DEPARTMENT OF THE INTERIOR

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Geologic Summary and Hydrocarbon Plays, Williston Basin, Montana, North and South Dakota, and Sioux Arch, South Dakota and Nebraska, U.S.

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CONTENTS

ILLUSTRATIONS

CONTENTS--Continued

TABLES

GEOLOGIC SUMMARY AND HYDROCARBON PLAYS, WILLISTON BASIN, MONTANA, NORTH AND SOUTH DAKOTA, AND SIOUX ARCH, SOUTH DAKOTA AND NEBRASKA, U.S.

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INTRODUCTION

The Williston basin is a structural-sedimentary intracratonic basin located on the western shelf of the Paleozoic North American craton. The present-day basin occupies a large segment of the northern Great Plains and extends northward into Canada (figs. 1-3). The basin region is a generally flat-lying, moderately dissected plain with minimum topographic relief. Average elevation ranges from approximately 1,500 to 3,000 ft (460 to 915 m). The climate of the region is middle latitude semiarid with precipitation ranging between 15 and 20 in. (40 and 50 cm) per year. The temperature averages approximately 65-70^{o}F during summer months and 10-25^{o}F during the winter. The basin is bordered on the east and southeast by the Canadian Shield and the Sioux uplift. The western and southwestern borders are defined by the Black Hills uplift, Miles City arch, Porcupine dome and Bowdoin dome. The United States part of the basin covers approximately 143,000 mi^2 with a total sedimentary rock volume of approximately 202,000 mi^3. Sedimentary rocks of Cambrian through Holocene age are present in the basin. Maximum thickness of Phanerozoic rocks is greater than 16,000 ft in northwestern North Dakota (figs. 4-8; tables 1, 2).

Paleozoic sedimentation, facies patterns, and paleogeography of the northern Great Plains are closely related to the tectonic history of the western border of the North American craton. The central part of the Paleozoic craton was made up of a stable core, the Canadian shelf of older Precambrian rocks and its southwestward extension, the Transcontinental arch (fig. 1). During the early to middle Paleozoic, the Transcontinental arch effectively separated the continent into eastern and western marine shelf and geosynclinal provinces as approximate mirror images of each other. To the west of the Canadian shelf and Transcontinental arch, the broad western flank of the Paleozoic craton made up the Cordilleran shelf, which was the site of shallow water marine cyclic sedimentation during most of Paleozoic and Mesozoic time. The shelf was bordered on the west by the Cordilleran miogeosyncline (miogeocline of some authors), which was a slowly subsiding complex of marginal basins where primarily shallow-water marine Paleozoic carbonates, sandstones, and shales, as much as 50,000 ft or more thick, accumulated along a belt extending from southwestern United States to northwestern Canada. The Antler orogenic belt, which began active growth in Middle Devonian time, lay to the west of the miogeosyncline and formed a linear, relatively narrow system of thrusting, mountain building, and island growth that underwent several stages of development in late Paleozoic and early Mesozoic time. West of the Antler orogenic belt, thick eugeosynclinal deposits of deep-water shale, fine-grained limestone, coarse clastics, and submarine volcanic deposits accumulated during most of the Paleozoic time.

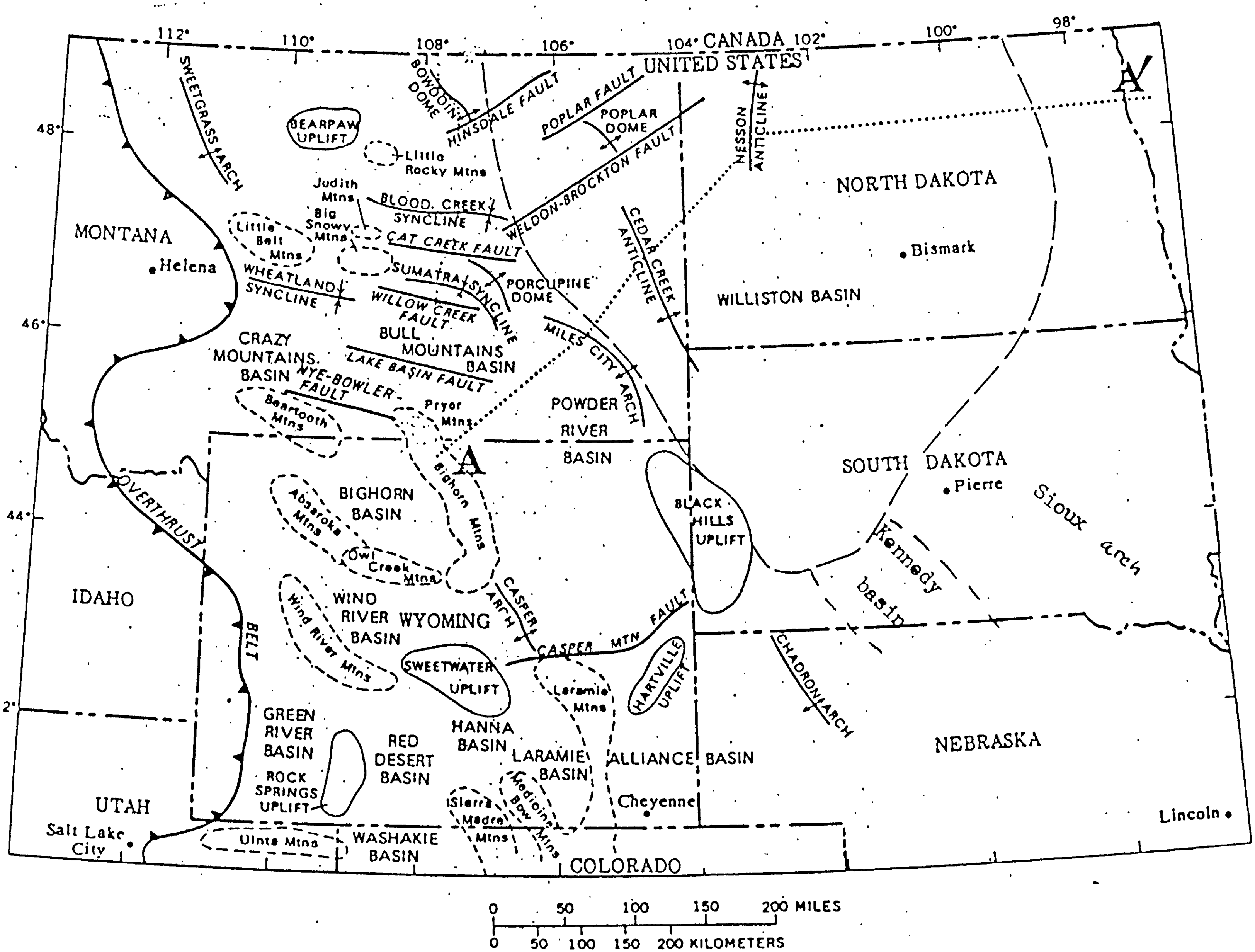

Figure 1. Map showing the major structural features in North and South Dakota, Montana, and Wyoming, Modified after Peterson, 1984.

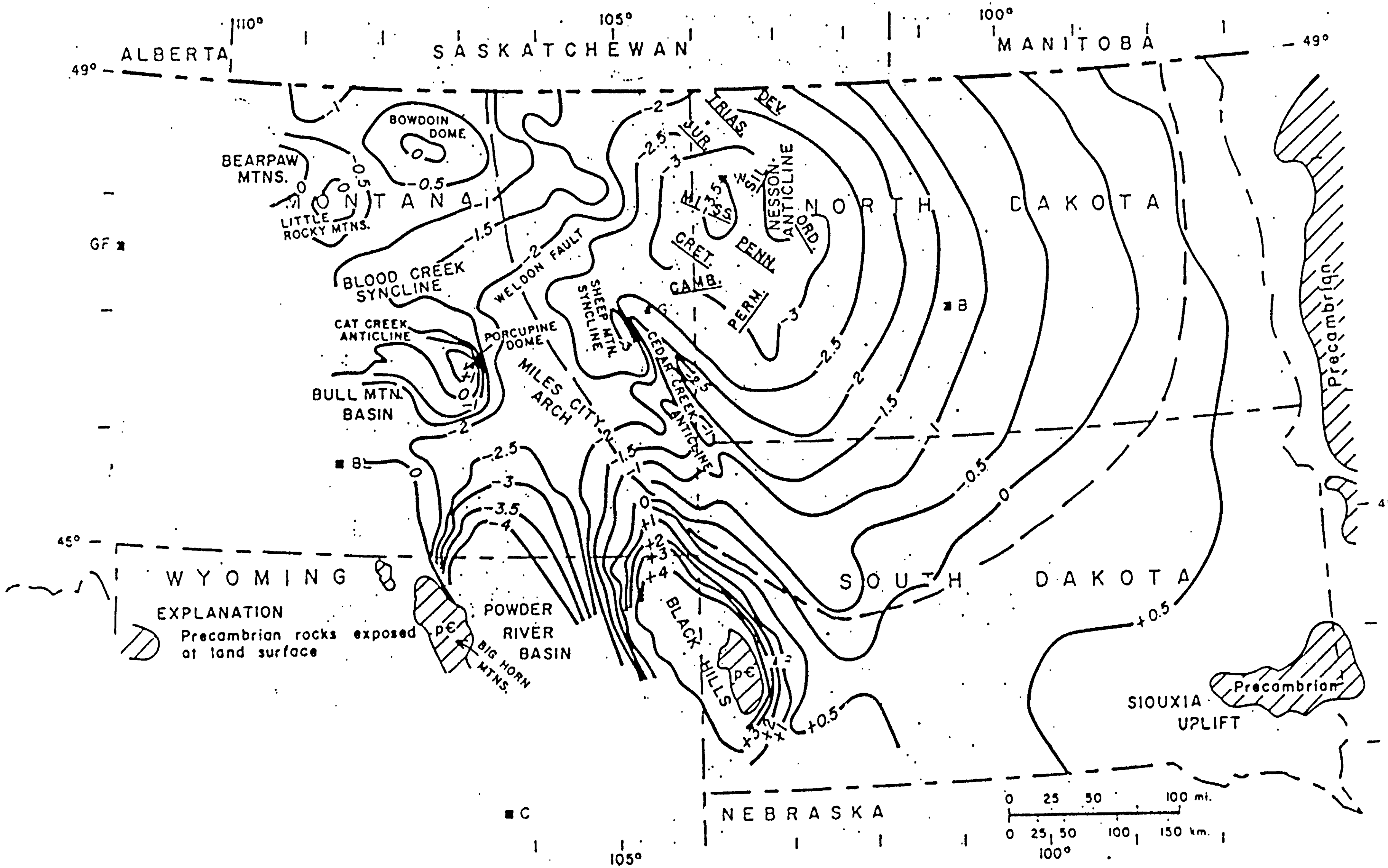

Figure 2. Structure contour map in thousands of feet on top of Dakota Sandstone and equivalents (Cretaceous). Positions of Williston basin depocenters during Paleozoic and Mesozoic time are shown in northwestern North Dakota. Dashed line is approximate boundary of Williston basin (From Peterson, 1985.

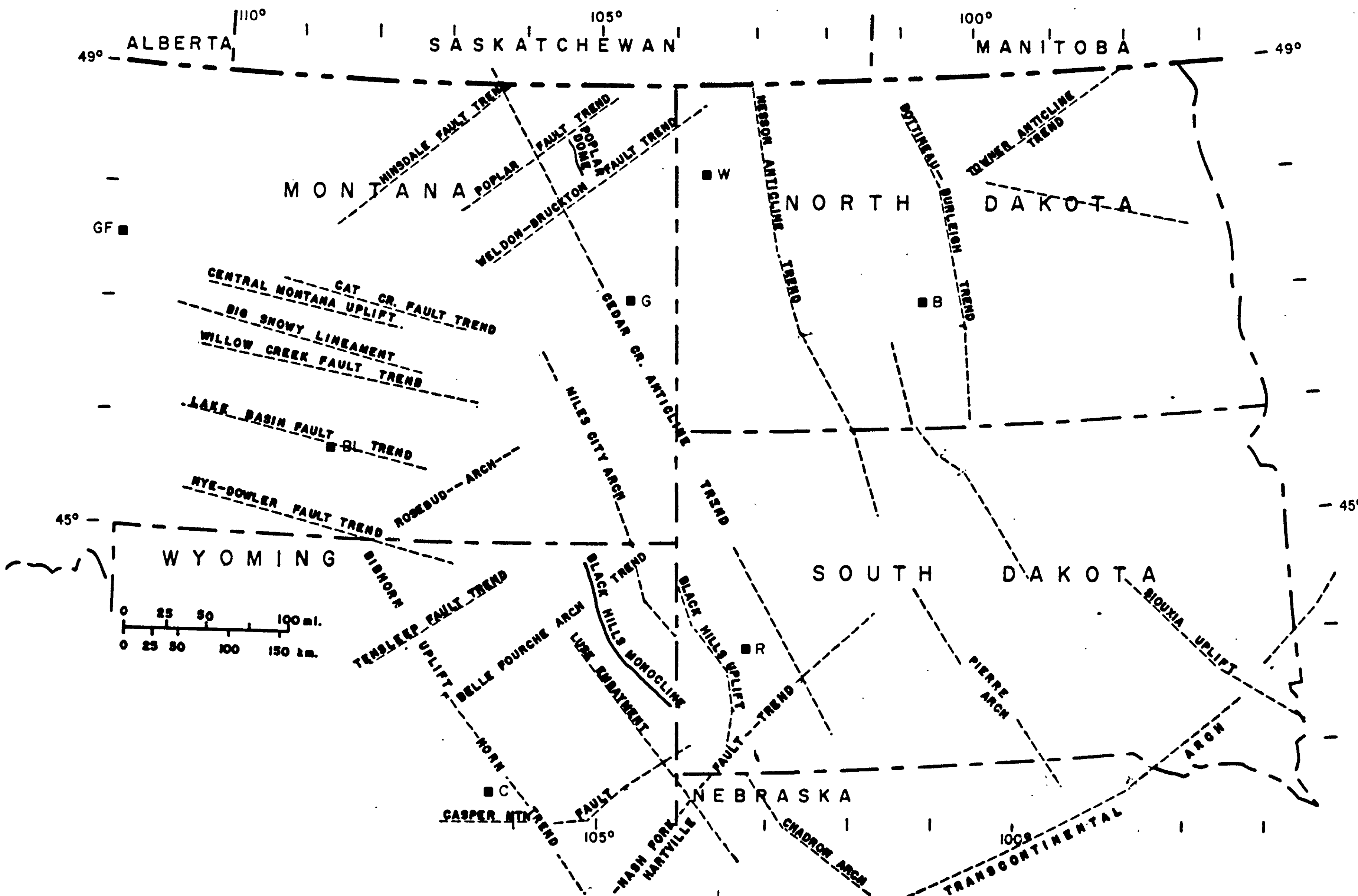

Figure 3. Major Paleozoic structural trends, Williston basin and adjacent areas. Modified after Brown and others, 1982. Cities shown: Montana - GF, Great Falls; G, Glendive; BL, Billings. North Dakota - W, Williston; B. Bismarck. South Dakota R, Rapid City. Wyoming - C, Casper.

