate buildups rich in stromatoporoids flourished during Duperow sedimentation (Hoganson, 1978). Birdbear (Nisku) rocks are marine carbonates with shallow-shelf faunas; farther north these rocks are reefal.

Red and green siltstones and shales cover Birdbear carbonates, marking a hiatus in the middle of the Kaskaskia sequence. These clastics are in turn overlain by initial transgressive deposits of the upper Kaskaskia — the Bakken Shale (Upper Devonian to Lower Mississippian), a petroleum source rock and producer.

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

Mississippian thicknesses, 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 and Lower Mississippian age along the eastern basin margin.

Kinderhookian sedimentation in the Mid-Continent 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 basin flank and basinal organic muds.

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

The carbonate-evaporite rocks are regressive, with evaporites climbing westward in the section (Fig. 11). Subaerial weathering of the skeletal wackestones has produced a variety of pisolitic and fenestrate fabrics which form important oil reservoirs (Fig. 12; Gerhard et al, 1978).

Evaporite deposition in the Charles Formation (salt) concluded Madison sedimentation. Sands, shales, and carbonates were deposited in alternating restricted and normal marine environments during Big Snowy deposition at the conclusion of the Kaskaskia sedimentary record. The extra basinal clastic sediments mark the influence of the Ancestral Rocky Mountain orogenic event west and south of the Williston basin.

Absaroka Sequence (Pennsylvanian-Triassic)

Regression during latest Mississippian time 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. 13). Basal Absaroka rocks in the Williston basin are the Tyler Formation estuarine, bar, and marine sands and shales (Ziebarth, 1964; Grenda, 1978). Dense, microcrystalline carbonates and fine-grained red and brown clastics of the Amsden Formation suggest more restricted depositional conditions. Broom Creek rocks are more sandy and contain dense carbonates, suggesting prograding sands into a shallow marine 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 dominantly red to red-orange sediments deposited around the margins as well as across the rest of the basin.

Zuni Sequence (Jurassic-Tertiary)

Jurassic and Cretaceous sedimentary rocks in the Williston basin comprise a single large cycle of sedimentation (Fig. 14). Although an unconformity is present between the Absaroka and Zuni sequences, the lithologies on either side of the unconformity are similar. Evaporites (including salt), fine-grained red and brown clastics, and a few dense microcrystalline carbonate beds comprise the lowest part of the Zuni cycle. These rocks are overlain by shallow marine sedimentary rocks of the Rierdon and Swift Formations, which also contain glauconitic sands and oolitic carbonate bars.

The top of the Jurassic is marked by a subaerial regressive exposure surface. It was followed first by terrestrial deposition of the lower Inyan Kara Formation, then by the marine transgressive phase of the upper Inyan Kara.

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 early Paleocene time, the last marine setting in North Dakota was the site of deposition of the Cannonball Formation. Later, Paleocene Fort 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 in nature, these deposits are one part of the combined Powder River and Williston basin detrital aprons from the Rockies.

Younger Sedimentary Deposits (Tertiary-Quaternary)

During the Tejas sequence (Tertiary-Quaternary), few indurated stratigraphic units formed. Scattered limestone and shaly sandstones with volcanic ash form the tops of the Killdeer Mountains and have been correlated with 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 glacial sediments cover over three-quarters of North Dakota and a considerable part of the Montana portion of the Williston basin. They have been carefully mapped and studied for their ground-water potential by many writers. These glacial deposits are a major source of sand and gravel for the construction industry. Glacially derived soils support one of the most important agricultural economies of the country.

STRUCTURAL HISTORY

Until seismic and oil drilling exploration programs were initiated, the Williston basin was generally regarded as a

Table 1. Characteristics of Dolomitization and Porosity Development in Red River Formation*

	A, B, and C Zones	D Zone
Environment	Sabkha	Subtidal and/or intertidal
Fluid movement	Evaporative pumping	Seepage refluxion
Water	Concentrated seawater with reduced salinity	Mixed hypersaline and/or fresh water
Dolomitization	Subtidal, "at surface"	Subsurface, interstitial

*Modified from Carroll (1979).

simple depressed saucer with two positive structures, the Cedar Creek and Nesson anticlines. This was obviously an oversimplified view based on 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 the 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 boundary. Salt dissolution in the Prairie Formation in the north-central part of North Dakota appears to coincide closely with the approximate location of this boundary. This may suggest later movement along the juncture. 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). Basin depression originated in the Ordovician (pre-Tippecanoe), with the main seaway connection apparently to the southwest (Fig. 16A). This early connection to the Cordilleran geosyncline was broken during the Devonian by uplift. Uplift tilted the Williston basin northward connecting it with the Elk Point basin sea (Fig. 16B).

Mississippian transgression coupled with subsidence of the Transcontinental arch system changed the seaway connection to the Cordilleran again, but due west through the Central Montana trough (Fig. 16C). This connection persisted during the Absaroka sequence, but with greatly reduced circulation. Clastics spread into the basin from the south (Tyler), southeast, and northeast. Sioux arch sediments are hypothesized from the southeast, whereas drainage from the Canadian shelf has been demonstrated from the northeast (Fig. 16D).

Cedar Creek and Nesson Anticlines

Two major structures in the Williston basin, the Cedar Creek and Nesson anticlines, are oil productive and can be mapped from surface outcrops (although the Nesson is

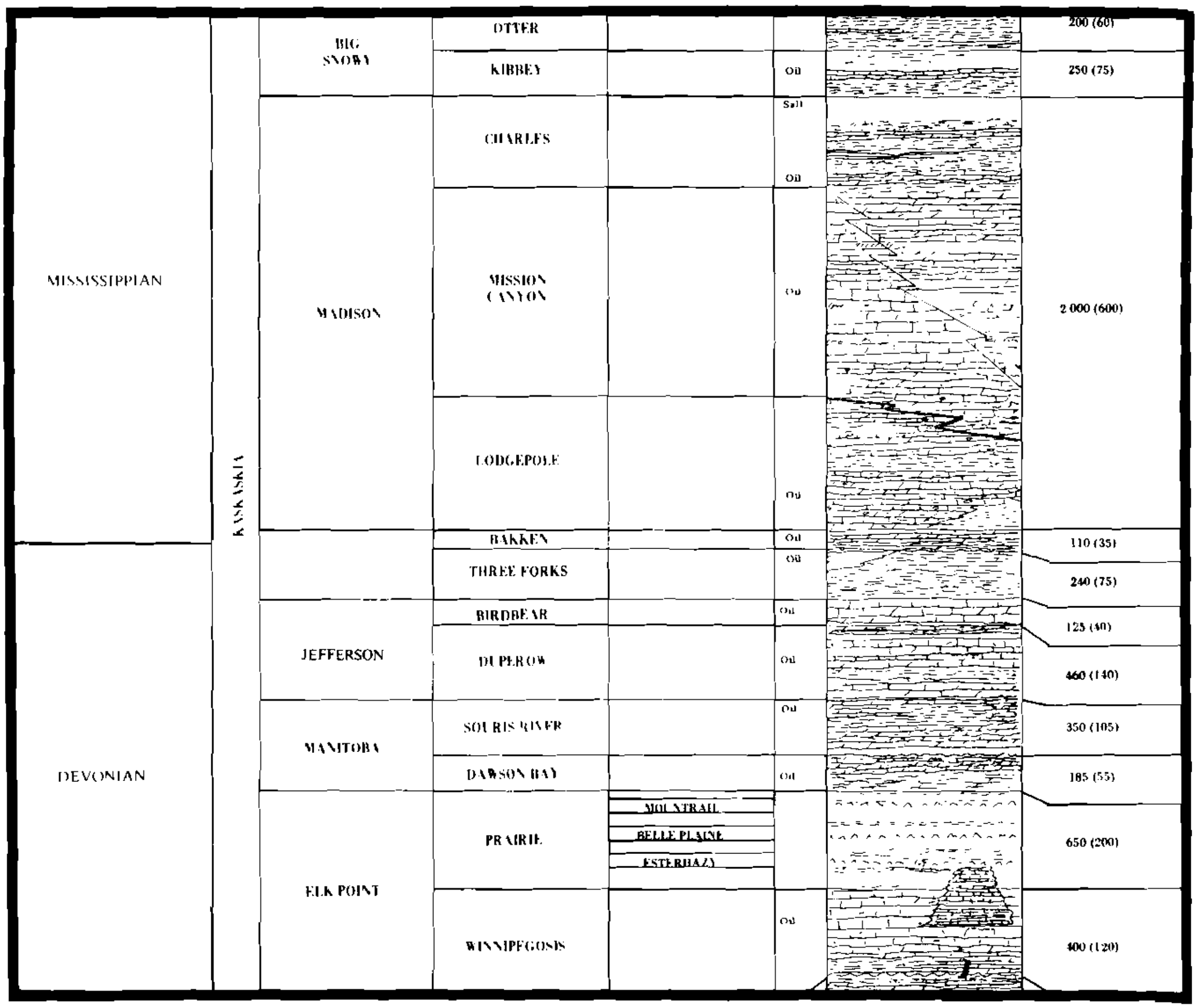


FIG. 9—Stratigraphic section of Kaskaskia rocks. Modified from Bluemle et al (1980).

largely obscured by glacial cover). Because of the large amount 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 where they onlap 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.

Evidence of Ancestral Rocky Mountain orogenic movement in the Williston basin may be reflected by a second period of vertical fault movement which occurred in the pre-Pennsylvanian, post-Mississippian Big Snowy interval. A mid-Permian event changed the stress regime. The former normal fault changes 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-Late 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 (Fig. 18) and on the Cretaceous Mowry Formation (Fig. 19) shows asymmetry 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, Billings, and Antelope anticlines, and

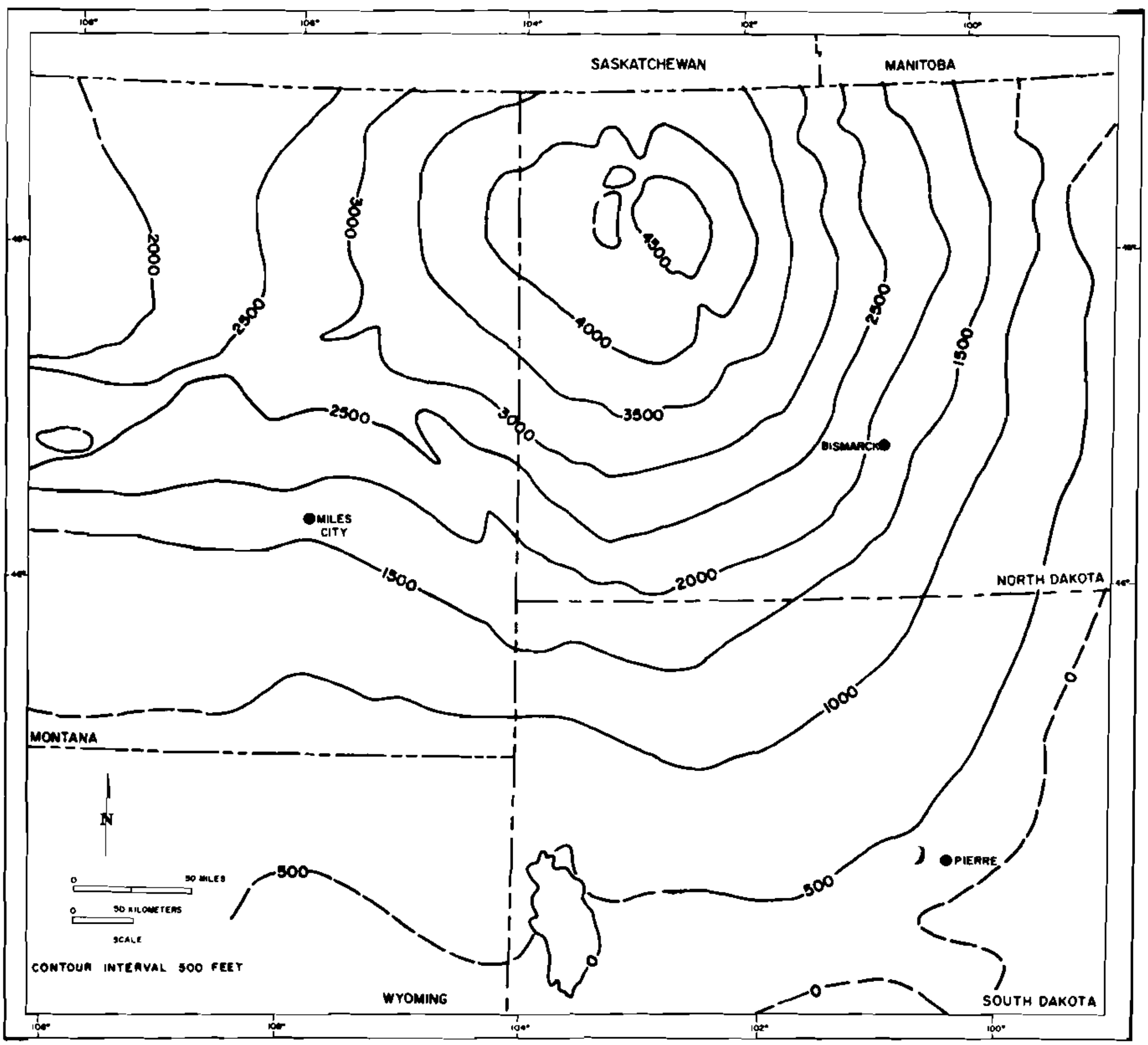


FIG. 10—Isopach map of Kaskaskia sequence in Williston basin. Modified in part from Craig (1972) and Baars (1972).

the Bismarck-Williston trend can be seen in Silurian 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 reflect 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 in eastern Montana has a somewhat similar history (Fig. 20; J. H. Clement, 1975-80, personal commun.). No data are available to establish a pre-Winnipeg or pre-Red River history. However, two periods of early fault movement on the west-bounding fault zone occurred: (1) pre-Middle Devonian and (2) Late Devonian-pre-Mississippian. Faulting then reversed direction during Late Mississippian (Chester) through Triassic time. At this point, a minor subsidiary fault in the Gas City area developed locally (J. H. Clement, personal commun.). No major fault displacement has been documented affecting Jurassic, Cretaceous, and Tertiary strata (J. H. Clement, personal commun.).

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 that 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 et al (1975) and Parson et al (1975) presented additional data supporting this hypothesis.

