UNITED STATES DEPARTMENT OF THE INTERIOR

U.S. GEOLOGICAL SURVEY

Petroleum Geology of the Powder River Basin, Wyoming and Montana

by

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U.S. Geological Survey Open-File Report 88-450 P

This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards and stratigraphic nomenclature.

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1990

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INTRODUCTION

The Powder River basin of the United States is a major intermontane basin of Laramide origin in the northern Rocky Mountains and occupies northeastern Wyoming and a small part of southeastern Montana (fig. 1).

The basin is a deep, northerly trending, asymmetric, mildly deformed trough, approximately 600 km (250 mi) long and 160 km (100 mi) wide. Its axis is close to its western margin, which is defined by reverse faults and hogbacks of steeply dipping and overturned strata of the Bighorn Mountains uplift and by the Casper arch. It is bordered on the south by the Laramie and Hartville Uplifts where reverse or thrust faulting is important, and on the east by the Black Hills where strata are mildly folded and locally faulted along monoclines associated with the Black Hills Uplift. The northern margin is defined by the subtle northwest-trending Miles City arch.

The Powder River basin is filled with a thick sequence of Phanerozoic strata. Exceeding 5,500 m (18,000 ft) in thickness in the basin axis, this sequence is comprised of a relatively thin blanket of Paleozoic shelf carbonates, sandstones, and shales, rarely exceeding 650 m (2,100 ft), followed by a thick succession of Mesozoic and early Tertiary terrigenous rocks that record the evolution, fill, and destruction of the Western Interior seaway, uplift of the western cordillera, and development of local uplifts and the present intermontane basin.

The basin is one of the richest petroleum provinces in the Rocky Mountains. More than 2.5 billion barrels of recoverable oil have been discovered in reservoirs ranging in age from Late Paleozoic to Upper Cretaceous and in both structural and stratigraphic traps. The hydrocarbon associations or plays of the basin are the subject of this report, which provides a brief summary of the geologic framework used in the assessment of conventional oil and gas resources for this province, which are reported in USGS/MMS Open-File Report 88-373.

STRUCTURAL GEOLOGY

General

The Powder River basin is a large, asymmetric, intermontane downwarp which is situated just north of the Precambrian uplifts of the Hartville and Laramie uplifts and between the Black Hills and Bighorn Mountain uplift (figs. 2 and 3). The long-axis of the basin is near its western margin and extends from Montana into east-central Wyoming. Precambrian igneous and metamorphic rocks form a very wide eastern basin floor that dips gently into the basin from the Black Hills uplift. This floor is broken at its western edge into large blocks which are thrust and uplifted into the Bighorn Mountains, Casper Arch, and an associated folded basin margin. In these areas, structural relief up to 8,000 m (26,000 feet) is noted between the

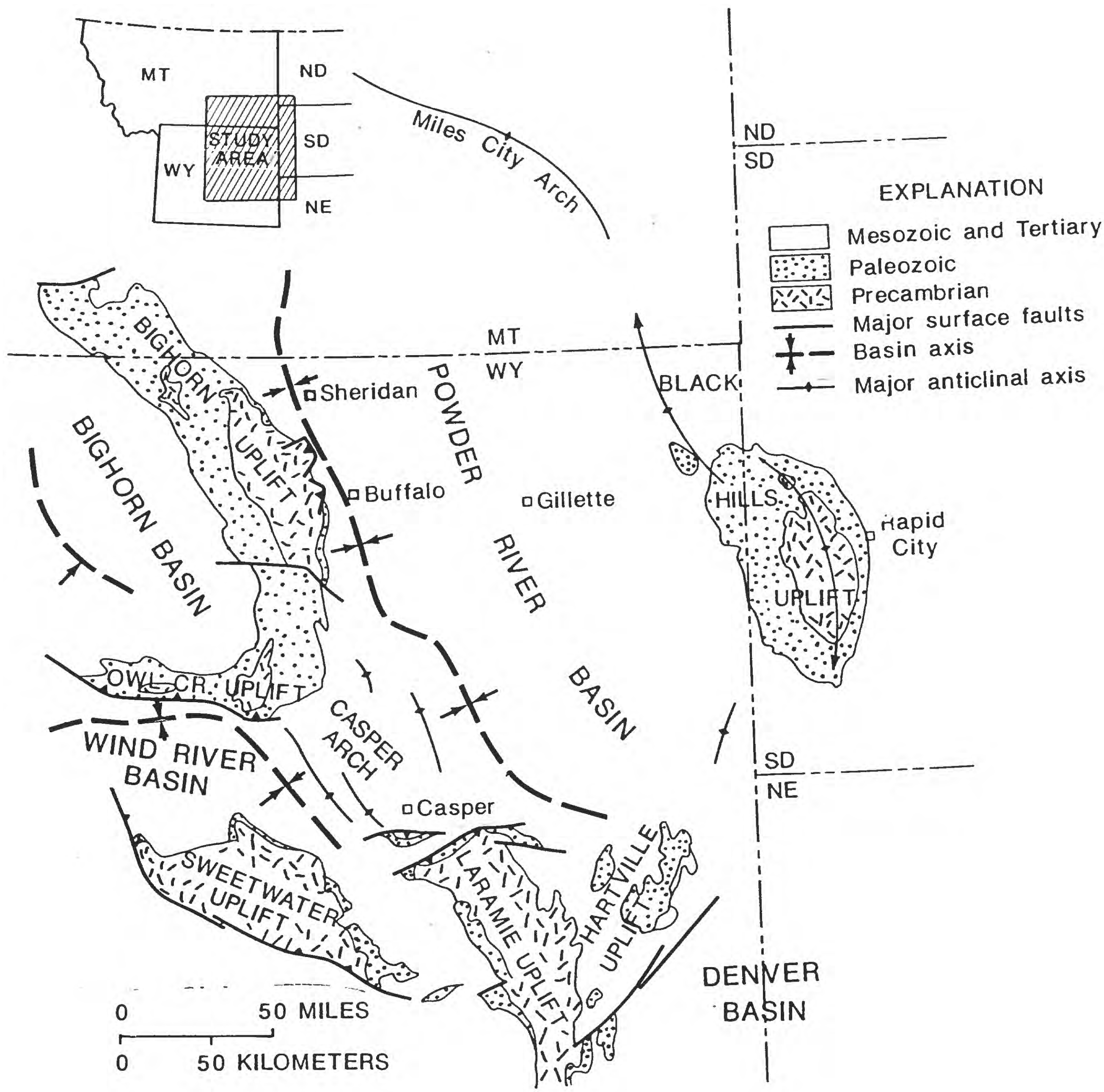

Figure 1.--Index map of Powder River basin showing major structural elements.

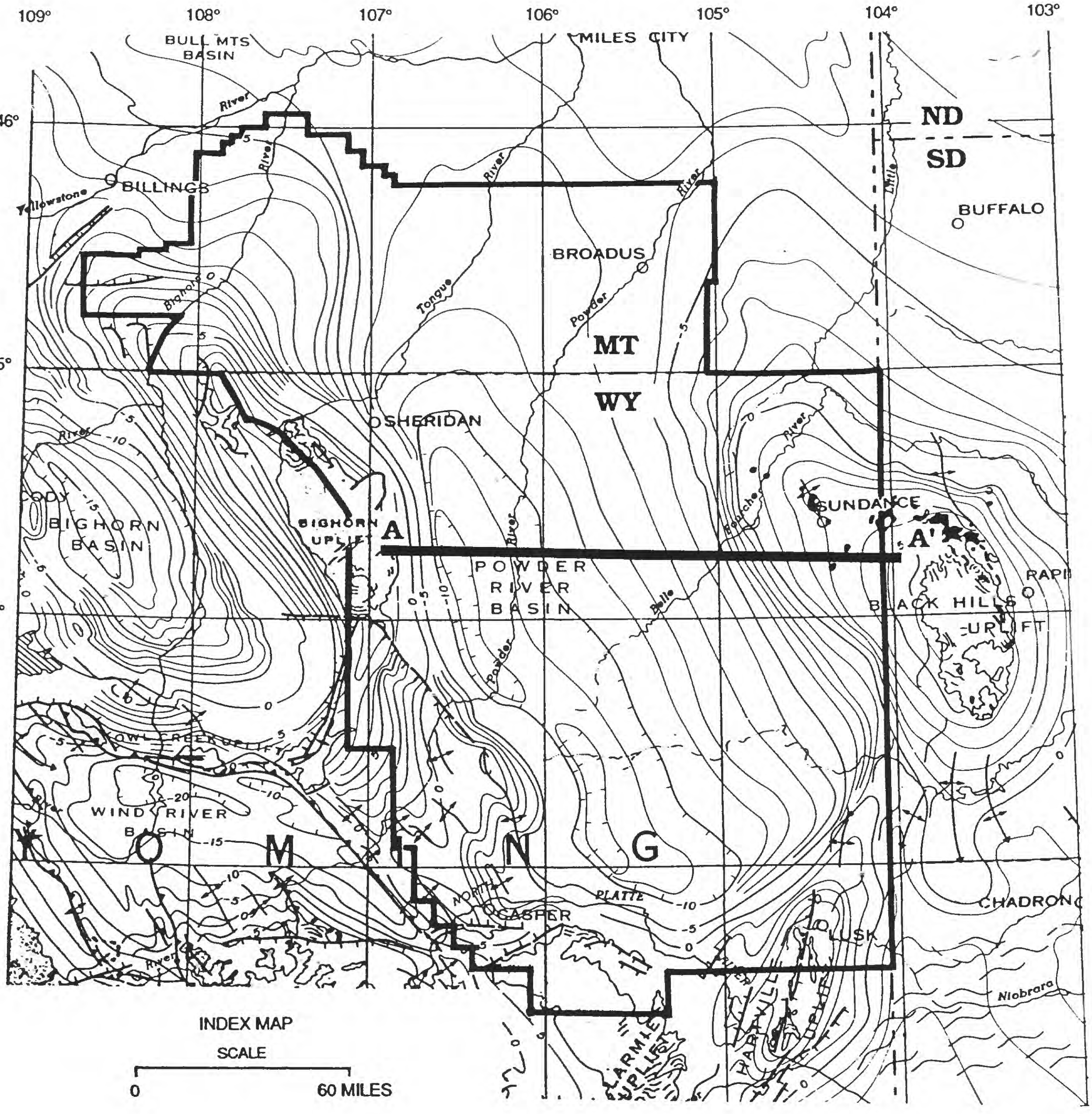

Figure 2.--Map showing structure on top Precambrian (after Bayley and Muehlberger, 1968). Structural contours in thousands of feet. Province boundary shown.