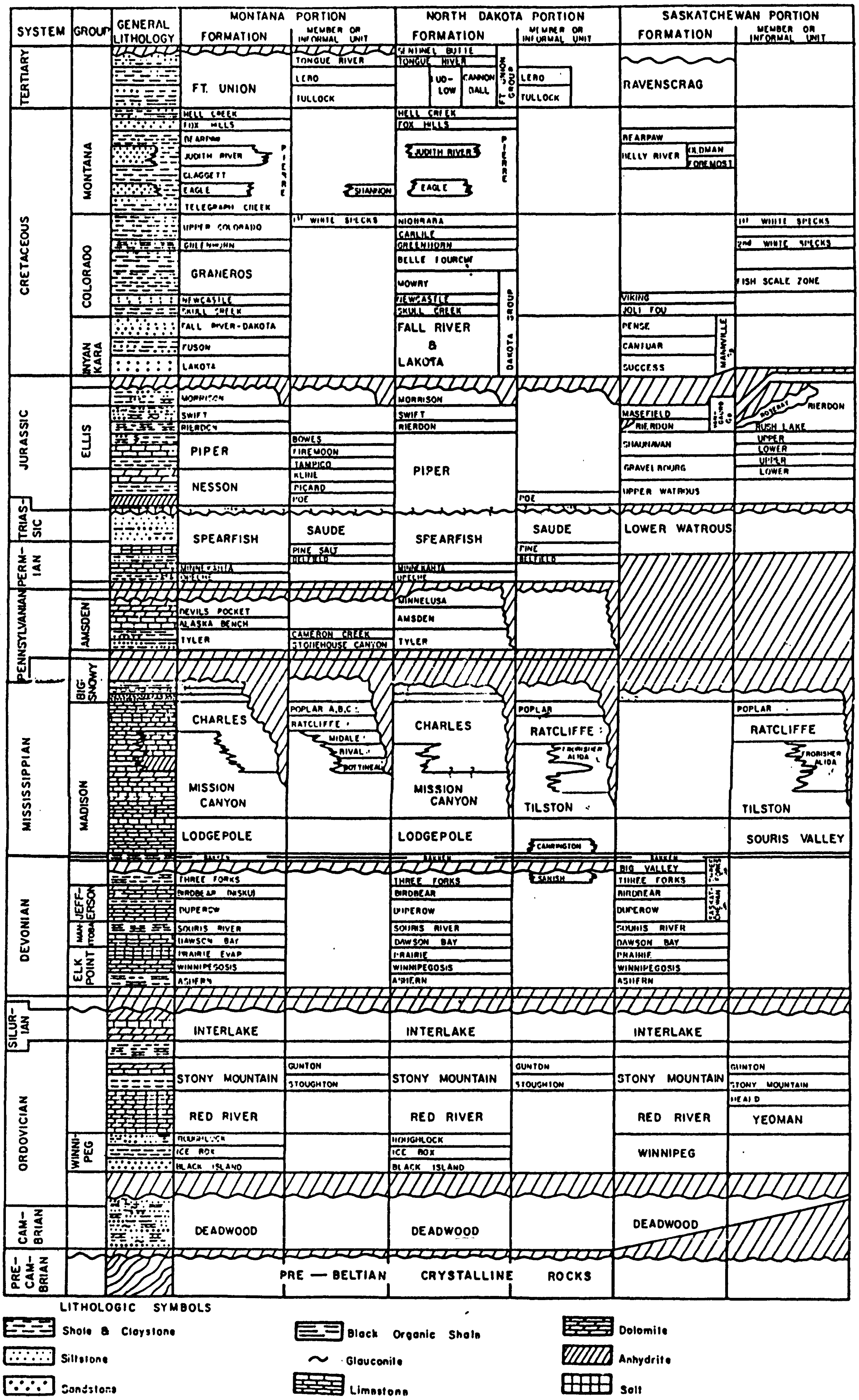

Figure 4. Correlation chart, Williston basin. Modified after Montana Geol. Soc., 1978.

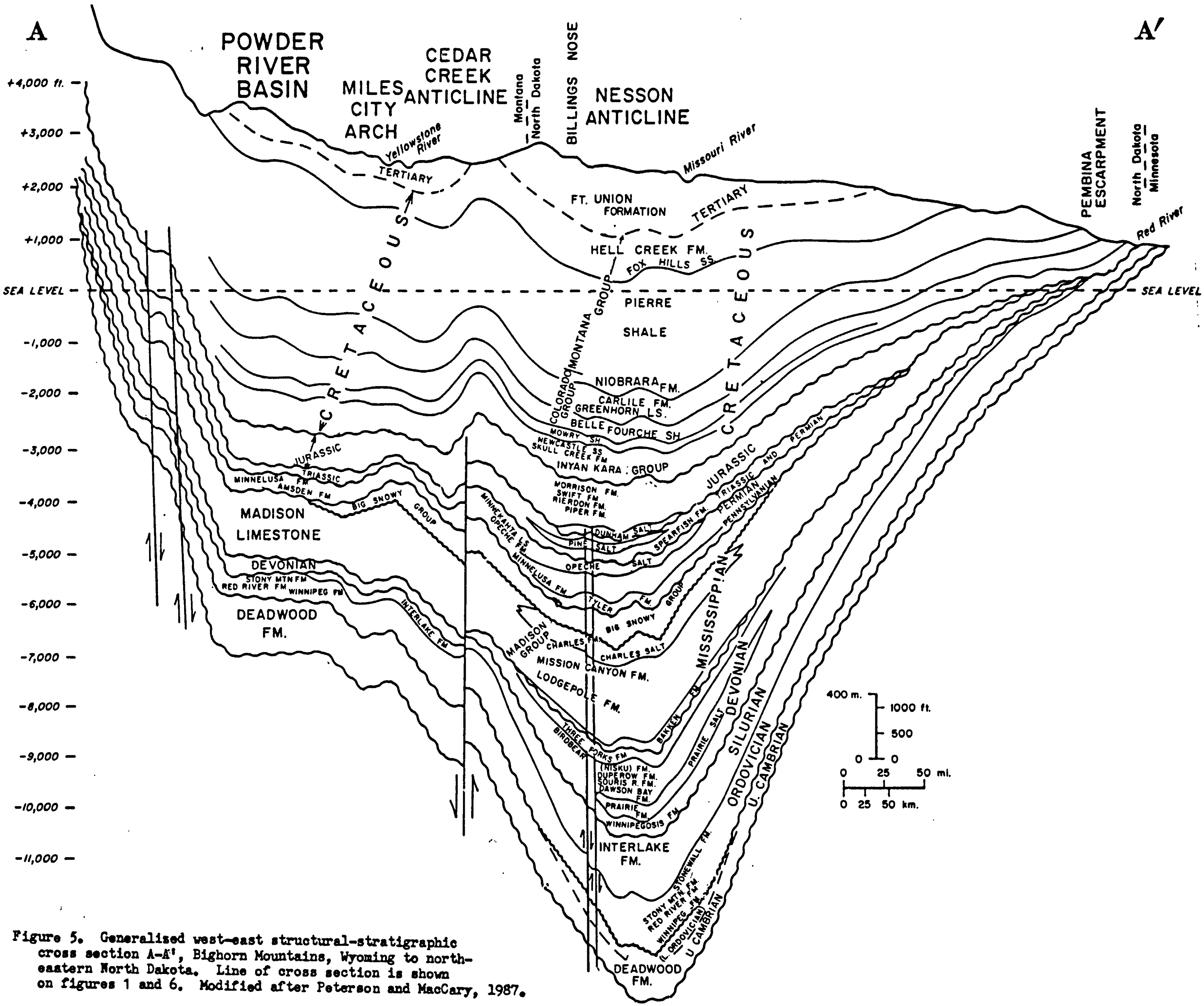

Figure 5. Generalized west-east structural-stratigraphic cross section A-A′, Bighorn Mountains, Wyoming to north-eastern North Dakota. Line of cross section is shown on figures 1 and 6. Modified after Peterson and MacCary, 1987.

9

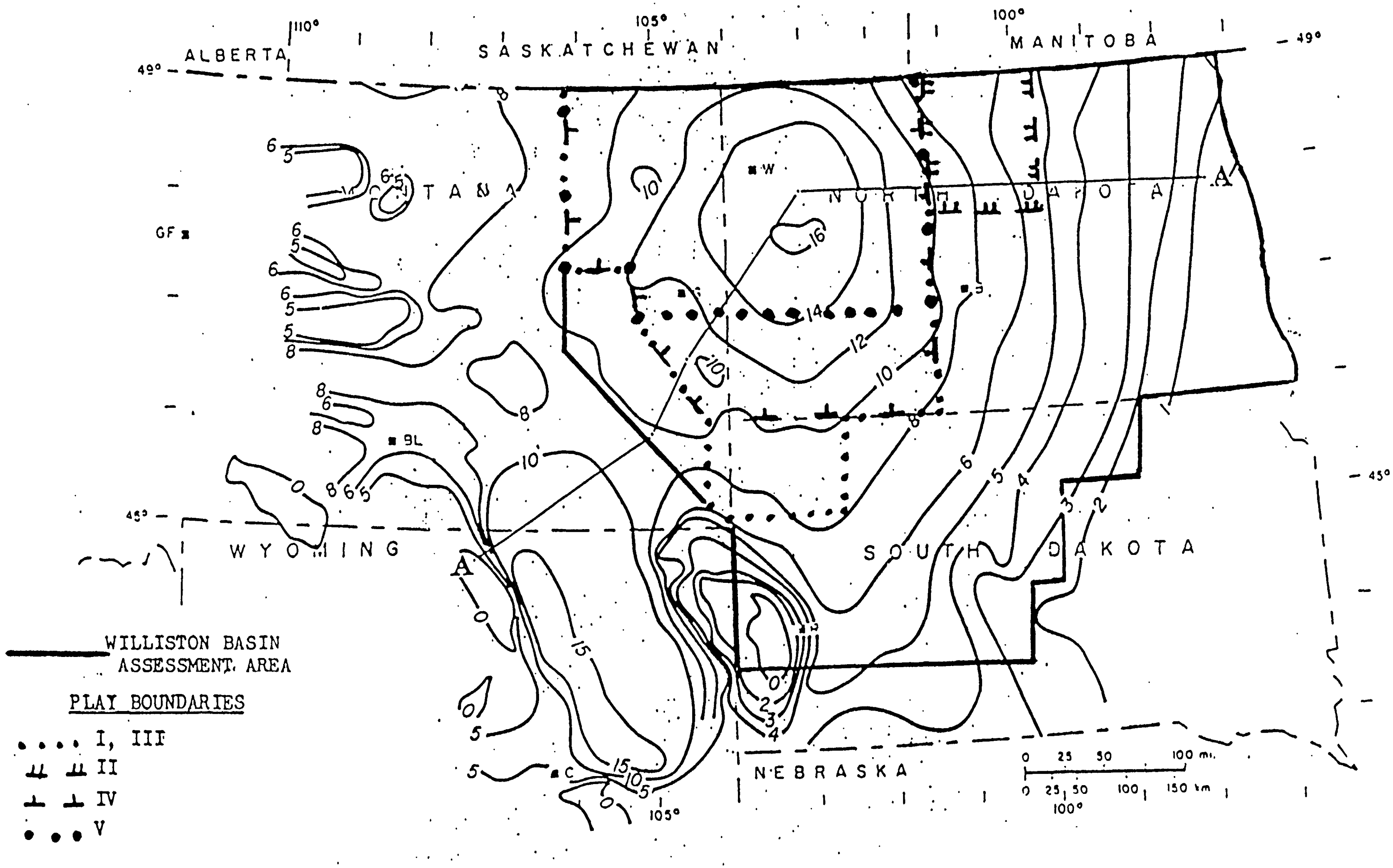

Figure 6. Thickness of sedimentary cover in thousands of feet, U.S. portion of Williston basin and adjacent areas. Line of cross section of figure 5, assessment areas and play boundaries are shown. Modified after Peterson and MacCary, 1987.

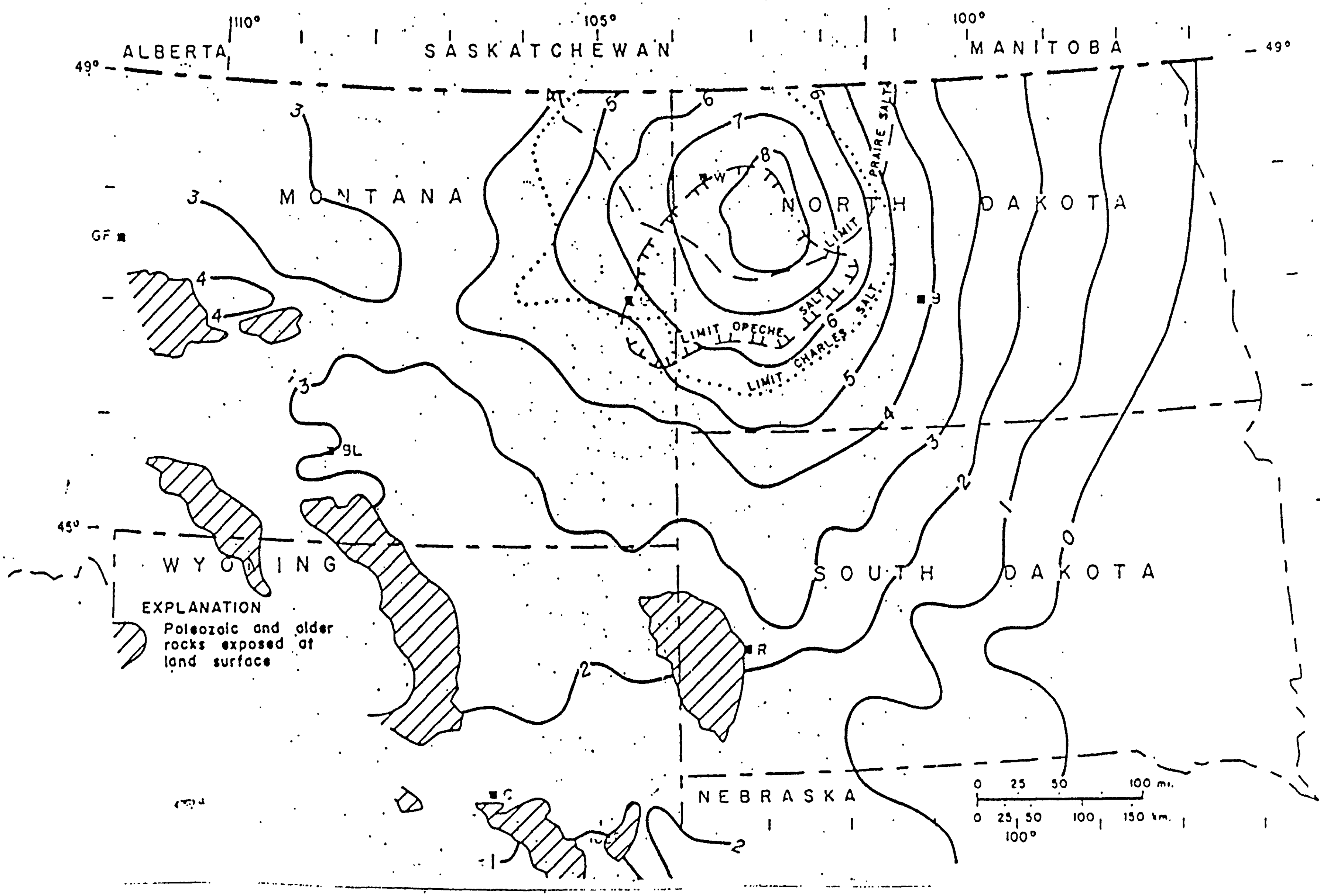

Figure 7. Thickness of Paleozoic rocks in thousands of feet, U.S. portion of the Williston basin and adjacent areas. Approximate limits of "Prairie salt" (Prairie Formation, Devonian), Charles salt (Charles Formation, Mississippian), and "Opeche salt" (Opeche Formation, Permian) are shown. Note location of oil accumulations concentrated beneath one or more of the main evaporite seals. Modified after Peterson, 1985.