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. 21), which has been interpreted by previously cited writers as a meteorite impact. This event was apparently pre-Piper Formation, since red sandstones and siltstones fill a ring depression on the Spearfish and below the Piper, although in samples it is

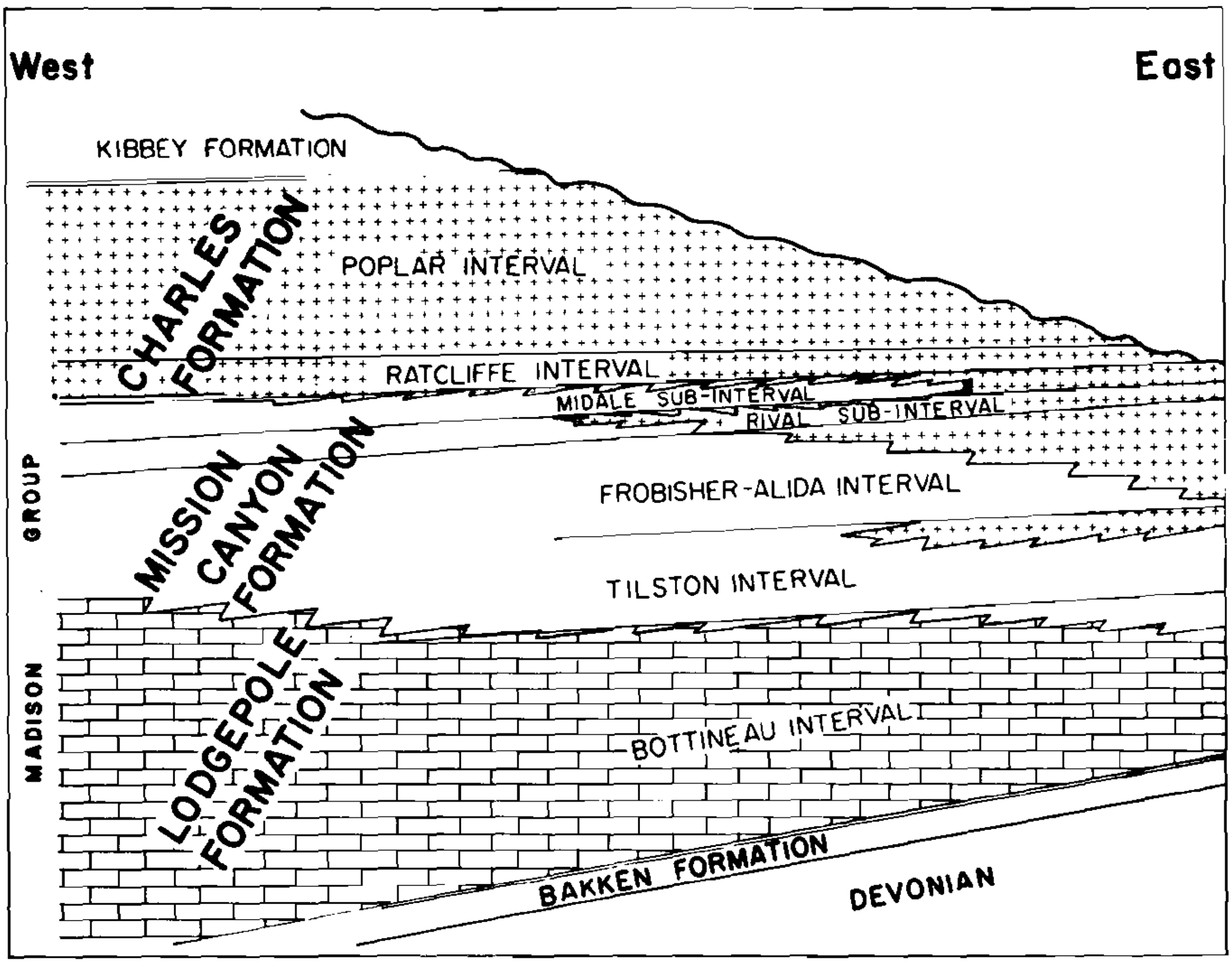


FIG. 11—Generalized cross section of Mississippian rocks in Williston basin showing relationship of facies and stratigraphic nomenclature. Modified from Carlson and Anderson (1966).

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 hypothesis of meteorite impact origin for this complex structure. Bridges (1978) suggested a section of several faults which change orientation through time (concentricline) as an alternate hypothesis. Others have suggested that this structure could also result from deep-seated igneous activity (diatreme). Detailed analysis of samples may determine the validity of the meteorite impact hypothesis.

Newporte Structure

In north-central North Dakota, the Shell 27X-9 Larson discovered oil in Deadwood Sandstone (Fig. 22; Clement and Mayhew, 1979). Continued development of this field demonstrated the complexities 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. 23) suggest that Deadwood Sandstone was deposited between Precambrian hills in part, and that pre-Winnipeg (post-Sauk, pre-Tippecanoe interval) erosion and faulting created a small basin of detritus from Deadwood and Precambrian rocks. Winnipeg sedimentation covered the structure, but was in part cut by at least one growth fault.

An alternate hypothesis, presented by Donofrio (1981), suggests that the Newporte structure is possibly a meteorite impact feature.

ORIGIN OF WILLISTON BASIN

Since Middle Ordovician time, the Williston basin has subsided approximately 16,000 ft (4,875 m) without undergoing severe orogenic deformation or severe peripheral tectonic distortion. Recent mapping of heat gradients in North Dakota (Harris et al, 1981) suggests no abnormally high heat flow that would indicate any "mantle plume" or "hot spot" beneath the basin to account for its subsidence. Several papers have advanced wrench-fault systems to account for the generation of known structural elements in Montana and North Dakota, but none have championed a specific origin for the Williston basin.

The change in structural grain between the central and northern Rockies takes place at the approximate location of the Fromberg fault zone at the north end of the Big Horn uplift. This fault zone, of unknown age, trends parallel with the Colorado-Wyoming shear zone. Casual observation demonstrates a northeastward linearity of the Fromberg zone with portions of the Yellowstone River course, the north end of the Cedar Creek anticline, the Watford deep of the Williston basin, and a saddle in the Nesson anticline (Fig. 24). To the southwest, west of the Beartooth uplift, the same linearity defines the Snake River plain.

We hypothesize that both the Fromberg and the Colorado-Wyoming shear zones were formed by left-lateral shearing in the edge of the pre-Phanerozoic continental plate. This shearing displaced the present northern and southern Rocky Mountain blocks, catching the present central Rocky Mountain block (with the Black Hills and Big Horn uplifts therein) as a slice between the shears, resulting in left-lateral drag.

Initial shearing resulted in the formation of numerous basement-rooted faults within the central Rockies, Black Hills, and Williston basin. Since that time, it is questionable if any significant motion has occurred along the two major shear zones. However, evers orogenic episode with major influence on the North American plate would apply stress to the system and many of the associated faults show some Laramide displacement. We theorize that the shear system

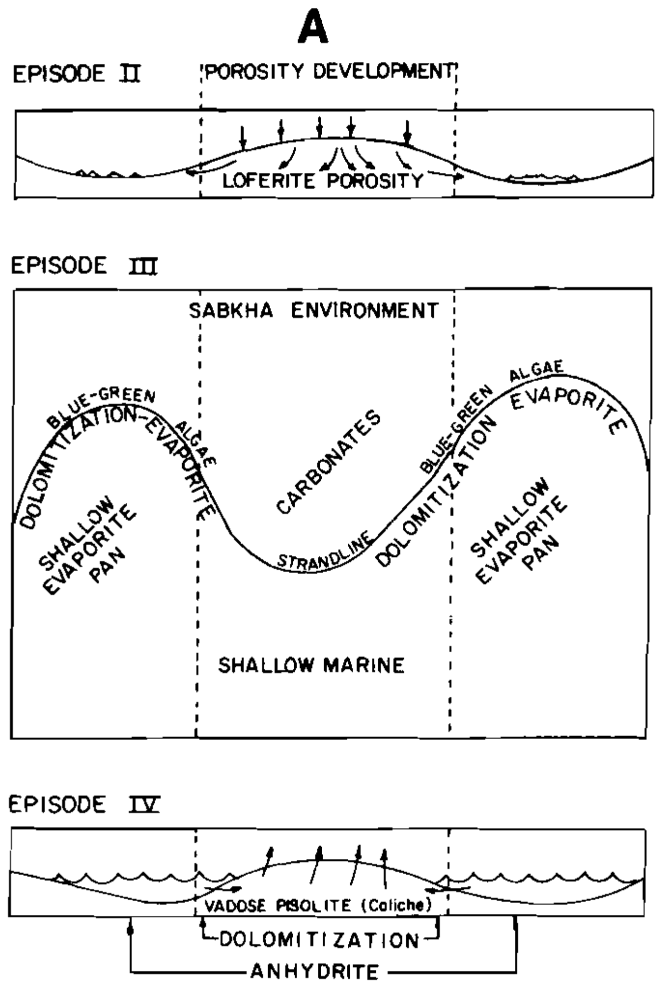


FIG. 12—A. Generalized sections of map showing porosity development in Frobisher-Alida zone, Glenburn field, North Dakota. Episode II illustrates porosity development by fresh-water weathering and desiccation. Episode III indicates relative position of several strandlines and depositional or diagenetic lithologies. Episode IV demonstrates 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 4,600 ft (1,406 m). Scale on photo is 3 cm long.

(Figure B on next page).

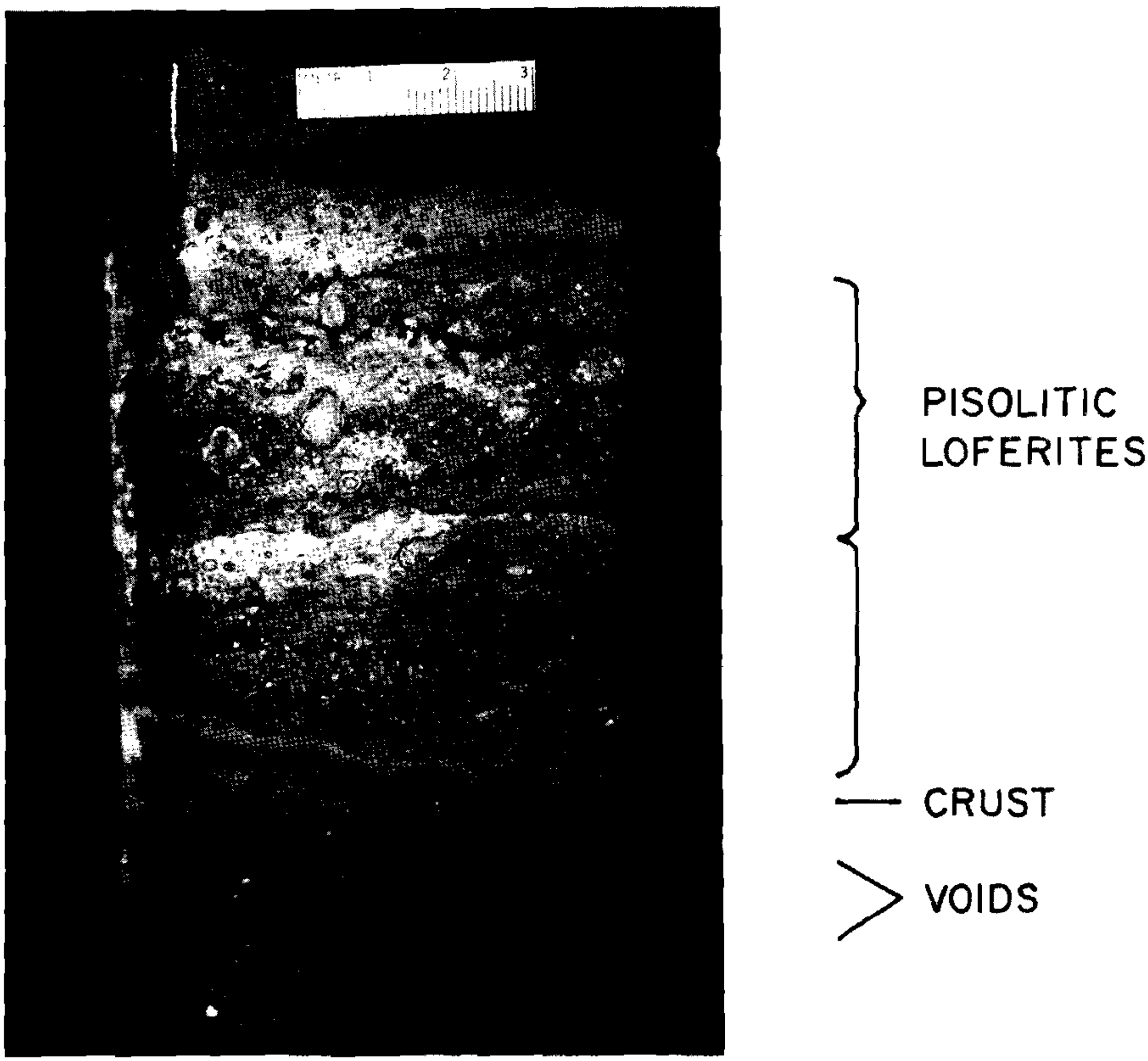
and its dragged blocks have been repeatedly "tensed," with resultant vertical motion along basement planes of structural discontinuity. This does not preclude motion along the major shears (e.g., Laramide displacement on the north end of the Big Horns along the Fromberg zone), but does not require it.

If this hypothesis is correct, the following conclusions can be drawn.

1. The central Rocky Mountains were a depressed block during Ordovician-Silurian (Tippecanoe) time, as demonstrated by the marine connection between the Williston basin and the Cordilleran sea during Tippecanoe sedimentation (Fig. 16A). The northwest extension of this depression is a "graben-like" or depressed Williston basin block. The geometry of the shears and block might lead to an aulacogen interpretation (Fig. 25), but we do not espouse that idea. An alternate idea is one of a large-scale "pull-apart basin" similar to that proposed by Burchfiel and Stewart (1966) for Death Valley, California (Fig. 25). However, the origin of the Williston basin as a structurally and asymmetrically depressed block formed at the Tippecanoe-Sauk sequence boundary as a northeast extension of the central Rocky Mountain block is attractive to us. This would be a complimentary distortion to the eastern North American Taconic orogenesis.

2. The Devonian movement of the Transcontinental arch, which we have previously suggested is responsible for the opening of the Williston basin into the Elk Point basin on the north (Fig. 16B), would be geometrically controlled by the

B



(Continued).

presence of the Colorado-Wyoming shear zone. The source of the tectonic stress could be both eastern (Acadian) and perhaps western (Antler) deformation.

3. The geometries of central Rocky Mountain structures in Wyoming, the Black Hills, and the Williston basin all fit a left-lateral strain model in both general morphology and angular relations (Fig. 24).