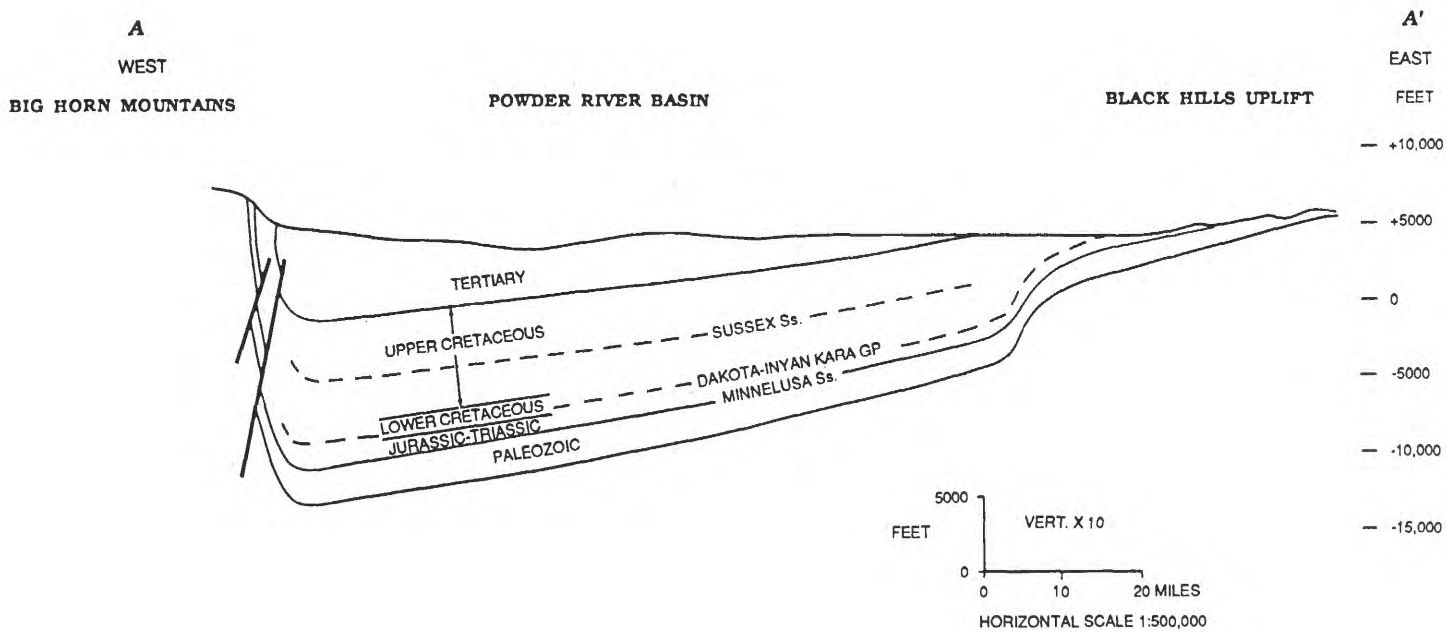

Figure 3.--Cross section of Powder River basin. Location shown on figure 2.

basin axis and crest of adjoining uplifts. Similar strong folding and reverse faulting and uplift is seen along the Laramie and Hartville Uplifts at the basin's southern margin.

Structural History

During the Paleozoic, the area of the present Powder River basin was a part of the Cordilleran shelf of the western edge of the Paleozoic craton. The region was stable through most of early Paleozoic time, with mostly broad warps or gentle depressions. Recurrent mild, early Paleozoic movement along basement zones of weakness, such as seen at Cedar Creek anticline in the nearby Williston basin, has been suggested (Maughan and Perry, 1986; Slack, 1981). In middle to late Pennsylvanian and early Permian time, this essentially stable shelf was broken up by orogenic events that produced the Ancestral Rocky Mountains, the fabric of which was influenced by older basement features. In the vicinity of the Powder River basin, late Paleozoic tectonism produced the Laramie Uplift, possibly an ancestral Bighorn uplift, and the Alliance or precursor Powder River basin. This was followed during Mesozoic by a long period of quiescence and relatively continuous sedimentation influenced by broad, low relief, regional arches and depressions, and ended with the advent of the Laramide orogeny.

Subtle pre-Laramide structural deformation in the interior of the Powder River basin may have influenced patterns of sedimentation and have had a control on oil entrapment. Chamberlain (1945) was one of the first geologists to postulate that the major folds in the northern Great Plains were intimately related to Precambrian basement fracturing of wide geographical extent. Slack (1981) suggested that virtually all of the stratigraphic production of petroleum in the Powder River basin can be directly related to subtle repetitive movements along linear structural trends representing faults extending upward from zones of basement weakness. According to Slack, the Belle Fourche arch extends southwest diagonally across the basin and is the major uplifted block in the basin. He states that movements along basement faults have been taking place perhaps since the Precambrian and have affected the occurrence of reservoir quality sandstones in strata as old as the Pennsylvanian and Permian Minnelusa Formation. Weimer and others (1982) also present evidence in support of recurrent movement of basement faults and its influence on development of reservoir-quality sandstone bodies in Lower Cretaceous strata of the east flank of the Powder River basin, and Rasmussen and Bean (1984) suggest a process of dissolution of Permian salt, influencing the growth and development of some of these Mesozoic sandstone bodies.

The present basin is the product of Laramide compressive forces. Subtle structural growth during mid-late Cretaceous is well documented by Merewether and Cobban (1986), however, the basin is fundamentally the product of later Cretaceous and early Tertiary structural growth. Laramide structural movements post-date deposition of the Lewis Shale (post-early Maestrichtian), which thickens to the south in the basin with no indication of tectonic activity (Curry, 1971). Thrusting along basin margin faults probably began during the late Paleocene or early Eocene, as evidenced by local unconformities and by conglomeratic debris shed into the basin (Jenkins 1986; Blackstone, 1981). Renewed uplift and downwarping occurred in Eocene and regional extensional adjustments occurred as late as the

Miocene. The major structural fields of the basin owe their origin to Laramide folding.

Structural Style

The style of Laramide structural deformation is the product of compressive forces and has been variously interpreted. Berg (1962) proposed that the uplifts were thrust and/or folded and thrust as a result of crustal compression; Stearns (1978) interpreted them to be forced folds resulting from dominantly vertical uplift. Drilling through the edges of several of the Laramide uplifts has revealed that they are bounded by thrust planes with dips in the range of 20 to 45 degrees (Gries, 1983), and work by Jenkins (1986) along the northeastern Bighorn Mountain front has substantiated low angle thrust planes. Jenkin's investigation has also revealed that the structural style is complex and that modifications of both Berg's and Stearns' models are necessary to interpret the structural geology of this area. Displacements along these thrust faults range from 3 to 10 km (2 to 6 mi).

To the south, a system of faults occurs along a broad structural terrace, the Casper arch. Folds on this structural terrace yield almost half of all the oil produced in the basin and include the giant Salt Creek anticline (fig. 4).

The steep south flank of the basin adjacent to the Laramie and Hartville uplifts may be structurally similar to the west flank. The eastern flank of the basin, however, is characterized by monoclines that formed adjacent to the Black Hills uplift as discussed by Lisenbee (1979; 1985). Here, Phanerozoic strata are drape-folded over basement blocks that were uplifted during the Laramide orogeny. It is not certain whether the faults in this area are high-angle normal, or reverse.

STRATIGRAPHY

The Powder River basin is filled with a sequence of Phanerozoic strata (fig. 5) which exceeds 5,500 m (18,000 ft) in the basin axis. It is composed of a relatively thin blanket of Paleozoic shelf carbonates, sandstones, and shales, rarely exceeding 650 m (2,100 ft), followed by a very thick succession of Mesozoic and early Tertiary terrigenous rocks that records the evolution, fill, and destruction of the Western Interior seaway, the uplift of the western cordillera, and the development of the local uplifts and present intermontane basin.

Pre-Pennsylvanian strata

During early to mid-Paleozoic, the area of the Powder River basin was a broad stable shelf along the western flank of the Paleozoic craton. It was the site of shallow water marine, cyclic sedimentation interrupted by episodes of erosion. Except for the Silurian, all of the early Paleozoic systems are represented and, except for Cambrian, these rocks are dominantly carbonate. Sedimentary processes were influenced to varying degrees by the growth of large low relief paleostructural elements, such as the Williston basin, and by subtle local features.

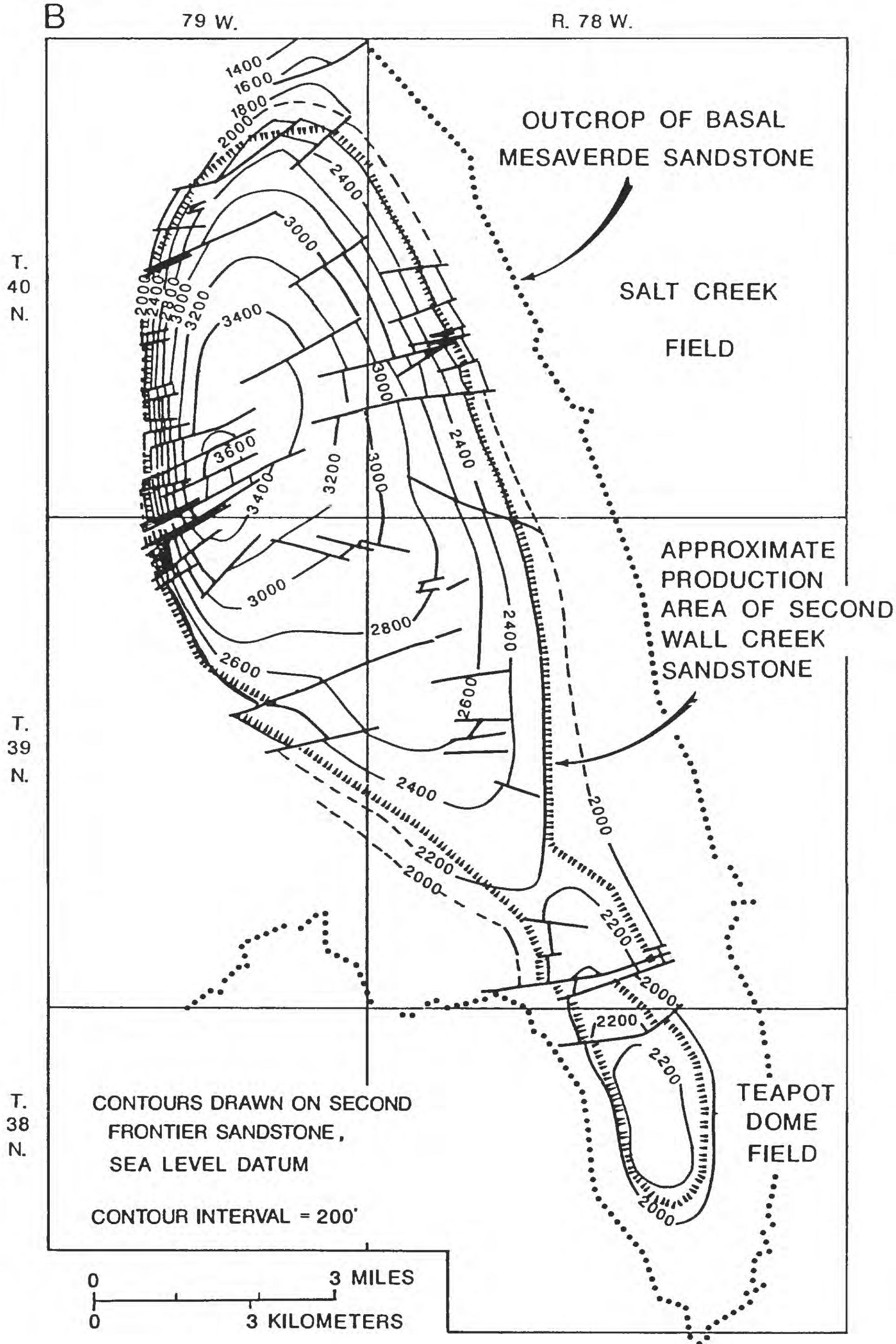

Figure 4.--Structure map of Salt Creek oil field (after Espach and Nichols, 1941).