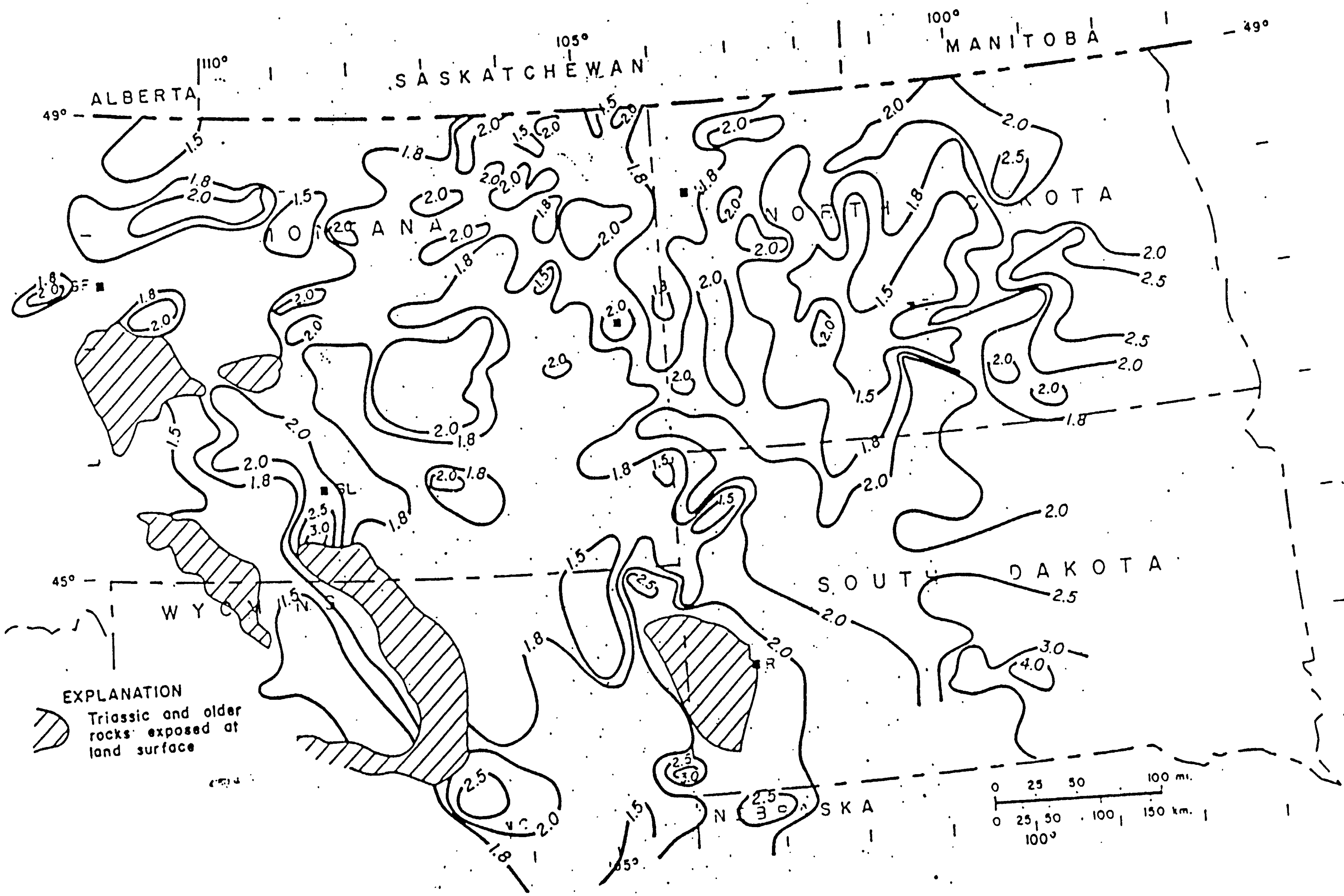

Figure 8. Thermal gradient map (F^{0}/100 ft). From MacCary, 1981.

Table 1.--Exploration and production summary, Williston Basin, U.S. Portion

Area 142,537 mi^2; Sediment Volume, 201,830 mi^3		
	Exploratory wells (1/84)	Fields (1/84)
North Dakota	3,360	522
Montana	2,200	141
South Dakota	440	20
Totals	6,000±	683

Comparative production, reserves, undiscovered resources

	Oil (Billion barrels)	Gas (Trillion cubic ft) Associated	Gas (Trillion cubic ft) Non-associated
Cumulative production			
1979	0.895	1.535	0.11
January 1984	1.140		
Measured reserves			
1979	0.365	0.710	0.100
January 1984 estimate	.340		
Original reserves			
1979	1.260	2.245	0.206
January 1984 estimate	1.700		
Undiscovered resources (1979)			
Median	1.18	2.13	0.66
Mode	0.82	1.48	0.47
Recovery factor	0.24		0.80

MAIN PLAYS

I. Madison-Upper Devonian
II. Northeast Basin
III. Red River-Interlake-Middle Devonian
IV. Post-Madison-pre-Jurassic
V. Deep basin gas

Table 1.--Exploration and production summary, Williston Basin, U.S. Portion--continued

Ultimate recovery for fields greater than 15 million barrels of oil

Field and State	Reservoir (1)	Estimated Ultimate recovery Oil (millions of barrels)	Gas (billions of cubic feet)
Pennel (Mont.)	Si, Or, Mm	138	
Beaver Lodge (N. Dak.)	Mm, D, Or	125	
Pine, Mont.	Or, Mm	115	
Little Knife, N. Dak.	Mm	110	55
Cabin Creek, Mont.	Or, Si, Mm	105	40
Tioga, N. Dak.	Mm, Dd, Si, Or	85	136
Poplar East, Mont.	(Mm, Mh, Dn	48	40
Charlson, N. Dak.	Mm, Si, Mb, Or	40	62
Antelope, N. Dak.	Mm, Dtf	37	66
T. R., N. Dak.	Mm, Dd, Or	30	
Newburg, N. Dak.	Trs, Mc	30	1.5
Lookout Butte, Mont.	Mm, Dd, Or	30	
Dickinson, N. Dak.	Mh, Mm	28	3
Mondak, N. Dak.	Mm, Or, Dd	25	10
Glenburn, N. Dak.	Mm	22	1
Flat Lake, Mont.	Or	20	
Sherwood, N. Dak.	Mm	17	5
Rough Rider, No. Dak	Mm, Mb	15	7
Little Beaver, N. Dak.	Or, Mm	15	
Hawkeye, No. Dak.	Mm	15	20
North Tioga, No. Dak.	Mm	15	21
Rival, N. Dak	Mm	15	25

(1) Trs - Spearfish; Mh - Heath; Mc - Charles; Mm - Madison; Mb - Bakken; D - Devonian; Dtf - Three Forks; Dn - Nisku; Dd - Dupero; Si - Interlake; Or - Red River

Table 2.--Data summary for the U.S. portion of the Williston basin

Prospective intervals					
Age	Rock unit	Reservoir lithology	Reservoir depth range (ft)	Average gross Reservoir Thickness (ft)	Oil or Gas
Tertiary-Late Cretaceous	Several intervals	sandstone	0-3,000	500-1,200	biogenic gas
Early Cretaceous		------do-------	0-6,500	800	biogenic gas
Jurassic	Saude (economic usage)	------do-------	2,000-7,000	150	oil
Triassic	Spearfish Formation	------do-------	2,000-7,500	150	oil
Pennsylvanian-Mississippian	Tyler and Heath formations	------do-------	2,500-8,500	200	oil
Mississippian	Big Snowy Group	------do-------	3,000-8,500	300	oil
Mississippian	Madison Group	limestone and dolomite	500-9,000	1,400	oil
Devonian	Birdbear (Nisku) Formation	dolomite and limestone	500-10,000	35	oil
Devonian	Duperow Formation	------do-------	500-11,000	200	oil
Devonian	Winnipegosis Formation	------do-------	500-12,000	100	oil
Mississippian-Devonian	Bakken Formation	siltstone and sandstone	7,000-10,000	75	oil
Silurian	Interlake Formation	dolomite	500-12,000	500	oil
Ordovician	Red River Formation	limestone and dolomite	500-12,000	400	oil and gas
Ordovician	Winnipeg Formation	sandstone	500-15,000	100	oil and gas
Ordovician and Cambrian	Deadwood Formation	sandstone	500-16,000	500	oil and gas

Table 2.--Data summary for the U.S. portion of the Williston basin--continued

	Probable Source Beds				
Age	Rock Unit	Depth (ft)	Quality	Maturity	Oil and gas
Tertiary-Late Cretaceous	Fort Union Formation and Montana Group	0-3,000	fair	immature	gas
Late Cretaceous	Niobrara, Carlile and Belle Fouche Formations	1,000-5,000	fair	immature	gas
Early Cretaceous	Mowry Formation	2,000-6,500	fair	immature	gas
Pennsylvanian-Mississippian	Tyler and Heath formations	3,000-8,500	fair to good	mature	oil
Mississippian	Lodgepole Formation	7,000-9,500	fair to good	mature	oil
Mississippian Devonian	Bakken Formation	7,000-10,000	good	mature	oil
Devonian	---	10,000-15,000	?	mature	oil
Ordovician	Stony Mountain and Red River Formations	9,000-15,000	good	mature	oil and gas
Ordovician-Cambrian	Winnipeg and Deadwood formations	10,000-15,000	?	?	?

The northern Great Plains region lies within the eastern part of the Cordilleran shelf adjacent to the Transcontinental arch. Within this region, sedimentary processes were influenced to varying degrees by the growth of several paleostructural elements associated with the development and growth of the Cordilleran shelf (figs. 1,3). The major Paleozoic paleostructural element in the northern Great Plains region was the Williston basin, which has undergone mild tectonic subsidence since Late Cambrian or Orodovician time. Other important elements of regional size include the central Montana trough, Alberta shelf, and Wyoming shelf, all of which were present during most of Paleozoic time. Other features that exerted important local influences on Paleozoic sedimentary patterns in the northern Rocky Mountains region include the Sweetgrass arch, central Montana uplift, Cedar Creek anticline, Miles City arch, and the ancestral Black Hills uplift, Chadron arch, Laramie uplift, Bighorn uplift, and Powder River basin.

Prospective petroleum intervals in the U.S. part of the Williston basin are mainly Paleozoic in age and include carbonate reservoirs of, in order of importance, Mississippian, Ordovician, Devonian, and Silurian age (fig. 4,table 2) and sandstone reservoirs of, in order of importance, Ordovician, Mississippian, Pennsylvanian and Triassic age. The major reserves of petroleum occur in carbonate reservoirs mainly of Mississippian and Ordovician ages. Thermal gradient in the basin averages approximately 2^{o}F/100 ft (fig. 8). Mature, organic-rich shale source rocks are present in the Mississippian (Bakken, lower Lodgepole, and Charles Formations), Ordovician (upper Red River Formation), and Pennsylvanian-Mississippian (Tyler and Heath Formations). Mature source rocks of lesser importance are also present in the Ordovician-Cambrian (Winnipeg and upper Deadwood Formations). Immature potential source beds of interest for biogenic gas are present in several parts of the Jurassic, Cretaceous, and lower Tertiary section.

Petroleum accumulations are almost exclusively oil and occur primarily in combination structural-stratigraphic traps related in part to carbonate buildups, discontinuous sandstone bodies, or intraformational porosity changes. As of January 1984, approximately 6,000 exploratory wells had been drilled in the basin, more than half of which are in North Dakota. As of that date, 683 oil fields had been discovered, 522 in North Dakota, 141 in Montana, and 20 in South Dakota, the most important of which are shown on figure 8. Cumulative production as of January 1984 was approximately 1.2 BBO (billion barrels oil) and 2.0 Tcf (trillion cubic feet) gas, mainly dissolved-associated gas (table 1). Historic pool sizes by plays are shown on table 3. Estimated undiscovered resources are summarized in table 4.

Five main plays are defined (figs. 4, 6):

I. Madison-Upper Devonian play, the main play of the basin. This play is based on the geographic and stratigraphic occurrence of several intervals of porous carbonate reservoirs with several interbedded anhydrite seals and a main seal (Charles salt and anhydrite) at the top.

Table 3.--Historic pool size distribution

Pool size	Greater than 50 MMB	25-50 MMB	10-24 MMB	5-9 MMB	1-5 MMB	Less than 1 MMB	Total pools	Approximate mean accumulation size
Play								
I. Madison-Upper Devonian & II. North East Basin	5	6	24	56	113	220	424	3.1 MMB (oil) 1.2 Bcf (gas)
III. Red River-Winnipeg, Silurian and Middle Devonian	2	0	8	8	124	183	325	2.33 MMB (oil) 2.33 Bcf (gas)
IV. Post Madison-pre-Jurassic	0	1	1	6	1	6	15	1.74 MMB (oil) 0.174 Bcf (gas)
Totals	7	7	33	70	238	409	764	2.15 MMB (oil) 2.0 Bcf (gas)

Table 4.--Statistical estimates of undiscovered petroleum resources.