4. The Mondak Mississippian field of the Williston basin is a very large (at least 100 million bbl) oil field, producing from fractured Mission Canyon Formation carbonates, without significant structural closure. The field and its "look alikes" lie on the homoclinal east-dipping flank of the Cedar Creek anticline. Although various schemes to explain this oil field have been advanced, such as underlying salt solution (Kearns and Traut, 1979), none has been satisfactory. Application of the "tensing" theory advanced here might be a more satisfactory explanation for the reservoir fracturing here and in other fields.

Well-indurated Mississippian carbonates are bounded below by Bakken shales and silts, and above by evaporite, both structurally incompetent lithologies. Tensing of these rocks would produce no apparent distortion of the incompetent beds, but the competent carbonates would develop closely spaced jointing (fractures). This hypothesis could also account for fractures reported from the Little Knife Madison field, as well as others by analogy.

As basin studies advance, new structures, evidence of greater amounts of fault displacement, and suggestions of long histories of structural distortion of major structures are being documented. All of the newest structural data available to the writers appear to complement our hypothesis.

No major relationship between our model for the origin of the Central Rockies, Black Hills, and Williston basin and the development of the Wyoming-Montana overthrust belt is apparent. Certainly, deformation of that tectonic province exerted stress on our area of interest. There is considerable evidence of Laramide and post-Laramide deformation in the Williston basin. In our opinion, however, the Laramide deformation created the stress that once again "tensed" the Wyoming block and provided for the vertical uplift of many Laramide structures now present. The structural grain of these structures is still inherited from the Proterozoic left-lateral shear system we have hypothesized.

OIL AND GAS RESOURCES

Oil was discovered in the Williston basin in Montana on the Cedar Creek anticline (1936), in Manitoba (1950), and in North Dakota on the Nesson anticline (1951). More recently, several significant cycles of exploration have been completed in North Dakota and another is in progress (Gerhard and Anderson, 1979, 1981). Annual production increased until 1966, then declined until 1974. It is now on an uptrend which, in 1979, surpassed the previous high (Fig. 26).

Although the initial discovery was from Silurian rocks, the early development of the Nesson anticline was primarily from Madison reservoirs. The peak discovery period was 1952-53. Development along this 75-mi (120 km) trend was nearly complete by 1960, with producing capacity exceeding the available market. Production was limited then by prorationing until November of 1965 when natural decline of these reservoirs equaled the market demand. The only significant deeper zones developed along the Nesson trend during that time were the Duperow and Interlake pools in Beaver Lodge and Antelope fields and the Sanish pool in Antelope.

Widespread wildcatting around the state in 1954 had a notable lack of success except for small discoveries in Bottineau County. The lack of success slowed exploration until 1957-58 when the Burke-Bottineau stratigraphic trap play met with success. The increasing production during 1958-61 (Fig. 26) largely reflects development of these pools. Production from this area was marketed first by rail and then, in 1963, via the Portal Pipeline to refineries in Minnesota and Wisconsin. The slight increase in wildcats in 1964 reflects the expanded market provided by the pipeline (Fig. 27).

In 1960, discovery of the Cedar Creek pool extended Red River production along the Cedar Creek anticline into North Dakota. The Bowman County Red River play extended production in this area to small "highs" along the eastern flank of the structure in the period from 1967 to the mid-1970s.

Tyler sand reservoirs which were discovered at Rocky Ridge in 1957 and Fryburg in 1959 became important developments in the mid-1960s in the Stark and Billings County areas. Peak production in 1966 at the Medora field and in 1967 at Dickinson field helped offset declines in the older producing areas.

The decline in production from 1966 to 1974 represents the

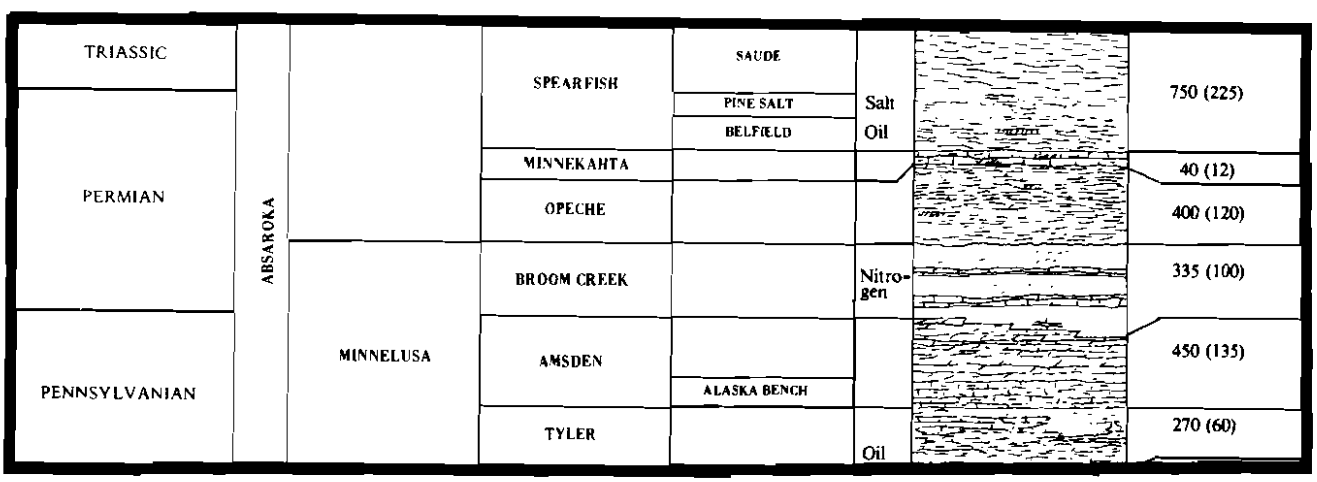


FIG. 13—Stratigraphic section of Absaroka sequence rocks.

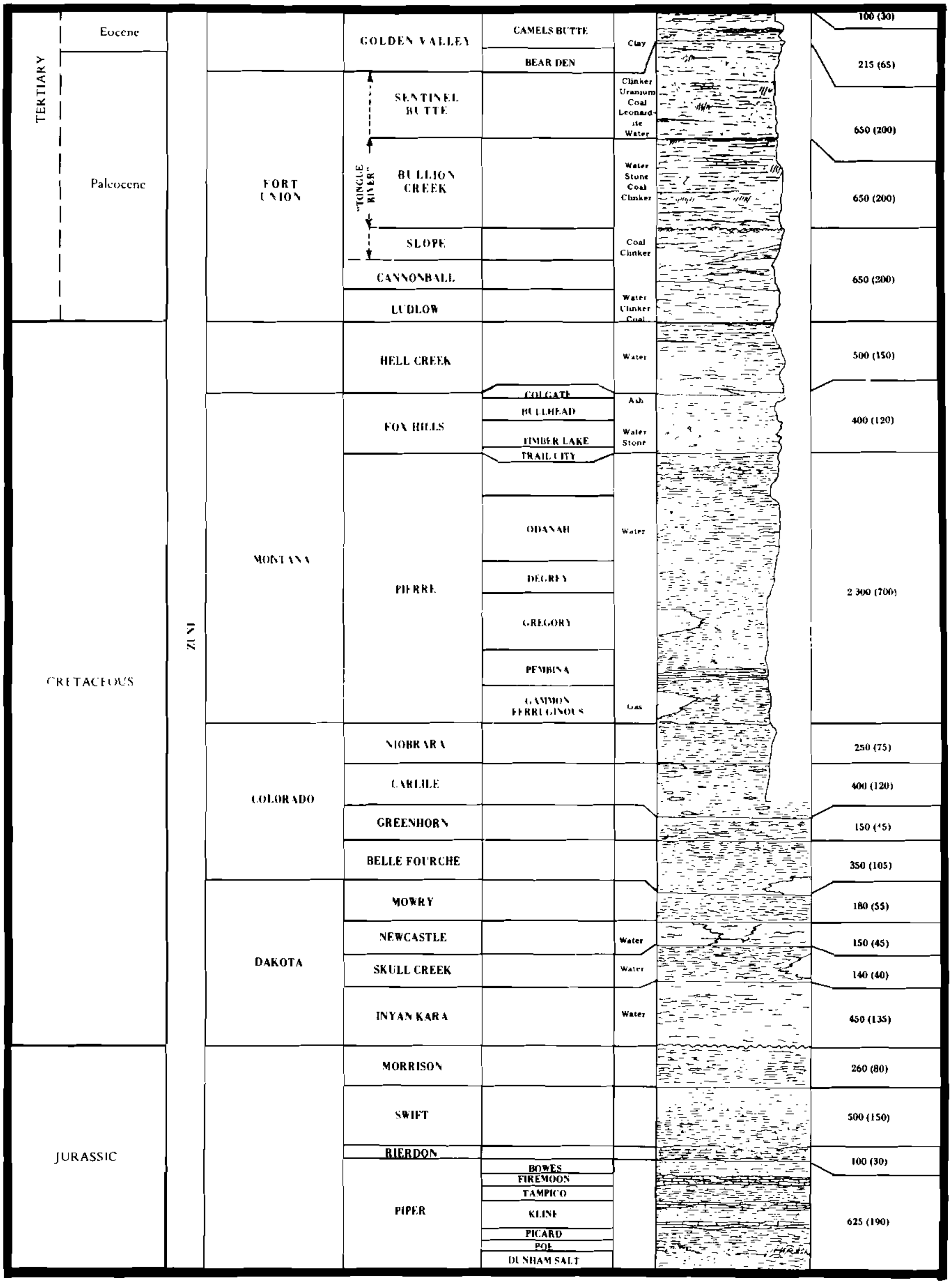


FIG. 14—Stratigraphic section of Zuni sequence rocks.

failure of new discoveries to replace the natural decline of the major producing areas. The normal pattern is discovery, followed by development leading to peak production (1 to 3 years) and then gradual decline. Secondary recovery methods usually alter this pattern. Water injection for pressure maintenance was installed in many of the Madison reservoirs along the Nesson trend, but was relatively unsuccessful. Similar programs in the Newburg-Spearfish, Madison reservoir in 1967 and in the Tyler sandstone reservoirs of Dickinson field in 1973 and Medora field in 1970 increased production levels above the initial development peaks in those fields. However, these successful programs could not offset the natural decline of the major producing areas.

The trend of lower exploratory activity of the 1960s generally followed the national trend. The upsurge of wildcatting in 1968 has been referred to as the "Muddy sand" play. It followed development of the Bell Creek field in Montana, but no similar occurrences were found in North Dakota and exploration activity again decreased.

However, two events, occurring close together, significantly changed Williston basin production history. The Red Wing Creek field was discovered in McKenzie County, North Dakota, and OPEC placed production controls (embargoes) and price increases on production by member nations.

The Red Wing Creek discovery excited basin oil operators because of the relatively high productivity of the wells and because of the anomalously thick pay section. Because no one really understood the nature of the Red Wing Creek structure at the time, industry's only possible response was to gain leaseholds in the area. The leasing activity set off by the Red Wing Creek discovery set the stage for further development. The now common 5-year-term leases of western North Dakota tended to increase exploratory activity as compared to 10-year leases. The lease play, coupled with the sudden availability of venture capital, caused exploratory drilling to begin to increase in 1975 and 1976, partly in response to the lease expiration dates.

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

It is interesting to note that exploration and production have followed technology. Initial production was from Nesson anticline seismic prospects. Amerada Petroleum Corp. drilled a string of successes 75 mi (120 km) long without a dry hole. As interpretation of basin geometry progressed, stratigraphic/structural traps were defined along the northeast basin flank. Later, in Bowman County, North Dakota, seismic surveys successfully defined small Red River structural "highs." Stratigraphic plays and long-shot deeper drilling sporadically generated interest until the well-known unusual seismic configuration at Red Wing Creek became productive.

Assessment of future production involves an evaluation of source rocks as well as reservoir capabilities. Geochemical studies have classified Williston basin oils into three types. Based on carbonate isotope studies it has been postulated that the source rocks for most of the oil are the Winnipeg shale for type I, the Bakken Formation for type II, and the Tyler shale for type III (Williams, 1974). Dow (1974, Fig. 2, p. 1258) further estimated reserve volumes as: type I, 600 million bbl; type II, 10 billion bbl; and type III, 300 million bbl. He estimated that 50% of type I, 30% of type II, and lesser quantities of type III oil had been discovered at that time.

The writers, and others who have studied the rock sections in the basin, would agree that the Winnipeg, Bakken, and Tyler represent the most concentrated source of organic materials; however, we believe that many producing zones contain sufficient organic material to have been the source themselves. Specifically, the Red River, Birdbear, Duperow, Winnipegosis, and Madison have sufficient indigenous organic material to provide large quantities of liquid hydrocarbons. If so, there is much more oil to be found in the Williston basin.

If new pool discoveries are compared to preceding curves, the significance of the present development boom becomes obvious (Fig. 28). High levels of wildcat activity have had a corresponding peak of new pool discoveries, except during the 1954 east side and 1968 "Muddy" Sandstone wildcat programs. The number of new pool discoveries per wildcat drilled has risen dramatically in the last 4 years. This increase in success is attributed to (1) the use of CDP seismic methods,

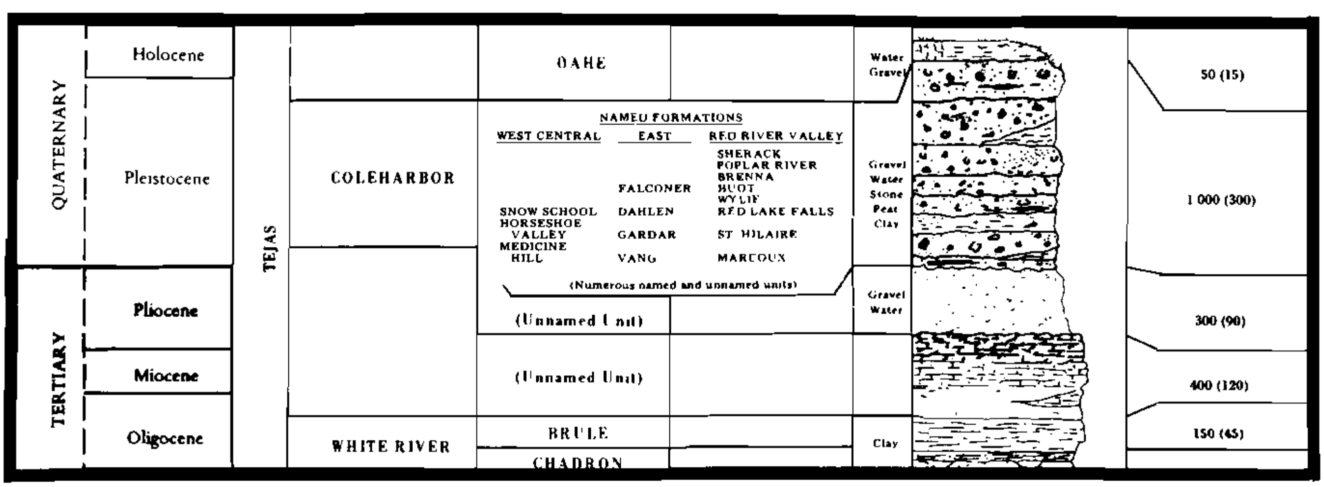


FIG. 15—Stratigraphic section of Tejas sequence rocks and sediments.