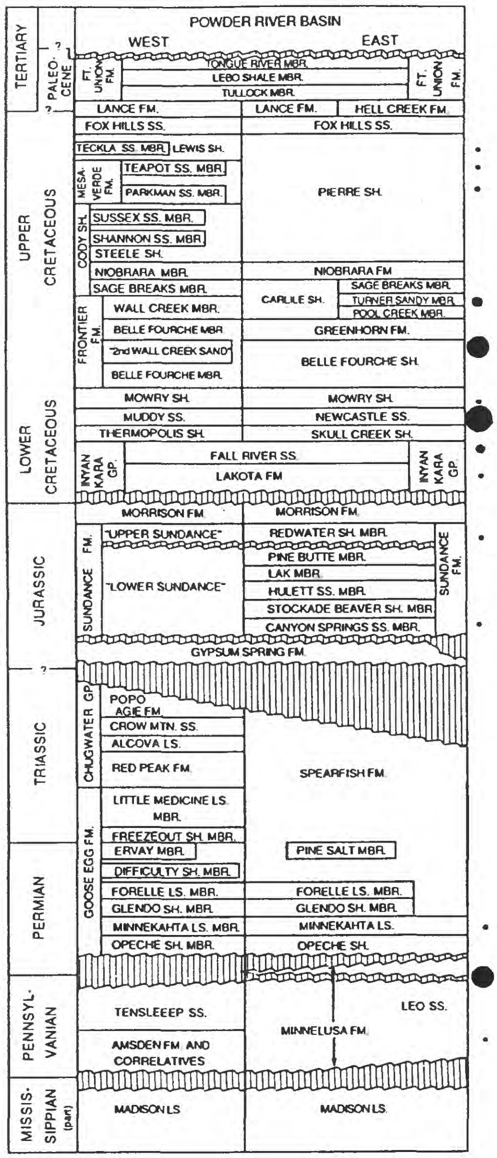

Figure 5.--Stratigraphic columns for the eastern and western Powder River basin, showing principal hydrocarbon bearing zones (size of circle proportional to importance).

In the Powder River basin, older Paleozoic rocks have not yielded significant amounts of petroleum. However, Pennsylvanian and younger beds, discussed in the following section, are major reservoirs for hydrocarbons.

Pennsylvanian and Lower Permian Strata

Pennsylvanian and early Permian (Wolfcampian) time was a period of major clastic influx, including marine, eolian, and alluvial deposits and is characterized by onset of the Ancestral Rocky Mountain orogeny. This orogeny produced uplift and subsidence of major basement blocks (Agatston, 1954; Mallory, 1967). In the immediate area, the Alliance basin formed, as did the high-standing Laramie Uplift, and probably the precursor Bighorn uplift. Worldwide eustatic sea level fluctuations also affected sedimentation and combined to produce the deposition of highly variable cyclothemic strata (Crowell, 1978).

Along the western side of the basin, rocks of Morrowan, Atokan and early Desmoinesian age consist of red mudstone and interbedded sandstone and cherty limestone of the Amsden Formation and are overlain by 30 to 150 m (98 to 492 ft) of white to tan crossbedded sandstone and sandy dolomite of the Tensleep Sandstone of late Desmoinesian and younger Pennsylvanian through Wolfcampian age (Mallory, 1975). At Casper Mountain, where the Pennsylvanian and early Permian are represented by sandstones of the Casper Formation, the Morrowan, Atokan, and much of the Desmoinesian strata, including the Amsden Formation, are absent.

The Minnelusa Formation comprises equivalent Pennsylvanian and Permian strata in the Black Hills and eastern Powder River basin (fig. 6). This formation ranges in thickness from about 100 m (330 ft) to more than 300 m (980 ft) and is correlated with the Hartville Formation to the south. It consists largely of interbedded sandstones, carbonates and evaporites, and subordinate shales. Unconformities within the Minnelusa and Hartville formations provide boundaries for lower, middle, and upper members (Maughan 1967, 1975; Lageson and others, 1979). The lower member is Morrowan and Atokan in age, the middle is Desmoinesian, Missourian, and Virgillian, and the upper member is early Permian, Wolfcampian age.

Uppermost Pennsylvanian and Wolfcampian rocks of the Minnelusa and Tensleep are absent in the northern part of the basin as a result of truncation by a profound regional unconformity of early Permian age. This unconformity bounds, variously, the Minnelusa and Tensleep Formations and is onlapped by a Permian and Triassic red-bed sequence of the Goose Egg Formation.

Sandstones of the Tensleep and Minnelusa formations are major oil-producing reservoirs within the basin. The Tensleep is productive, usually in structural settings; the Minnelusa is productive in both structural and stratigraphic settings. The oldest Minnelusa productive interval, informally called "Leo Sandstone", is in the Pennsylvanian middle part of the formation, and is separated from the major production of the Upper Minnelusa Formation by the "red marker zone". This terra rosa zone of oxidized red claystone and siltstone formed from subaerial exposure of strata during the time marking the systemic boundary between the Pennsylvanian and Permian.

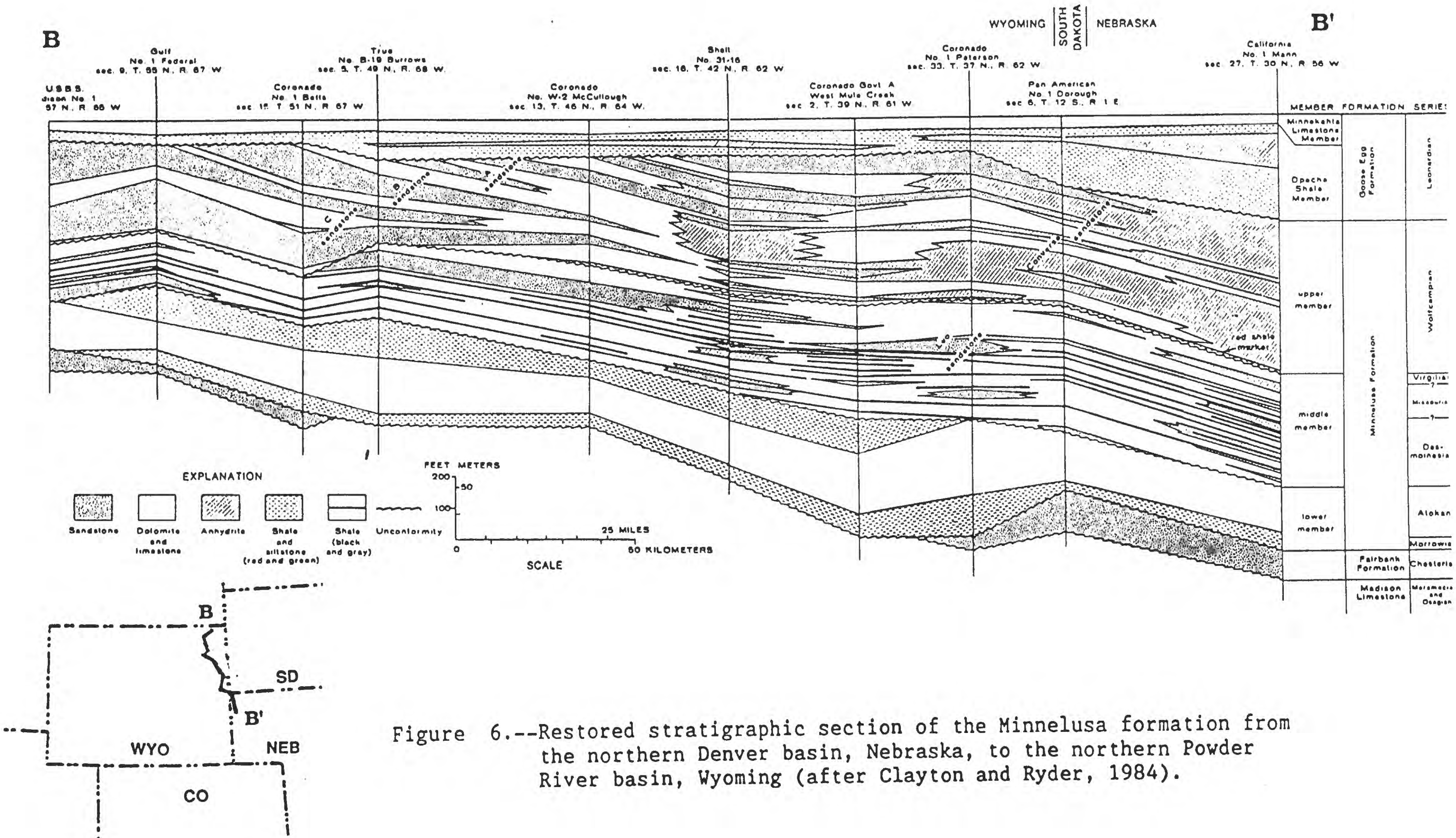

Figure 6.--Restored stratigraphic section of the Minnelusa formation from the northern Denver basin, Nebraska, to the northern Powder River basin, Wyoming (after Clayton and Ryder, 1984).

Upper Permian and Triassic Strata

The Goose Egg Formation overlies the Minnelusa Formation and is dominantly a red-bed seqeuence. It contains interbedded tongues of shale, siltstone, limestone, and salt. Members include from bottom to top, the Opeche Shale, Minnekahta Limestone, Glendo Shale, Forelle Limestone, Difficulty Shale, and Ervay of Permian age; and the Freezeout Shale and Little Medicine Limestone Members of Early Triassic age (fig. 5). Much of the Guadalupian and the Ochoan is missing (Schock and others, 1981) and the Permian-Triassic boundary is paraconformable within the formation. The upper members are sometimes included within the overlying Spearfish Formation. The carbonate beds are considered tongues of the Permian Park City Formation and Triassic Dinwoody Formation of western Wyoming. The sequence regionally onlaps the Minnelusa in a northerly to northwesterly direction (Maughan, 1967).

Triassic strata which overlie the Goose Egg Formation in the western and southern portion of the basin are designated Chugwater Group; equivalent strata of the eastern basin are included within the Spearfish Formation. Dominant lithotypes of red mudstones, siltstones and silty sandstones with thin beds of gypsum and limestone are as much as 245 m (804 ft) thick. The younger units are recognized only in the extreme southern part of the basin, having been removed by pre-Jurassic erosion elsewhere.

Although a small amount of petroleum is recovered from Triassic rocks, no substantial production is established. These rocks provide a regional seal for Paleozoic reservoirs.

Jurassic Strata

Jurassic strata rarely exceed a thickness of 215 m (705 ft) in the Powder River basin. They are entirely of Middle and Upper Jurassic age. Middle Jurassic rocks include the Gypsum Spring Formation, which occurs only in the northern one-third of the basin, and the lower Sundance Formation of Callovian age ("Lower Sundance Formation" of subsurface usage) (fig. 5). An unconformity at the top of this Middle Jurassic sequence is overlain by Oxfordian rocks of the upper part of the Sundance Formation ("Upper Sundance Formation" of subsurface usage) and are, in turn, overlain by the Morrison Formation of uppermost Jurassic age.

The Sundance Formation is present throughout the basin and is almost entirely clastic, consisting typically of dark gray and greenish-gray shales, glauconitic quartzose sandstone, and minor amounts of thin-bedded oolitic limestone. The sequence includes strata of both marine and non-marine origin and has been subdivided along the eastern side of the basin by Imlay (1947; 1980) into Canyon Springs Sandstone, Stockade Beaver Shale, Hulett Sandstone, Lak, Pine Butte, and Redwater Shale Members (fig. 5). Several of the sandstones are productive of oil and gas.

The Morrison Formation is composed of non-marine variegated shales and highly lenticular alluvial sandstones and conglomerates and is overlain by the Lower Cretaceous Inyan Kara Group. Morrison sandstones are infrequent petroleum reservoirs.

Lower Cretaceous strata

Lower Cretaceous strata occur throughout the basin, although they are typically less than 300 m (984 ft) thick. They represent continental and marine strata deposited during gradual transgression of the craton by a boreal Lower Cretaceous sea that occupied part of the western interior region. This seaway, part of the Western Interior Seaway, eventually reached to the Gulf of Mexico.