Fields greater than 1 MMBO or 6 BCF gas:

Play	Mean	F95	F50	F5
I	166.9 MMBO 66.8 BCF gas	81.9 MMBO 32.7 BCF gas	154.8 MMBO 61.9 BCF gas	292.9 MMBO 117.2 BCF gas
II	9.8 MMBO 2.9 BCF gas	2.9 MMBO 0.9 BCF gas	8.0 MMBO 2.4 BCF gas	22.5 MMBO 6.8 BCF gas
III & V	223.7 MMBO 332.2 BCF gas	138.0 MMBO 204.3 BCF gas	215.6 MMBO 320.1 BCF gas	336.9 MMBO 501.5 BCF gas
IV	10.0 MMBO 1.0 BCF gas	0.0 MMBO 0.0 BCF gas	9.0 MMBO 0.9 BCF gas	24.8 MMBO 2.5 BCF gas

Small fields (less than 1 MMBO or 6 BCF gas):

Oil	366.2 MMBO	290.0 MMBO	350.0 MMBO	480.0 MMBO
Non-assoc. gas	83.4 BCF gas	68.0 BCF gas	80.0 BCF gas	105.0 BCF gas
Assoc.-dissolved gas	256.0 BCF gas	192.1 BCF gas	252.8 BCF gas	332.8 BCF gas

Total for basin:

Oil 0	780.0 MMBO	490.0 MMBO		1,150.0 MMBO
Assoc. & non-assoc. gas	740.0 BCF gas	490.0 BCF gas		1,070.0 BCF gas

II. Northeast basin play. This play is based on an area of the basin where updip stratigraphic changes and pinchouts in Paleozoic reservoirs occur beneath the Mesozoic unconformity, sealed by overlying Mesozoic shale.

III. Red River-Interlake-Middle Devonian play. This play, which is second in importance, is based on the geographic occurrence of major seals, the regional Prairie salt (Middle Devonian) and the upper Red River and Stony Mountain (Upper Ordovician) anhydrites, which are interbedded with carbonate reservoirs and source rocks.

IV. Post-Madison-pre-Jurassic play. This play is based on the geographic occurrence of Pennsylvanian-Mississippian discontinuous sandstone and minor carbonate reservoirs with associated shale source rocks, sealed by overlying Pennsylvanian shale beds.

V. Deep basin gas play. This play is based on the occurrence of Ordovician carbonate and sandstone reservoirs buried below the oil window in the deeper part of the basin.

PRINCIPAL PLAYS

I. Madison-Upper Devonian Play

This is an oil play with moderate amounts of associated gas, primarily related to accumulations in Madison carbonate reservoirs (figs. 6, 9-14). Devonian dolomite reservoirs have been explored more heavily in the past ten years, but so far accumulations have been relatively small, and much of the Devonian production has been found in new pool discoveries involved with deeper drilling in areas of earlier production.

Geologic Characterization

Reservoirs - These are mainly dolomitized carbonate reservoirs in oolitic, crinoidal or bioclastic bank or mound buildups in several Madison carbonate-evaporite cycles, mainly in the Mission Canyon and Charles Formations. The largest reserves have been found in Mission Canyon reservoirs in several informally named zones, such as the Frobisher-Alida, Tilston, Midale, Rival, and Bottineau zones. Substantial reserves also have been found in Charles Formation zones, such as the Poplar, Ratcliffe, Charles A, B, and C and other zones. Upper Devonian reservoirs are porous dolomite beds in carbonate-evaporite cycles of the Duperow and Birdbear (Nisku) Formations. A few small oil accumulations have been found in siltstone, fine sandstone, or dolomite beds in the middle part of the Bakken Formation, an important source rock unit.

Source Rocks - Identified and probable source rocks are high-organic black shale and siltstone of the Mississippian-Devonian Bakken Formation (the primary source), black to dark gray marine shale and argillaceous limestone beds in the lower Lodgepole Formation, and black to dark gray shale and argillaceous carbonate of the Mission Canyon and Charles

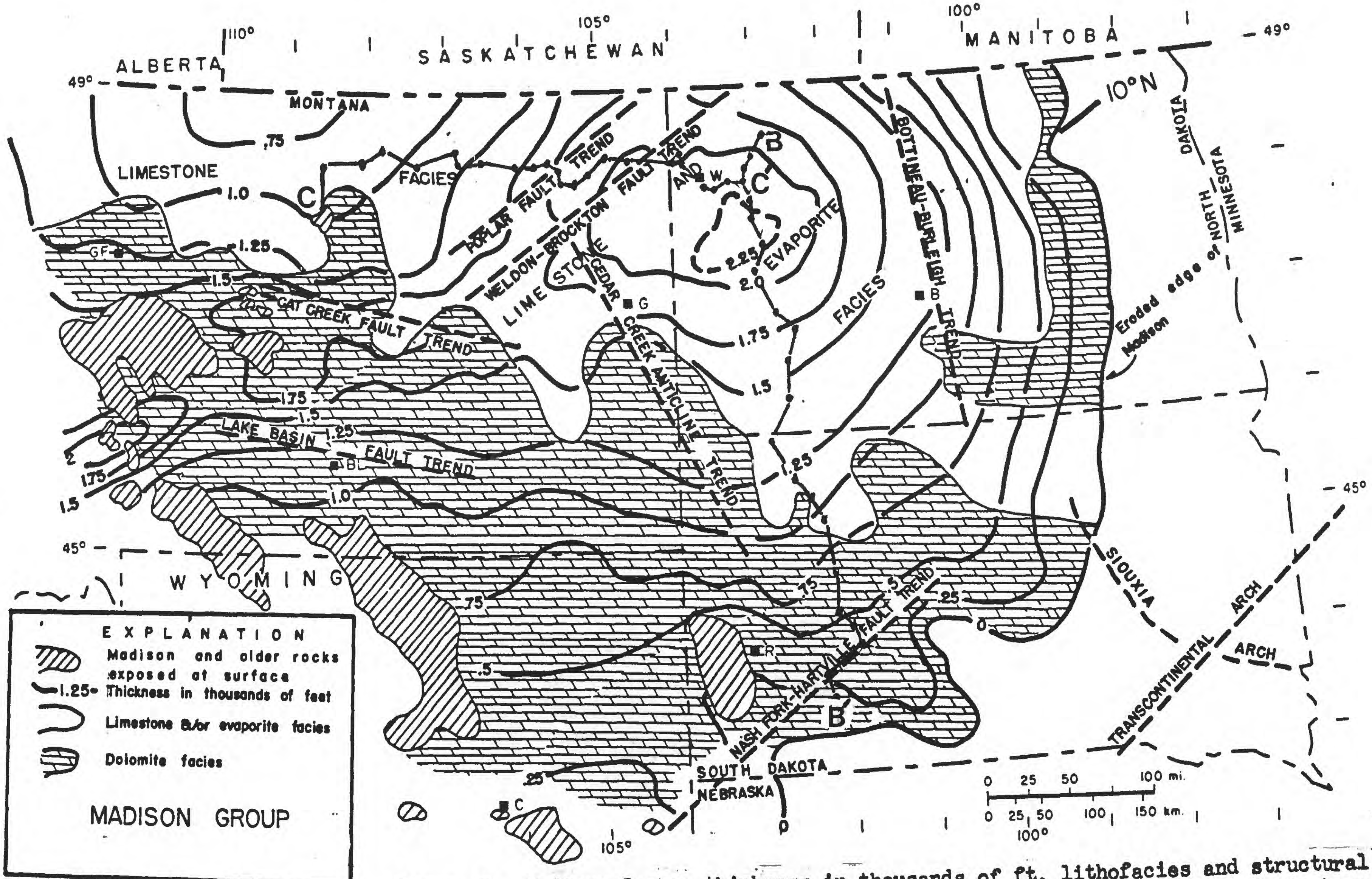

Figure 9. Madison Group; thickness in thousands of ft, lithofacies and structural trends. From Peterson, 1987. Lines of cross sections of figures 11 and 12 shown.

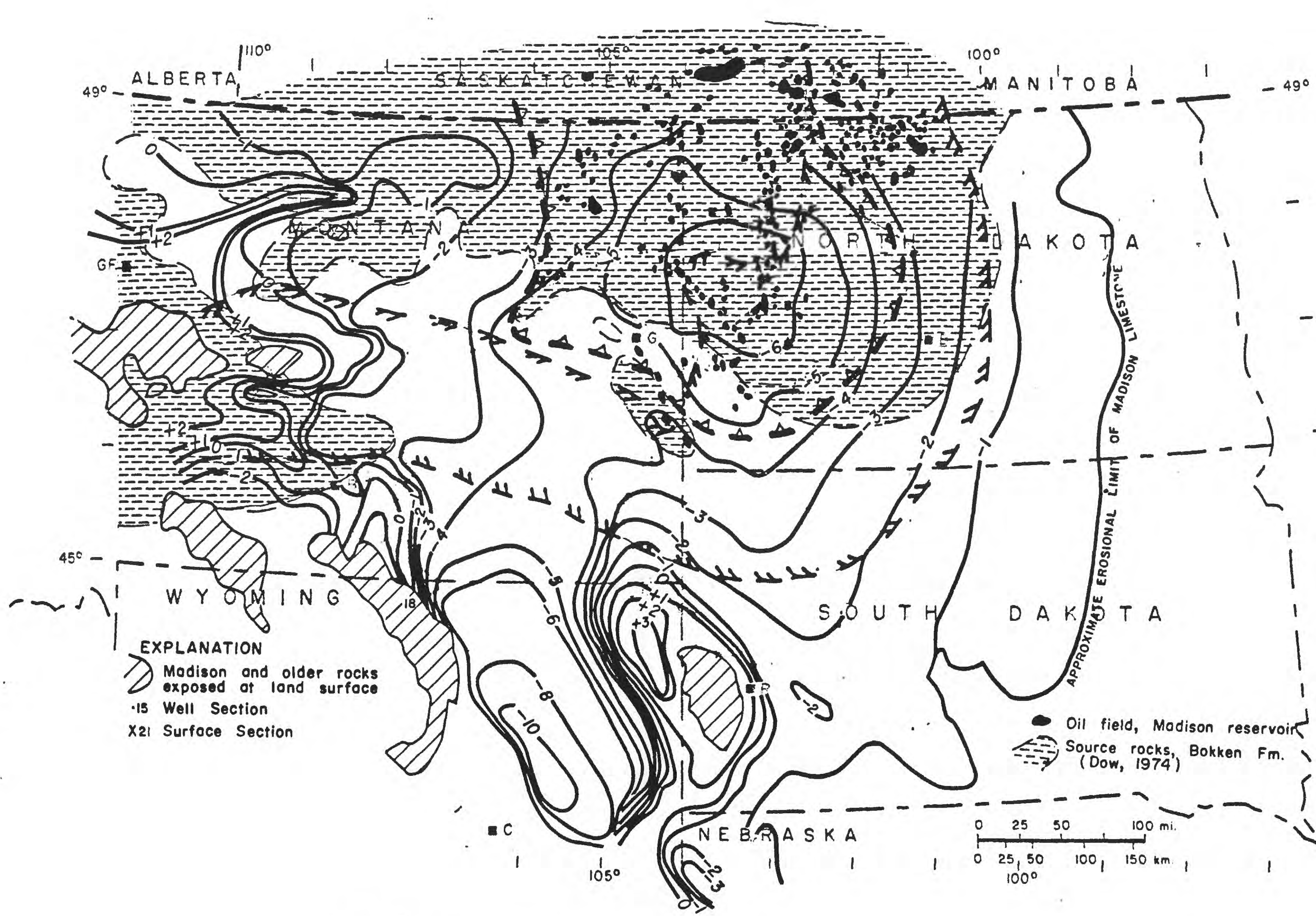

Figure 10. Structure contours in thousands of feet on top of Madison Formation. Areas of districution of Charles Salt (barbed line), middle Madison anhydrite (hachured line), and Bakken Formation facies are indicated to show relationship among oil pool accumulations, major source rock facies, and regional evaporite seals. Modified after Peterson and MacCary, 1987.

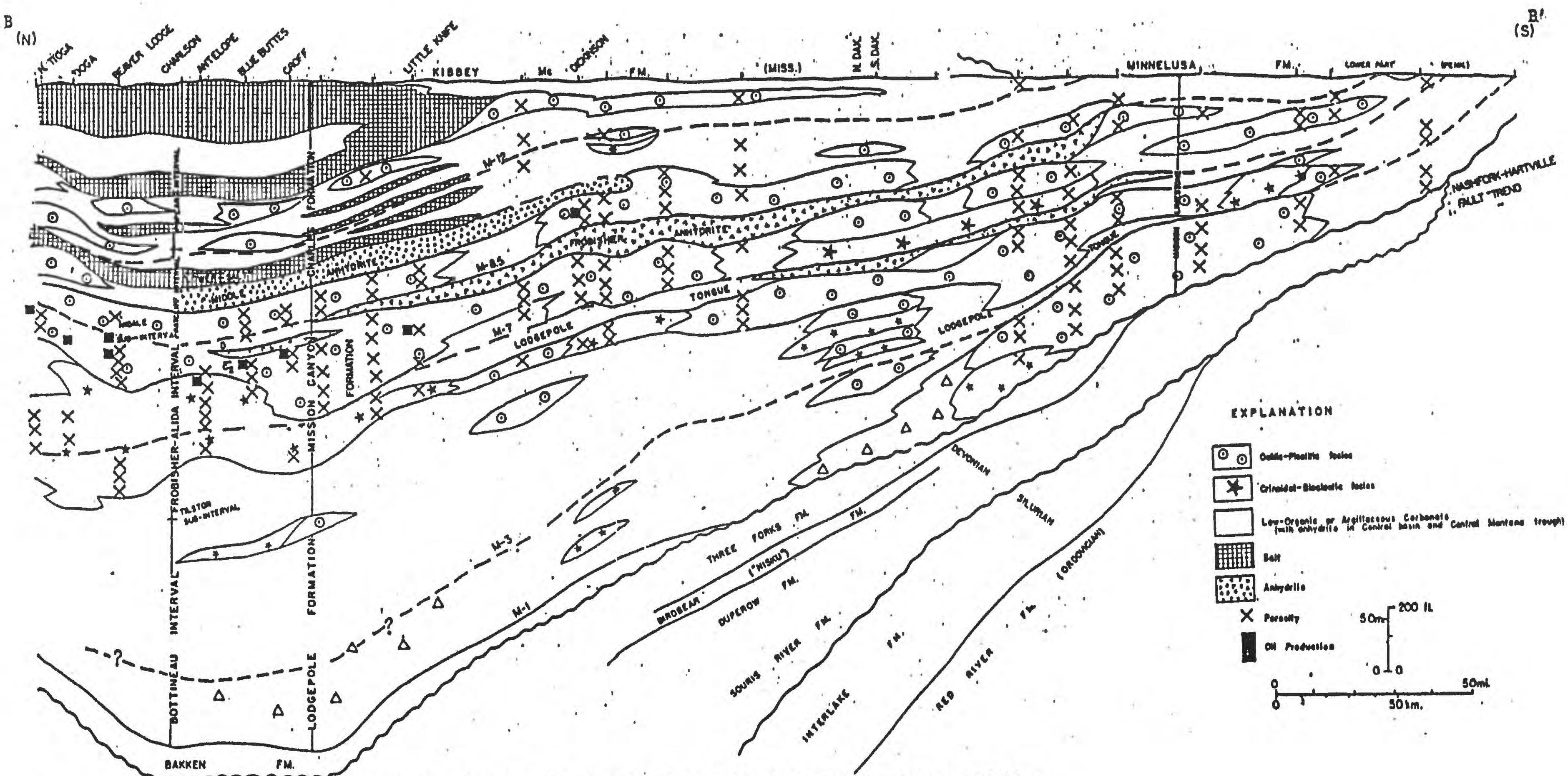

Figure 11. North-south stratigraphic cross section B-B', Nesson anticline to south-central South Dakota, showing Madison marker system, crinoidal and oolitic banks, and main evaporite beds. Location shown on figure 9. Approximate boundary of coral zones C-2 and D (Sando, 1978) is shown. From Peterson, 1987.