(2) better reservoir geology, and (3) completely revised testing and completion techniques.

Dramatic expansion of producing areas has occurred during the present cycle, including new producing counties, new pay zones, and new producing depths. The maps of North Dakota producing fields in 1970 (Fig. 29) and 1980 (Fig. 30) illustrate the resurgence of the Williston basin as a major oil province. During 1970 there was an average of 20 active drilling locations in the entire United States portion, whereas during 1980 there was an average of 150 active drilling locations.

Current activity is centered in western North Dakota and the bordering Montana counties. Significant new discoveries have been the Little Knife Madison in 1977 (109 wells, 125

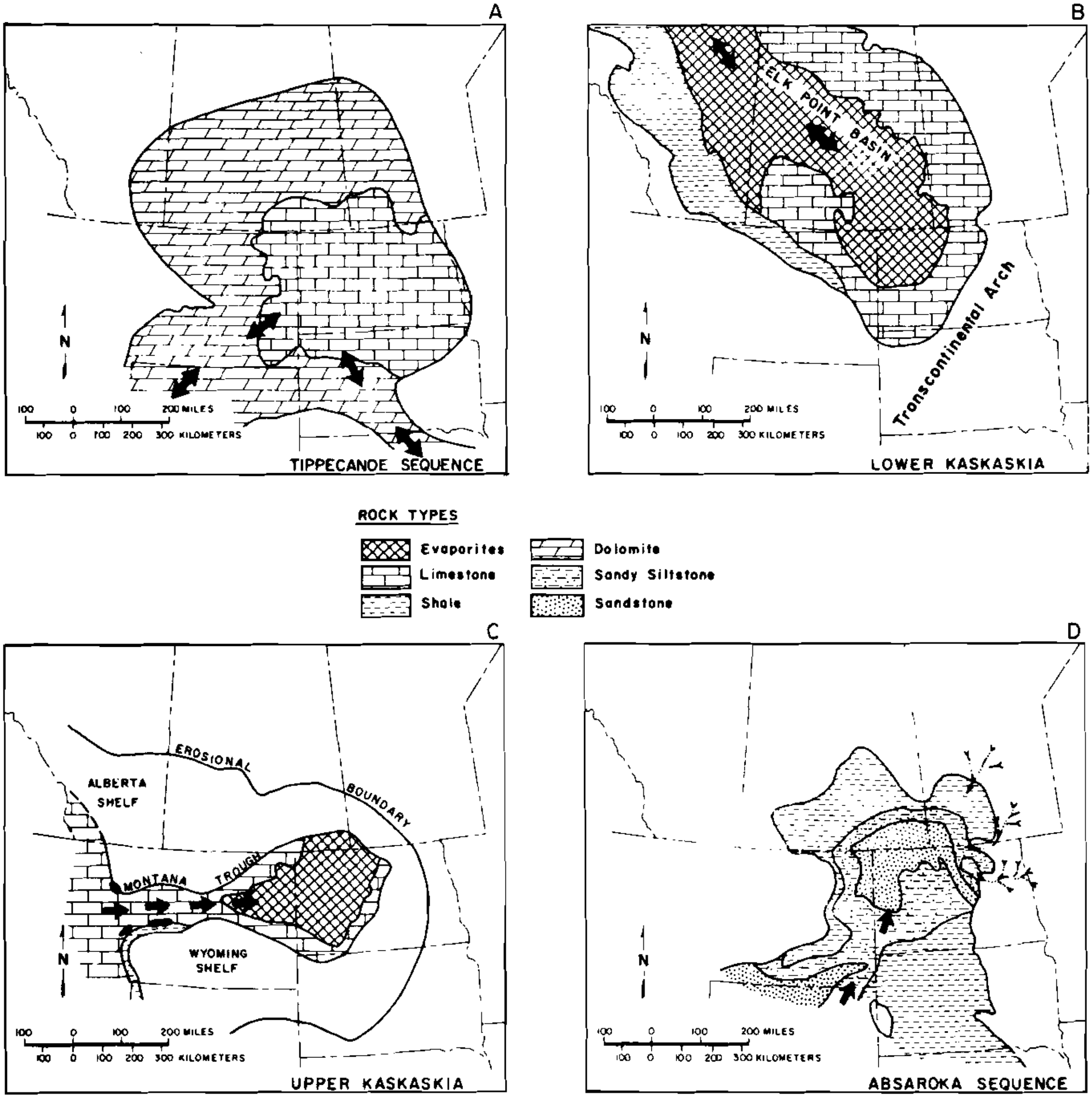


FIG. 16—Sequential maps showing marine communication directions during times indicated for Williston basin. A. Tippecanoe sequence, showing connection with Cordilleran miogeosyncline on southwest and eastern interior on southeast across Transcontinental arch. Modified from Foster (1972). B. Lower Kaskaskia sequence communication to Elk Point basin in Canada. Modified from Clark and Stern (1968). C. Upper Kaskaskia, showing communication of Cordilleran miogeosyncline through Montana trough. Dark spots at entrance and along edges of Montana trough represent bank development. Some bank development is also hypothesized within basin. Modified from Bjorlie and Anderson (1978). D. Absaroka sequence, showing flood of clastics from southwest as well as from drainages to northeast and east. Sediment flow probably occurred from farther southeast also. Modified from Mallory (1972a, b) and Rascoe and Baars (1972).

million bbl reserve), the Mondak Madison in 1977 (112 wells, > 100 million bbl reserve), and the Billings Nose area where there are Madison reservoirs and Duperow wells that have recorded initial potentials over 2,000 bbl/day and a few with potentials over 3,000 bbl/day (158 wells, 100 million bbl reserve).

Another significant recent development is exploration of deeper zones along the Nesson trend.

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), "Muddy," Inyan Kara, and Niobrara rocks, but these rigs 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 industry has only recently begun to delineate as a major potential hydrocarbon area. Stratigraphic traps around the Cedar Creek, Nesson, and Poplar anticlines are mostly untested, 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.

In 1970, the total bonuses paid for the year for state leases was $294,000. In 1978, the annual total was near $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 under way, and high lease prices all support a continuation of the present exploratory boom, with several years of developmental drilling needed after exploratory drilling decreases.

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

OTHER MINERAL AND ENERGY RESOURCES

The Williston basin contains two major resources besides hydrocarbons, although present production of either does not begin to compare with 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 damper on potash prices in the world market, especially on Canadian resources.

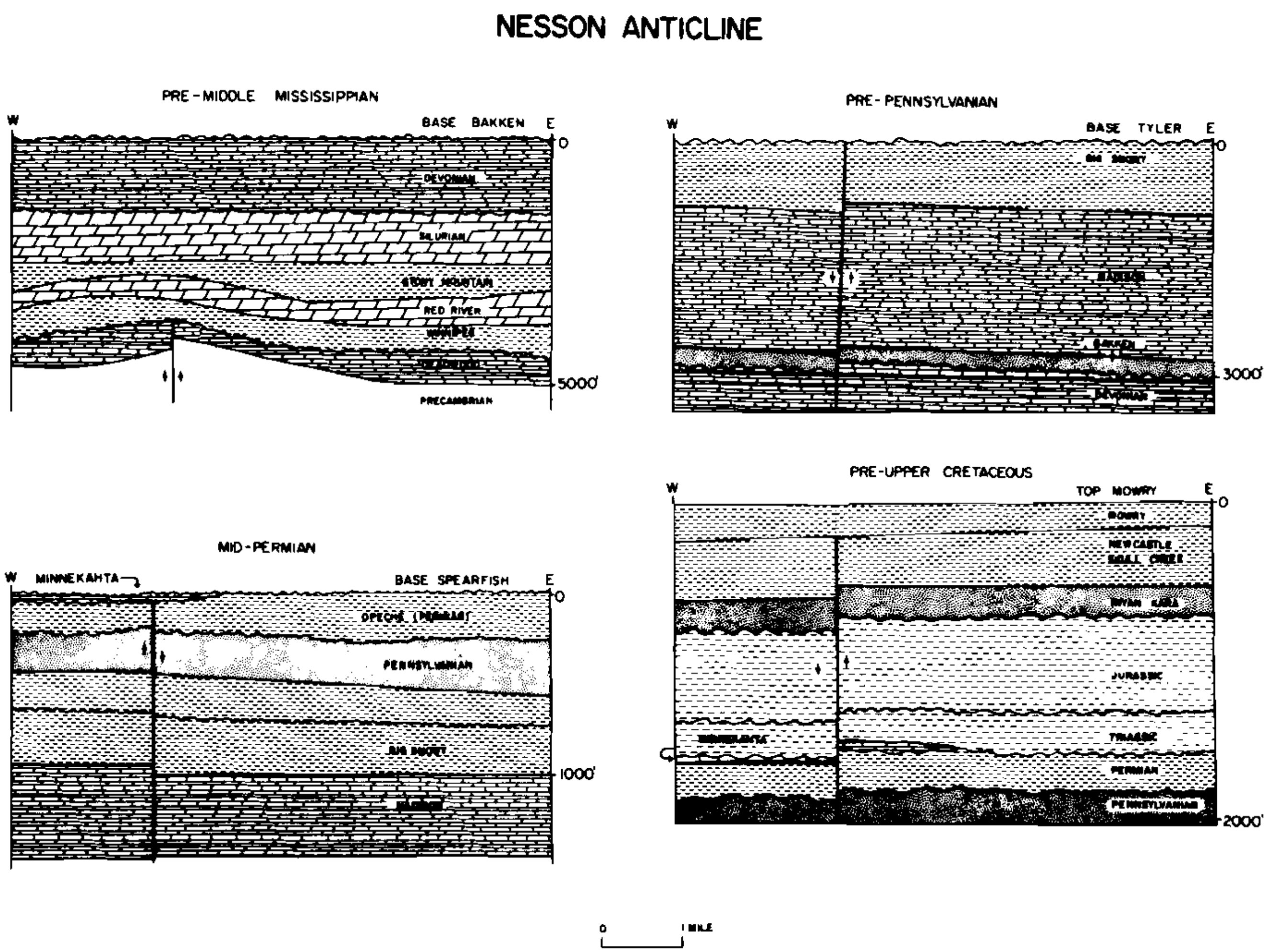


FIG. 17—Diagrammatic cross sections of Nesson anticline showing structural development. Note apparent reversal of fault movement during mid-Permian. Some of pre-Upper Cretaceous movement may be related to salt solution.

Deposition of Prairie Formation evaporites, after restriction of circulation in the Elk Point basin of Devonian time, created a very large resource of salt and potash in the Williston basin (Figs. 9, 16, 31, 32). Within the Prairie salt section of North Dakota and Montana, three potash units occur: the Esterhazy, Belle Plaine, and Mountrail Members (Anderson and Swinehart, 1979). At the present time, potash is being mined by both conventional underground and solution methods in southern Canada. Approximately 50 billion tons (45 billion Mg) of potash lie south of the international border in North Dakota, with additional resources in Montana.

During the mid-1970s increasing world market prices coupled with both export taxes on Canadian potash and action by Canadian government to take control of the Canadian potash mines created a flurry of leasing and pre-mining activity in North Dakota and Montana. Since 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 price stabilization occurred with renewed exploration and plans for development in 1976. As production from the New Mexico deposits wanes, the Williston basin deposits will serve to prevent any world potash cartel from major price increases. Our 50 billion tons (45 billion Mg) of resources insure the domestic supply of this critical mineral.

Lignite is a major energy resource in the North Dakota part of the basin (Fig. 33). Lignite occurs as part of the Cenozoic rock suite derived from erosion of the Laramide Rocky Mountains. These rocks, generally called the Fort Union Group, are mostly of terrestrial origin, although the Cannonball Formation, in the lower part of the Fort Union, is the youngest marine stratigraphic unit in this area (Fig. 34). Mining is now exclusively by surface techniques, but earlier in the history of North Dakota underground workings were common (now a source of major environmental concern as they collapse).

Because this lignite has low-sulfur but high-water content, most of it is utilized close to the mining site for electrical generation (Fig. 35). Despite the national need for additional energy resources, severe restriction on leasing of reserved federal coal and stiff reclamation policies have held down production increases. Still, production in North Dakota has doubled in the last 5 years as new electrical generation plants have gone on stream (Fig. 36). The 20 billion ton (18 billion Mg) reserves and 350 billion ton (318 billion Mg) 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 by renewed oil exploration, application of computer techniques to data han-

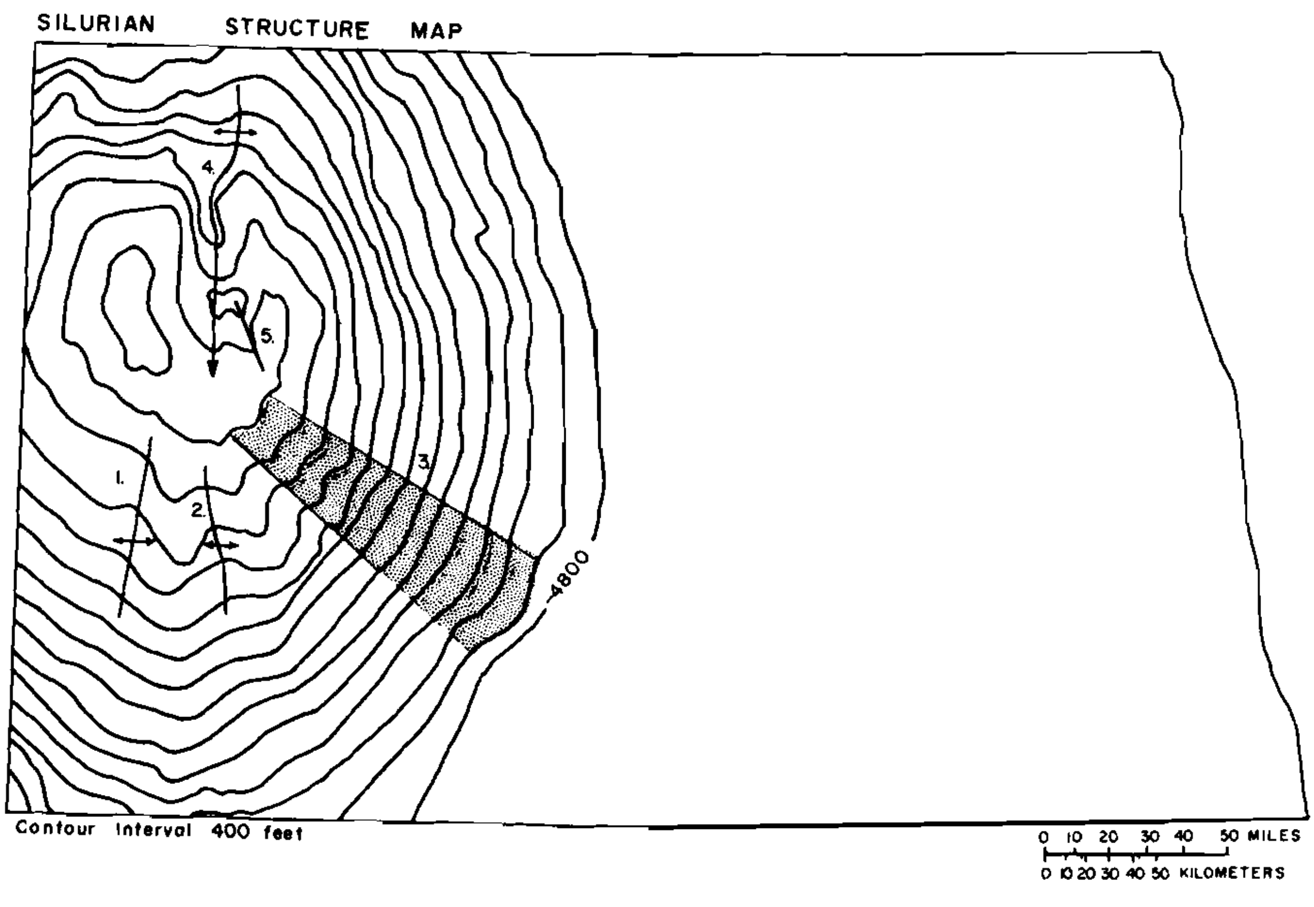


FIG. 18—Structure map of top of Silurian Interlake Formation showing geometry of Williston basin in North Dakota. 1. Billings anticline; 2, Little Knife anticline; 3, Bismarck-Williston trend; 4, Nesson anticline; 5, Antelope anticline.