Wedges of continental, transitional and nearshore marine arenaceous strata, derived from the east, including the Fall River and Muddy Sandstones, intertongue with marine Skull Creek and Thermopolis Shales to the north and west (fig. 7). The initial Cretaceous deposit, the Lakota Formation of the Inyan Kara Group, is fluvial in origin and contains discontinuous sandstone bodies within varicolored shales. Strata of the succeeding Fall River Formation (informally "Dakota sandstone") are variously interpreted as fluvial, deltaic, estuarine, and nearshore marine and may comprise elements of all three of these depositional facies. The Fall River Formation is a major petroleum reservoir interval. Deposition of the Fall River marks the beginning of a prolonged period of marine deposition which prevailed with few interruptions until the seas finally withdrew near the end of the Cretaceous Period. "Dakota silt" describes a thin sequence of silty shale above the Fall River Sandstone and is usually considered part of the overlying Thermopolis or Skull Creek Shale. The Muddy, or Newcastle sandstone, is the single most productive reservoir in the Powder River Basin and consists of a highly varied complex of alluvial, transitional and marine rocks, resting on a regional unconformity at the top of the Skull Creek Shale.

The organic-rich, siliceous Mowry Shale, which overlies the Muddy Sandstone, marks the beginning of Upper Cretaceous (Cenomanian) deposition and is the single most important petroleum source rock in the basin. The contact between Lower and Upper Cretaceous strata is at a stratigraphic position within or near the base of the Mowry Shale (Cobban and Kennedy, in press).

Upper Cretaceous Strata

Upper Cretaceous rocks thicken from about 1,525 m (5000 ft) at the northern margin of the basin to about 2,745 m (9000 ft) at the southern margin. They represent a clastic wedge that prograded into the Western Interior seaway largely from the west. Within this wedge are major transgressive and regressive cycles which provide a basis for mapping (fig. 8) (Weimer, 1961; Gill and Cobban, 1966, 1973; McGookey and others, 1972). Deltaic, strandline, and shelf sandstones intertongue with marine shales, reflecting deposition in a seaway with an oscillating shoreline. This oscillation was due, in part, to episodic local tectonic movements, shifting deltaic depocenters, and eustatic sea level changes.

Upper Cretaceous strata are primarily shale, siltstone, and sandstone. Minor volumes of coal, limestone, marl, and bentonite are present. Marine shales are predominant in the eastern part of the basin and contain only one significant sandstone unit, the Turner Sandy Member of the Carlile Shale (fig. 5). Small sandstone bodies of the Shannon Sandstone Member of the

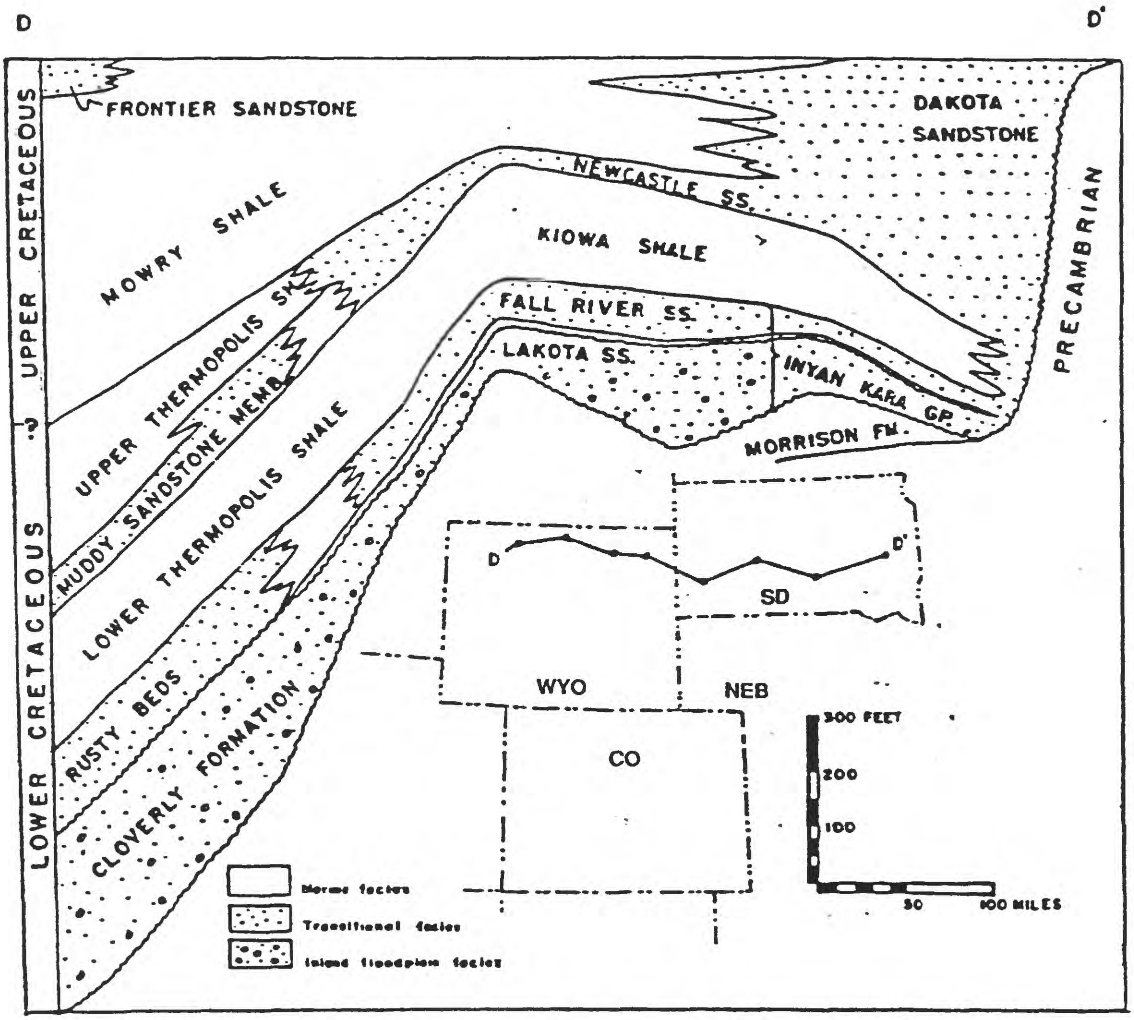

Figure 7.--East-west stratigraphic section of Lower Cretaceous rocks across northern portion of region (modified from Young, 1969).

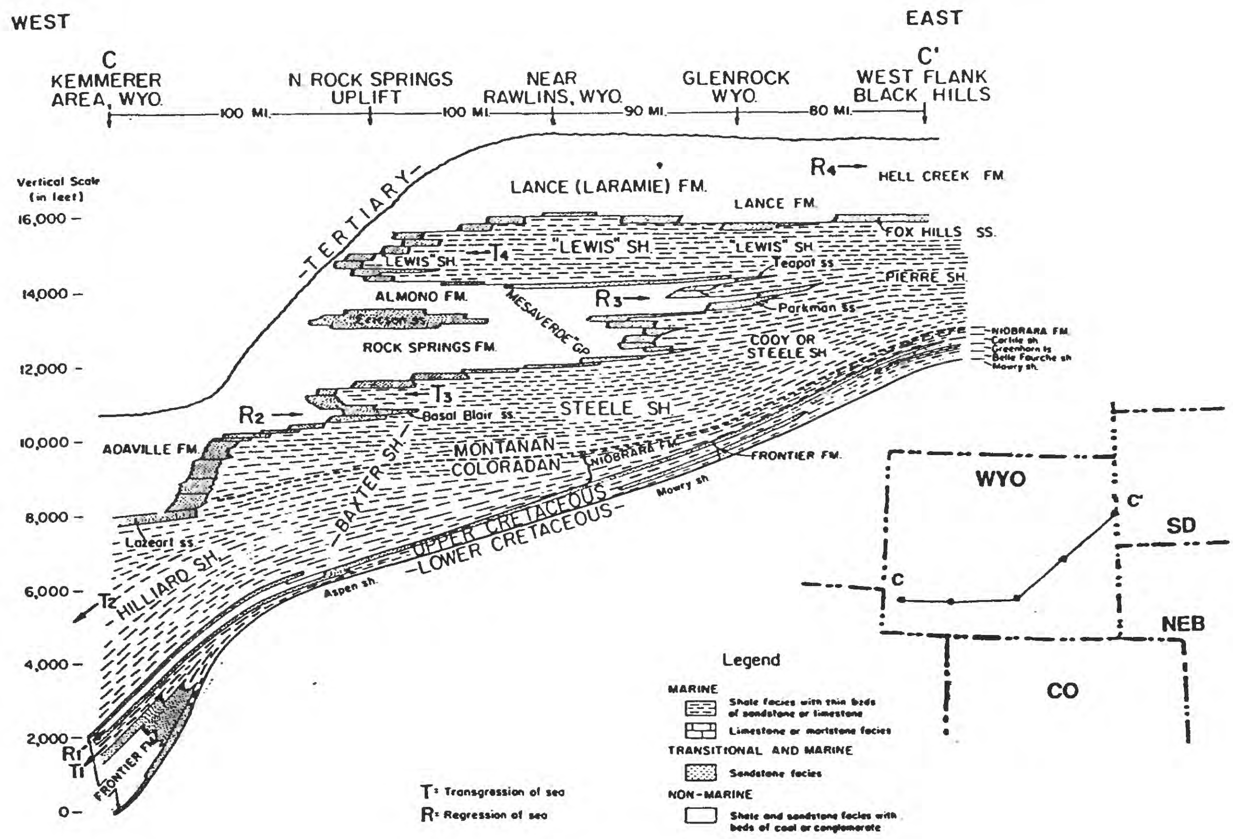

Figure 8.--Diagrammatic restored section of Upper Cretaceous rocks extending from southwest Wyoming to west flank of Black Hills in northeast Wyoming. Tertiary rocks regionally cover erosional surface of Cretaceous strata and diagram structurally distorts this surface (after Weimer, 1960).

Pierre Shale extend quite far east as reported by Rice and Shurr (1983). In contrast, the western part of the basin contains numerous sandstone beds, among them the "1st", "2nd and "3rd Wall Creek sands" of the Frontier Formation, the Shannon and Sussex Sandstone Members of the Steele Shale, the Mesaverde Formation (Parkman and Teapot Sandstone Members) and the Teckla Sandstone Member of the Lewis Shale. The Fox Hills Sandstone was deposited as the final phase of marine deposition and is overlain by the alluvial and paludal Lance Formation. The Upper Cretaceous sandstones provide major petroleum reservoirs.

THERMAL HISTORY AND PETROLEUM SOURCE ROCKS

The thermal history of the Powder River basin is directly related to the burial history of the basin (Fox, Dolton and Clayton, in press). Owing to burial beneath a thick Upper Cretaceous and Tertiary sedimentary sequence, petroleum source rocks of Early and Late Cretaceous age began expelling oil in early Eocene time (Momper and Williams, 1979). Thermal maturity measurements by Momper and Williams (1979, 1984) show that the pattern of thermally mature Cretaceous source rocks parallels the structural contours of the basin (fig. 9). Oil expulsion usually occurred above about 190° F (88° C), corresponding to present burial depths between about 2,438 m (8,000 ft) and 3,658 m (12,000 ft). Cooling probably occurred in some parts of the basin in the late Cenozoic because of uplift and erosion, invasion of relatively cool meteoric water, and possibly climatic cooling (Momper and Williams, 1984). Cooling by invasion of meteoric water is a possible explanation for the anomalously low present-day geothermal gradients observed in the deep part of the basin near the Big Horn Mountains. Movement of water into the west side of the basin along fault-plane conduits on the flank of the Big Horn uplift could have occurred more-or-less continuously since the Laramide orogeny. This would account for moderate thermal maturities of Cretaceous source rocks in the area despite relatively great burial depths (generally greater than 3,660 m or 12,000 ft). The existence of relatively low geothermal gradients in this area throughout much of the basin's history is also indicated by the occurrence of oil (instead of gas) at approximately 4,570 m (15,000 ft) in Paleozoic (Minnelusa Formation) reservoirs at Reno field (fig. 11, no. 38) and other fields in the basin axis. A higher geothermal gradient would have resulted in thermal cracking of oil to form mostly gas and condensate at these depths, especially in Paleozoic age source rock-reservoir systems. A similar structural and hydrodynamic setting associated with the Black Hills uplift may be the cause of the low geothermal gradients [1.4° F/100 ft (2.4° C/100 m)] along the west side of the Black Hills.