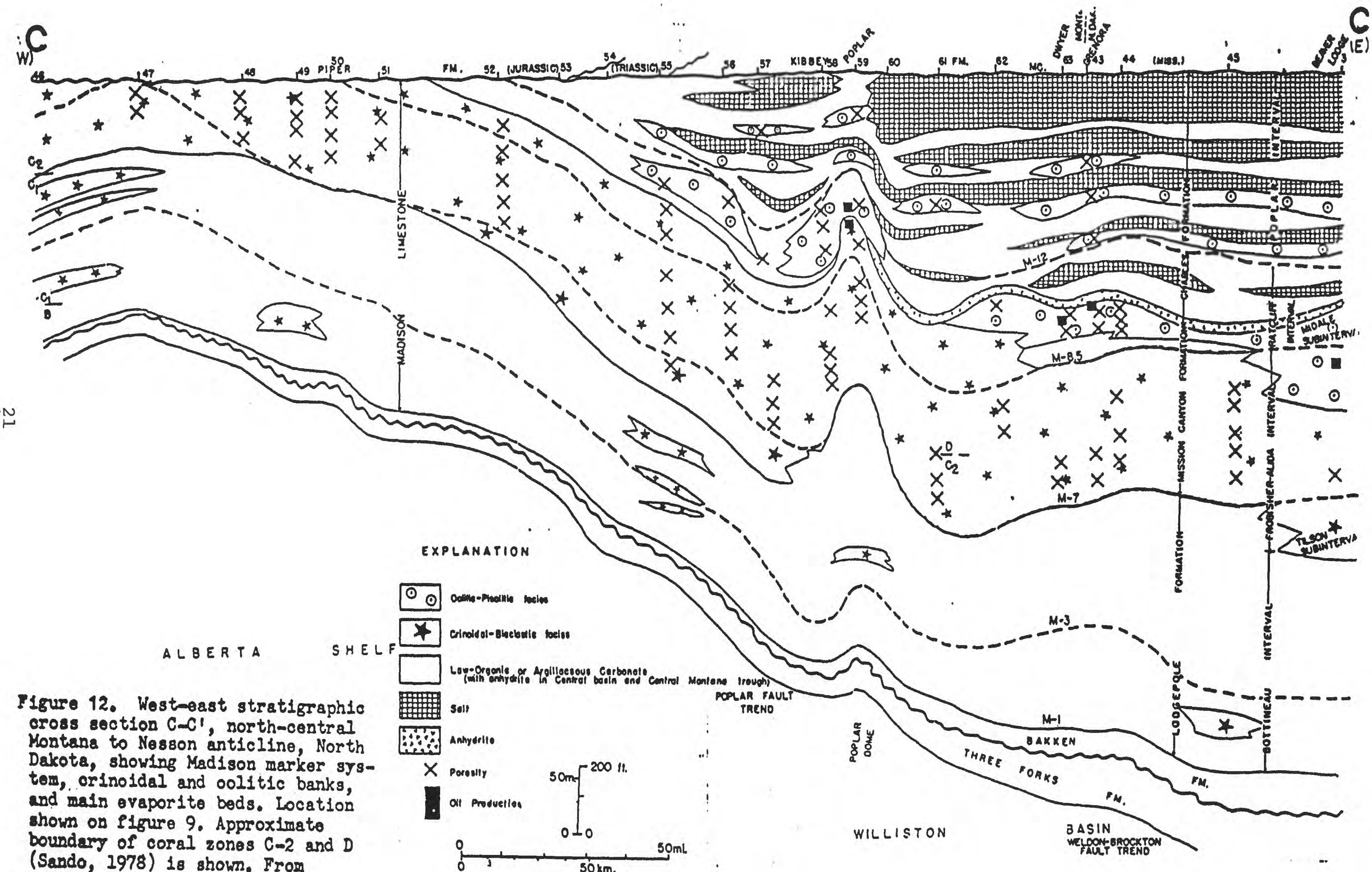

Figure 12. West-east stratigraphic cross section C-C', north-central Montana to Nesson anticline, North Dakota, showing Madison marker system, crinoidal and oolitic banks, and main evaporite beds. Location shown on figure 9. Approximate boundary of coral zones C-2 and D (Sando, 1978) is shown. From Peterson, 1987.

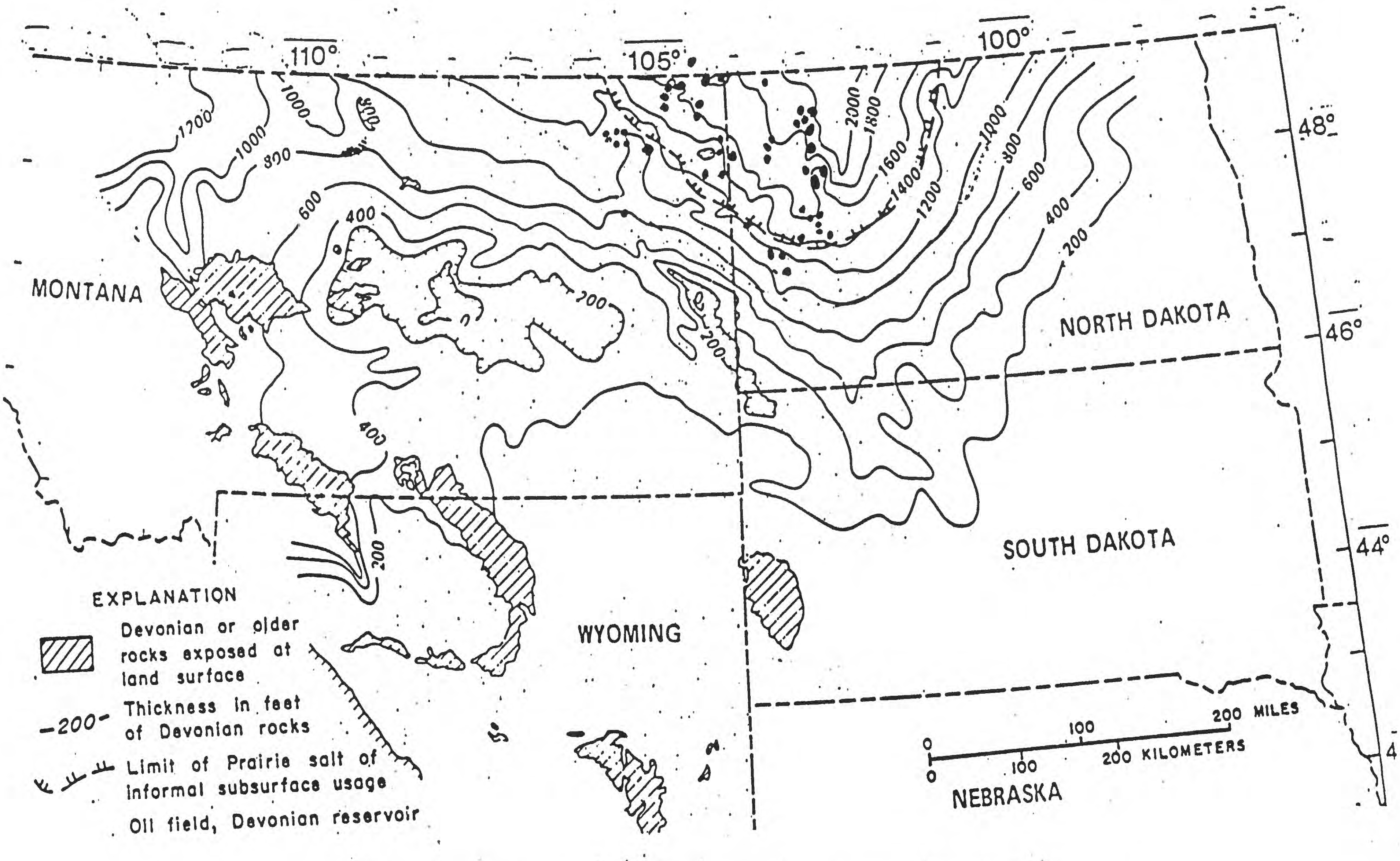

Figure 13. Thickness of Devonian rocks in feet, showing approximate limit of "Prairie salt" (Prairie Formation, Middle Devonian), and oil fields producing from Devonian reservoirs. Modified after Peterson and MacCary, 1987.

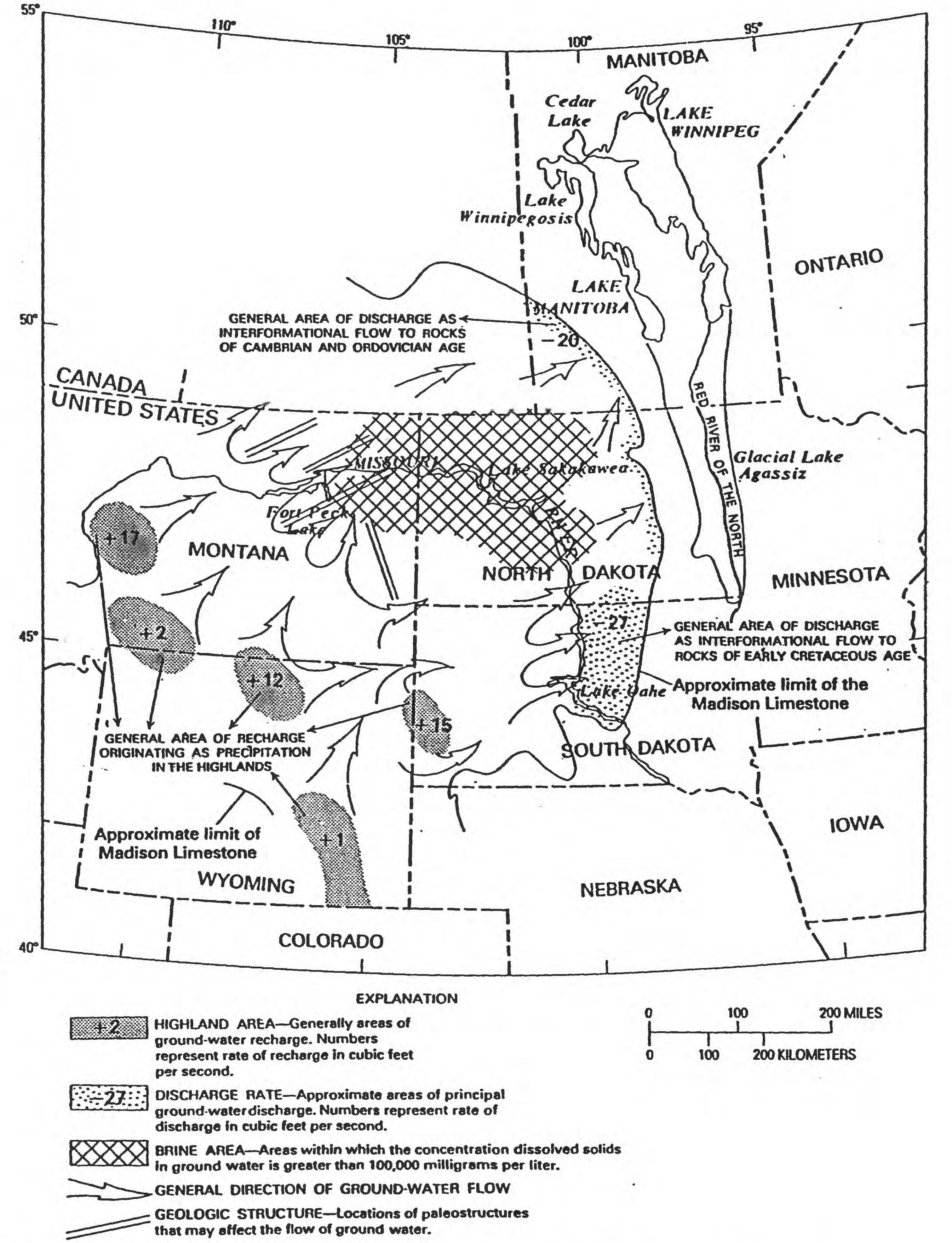

Figure 14. Conceptual model of groundwater flow in the Paleozoic aquifers of the northern Great Plains. From Downey, 1984.

Formations, cyclically interbedded with carbonate and evaporite beds. Dark marine shale and argillaceous carbonate beds are cyclically interbedded with porous Devonian dolomite beds, but they probably are of intermediate source rock quality.

Traps and Seals - Accumulations are found primarily in gentle folds and closures related to carbonate bank buildups overlain by cyclically interbedded anhydrite beds in the Mission Canyon and Charles Formations. Updip stratigraphic traps related to facies changes are common on the larger structures. Interbedded shale or argillaceous carbonates probably contribute to trapping in many cases, but evaporite beds make up almost all of the seals. The thick Charles salt at the top of the Madison section is a major regional seal in the basin interior. The largest traps and a major part of the reserves in this play are associated with major structures such as the Nesson anticline and Billings nose trends and the Poplar anticline (figs. 1, 3).

Generation, Timing and Migration - Oil generation probably began in the Madison Formation rocks by middle to Late Cretaceous time and probably has continued to the present. In most cases, migration was probably coincident with generation with some adjustment related to late structural growth.

Depth Range - 5,000 to 13,000 ft (1,650 to 4,300 m).

Exploration Status

This play is moderately to well explored, but use of refined seismic data probably will result in numerous additional new field or new pool discoveries, partly related to stratigraphic trap accumulations. Most of the new fields probably will be of moderate to small size, although there is potential for a few moderate to large sized accumulations. Federal lands in this play are moderately to well explored.

Cumulative Production - Approximately 685 MMBO (1/84); estimated 750 MMBO (1/85).

Estimated Ultimate Recovery from Existing Fields - Approximately 1 BBO, of which about one-third or more is in pools on the Nesson anticline.

Number of Pools - Approximately 325; 30 are greater than 10 MMB, about 12 are greater than 20 MMB, and about 5 greater than 50 MMB; largest is about 105 MMB, Mean pool size is 3.35 MMBO, 1.34 Bcf gas.

Mean Estimate of Undiscovered Petroleum Resources - 166.9 MMBO in fields greater than 1 MMB, 66.8 BCF gas in fields greater than 6 BCF.