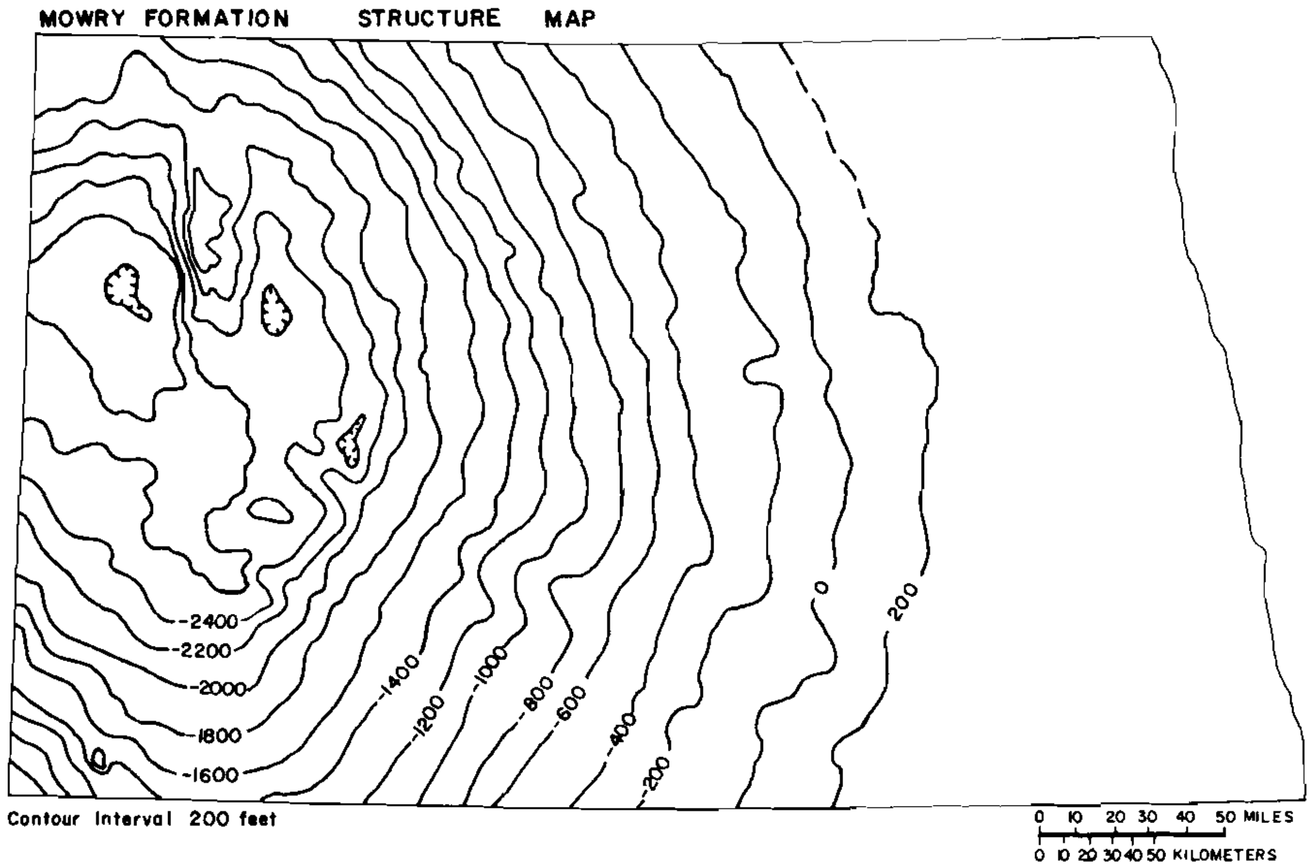


FIG. 19—Structure map of top of Mowry Formation (Cretaceous). Compare Figure 18. Closely spaced contours on west side of Nesson anticline suggest post-Mowry faulting on that structure. Bismarck-Williston trend also appears to be well developed as is Billings anticline. Little Knife anticline does not appear to be so well defined at this horizon.

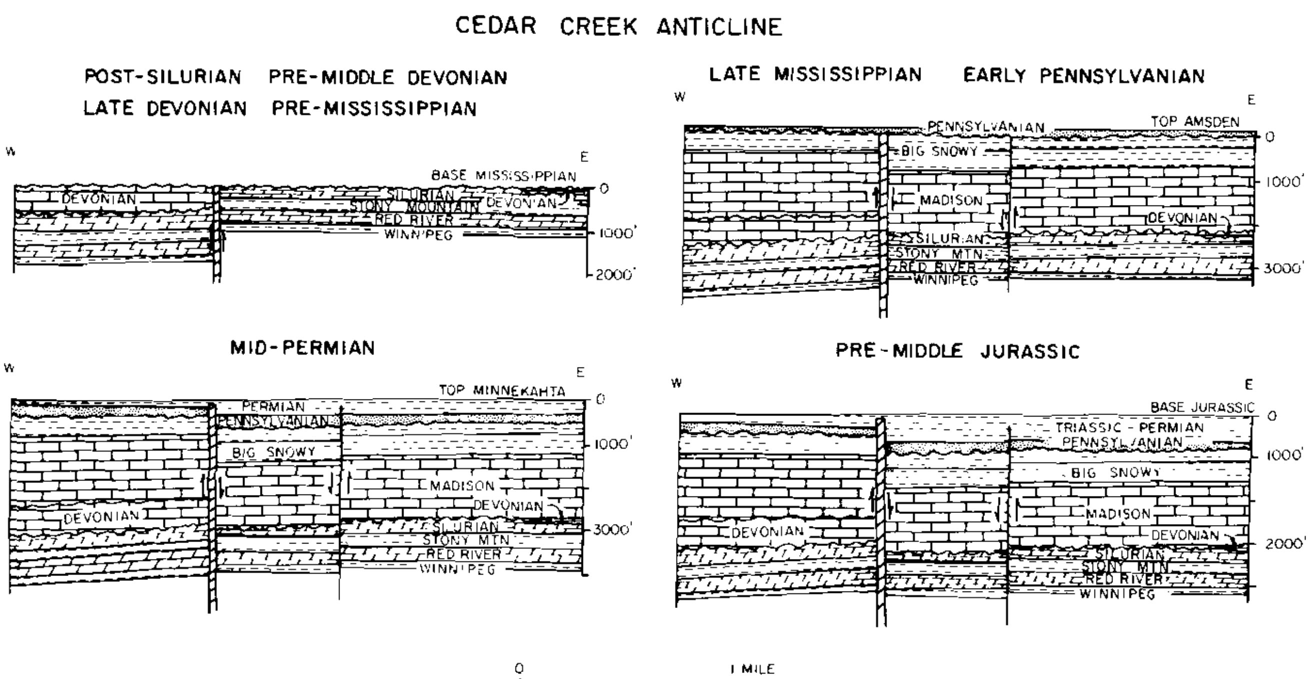


FIG. 20—Diagrammatic cross sections across Cedar Creek anticline at Gas City field. Modified from Clement (1976). Minor second fault generated locally in Gas City area during Late Mississippian-Early Pennsylvanian episode was concurrent with minor reversal of movement on principal west fault zone.

dling, and detailed environmental and diagenetic analysis of cores and cuttings. The study of these new data indicates a much more structurally complex basin than heretofore was realized.

Basin evolution in Phanerozoic time begins with Sauk (Late Cambrian) transgression across a rough Precambrian topographic surface, but without definition of the basin. Tippecanoe sequence rocks show the initial depression of the Williston basin with seaway connections west and southwest to the Cordilleran miogeosyncline and a probable connection to the Mid-Continent as well.

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

Pennsylvanian structural disturbance in the southern Rockies (Ancestral Rocky Mountains) disrupted sedimentation patterns of primarily carbonate-dominant lithologies in the basin. Beginning with the Absaroka sequence, clastic sedimentary facies predominate 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 that trapped much sediment moving eastward from the Rockies in Paleocene time and assisted in the formation of extensive lignite deposits.

The basin appears to be the result of drag along two left-lateral shear systems. These shear systems formed a depressed block which now encompasses the central Rocky Mountains and southern Williston basin. Tensing of this block during plate-wide orogenic stress created the vertical structure seen today.

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, as several new structural trends have been mapped in recent years. A very high success rate in exploration drilling has doubled oil production in the last 4 years. Continued increases in oil production are forecast for the next few years. Several of the structural trends now being mapped have not been substantially explored, and shallow gas potentials have been largely ignored.

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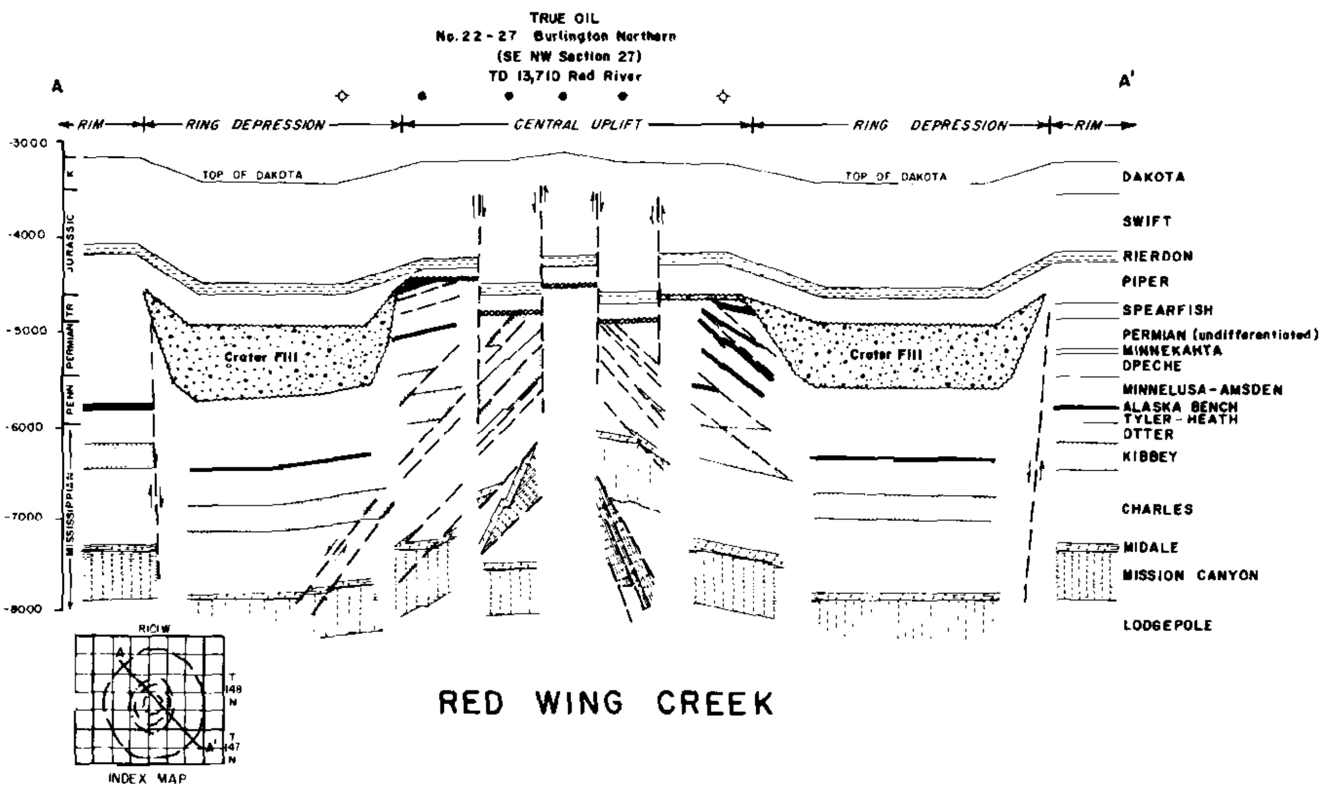

FIG. 21—Cross section through Red Wing Creek structure, McKenzie County, North Dakota, demonstrating meteorite-impact hypothesis for origin of this structure. True Oil 22-27 Burlington Northern discovery well was drilled on top of central uplift. Modified from Exhibit 6, case 1152, North Dakota Industrial Commission, submitted by Union Oil Co. of California.