Another noteworthy feature of the present geothermal gradient distribution in the basin is the occurrence of relatively high gradients (approximately 2.0° F/100 ft) in the southeastern and northeastern areas. In the southeastern part of the basin, high heat flux coincides with the Hartville uplift and is probably related to loss of sedimentary cover through erosion during and after the uplift. Here, an abrupt increase in geothermal gradients from less than 1.8° F/100 ft (3.1 C/100 m) to greater than 2.0° F/100 ft (3.5° C/100 m) occurs across the fault system bounding the north side of the Hartville uplift, with the higher gradients occurring on the uplifted side of the faulted area. No explanation is generally

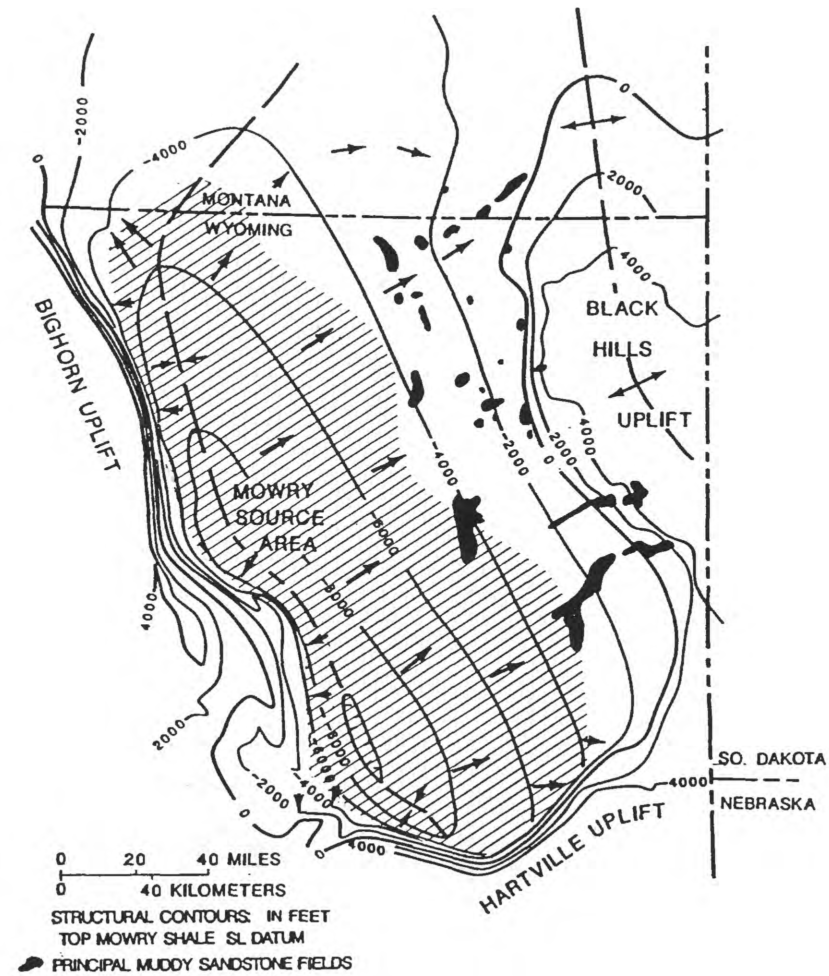

Figure 9.--Map showing distribution of Mowry source rocks (hachured) (after Momper and Williams, 1979).

agreed upon for the area of high geothermal gradients in the northeastern part of the basin (greater than 2.0° F/100 ft (3.5° C/100 m)).

Figure 10 shows reconstruction of the burial history and calculation of time-temperature index (TTI) values according to the methods of Lopatin (1971) and Waples (1980) for the Superior Government-Tracy #1 well (Meissner, F. F., personal communication). Located near the basin axis in the area where thermally mature Cretaceous source rocks occur, this well illustrates the relationship between thermal history in the basin and generation of oil. The TTI calculation of figure 10 is based on the present geothermal gradient and does not consider possible compactional effects or temporal changes in the geothermal gradient. Some minor erosion (approximately 305 m or 1,000 ft) is estimated to have occurred. As the burial history diagram and TTI calculations show, the episode of Late Cretaceous-early Tertiary sedimentation and attendant burial heating was critical for maturation of source rocks in the basin. The calculated TTI and measured vitrinite reflectance data show that the Minnelusa Formation is in the wet gas zone of thermal maturity at this location. This observation supports the hypothesis discussed previously that a lower geothermal gradient must have existed throughout much, if not all, of the post-Laramide period in the area east of the Big Horn uplift in order for oil to have been preserved in Minnelusa Formation reservoirs at burial depths in excess of 4,500 m (15,000 ft).

Burtner and Warner (1984) studied the potential for hydrocarbon generation from the Cretaceous Mowry and Skull Creek Shales in this region. The Mowry and Skull Creek Shales were found to contain a mixture of types II and III organic matter. Because it has a generally higher proportion of type II material, the Mowry is a better petroleum source than the Skull Creek Shale. Momper and Williams (1984) estimate that the Mowry Shale may have expelled about 11.9 billion barrels of oil.

According to Momper and Williams (1984), the Niobrara Formation and Carlile Shale, collectively, are also a major source of oil found in Upper Cretaceous reservoirs. However, the areal extent of effective source rocks in these formations is less extensive than the deeper Mowry Shale. Also, data of Momper and Williams (1984) indicate that the Lower Cretaceous Fuson Shale and Upper Cretaceous shale in the Frontier and Steele Formations have expelled oil in amounts secondary to the major Cretaceous source rocks. Based on limited data they estimate the Frontier may have expelled 0.8 billion barrels of oil.

Merewether and Claypool (1980) analyzed lowermost Upper Cretaceous potential hydrocarbon source rocks from well bores in three areas. The Belle Fourche Shale, Greenhorn Formation, and Carlile Shale from the shallow eastern side of the basin contain calcareous shale of offshore and open marine origin with abundant, hydrogen-rich, organic material, derived largely from marine organisms. These rocks are in immature stages of thermal alteration with respect to oil generation. The Frontier Formation and most of the Sage Breaks Member of the Cody Shale along the western flank of the basin at a depth of about 318 m (1,040 ft) contain noncalcareous shale of nearshore-marine origin with abundant hydrogen-deficient organic matter derived mainly from land plants. These rocks are potential sources of gas at optimum levels of thermal maturity, but are currently thermally

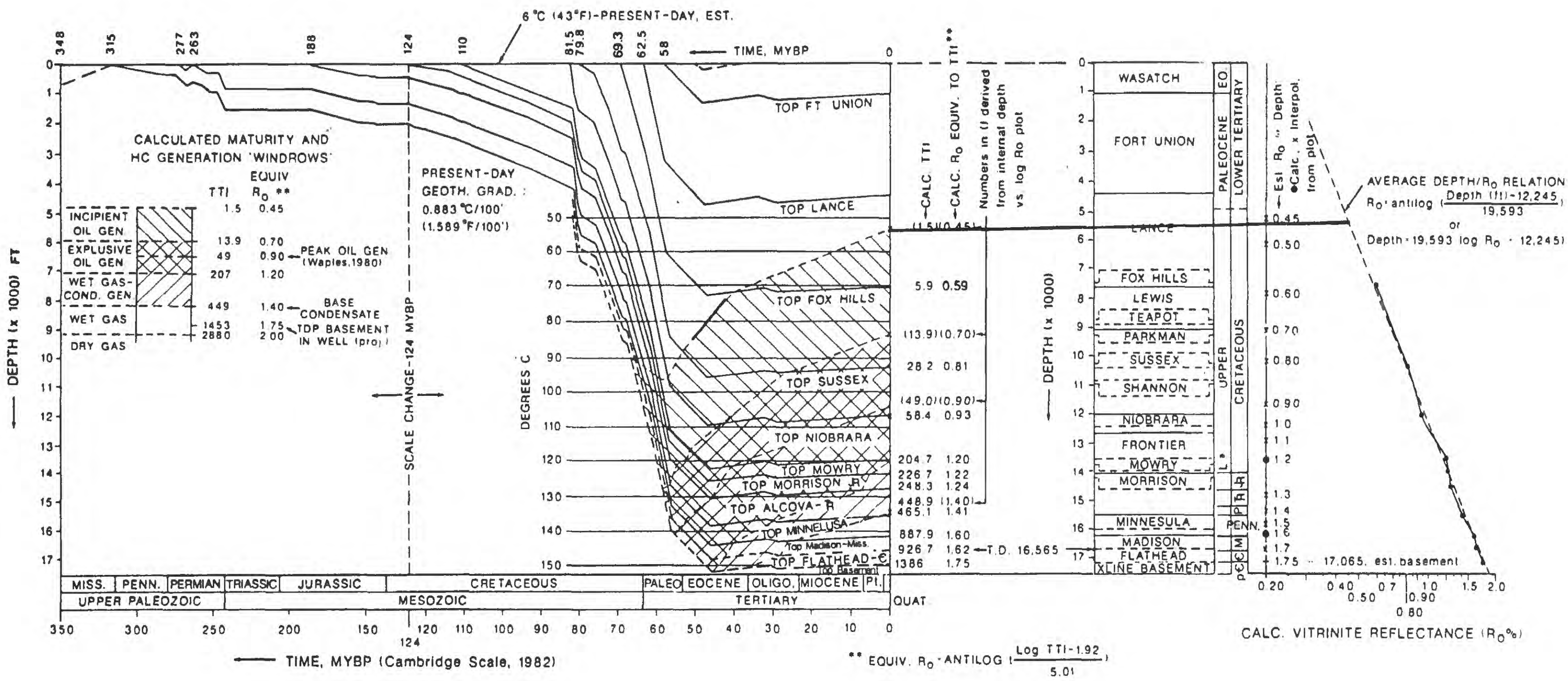

Figure 10.--Lopatin diagram illustrating thermal history of a portion of the Powder River basin based on Superior Government Tracy No. 1 well, SE¼NW¼ sec. 26, T. 38 N., R. 75 W., Converse County, Wyoming. Burial profiles are based on present day thickness and interpreted erosion; no correction was made for compaction. The temperature profile is based on present-day temperatures measured during log runs, with cooling corrections (after Fox, Dolton, and Clayton, in press).

immature with respect to hydrocarbon generation. The Frontier Formation and Cody Shale near the axis of the basin are noncalcareous and of nearshore-marine origin. They contain low amounts of hydrogen-deficient organic matter. The organic matter in these rocks has undergone sufficient thermal alteration to have generated appreciable quantities of hydrocarbons, especially if the original (before thermal alteration) organic matter was predominantly hydrogen-rich.

The source rocks for petroleum in the middle ("Leo") and upper members of the Minnelusa Formation may have been Permian shales in the present area of western Wyoming and eastern Idaho or Pennsylvanian shales indigenous to the Minnelusa (fig. 6). Permian black shales in the area of western Wyoming and eastern Idaho would probably have been buried deeply enough to generate hydrocarbons by Jurassic time. Organic carbon-rich facies of the Minnelusa Formation on the west side of the basin had sufficiently high thermal histories to produce hydrocarbons contemporaneously with or subsequent to the Laramide orogeny. If petroleum was supplied from both distant and local sources, some of it could have moved into the area of the present basin during the Jurassic. It could have been trapped until the Laramide orogeny, when surrounding mountain blocks were uplifted. At this time, the oil may have moved again and been redistributed into new structures forming around the flanks of the basin or into newly-formed, updip pinchout stratigraphic traps.