Total area of play - 40,800 mi^2 (110,000 km2)

Area of Federal Lands - 20,400 mi^2 (53,000 k^2)

II. Northeast Basin Play

This is an oil play, which involves updip stratigraphic facies changes and pinchouts in Paleozoic reservoirs of Cambrian through Permian age beneath the Mesozoic unconformity, as well as basal Triassic sandstones above the unconformity (figs. 6, 10, 11). Fractured Precambrian basement rocks also are involved to a minor degree. The main part of the play is in updip facies changes of dolomitized skeletal and oolitic Mississippian Madison carbonates, which grade eastward to anhydrite, anhydritic carbonates and dense carbonates. To some degree, similar stratigraphic changes occur in the Devonian carbonate section. However, these and older beds are probably in vertical communication with Madison carbonate reservoirs almost everywhere, diminishing the prospects for separate traps in pre-Madison reservoirs, except where they pinch out against the Mesozoic unconformity. Furthermore, source rocks are generally lacking or of lesser quality in the pre-Mississippian rocks in this region. Oil accumulations in the Triassic basal Spearfish and the Cambrian sandstone reservoirs and in fractured Precambrian are small and related to migration of oil from Madison carbonate reservoirs and source rocks.

Progressively older beds are truncated by Mesozoic clastic rocks from west to east toward the margin of the basin. Potentially, this play covers the entire eastern flank of the basin and was one of the earliest major exploration plays of the basin during the 1950's. However, after being tested by numerous exploratory wells, it is now apparent that, except for north-central North Dakota and Saskatchewan, where all the known oil accumulations of this play are located, most of the eastern flank of the basin has been hydrologically flushed by waters primarily from the Black Hills Uplift in South Dakota (figs. 1, 14).

Geologic Characterization

Reservoirs - Important reservoirs are mainly dolomitized Madison oolitic, crinoidal, or bioclastic beds on the basin flanks. Updip truncated porous dolomite beds of reservoir quality also are present in the Ordovician Red River, Silurian Interlake, and the Devonian section. However, little or no accumulations are known in these beds, probably because of vertical communication with overlying Madison carbonate reservoirs and lack of good source rocks in the pre-Madison beds. Basal Triassic (Spearfish) sandstones are moderately porous, but accumulations depend on communication with underlying Madison reservoirs. Cambrian Deadwood and Precambrian accumulations are anomalous and small and probably are related to lateral fracture communication with Madison or other reservoirs.

Source Rocks - Organic-rich shale and siltstone of the Madison-Devonian Bakken Formation, mainly downdip, are the main source rocks. Dark gray or black moderately organic shale and argillaceous carbonate beds interbedded updip with Madison carbonate reservoirs are a secondary source.

Traps and Seals - Accumulations are present primarily in updip facies-related stratigraphic traps and gentle closure on carbonate buildups or mild tectonic folding. Seals are mainly upper Madison anhydrite beds cyclically deposited with the Madison carbonate beds. Triassic lower Spearfish red shale and perhaps Jurassic Piper red shale and evaporites provide effective seals in some cases.

Generation, Timing, and Migration - Oil probably migrated into these reservoirs from the west in slightly deeper parts of the basin where the Bakken and Madison source rocks are richer and thicker. Oil generation and migration probably began by middle to Late Cretaceous time and continued at least through middle Tertiary time. Stratigraphic traps were developed very early. Tectonically generated folding is very mild, and probably was fully developed by late in the Mesozoic or early Tertiary.

Depth Range - 3,000 to 6,000 ft (900 to 1,800 m)

Exploration Status

This play is moderately well explored, although numerous down-flank and other stratigraphic traps probably are undiscovered. Most of these will be of small to moderate size. Federal lands in this play are well explored, although very little Federal land is involved.

Cumulative Production - Approximately 95 MMBO (1/84); estimated 100 MMBO (1/85).

Estimated Ultimate Recovery from Existing Fields - 125 MMBO.

Number of Pools - About 75, of which about 25 are greater than 1 MMB and 5 are greater than 10 MMB; largest is about 20 MMB. Mean pool size, 1.34 MMBO, 0.52 Bcf gas.

Mean Estimate of Undiscovered Petroleum Resources - 9.8 MMBO in fields greater than 1 MMB, 2.9 BCF gas in fields greater than 6 BCF.

Total Area of Play - 7,500 mi^2 (19,500 km^2)

Area of Federal Lands - 1,250 mi^2 (3,250 km^2)

III. Red River-Interlake-Middle Devonian Play

This play, the second most important play of the basin, is an oil and associated gas play primarily related to accumulations in carbonate reservoirs of the Upper Ordovician Red River Formation (figs. 6, 15-17). Some oil has been found in uppermost Ordovician Stony Mountain carbonate reservoirs, some in Silurian dolomite reservoirs of the Interlake Formation, and some in Middle Devonian carbonate reservoirs of the Winnipegosis and Souris River Formations. However, these latter reservoirs are not associated with good source rocks and probably most of the accumulations are related to vertical migration from underlying Red River carbonate reservoirs, or in isolated cases to vertical or lateral fracture communication with Upper Devonian or Madison reservoirs.

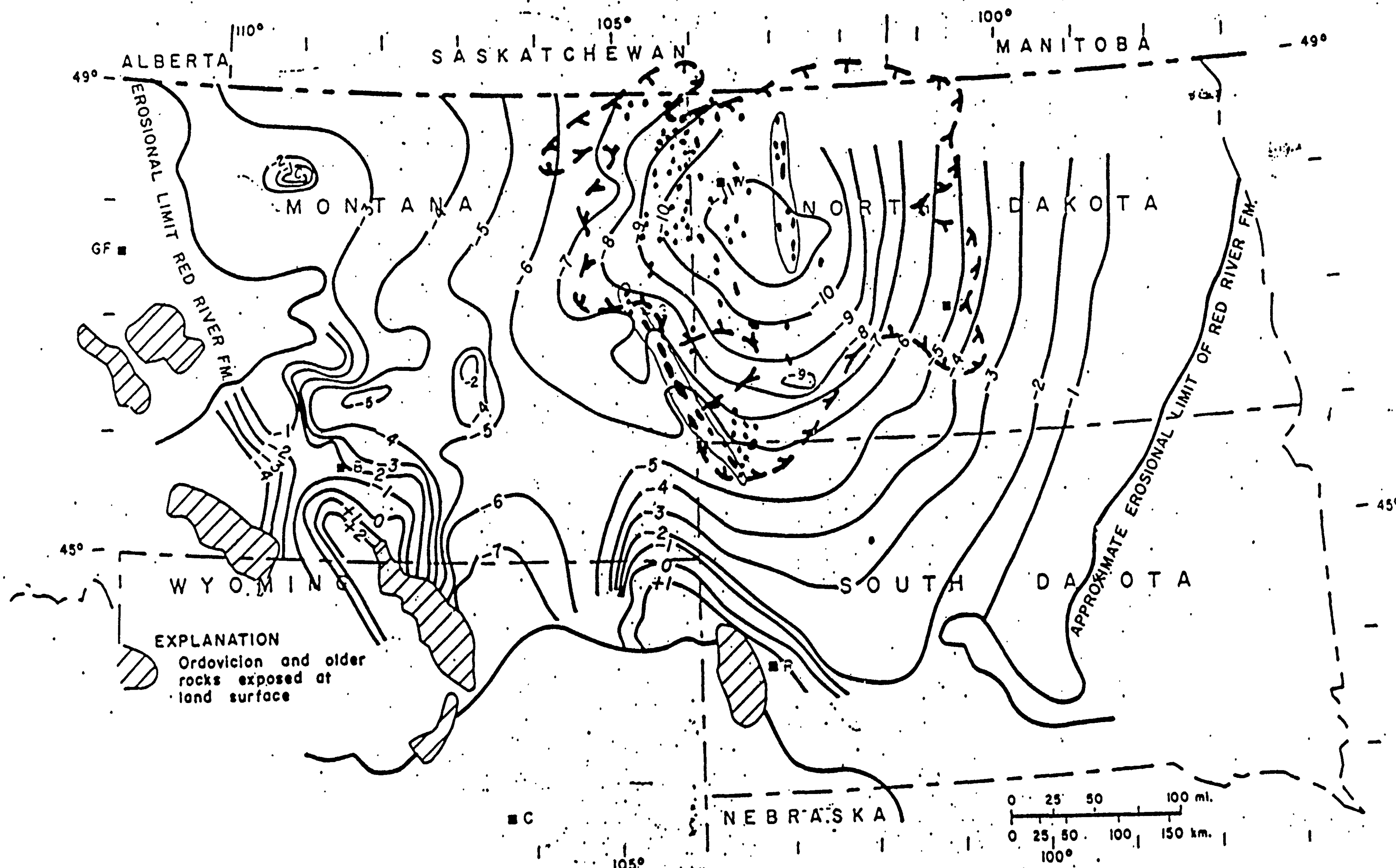

Figure 15. Structural contours in thousands of feet on top of Red River Formation (Ordovician). Area of distribution of upper Red River anhydrites is indicated by barbed line to show relationship among oil pool accumulations, upper Red River carbonate-evaporite-bituminous shale cycles, and regional evaporite seals. The two major structural trends in the basin (Cedar Creek and Nesson anticlines) are outlined (see fig. 1). Modified after Peterson and MacCary, 1987.

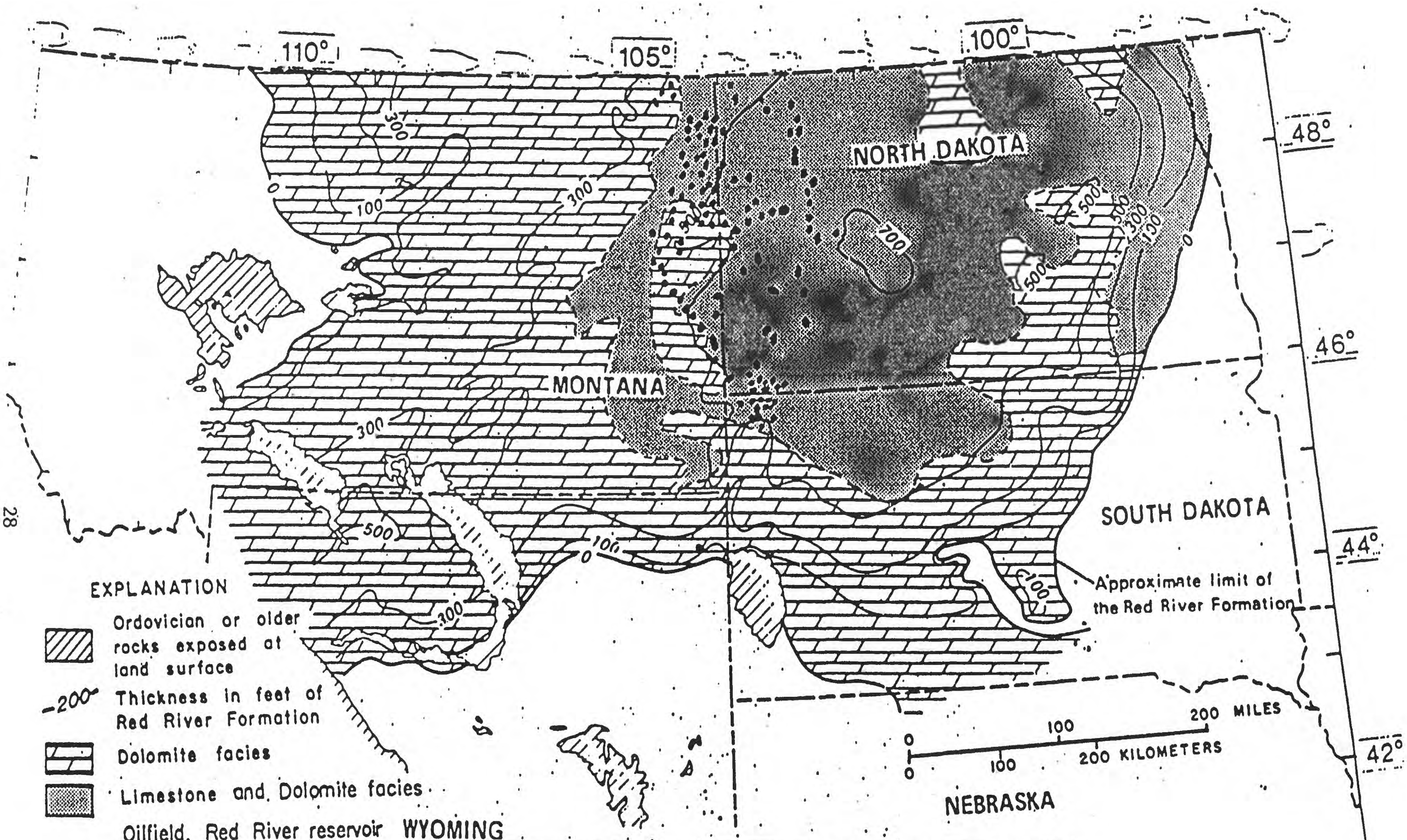

Figure 16. Thickness in hundreds of feet and generalized carbonate facies distribution for the Red River Formation (Ordovician) and equivalent rocks; U.S. portion of the Williston basin and adjacent areas. Oil fields producing from Red River carbonate reservoirs are shown. Modified after Peterson and MacCary, 1987.

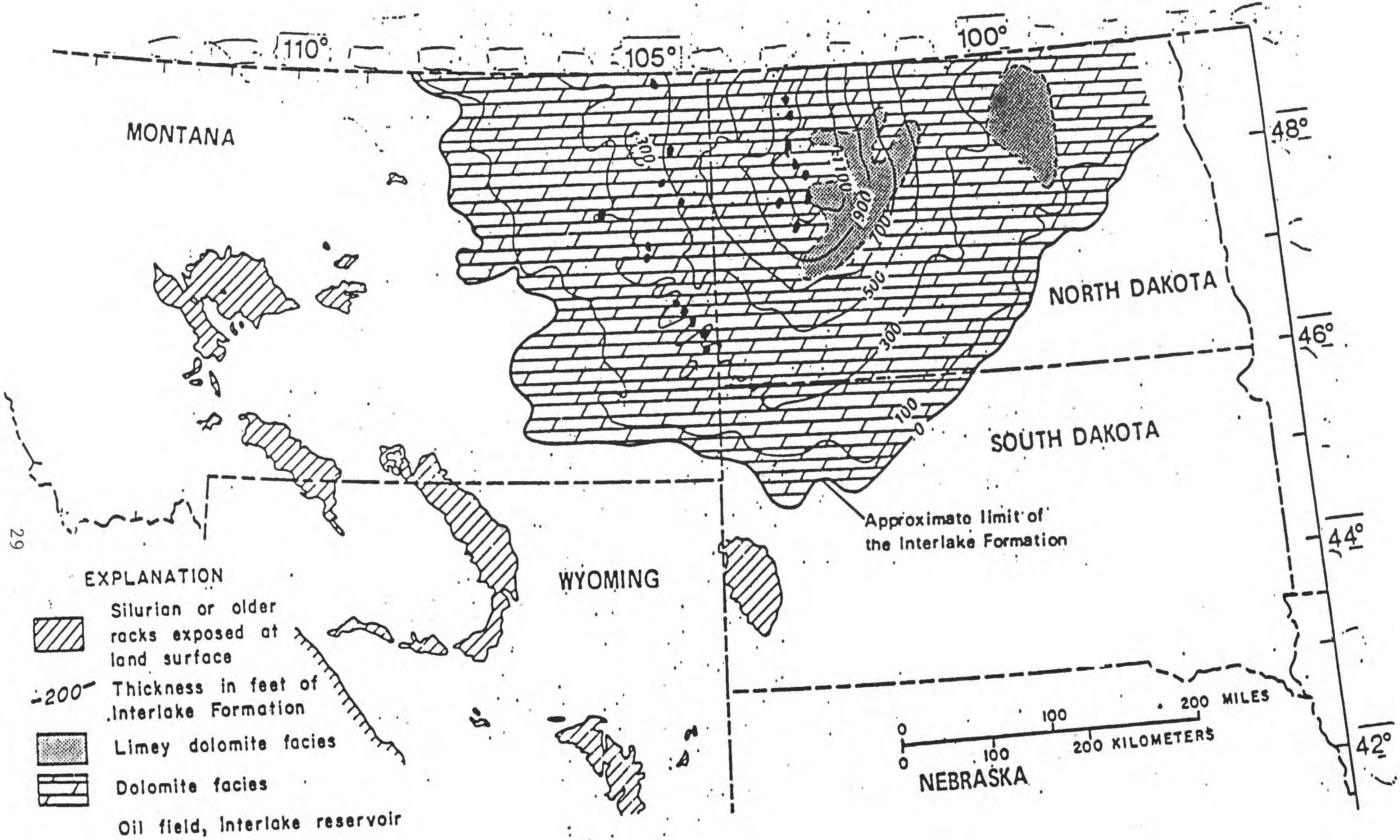

Figure 17. Thickness of Interlake Formation (Silurian and uppermost Ordovician) in hundreds of feet. Limy carbonate facies in east-central part of basin is shown. Formation is dolomite in remainder of area. Oil fields producing from Interlake reservoirs are shown. Modified after Peterson and MacCary, 1987.