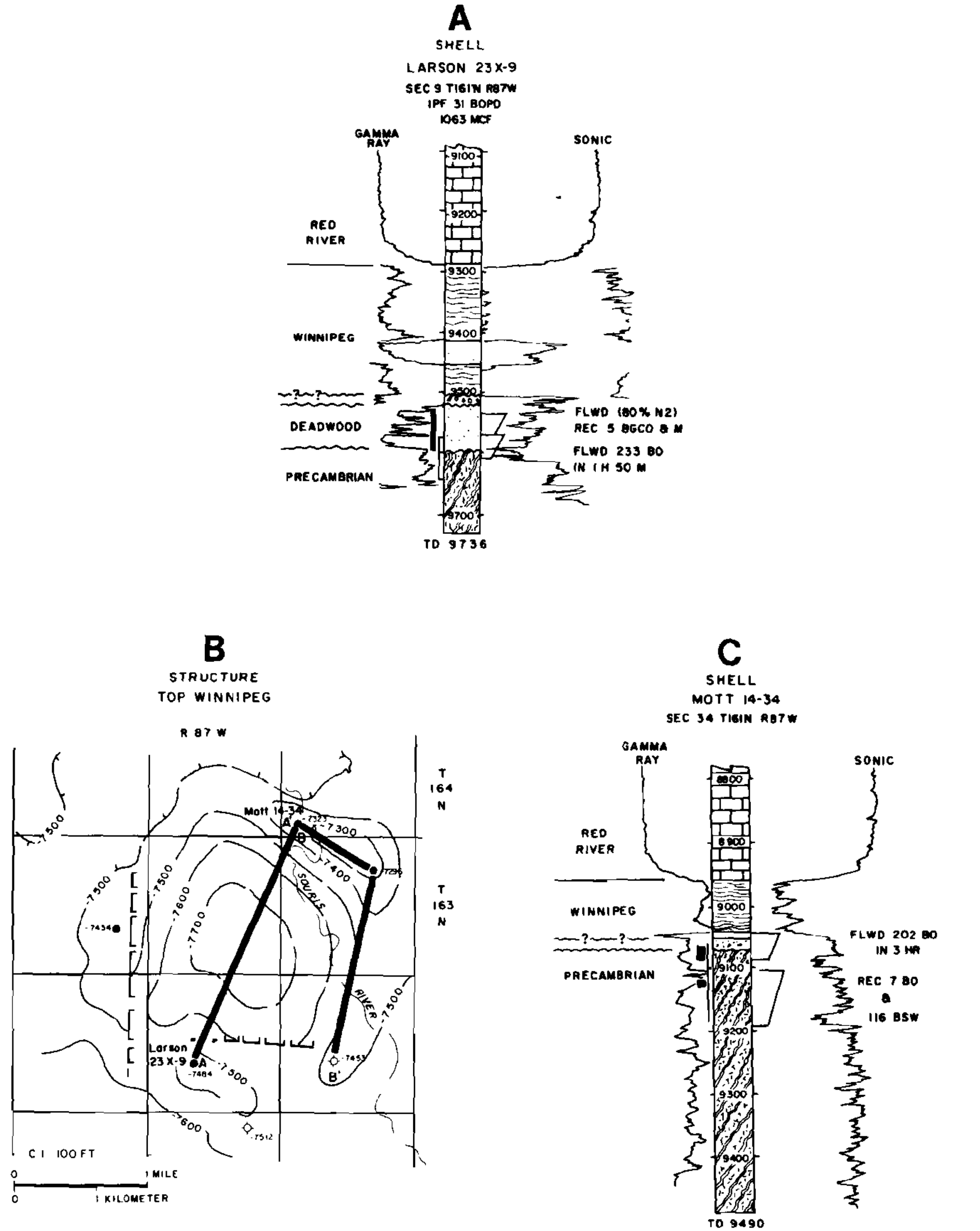

FIG. 22—Newporte field structure map and lithologic sections. A. Shell Larson 23 X-9, showing producing interval in Deadwood Formation. B. Structure of top of Winnipeg Formation in Newporte field. C. Shell Mott 14-34, showing producing intervals in Precambrian and at Winnipeg Precambrian contact. Modified from Clement and Mayhew (1979).

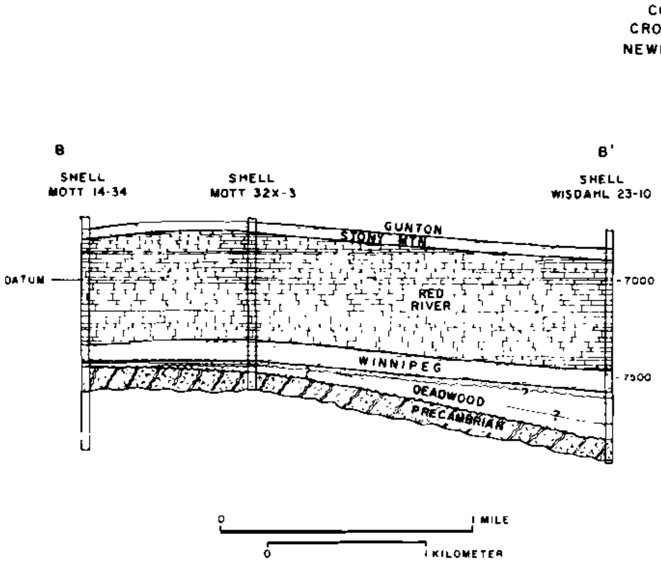

FIG. 23—Cross sections across Newporte field. See Figure 22 for lines of section. Modified from Clement and Mayhew (1979).

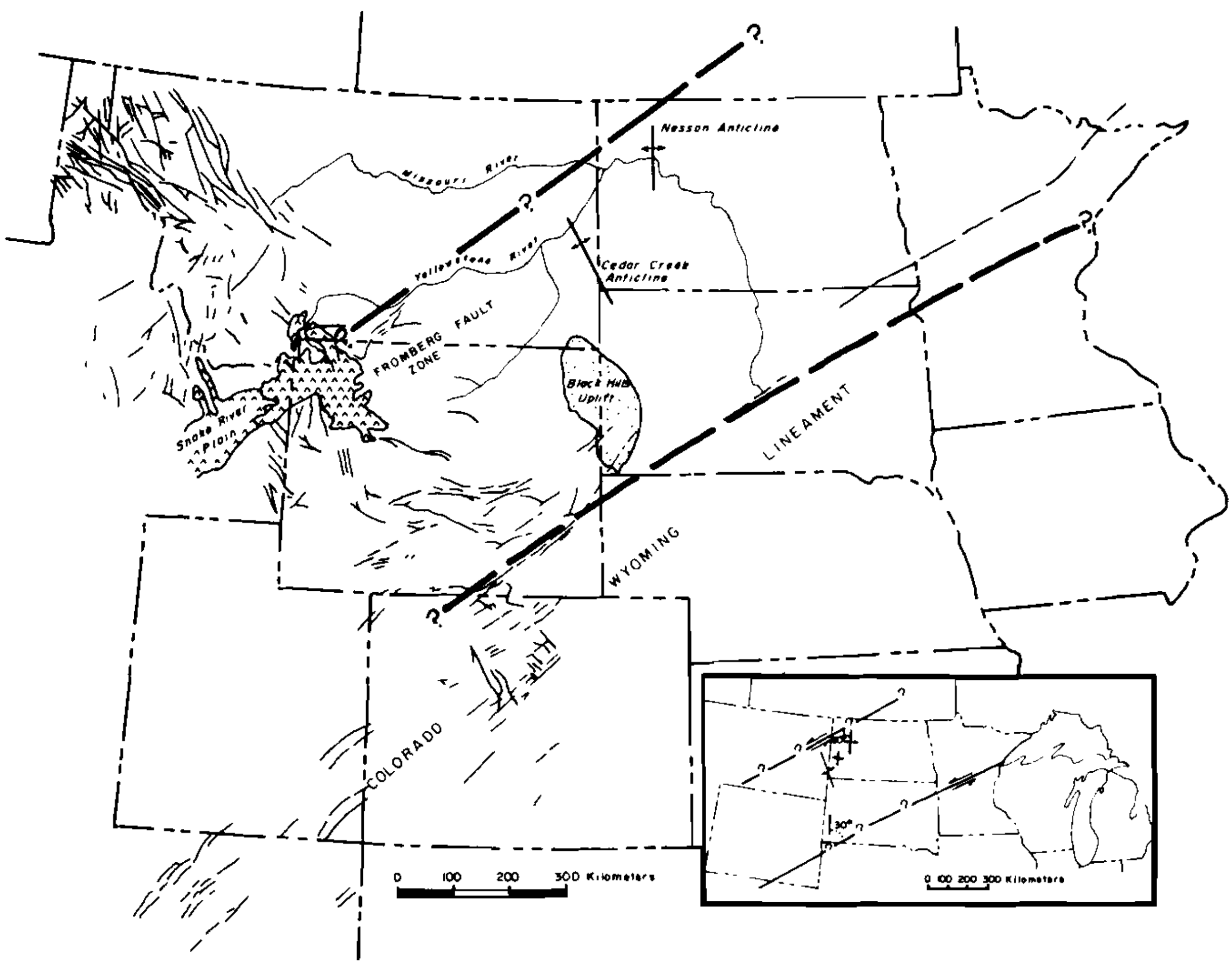

FIG. 24—Diagram showing relationship of Fromberg-Colorado-Wyoming shear zones to structural features of Rocky Mountains and Williston basin.

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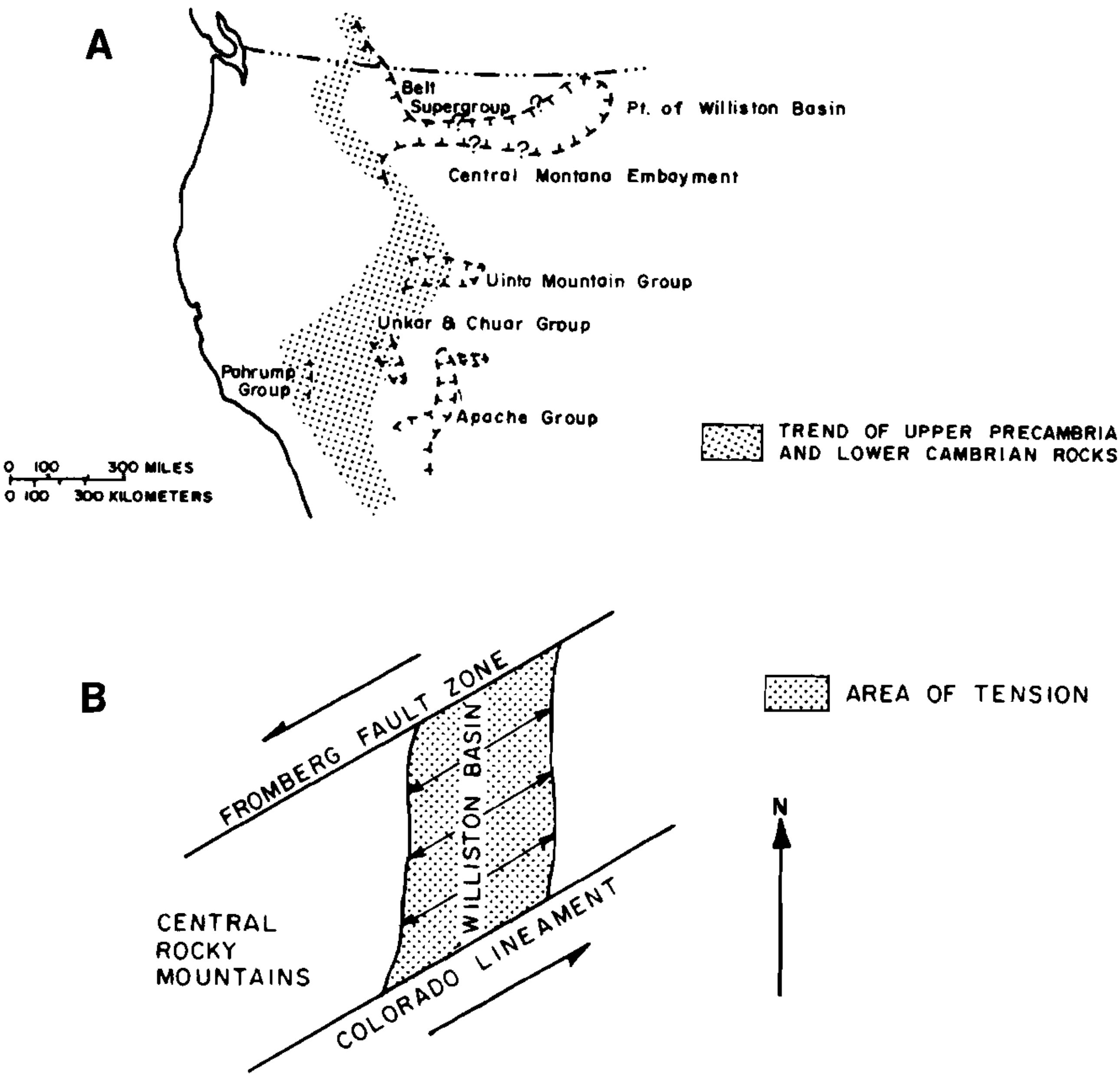

FIG. 25—A. Aulacogen origin for Williston basin. Basin is shown as possible extension of Central Montana embayment during Precambrian time. Modified from Stewart (1972). B. Pull-apart origin for Williston basin. Basin was placed under tension due to movement along major shear zones causing grabenlike downdropped blocks. Modified from Burchfiel and Stewart (1966).