Clayton and Ryder (1984) found that black shales in the middle member ("Leo") of the Minnelusa Formation and equivalent rocks of Desmoinesian age in Nebraska are excellent source rocks (fig. 6). Organic carbon content ranges from less than 1 to 26 weight percent and averages 5.4 percent. Furthermore, the black shales have reached sufficient thermal maturity to generate substantial quantities of liquid hydrocarbons. Momper and Williams (1984) also consider black shales in the middle member to be a source of oil in reservoirs of the middle member in the southeastern part of the basin. They believe, however, that long-distance migration from Permian Phosphoria Formation source rocks accounts for oil in the upper member.

HYDROCARBON OCCURRENCE

The Powder River basin is one of the major petroleum producing areas in the United States. Although this basin contains large quantities of oil, it contains relatively small amounts of gas. The geographic distribution of oil and gas fields is shown on figure 11 and the principal fields are listed in Table 1. Production area by reservoir age is shown on figures 12, 13, and 14.

To date, approximately 2.5 billion barrels of recoverable oil have been discovered. About 75 percent of this oil is in Cretaceous reservoirs while most of the remainder is in Pennsylvanian-Permian rocks. Only minor amounts have been found in Mississippian, Triassic and Jurassic reservoirs, and virtually none in the older Paleozoic or Tertiary. Almost half has been found in large anticlinal structures around the basin margin. Stratigraphic traps account for most of the remainder. Gas is principally in association with the oil, except for minor non-associated gas in Upper Cretaceous and Tertiary rocks. Production ranges in depth from a few hundred meters to more than 4,575 m (15,000 ft) in the deep axial portion of the basin.

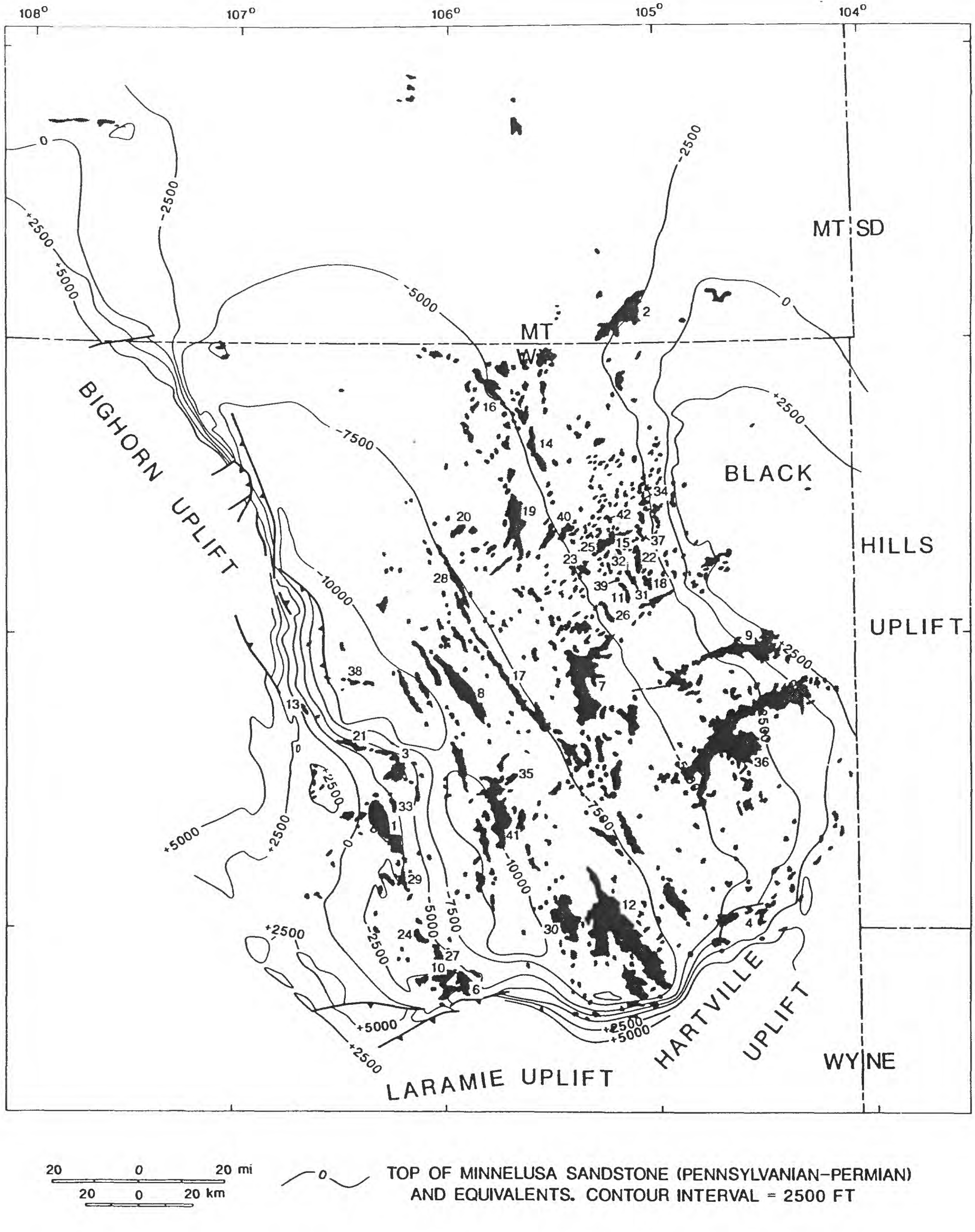

Figure 11.--Oil and gas fields of the Powder River basin (shaded areas). Generalized structural contours on top of Minnelusa Formation (Pennsylvanian-Permian). Larger fields numbered and keyed to field list (Table 1).

Table 1.—Principal oil and gas fields of the Powder River Basin

[Data in part from NRG Associates, 1986; Wyoming O&G CC, 1986; and Montana O&G CC, 1986]

	Name		Major Pay Zones	Estimated Size (ult. recoverable as of 12/1983) Oil (MMBO)	Gas (BCFG)
1	Salt Creek	1908	1st Wall Cr Ss, 2nd Wall Cr Ss, 3rd Wall Cr, Lakota Ss, Sundance Fm, Tensleep Ss	675.0	708.3
2	Bell Creek	1969	Muddy Ss	139.0	23.1
3	Meadow Creek-Sussex	1948	Shannon Ss, Sussex Ss, Frontier Fm, Lakota Ss, Tensleep Ss	113.0	118.8
4	Lance Creek	1918	Muddy Ss, Dakota Ss, Lakota Ss, Sundance Fm, Leo Ss, Converse Ss	106.5	139.8
5	Clareton Trend	1950	Newcastle Ss	90.0	29.0
6	Glenrock, South	1950	Muddy Ss, Dakota Ss	78.5	28.6
7	Hilight	1969	Newcastle Ss	75.0	231.0
8	Hartzog Draw	1975	Shannon Ss	60.0	25.8
9	Fiddler Creek Trend	1948	Newcastle Ss	56.4	2.2
10	Big Muddy	1916	Shannon Ss, Frontier Fm, Dakota Ss, Lakota Ss	54.4	<.1
11	Raven Creek	1956	Minnelusa Ss	51.7	-
12	Well Draw	1972	Teapot Ss	43.5	84.0
13	North Fork-Cellars Ranch	1951	Tensleep Ss	27.5	-
14	Gas Draw	1968	Muddy Ss	26.6	10.9
15	Rozet	1959	Muddy Ss, Minnelusa Ss	23.5	8.0
16	Recluse	1967	Muddy Ss	22.4	84.3
17	House Creek	1968	Sussex Ss	22.4	18.6
18	Coyote Creek	1958	Dakota Ss	21.7	25.4
19	Kitty	1965	Muddy Ss	20.0	110.0
20	Amos Draw	1982	Muddy Ss	20.0	50.0
21	Sussex, West	1951	Shannon Ss	18.8	8.8
22	Donkey Creek	1953	Minnelusa Ss, Dakota Ss, Muddy Ss	18.2	3.5
23	Timber Creek	1958	Minnelusa Ss	18.2	0.8
24	Cole Creek	1938	Shannon Ss, Dakota Ss	17.3	0.5
25	Stewart	1965	Minnelusa Ss	17.1	-

Table 1.—Principal oil and gas fields of the Powder River Basin—continued

[Data in part from NRG Associates, 1986; Wyoming O&G CC, 1986; and Montana O & G CC 1986]

	Name		Major Pay Zones	Estimated Size (ult. recoverable as of 12/1983) Oil (MMBO)	Gas (BDFG)
26	Dillinger Ranch	1964	Minnelusa Ss	16.5	-
27	Cole Creek, South	1948	Dakota Ss, Lakota Ss	16.5	0.1
28	Dead Horse Creek-Barber Creek	1957	Ferguson Ss	16.0	3.7
29	Sage Spring Creek	1949	Dakota Ss	15.7	4.3
30	Scott	1978	Parkman Ss	15.0	13.2
31	Duvall Ranch	1964	Minnelusa Ss	14.8	-
32	Halverson	1962	Minnelusa Ss	14.6	0.2
33	Salt Creek, East	1951	Wall Cr Ss, Lakota Ss, Tensleep Ss	12.8	0.8
34	Semlek & West	1962	Minnelusa Ss		
35	Buck Draw	1973	Frontier Fm, Dakota Ss	12.0	22.5
36	Finn-Shurley	1963	Turner Ss	12.0	7.0
37	Kummerfeld	1960	Minnelusa Ss, Dakota Ss	11.8	0.9
38	Reno	1965	Minnelusa Ss	11.5	-
39	Reel	1962	Minnelusa Ss	11.0	-
40	Springen Ranch	1968	Muddy Ss	10.6	11.7
41	Powell-Ross	1954	Frontier Fm, Dakota Ss	10.5	30.0
42	Hamm	1967	Minnelusa Ss	10.3	<0.1