Geologic Characterization

Reservoirs - Dolomite and dolomitic limestone reservoirs in cyclically deposited bioclastic carbonate and tidal flat dolomite beds in the upper part of the Upper Ordovician Red River Formation. Three main cycles are recognized, along with at least three additional carbonate-evaporite cycles in the overlying Upper Ordovician Stony Mountain Formation, from which minor production has been obtained in some fields. Silurian Interlake reservoirs are porous or fractured dolomite beds in the reefoid and tidal flat facies, which is present only in the subsurface of the interior basin. Middle Devonian Winnipegosis reservoirs are small dolomitized reef or mound buildups, capped by the Middle Devonian Prairie salt. Middle Devonian Souris River and Dawson Bay dolomitized cyclic beds are minor reservoirs in a few places where capped by the overlying upper Souris River shales or the basal Duperow shales.

Source Rocks - The main source rocks are organic-rich marine shales cyclically interbedded with carbonate and anhydrite beds in the upper Red River Formation. Shale beds in the overlying Stony Mountain Formation may be a secondary source. Some dark gray shale beds are present in the Middle Devonian Souris River Formation cyclic deposits but are not considered to be an important source.

Traps and Seals- -Major Red River traps are associated with the Cedar Creek anticline trend and to a lesser extent with the Nesson anticline and Billings nose trends. Many small fields are on gently draped rootless folds associated with Red River carbonate mound or bank buildups identified by refined seismic methods. Success ratio in drilling these anomalies is very high, although many are very small accumulations; some are one- or two-well fields. Interlake traps are mainly related to porous dolomite reservoirs trapped by updip porosity changes or by the overlying Middle Devonian Ashern Formation shales. Middle Devonian Winnipegosis reservoir traps are related to dolomitized reefoid buildups overlain by the Prairie salt. Dawson Bay and Souris River carbonate accumulations are mainly in dolomite reservoirs trapped by updip porosity changes and overlying Middle Devonian shales.

A major share of the reserves in this play are on the Cedar Creek Anticline, where the upper Red River anhydrite and bituminous shale section is not present. This oil probably migrated from the basin interior into the regional Cedar Creek paleostructural trend.

Generation, Timing, and Migration - Source rocks probably reached the oil generation stage by late Paleozoic time. Migration into early-formed dolomitized carbonate stratigraphic traps was probably coincident with generation. The main tectonic features were in place by late Paleozoic or early Mesozoic time, and minor reactivation probably took place during Laramide tectonism, which only mildly affected the basin.

Depth Range - 7,000 to 15,000 ft (2,100 to 4,500 m).

Exploration Status

This play is moderately well explored. Almost all of the large accumulations probably have been found. There is good potential for many additional small accumulations and a few moderate-sized ones, although these will require good seismic work and relatively deep expensive exploratory drilling, with a resulting lesser payout.

Cumulative Production - 365 MMBO (1/84); estimated 390 MMBO (1/85)

Estimated Recovery from Existing Fields - Approximately 700 MMBO, of which about half is on the Cedar Creek anticline.

Number of Pools - About 325, of which about 140 are greater than 1 MMB, 8 or 10 are greater than 10 MMB, 3 or 4 are greater than 20 MMB. Almost all large pools are in Red River Formation; largest is 115 MMB, next largest is approximately 87 MMB. Mean pool size, 2.33 MMBO, 2.33 BCF gas.

Mean Estimate of Undiscovered Petroleum Resources - 223.7 MMBO in fields greater than 1 MMB, 332.2 BCF gas in fields greater than 6 BCF.

Total Area of Play - 40,800 mi^2 (110,000 km^2)

Area of Federal Lands - 20,400 mi^2 (53,000 km^2)

IV. Post-Madison-Pre-Jurassic Play

This play is an oil and minor associated gas play involving primarily the marine and deltaic sandstone and shale with minor carbonate section of the post-Madison, Upper Mississippian Big Snowy Group and the Pennsylvanian Tyler Formation (figs. 6, 18). The overlying Upper Pennsylvanian, Permian, and Triassic sequence of redbeds, sandstones, and some carbonates is part of the play, although thus far no production has been obtained from this section. The Big Snowy and Tyler, the main section of interest, is present only in the central part of the basin.

Geologic Characterization

Reservoirs - Marine or deltaic discontinuous sandstone beds in the lower part of the Upper Mississippian Big Snowy Group and the basal part of the Pennsylvanian Tyler Formation are the main reservoirs. Carbonate beds in the upper part of the Big Snowy (Heath Formation) and in the Amsden Formation are minor producers.

Source Rocks - Dark gray and black organic-rich marine shales in the Tyler Formation are the main source rocks in North Dakota. Similar beds are present in the Tyler Formation in Montana. High-organic black shale and argillaceous dolomite are present in the Heath Formation in Montana.

Traps and Seals - Thus far, traps are mainly on anticlines with a strong stratigraphic trapping component. Isolated, perhaps small, accumulations may be expected in discontinuous Tyler sandstones but will be difficult to explore for.

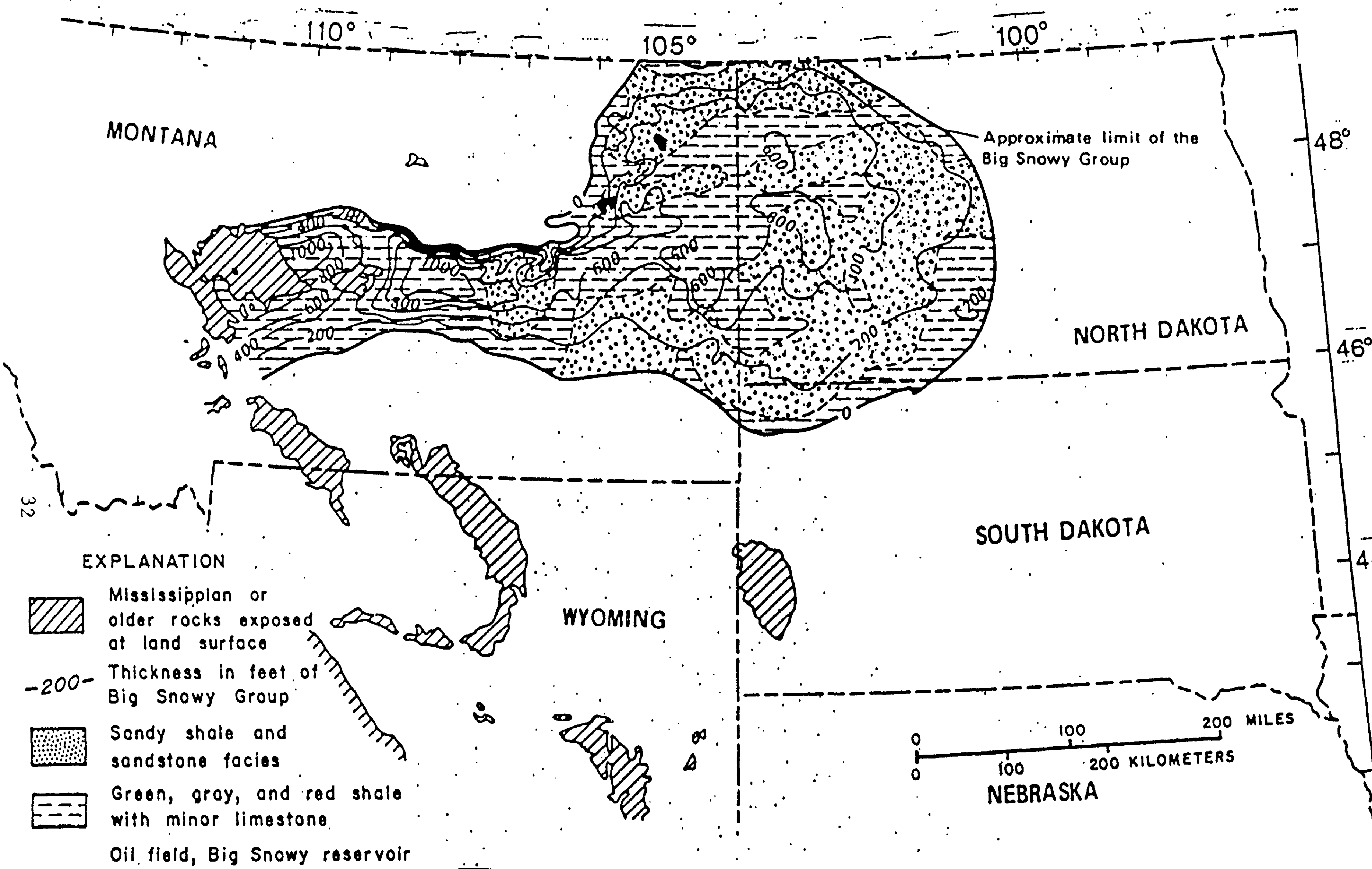

Figure 18. Thickness in feet and facies of Big Snowy Group (Mississippian). Modified after Peterson and MacCary, 1987.

Generation, Timing, and Migration - Tyler and Heath source rocks probably reached oil maturity by late Mesozoic or early Tertiary time in the deeper central part of the basin. Stratigraphic traps were formed very early, mainly by sandstone depositional processes. Structural traps were formed prior to early generation and migration, with only minor later modification. Generation and migration of oil from these source rocks probably is still underway.

Depth Range - 4,000 TO 8,000 FT (1,200 TO 2,400 M)

Exploration Status

This play is moderately well explored. Potential is fair to good for additional stratigraphic accumulations, but the discovery rate probably will be low and mainly related to accumulations found in drilling for other better prospects in the pre-Upper Mississippian carbonate section. Federal lands are moderately well explored.

Cumulative Production - Approximately 61 MMBO (1/84); estimated approximately 65 MMBO (1/85).

Estimated Recovery from Existing Fields - 75 MMBO

Number of Pools - About 20, of which 7 are greater than 1 MMBO, 2 are greater than 10 MMBO; largest is about 25 MMBO. Mean pool size, 1.74 MMBO, 0.17 BCF gas.

Mean Estimate of Undiscovered Petroleum Resources - 10.0 MMBO in fields greater than 1 MMB, 1.0 BCF gas in fields greater than 6 BCF.

Total Area of Play - 38,000 mi^2 (100,000 km^2).

Area of Federal Lands - 19,500 mi^2 (50,000 km^3)

V. Deep Basin Gas Play

During the past several years, gas has been found in Ordovician carbonate, sandstone, or quartzite rocks in several deep wells in the central basin region. The gas has a high H_2S content, and so far drill stem test flows have been variable, although some are quite high (as high as 5-10 MMCF/D).

Geologic Characterization

Reservoirs - Sandstone or quartzite beds, probably fractured, matrix porosity generally low, reservoir quality may be highly variable and related to fracturing of the Middle and Upper Ordovician Winnipeg Formation; dolomitized limestone beds of the Upper Ordovician Red River Formation, with variable porosity, some good porosity.

Source Rocks - Dark gray to black marine shale of the upper Deadwood Formation (Lower Ordovician part) and dark gray to black marine shales interbedded with Winnipeg sandstone beds. Shales are post-mature and in the gas window.

Traps and Seals - Mostly gentle folds of small closure. Carbonate traps are mainly stratigraphic, related to dolomitized mound or bank buildups of small vertical dimension, or to discontinuous sandstone bodies or variable fracture patterns in sandstones or quartzites. Ordovician shales may form seals in some cases. The anhydrite beds are the probable source of the high H_2S.

Generation, Timing, and Migration - Source rocks probably reached the oil generation stage by late Paleozoic time and the gas stage by Late Cretaceous or early Tertiary time. Stratigraphic traps and structure patterns probably were not changed substantially after the end of the Paleozoic, except for fracturing.

Depth Range - 13,000 to 16,000 ft (4,000 to 5,000 m) or slightly greater in places.

Comment - The deep gas play received considerable industry attention in the late 1970's, but is not being explored at this time because of high drilling costs related to depth of reservoirs, severe drilling and completion problems related to high H_2S content of gas, and the present low market price of sulfur. The play may become important in the future.

Exploration Status

This play is in the early stage of exploration. Gas had not been produced, except on DST. Federal lands are lightly explored.

Because of difficulties at the present time in separating this play from III, resource estimates are combined with play III.

Total Area of Play - 27,500 mi^2 (7,000 km^2)

Area of Federal Lands - 13,500 mi^2 (35,000 km^2)

SIOUX ARCH

The Sioux arch province extends along the northeastern portion of the Transcontinental arch and separates the Williston basin to the north from the Denver basin and Salina to the south; the Powder River basin adjoins on the west. Three tectonic subdivisions are recognized along the Sioux arch, from east to west: the Sioux arch proper or Sioux ridge, the Kennedy basin, and the northern part of the Chadron arch. Each subdivision is characterized by unique structural styles and by different Precambrian basement rocks. The Sioux ridge is a broadly positive feature underlain by Sioux Quartzite (approximately 1.2 by); the Kennedy basin is a slight downwarp lying west of the main arch and probably underlain by granite and gneiss (approximately 1.8 by); the Chadron arch is a Laramide feature situated off the south flank of the province (greater than 2.5 by). The Chadron arch portion of the province is included in a separate Powder River basin assessment. Two plays are recognized in the remainder of the province, one with shallow gas potential in Cretaceous rocks present in both the Sioux ridge and the Kennedy basin tectonic subdivisions. The second is a minor oil play in Paleozoic rocks preserved in the Kennedy basin.