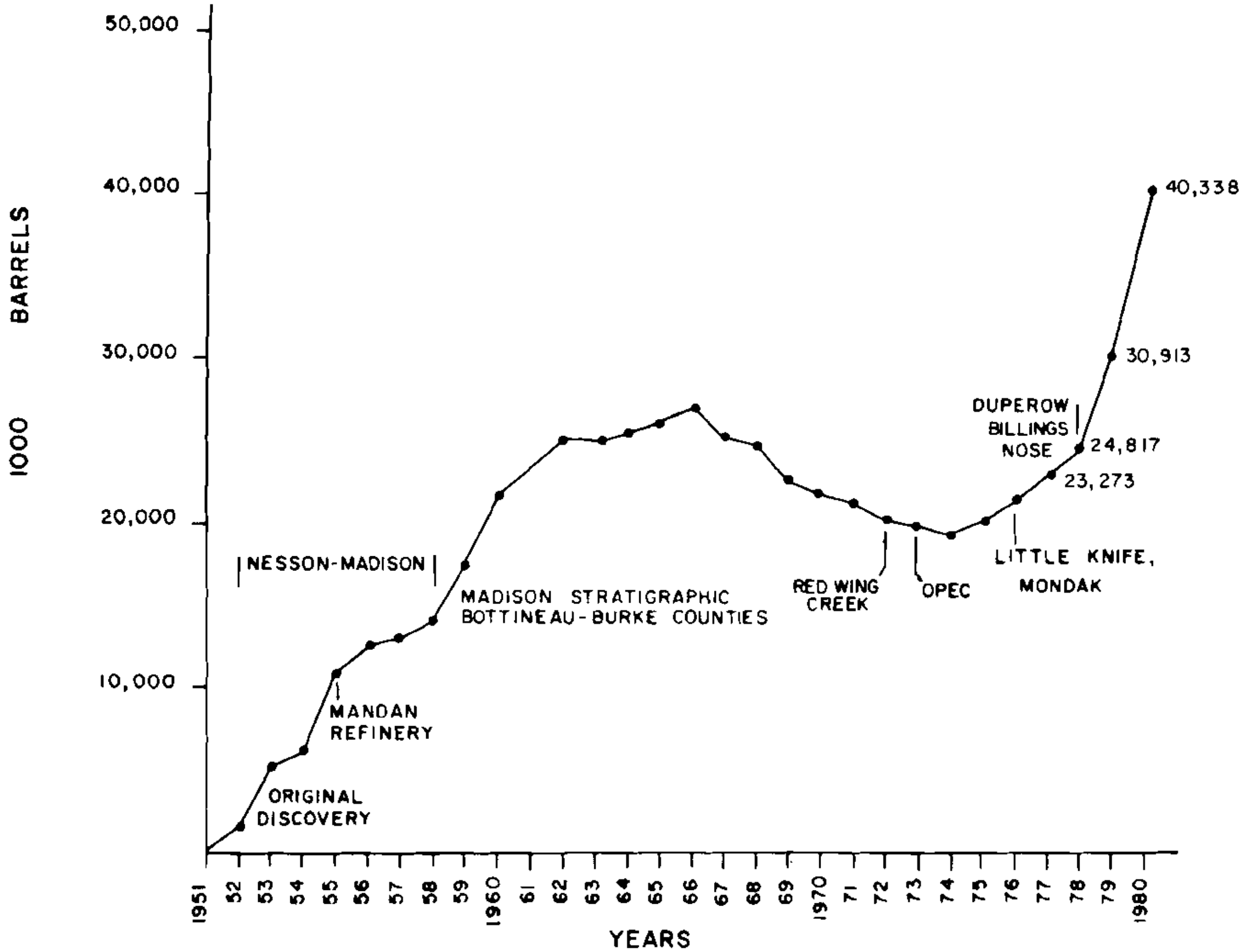

FIG. 26—Annual oil production in North Dakota, 1951-80 (in 1,000 bbl). See text for discussion of events on graph.

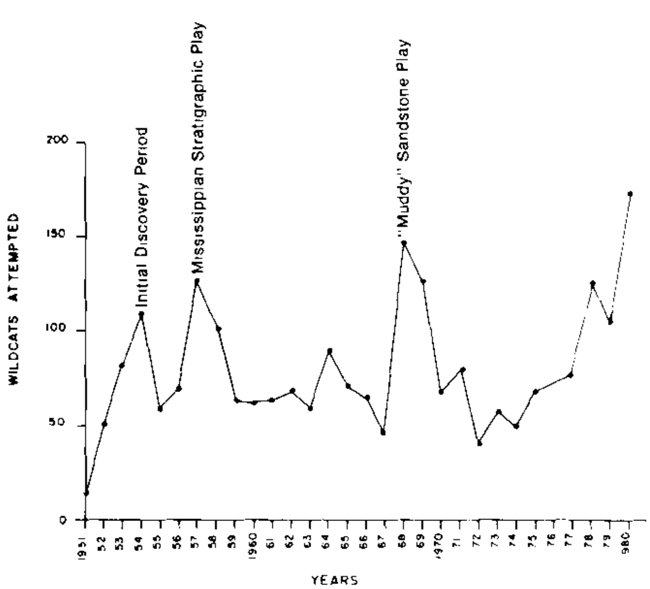

FIG. 27—Graph showing number of wildcat wells, 1951 through 1980.

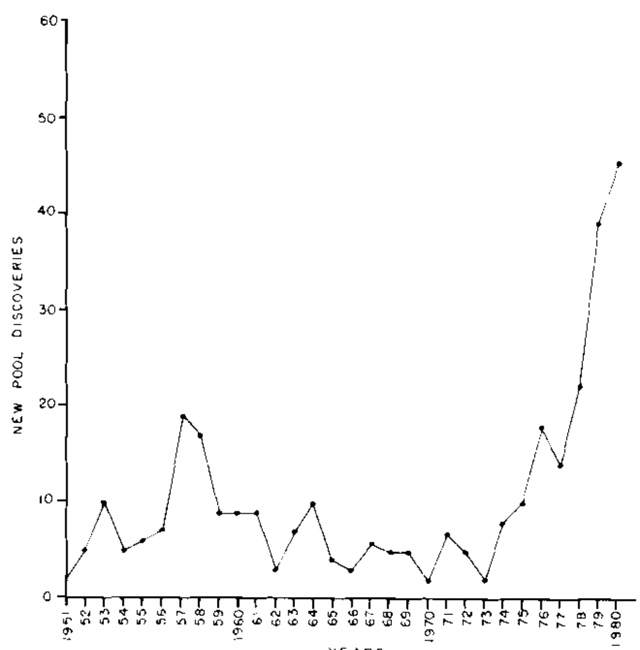

FIG. 28—Graph showing number of new pool discoveries, 1951 to 1980. The 1980 number is 55 discoveries.

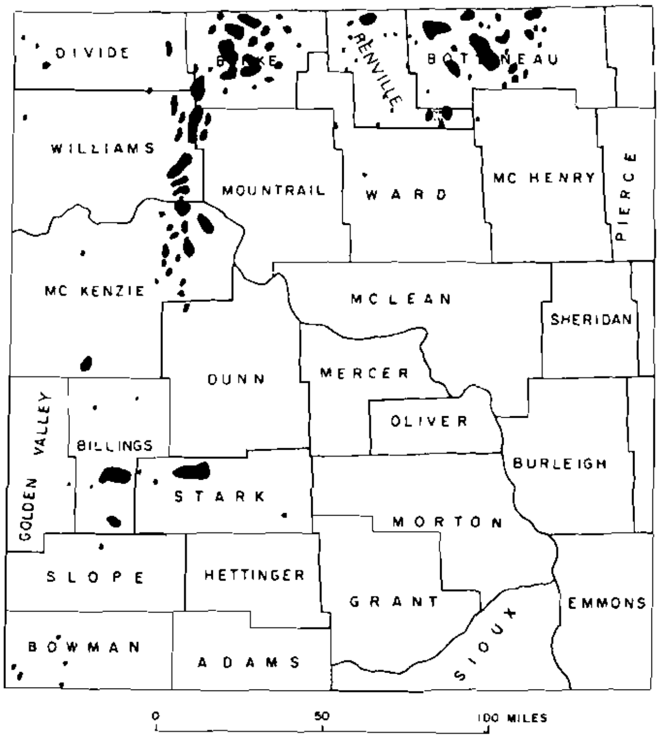

FIG. 29—Producing fields in North Dakota, 1970.

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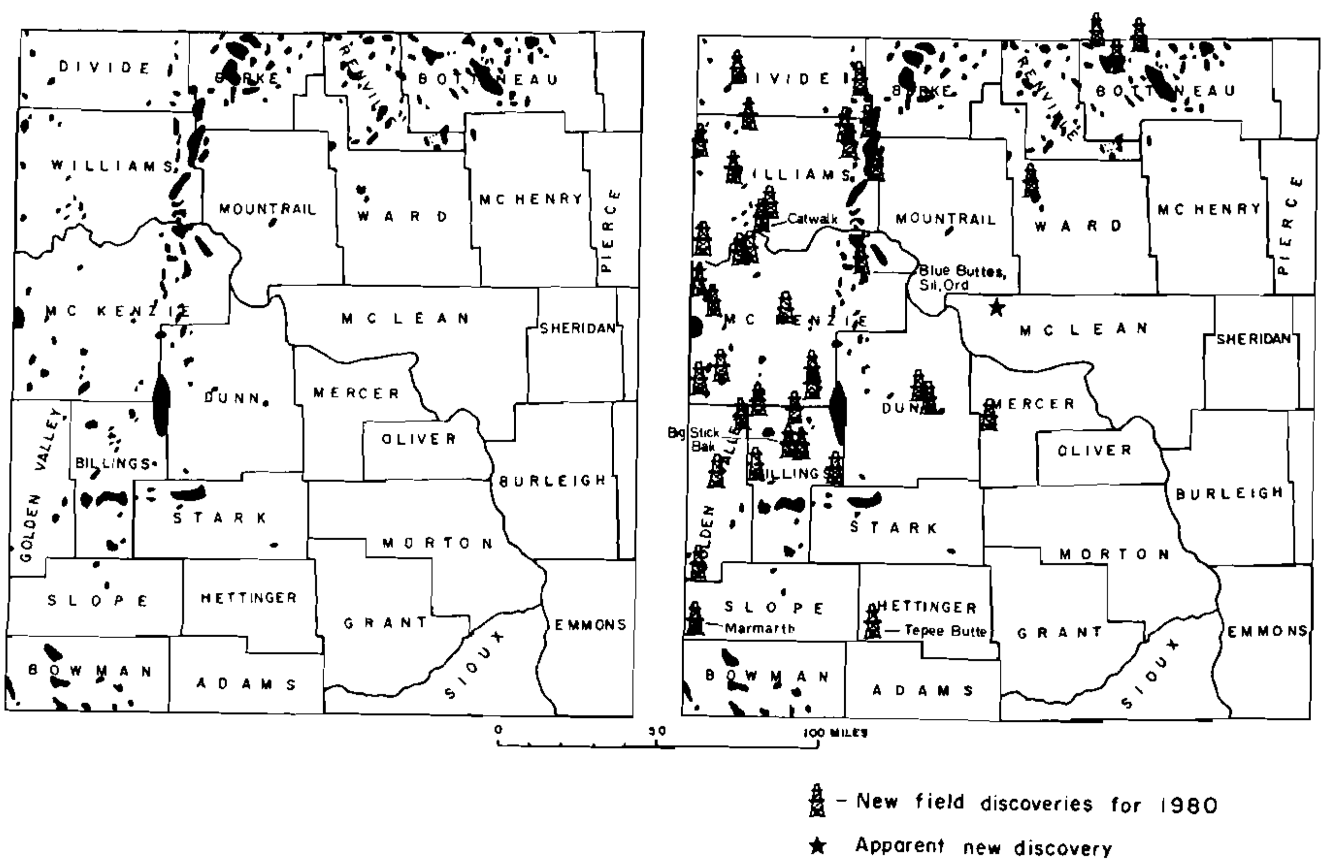

FIG. 30—Producing fields in North Dakota, 1980. Note large number of new fields in western North Dakota south and west of Nesson anticline.

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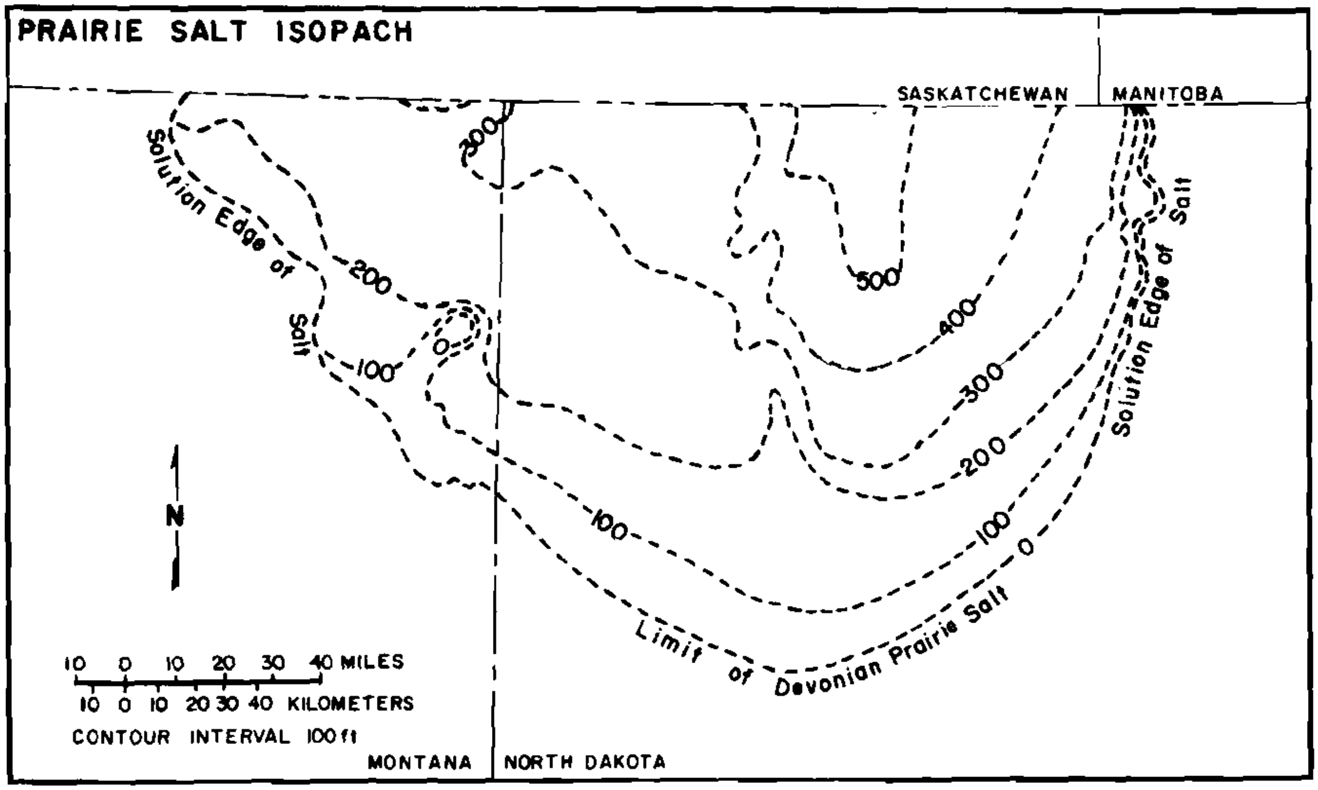

FIG. 31—Isopach map of Prairie salt in Montana and North Dakota, showing limit of Prairie salt. Modified from Anderson and Swinehart (1979).