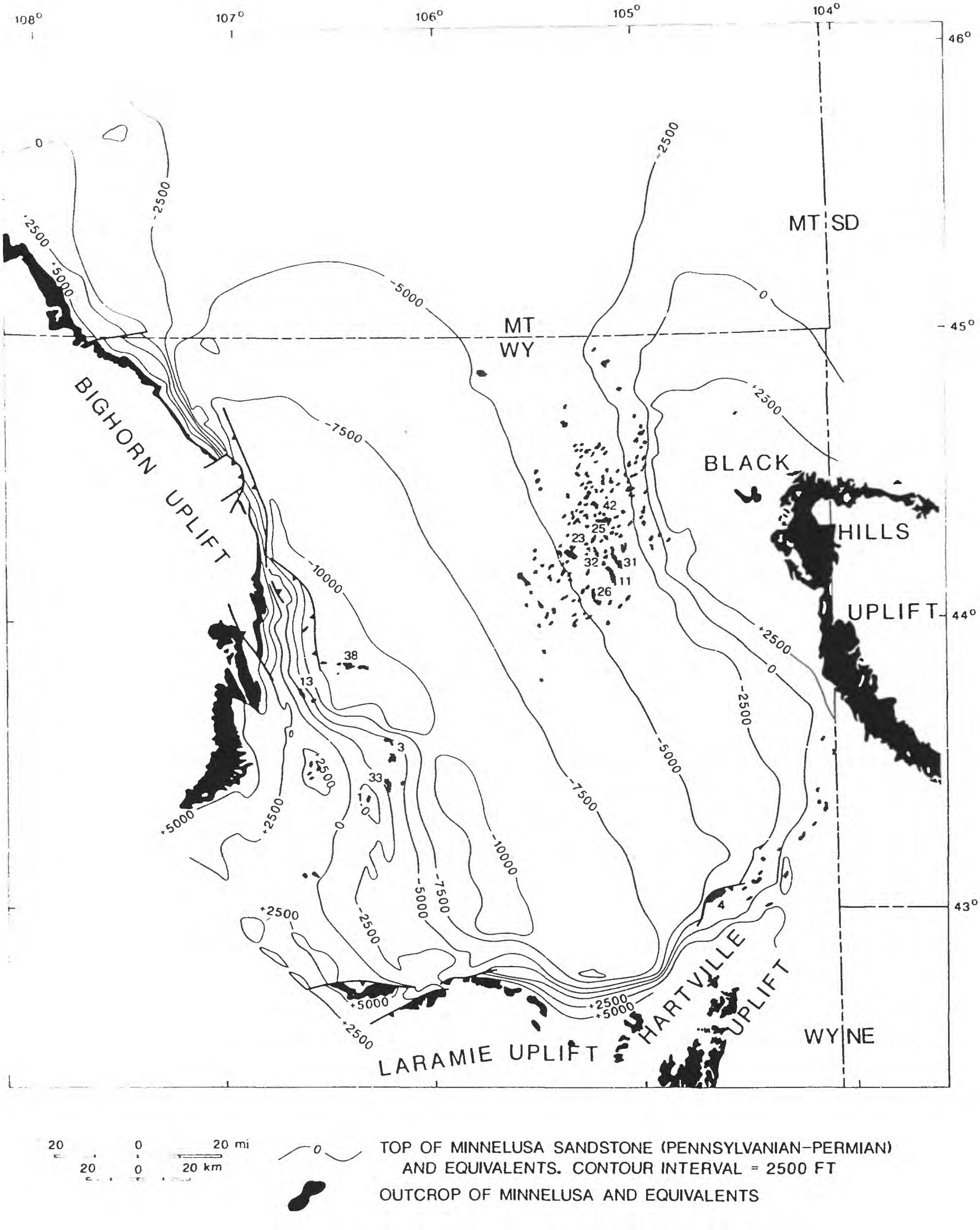

Figure 12.--Generalized structure map of the Minnelusa Formation (Pennsylvanian-Permian) showing distribution of Pennsylvanian & Permian oil production (shaded areas). Larger pools numbered and keyed to field lists (Tables 1 & 2).

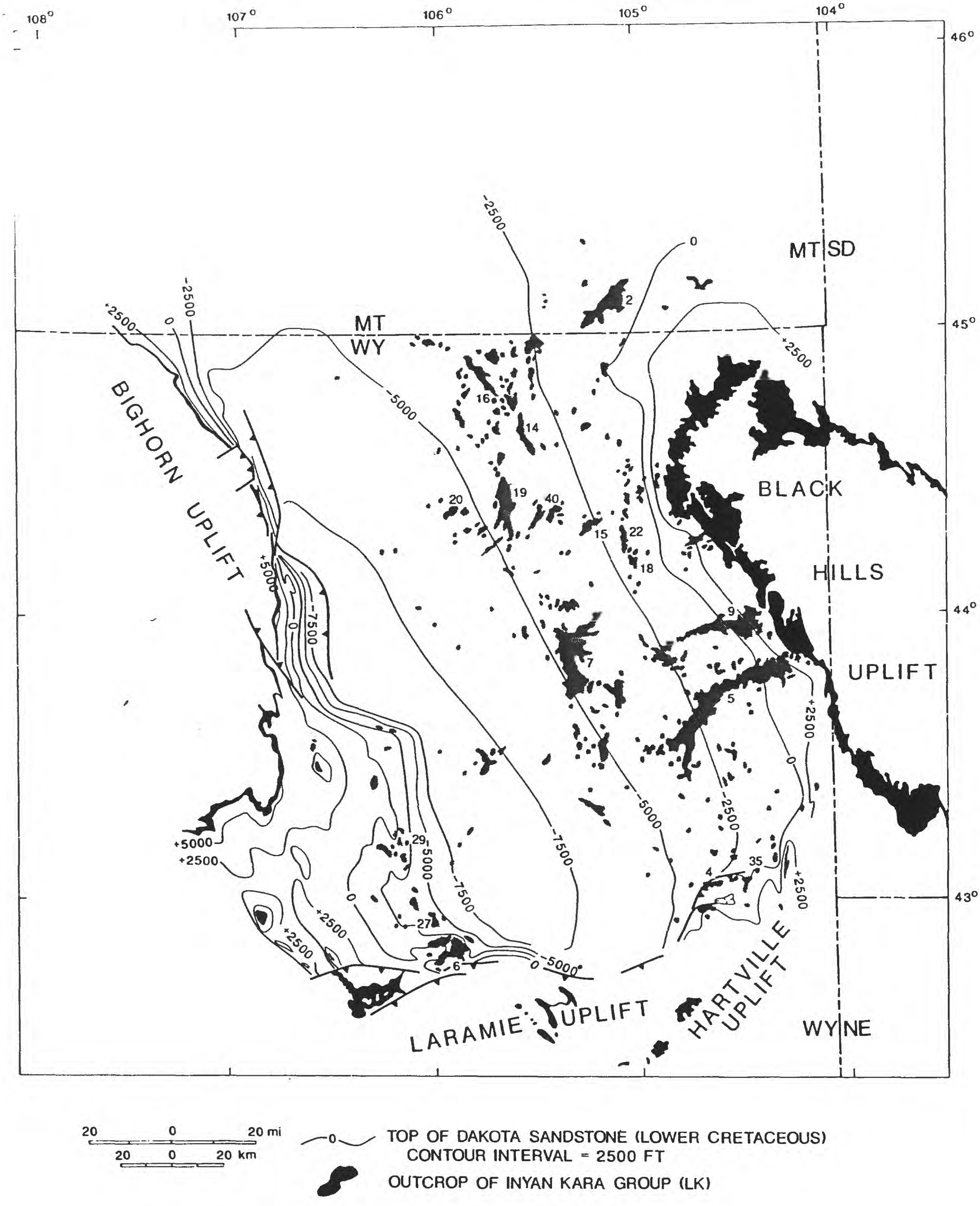

Figure 13.--Generalized structure map of the Dakota Sandstone (Lower Cretaceous) showing distribution of Lower Cretaceous and Jurassic oil and gas production (shaded aeas). Larger pools numbered and keyed to field lists (Tables 1 & 2).

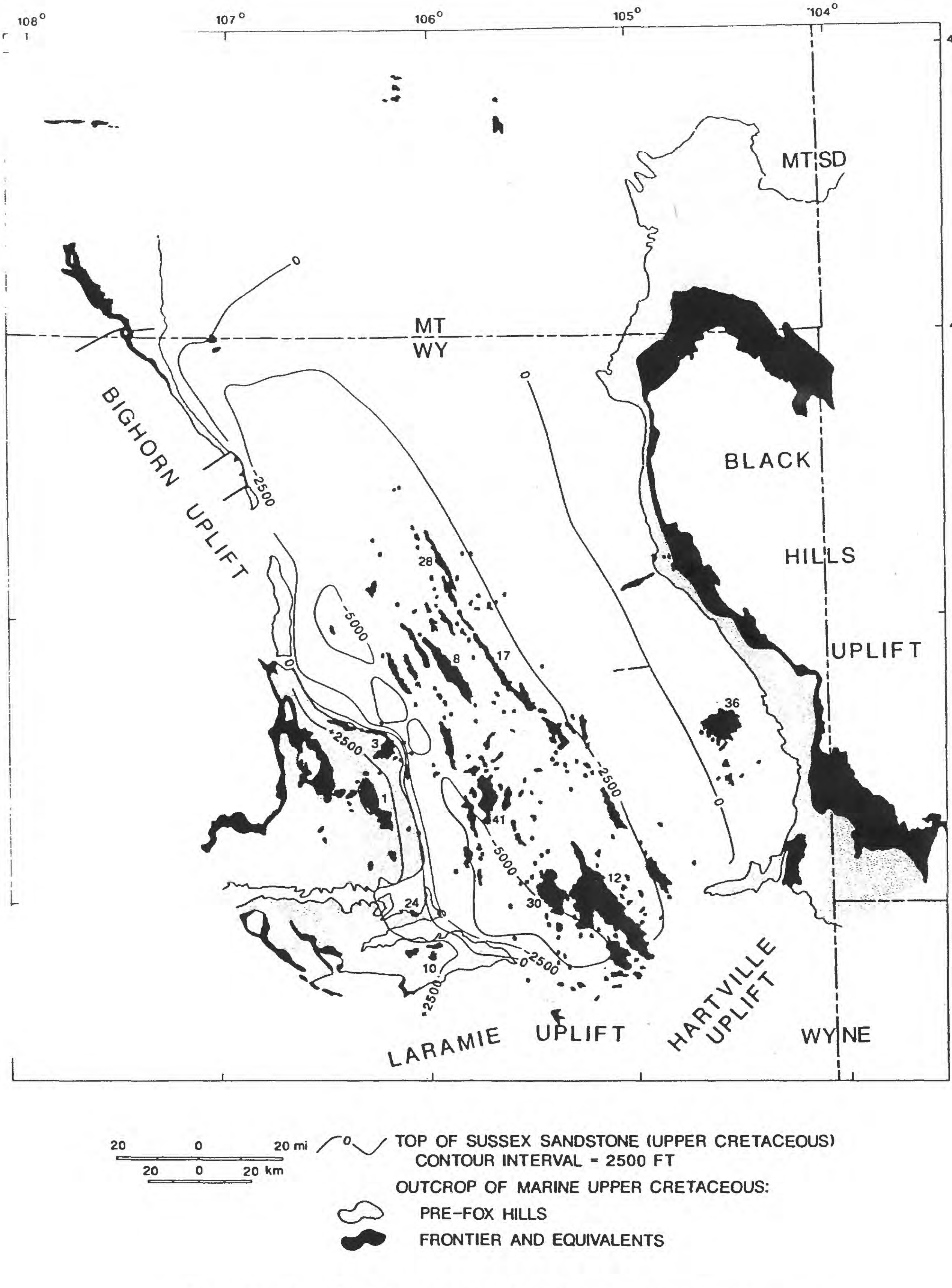

Figure 14.--Generalized structure map of the Sussex sandstone (Upper Cretaceous) showing distribution of Upper Cretaceous oil and gas production (shaded areas). Larger pools numbered and keyed to field lists (Tables 1 & 2).

Table 2.--Principal pools by age (pools larger than 10 MMBO), in order of decreasing size. Keyed to maps by number:

Map Key	Field name	Pool discovery date	Producing formation
Pennsylvanian-Permian:			
3	Meadow Creek-Sussex	1948	Tensleep
11	Raven Creek	1960	Minnelusa
4	Lance Creek	1936	Leo, Converse
1	Salt Creek	1930	Tensleep
13	North Fork-Cellars Ranch	1951	Tensleep
23	Timber Creek	1958	Minnelusa
25	Stewart	1965	Minnelusa
26	Dillinger Ranch	1964	Minnelusa
31	Duvall Ranch	1964	Minnelusa
33	Salt Creek, East	1951	Tensleep
32	Halverson	1962	Minnelusa
38	Reno	1965	Minnelusa
39	Reel	1962	Minnelusa
42	Hamm	1967	Minnelusa
Lower Cretaceous and Jurassic:			
2	Bell Creek	1967	Muddy
5	Clareton Trend	1950	Newcastle
6	Glenrock, South	1950	Dakota, Muddy
7	Hilight	1969	Newcastle
1	Salt Creek	1919	Sundance, Morrison, Lakota, Dakota
9	Fiddler Creek Trend	1948	Newcastle
4	Lance Creek	1918	Sundance, Lakota, Dakota, Muddy
14	Gas Draw	1968	Muddy
16	Recluse	1967	Muddy
18	Coyote Creek	1958	Dakota
19	Kitty	1965	Newcastle
20	Amos Draw	1982	Newcastle
15	Rozet	1959	Muddy
27	Cole Creek, South	1948	Lakota, Dakota
29	Sage Spring Creek	1949	Dakota
35	Buck Draw	1973	Dakota
22	Donkey Creek	1953	Dakota
40	Springen Ranch	1968	Muddy