Cretaceous Gas - During the Paleozoic and Mesozoic, the Sioux arch bordered the Williston basin on the southeast. Coarse Cretaceous clastics were deposited in the vicinity of the arch; marine shales and chalks dominated deposition in the thick overlying section. The play is limited on the east by extensive subcrops around the high part of the uplift overlain by Pleistocene drift and on the west by outcrops and subcrops on the Chadron arch and Black Hills uplift.

Unconventional gas in chalk and shelf sandstone reservoirs constitute the main potential of this play. Enclosing marine shales provide seals for these reservoirs; organic-rich, low-porosity shaly carbonates constitute reservoirs and seals and probably also are source rocks for biogenic gas generated shortly after deposition. Traps probably will be stratigraphic and structural. Some small conventional gas accumulations may be locally present in thicker Cretaceous shelf sandstones. The unconventional, tight chalk and shelf sandstone reservoirs are fairly continuous throughout the area. At least two chalk units are extensive, but shelf sandstones may be more localized in the eastern and western parts of the area. Reservoirs are generally less than 2,000 ft (608 m) deep.

The play is relatively unexplored, fairly speculative, and is defined by analogy with production in shelf sandstones of the western Williston basin and in chalk (Niobrara and Greenhorn) of the northeastern Denver basin. There is no gas production from Cretaceous rocks on the Sioux arch. Federal lands include large Indian reservations, where subsurface control is particularly sparse, and Federal grasslands.

Paleozoic Rocks, Kennedy Basin - Erosional remnants of Paleozoic rocks are preserved in the Kennedy basin, including Ordovician and Mississippian carbonate rocks that produce oil to the north in the Williston basin. The petroleum potential is defined on the basis of known occurrences of Paleozoic reservoirs; however, well control is very sparse. Consequently, distribution of Paleozoic rocks could be more widespread than currently documented, and correlation of specific lithostratigraphic units with productive units in the Williston basin is questionable.

The play is relatively unexplored and highly speculative. There is some possibility that Paleozoic oil could have migrated updip long distances out of the Williston basin. Potential reservoirs are generally at depths ranging from 2,000 ft (608 m) to 4,000 ft (1,216 m). There is no current production within the area and only a remote possibility exists for accumulations larger than 1 MMBO or 6 BCF gas. Two large Indian reservations are present.

The potential for significant oil or gas accumulations in the Sioux arch province, which includes the Sioux uplift, Kennedy basin, and northern Chadron arch areas, is considered remote, although some small localized accumulations of less than 1 MMBO or 6 BCF gas may be present. These are included with assessment figures for the Powder River, Williston, or Denver basin provinces.

SUMMARY

Petroleum exploration activity in the Williston basin falls into two main episodes, beginning in 1951 with the discovery of a Madison (Mississippian) oil pool at the Richey field in Montana and an Interlake (Silurian) oil pool at the Beaver Lodge field in North Dakota. During this early phase, which lasted through the 1950's, most of the major Madison accumulations of the basin were discovered along the Nesson anticline trend in North Dakota and the major Red River and Interlake pools on the Cedar Creek anticline trend in Montana. The relatively quiescent period during the 1960's and early 1970's resulted mostly in the discovery of smaller pools, less than 2-5 MMB, except for a few larger discoveries such as Goose Lake, Flat Lake, Dwyer, Medora, and Tioga (Madison pools) and Cedar Creek (N. Dakota), Fairview, and Tioga (Red River pools) (figs. 19, 20). The second main exploration phase beginning in the mid-1970's coincided with the major increase in oil prices at that time and lasted until the rapid decline in prices in the mid-1980's. Several large Madison pools were discovered during this period of intense exploratory drilling and high discovery rates, the largest of which was Little Knife (approximately 75 MMB) in North Dakota. Increased emphasis on deeper drilling at this time also resulted in discovery of a large number of Red River and Interlake pools, most of which tend to be somewhat smaller than the larger Madison pools. This discovery phase reached a peak in 1981, when at least 80 new pools were found in the Madison, Duperow, Red River, and Interlake (figs. 19, 20).

Mean undiscovered resources in the basin for all fields, including those less than 1 MMBO and less than 6 BCF gas, estimated as of 8/87, are 780 MMBO, 740 BCF natural gas, and 40 MMB natural gas liquids.

With somewhat over 6,000 exploratory wells having been drilled, much of the basin has been moderately well explored, particularly for the major structural prospects. Most of the remaining prospects probably contain a strong stratigraphic trapping component, and much of the potential involves deeper drilling. Prospects deserving particular attention in future exploration programs include the following considerations:

1. Carbonate buildups or porosity variations in the Ordovician Red River and Stony Mountain, Devonian Duperow, Winnipegosis, and Birdbear (Nisku), and Silurian Interlake units.
2. New pools, probably strongly stratigraphic-related, in existing fields of clusters of fields on structural trends.
3. Updip stratigraphic traps, primarily carbonate, related to porosity variations, evaporite sealing, or pinchouts on the eastern and southeastern basin flanks. Hydrology studies suggest that much of this region may be flushed by waters from the Black Hills (fig. 14). The region involves exploratory risk, but detailed hydrology studies and regional to semi-regional analysis of reservoir and other stratigraphic properties should enhance evaluation of these prospects.
4. Hydrodynamic traps in carbonate units of the basin interior, particularly those associated with porosity-permeability changes.

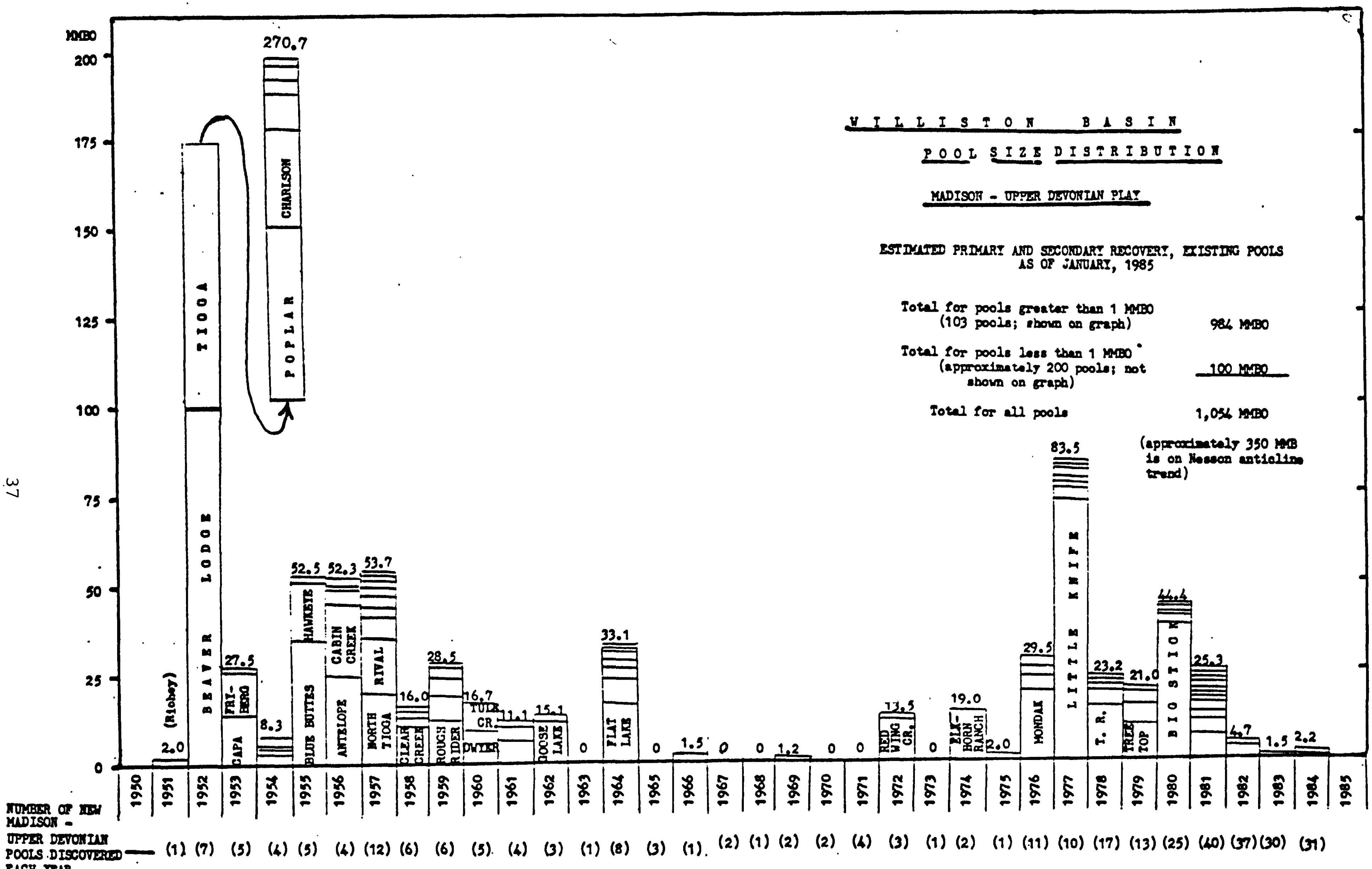

Figure 19. Pool size distribution, Play I, Madison-Upper Devonian, showing size distribution of existing pools greater than 1 MMBO, 1951-1984. Number at top of each column is estimated ultimate recovery from pools discovered that year. Total number of pools of all sizes discovered by year is shown at bottom of graph.

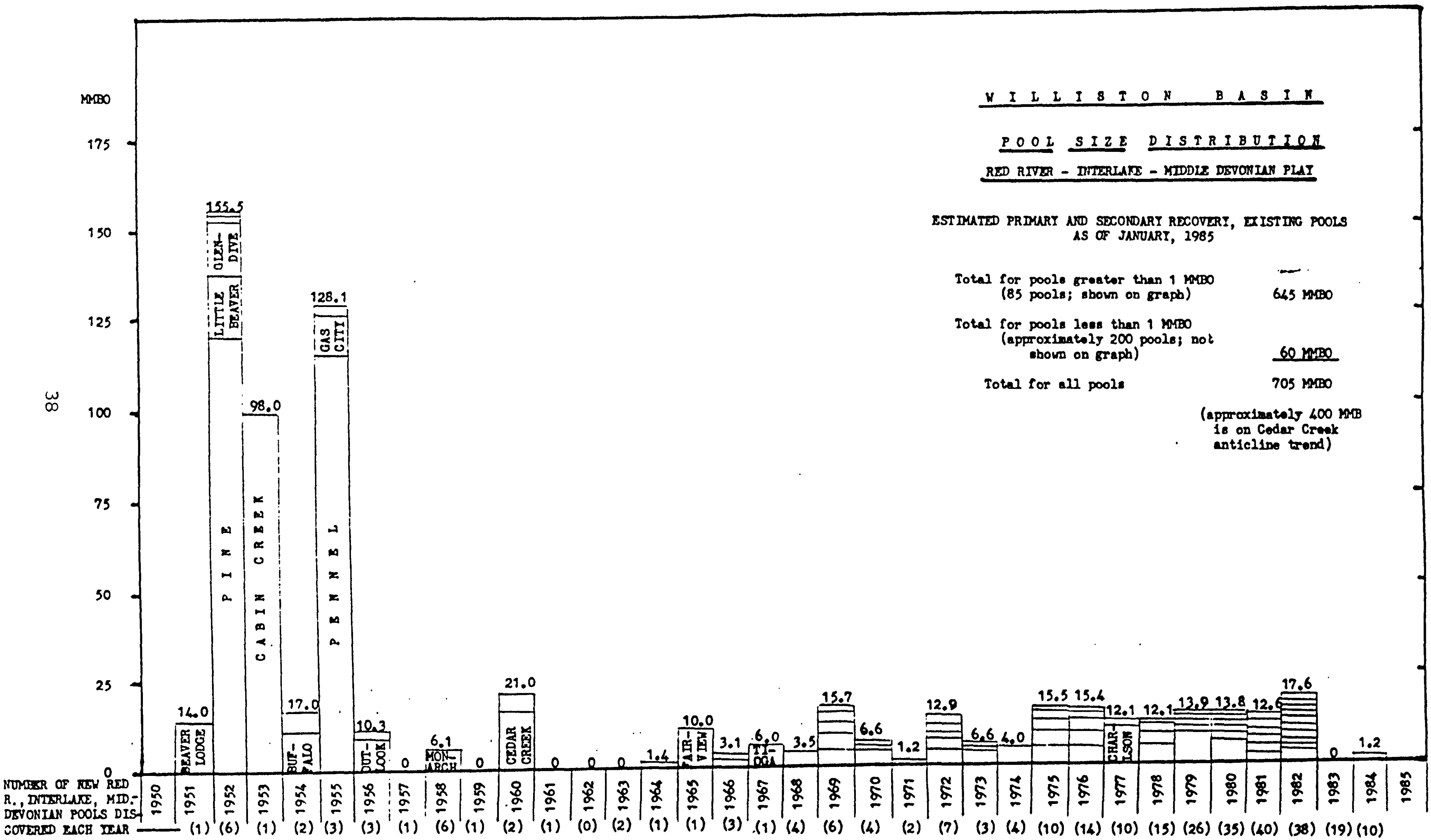

Figure 20. Pool size distribution, Play III, Red river-Interlake-Middle Devonian, showing size distribution of existing pools greater than 1 MMBO, 1951-1984. Number at top of each column is estimated ultimate recovery froom pools discovered that year. Total number of pools of all sizes discovered by year is shown at bottom of graph.

5. Subtle structural or combination traps associated with small-scale basement tectonics, faulting, salt solution, or draping over localized carbonate buildups. Refined geophysical work is required.
6. Deep basin gas, particularly in the Red River, Winnipeg, and Deadwood, in part associated with fracture trends.
7. Shallow gas deposits, perhaps mostly unconventional, in Cretaceous and Jurassic sandstone, siltstone, or calcareous units, particularly the Judith River, Eagle, Niobrara, Greenhorn, Muddy (Newcastle), Inyan Kara (Dakota, Fall River, and Lakota), and lignite or coalbed methane in the Fort Union beds.
8. Increased oil recovery from the organic-rich Bakken Formation. Recent successes in horizontal drilling enhance the possibility of substantial future resources from this and other hydrocarbon-rich units, particularly in the central part of the basin.

Many of the future discoveries likely will be relatively small and the success ratio may tend to diminish. However, applications of refined geophysical, geological, and hydrologic studies should result in addition of significant reserves to fit the existing price structure.

ACKNOWLEDGMENTS

This report includes only a brief geological summary of the Williston basin. More detailed analyses are found in the references listed, many of which were freely used in developing the geologic background for this resource assessment. Critical review with many useful observations and recommendations were provided by G.L. Dolton, R.B Powers, and D.D. Rice, U.S. Geological Survey. G.W. Shurr provided information on the Sioux arch province. Team assessment of petroleum resources was made by D.L. Dolton, R.F. Mast, C.D. Masters, R.B. Powers, and J.A. Peterson.

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