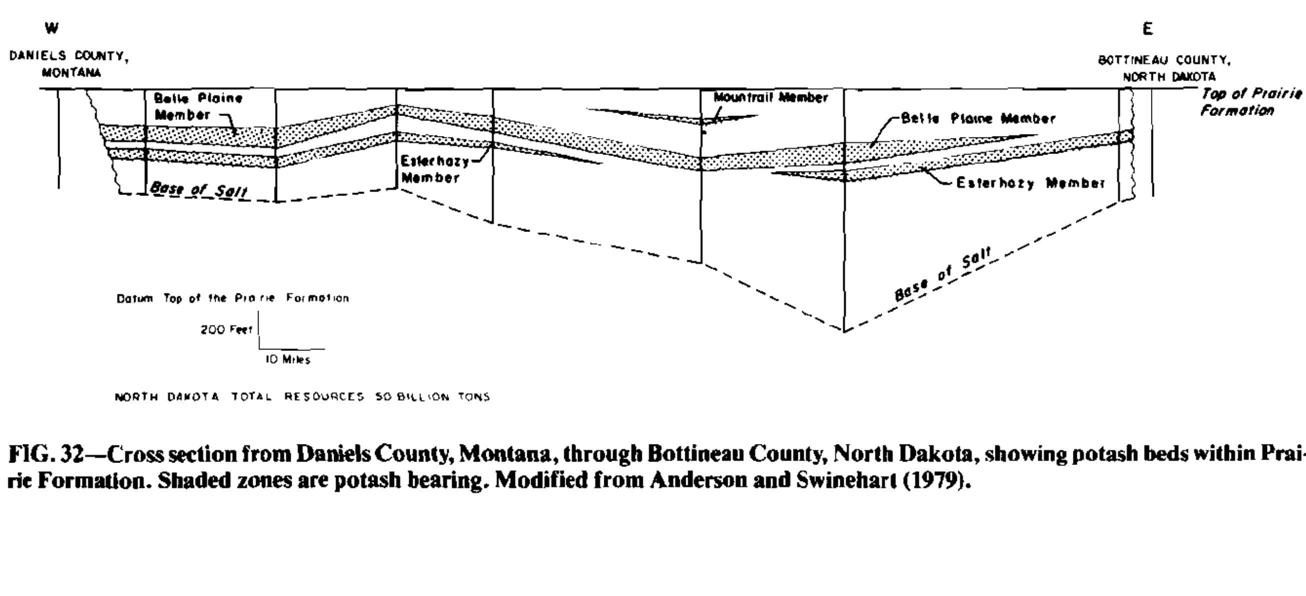

FIG. 32—Cross section from Daniels County, Montana, through Bottineau County, North Dakota, showing potash beds within Prairie Formation. Shaded zones are potash bearing. Modified from Anderson and Swinehart (1979).

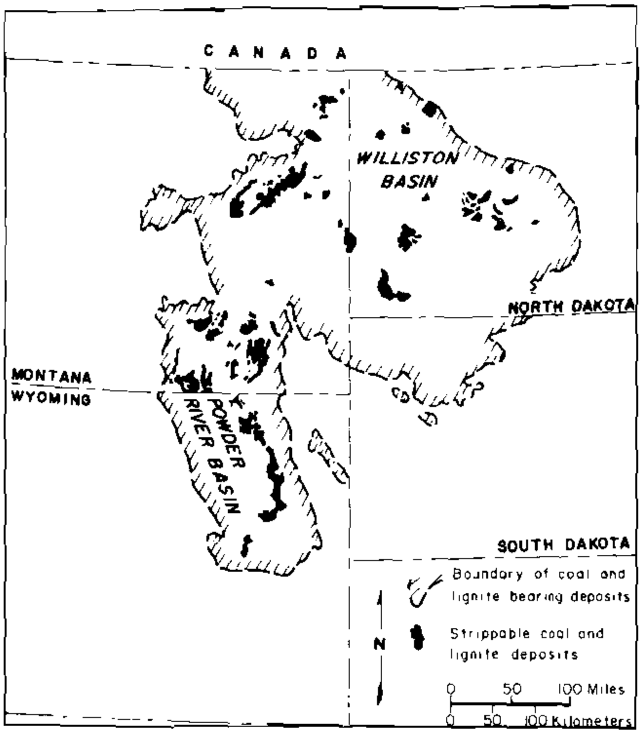

FIG. 33—Map showing distribution of strippable coal deposits in Williston and Powder River basins of North Dakota, Montana, and Wyoming. *Modified from USGS Miscellaneous* Map MF-540 (1974).

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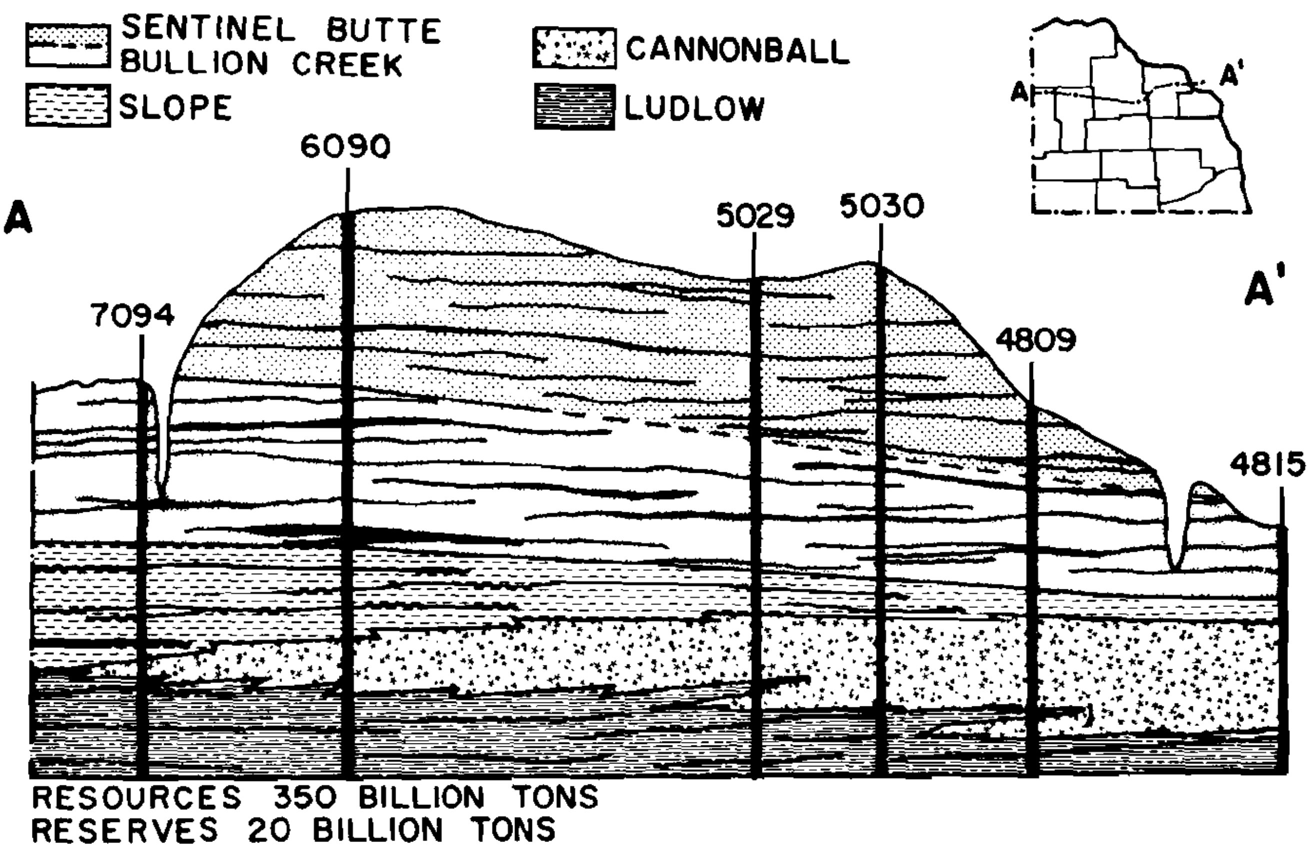

FIG. 34—Diagrammatic cross section of Paleocene rocks in western North Dakota showing relationship of lignite beds and stratigraphic units. Numbers at vertical dark lines refer to North Dakota Geological Survey drill-hole control.

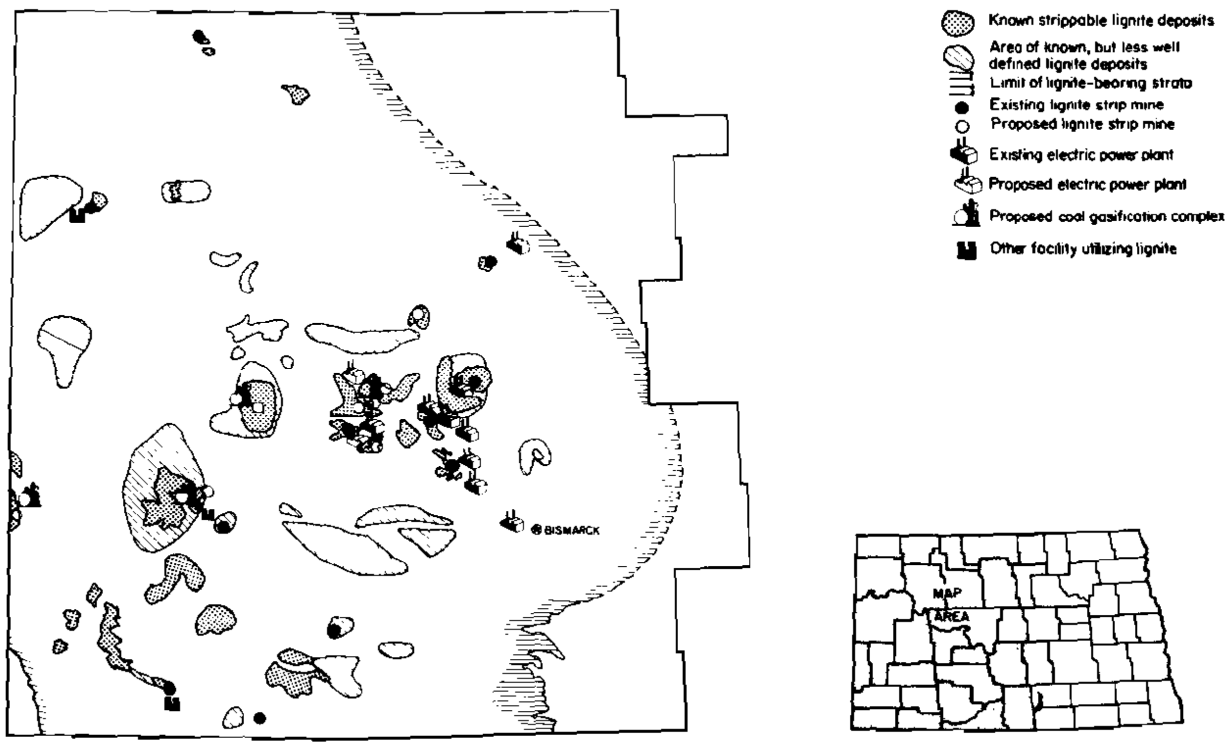

FIG. 35—Map showing strippable lignite deposits and development areas of lignite in North Dakota. Note heavy concentration of active or proposed usage of lignite northwest of Bismarck. Modified and redrawn from Groenewold (1979).

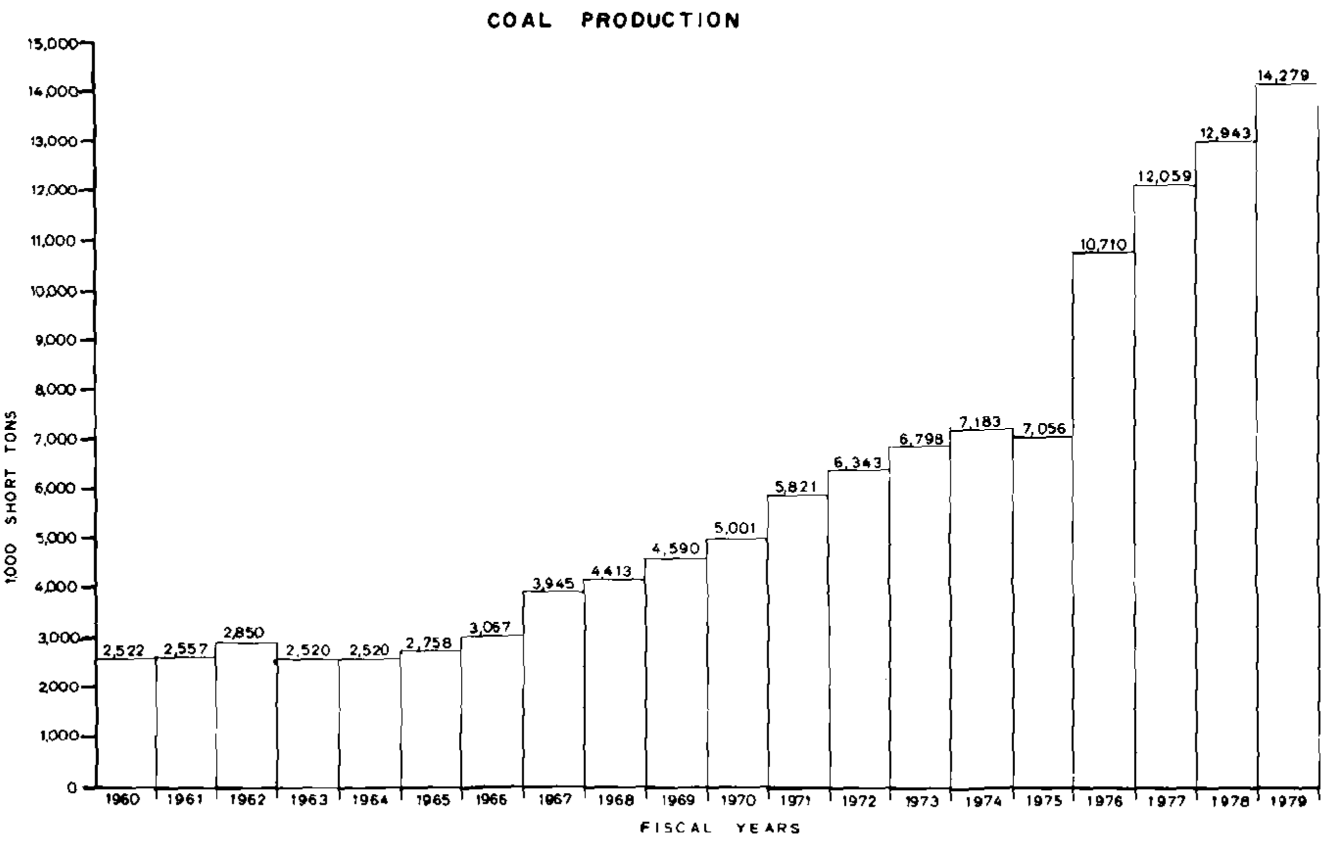

FIG. 36—Graph showing production of coal (lignite) in North Dakota 1960-79. Note steady increase in production from 1966 to 1974 with jump in 1976 and additional increases following. The increases in 1976-79 apparently reflect increasing demand for electrical generation replacing other sources of energy.

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