Table 2.--Principal pools by age (pools larger than 10 MMBO), in order of decreasing size. Keyed to maps by number:--continued

Map Key	Field name	Pool discovery date	Producing formation
Upper Cretaceous:			
1	Salt Creek-Teapot Dome	1908	1st Wall Creek, 2nd Wall Creek, Carlile, Niobrara
8	Hartzog Draw	1975	Shannon
12	Well Draw	1972	Teapot
10	Big Muddy	1916	Frontier, Shannon
17	House Creek	1968	Sussex
28	Dead Horse Creek-Barber Creek	1957	Parkman
30	Scott	1978	Parkman
3	Meadow Creek-Sussex	1928	Frontier, Shannon, Sussex
36	Finn-Shurley	1963	Turner
41	Powell-Ross	1954	Frontier
24	Cole Creek	1938	Shannon

EXPLORATION STATUS

The history of petroleum exploration in the Powder River basin dates back to the late 1800's (Strickland, 1958). Numerous oil seeps were known to exist along the margins of the basin in territorial days and, by 1887, at least 60 wells had been drilled on its eastern side near Moorcroft, Wyoming. The first oil field in the basin was established there in 1887 producing from the Newcastle Sandstone. In 1889, the first successful well was drilled on the west side of the basin on the north plunge of the huge Salt Creek anticline, resulting in discovery of the Shannon pool, a fault closure of Upper Cretaceous Shannon Sandstone. In 1908, a major oil strike was made on the crest of the anticline, resulting in discovery of the giant Salt Creek field. Discovery of the "First Wall Creek sand" (Frontier Formation) there was followed by the extraordinary "Second Wall Creek sand" pool, which has produced over 300,000,000 barrels of oil (figs. 5, 11, 14), and by other pays. Subsequent exploration of surface-mapped anticlines around the margin of the basin resulted in the discovery of Teapot Dome, Big Muddy, Lance Creek, and other significant fields.

Exploration was renewed in the late 1940's, augmented with geophysical techniques and, from 1948 until 1952, a series of large oil fields were found at depths of generally less than 2,700 m (9000 ft), including structural and combination traps at Sussex, Sage Spring Creek, South Glenrock, Meadow Creek, and North Fork-Cellars Ranch, and large stratigraphic traps at the Fiddler Creek and Clareton Trends.

The latter success stimulated exploration for a variety of subtle stratigraphic traps along the east flank of the basin, principally in Lower Cretaceous Newcastle (Muddy) and Dakota sandstones and in the Minnelusa sandstone, and produced a large number of discoveries, including Raven Creek, Hilight, Recluse, and Bell Creek fields.

The discovery of oil in the Ferguson Sandstone of the Upper Cretaceous Parkman Sandstone Member of the Mesaverde Formation, at Dead Horse Creek field in 1957, began expansion of the exploration "fairway" into the central part of the basin and, by 1975, extended to stratigraphic traps in Upper Cretaceous sandstones of the Teapot, Teckla, Sussex and Shannon Sandstone Members and Frontier Formation. Recent exploration has generally expanded the geographic limits of the stratigraphic plays, particularly in deeper parts of the basin.

PRINCIPAL PETROLEUM PLAYS

Petroleum plays in this basin are of both structural and stratigraphic types and occur in three major petroleum source and reservoir systems: Pennsylvanian-Permian, Lower Cretaceous, and Upper Cretaceous. Plays which describe the principal occurrences of petroleum within these units are the basis for oil and gas resource assessment.

Structural Plays

Basin Margin Anticline Play (fig. 15).--The Powder River basin has a long history of oil and gas production from large anticlines along its southern and western margins. The majority of these are relatively simple

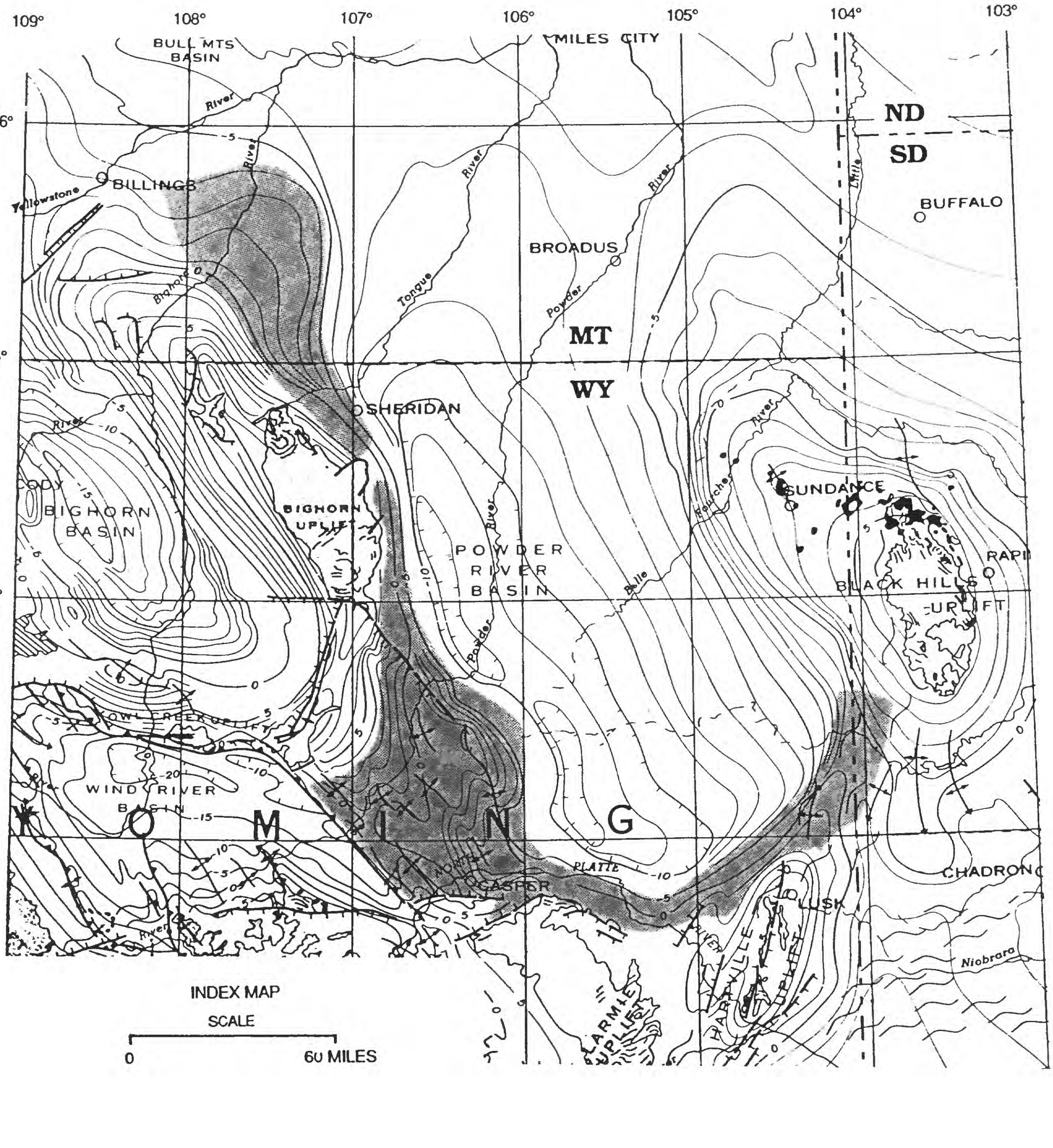

Figure 15.--Map showing area of Basin margin anticline play (shaded). Structural contours on top Precambrian, in feet (after Bayley and Muehlberger, 1968).

folds which are reverse-faulted at depth and contain extensional faults on their crests, such as Salt Creek field (fig. 4). Fault closures and faulted, plunging anticlinal noses produce at Ash Creek and in other fields and several combination traps are associated with structures.

Reservoir lithotypes include sandstones, carbonates and minor fractured shales. Principal reservoirs are the Cretaceous Frontier, Muddy and Dakota sandstones and the Pennsylvanian-Permian Tensleep-Minnelusa sandstone. Multiple pay zones are common, however, Mississippian rocks are rarely productive and older producing reservoirs are unknown.

Fine grained rocks intercalated with the reservoirs provide seals. A Permian-Triassic redbed sequence forms a regional seal, which separates Paleozoic and Mesozoic reservoirs in most fields.

Principal source rocks for Paleozoic reservoirs include Desmoinesian black shales and, possibly, organic rich rocks of the Park City (Phosphoria) Formation west of the basin. Early and late Cretaceous source rocks, especially the Mowry and Niobrara, have provided the principal charge to the Cretaceous reservoirs (Momper 1979, 1984) and may have contributed to older reservoirs where migration paths were available, particularly where source and reservoirs have been juxtaposed by faults. However, Cretaceous producing zones are almost always segregated from underlying Paleozoic reservoirs and typically have distinct oil types related to their different sources.

Permian black shales in the area of western Wyoming and eastern Idaho probably were buried deeply enough to have generated hydrocarbons by Jurassic time and, if petroleum was supplied from both distant and local sources, some of it could have moved into the area of the present basin during the Jurassic and been trapped, until redistributed during the Laramide orogeny and augmented by locally produced hydrocarbons.

In early Eocene time, source rocks of Early and Late Cretaceous age began expelling oil to structures which were developing around the basin margins. Principal among these were the Mowry Shale, which expelled a very large quantity of oil, and the less prolific Skull Creek Shale. The Niobrara Formation and Carlile Shale are significant sources of oil found in Upper Cretaceous reservoirs, however, the areal extent of effective source rocks in these formations is less extensive than the underlying Mowry Shale. The Lower Cretaceous Fuson Shale and the Upper Cretaceous shales of the Frontier and Steele Formations have expelled oil in amounts secondary to other Cretaceous sources.

Exploration of the play has proceeded for approximately 100 years with discovery of major fields such as Salt Creek, Teapot Dome, Big Muddy and Lance Creek Fields. Most were found early in the exploration history of the basin (Appendix). Total discovered oil exceeds one billion barrels of oil, with substantial dissolved-associated gas. Salt Creek Field alone has produced almost three-quarter of a billion barrels. Nevertheless, exploration in the play is nearing its conclusion and little potential remains; future discoveries will probably be made in small and subtle traps.

Basin Margin Subthrust Play (fig. 16).--As discussed by Gries (1983), many of the Laramide basins of the Rocky Mountain Foreland have thrust faults along their margins. The subthrust play describes the occurrence of petroleum trapped in deformed strata below such thrusts. The overthrust wedge of Precambrian rocks may act as a trap and seal of fluids in the underlying sedimentary rocks, or simply conceal traps which have formed in underlying folds or faults.

Reservoir lithotypes are primarily sandstones; most important are the Cretaceous Frontier, Muddy and Dakota sandstones and the Pennsylvanian-Permian Tensleep-Minnelusa sandstone. Both single and multiple pays are anticipated.

Fine grained rocks intercalated with the reservoirs provide seals. A regional seal is the Permian-Triassic redbed sequence, which separates Paleozoic and Mesozoic reservoirs.

Principal source rocks for Paleozoic reservoirs include Desmoinesian black shales and, probably, organic rich rocks of the Park City (Phosphoria) Formation to the west of the basin. Cretaceous source rocks, especially the Mowry and Niobrara, have provided the principal charge to the Cretaceous reservoirs and may have contributed to older reservoirs where migration paths were available, particularly where source and reservoir were juxtaposed by faults. However, Cretaceous producing zones are almost always segregated from underlying Paleozoic reservoirs and typically have distinct oil types related to their separate sources.

Permian black shales in the area of western Wyoming and eastern Idaho probably were buried deeply enough to have generated hydrocarbons by Jurassic time and, if petroleum was supplied from both distant and local sources, some of it could have moved into the area of the present basin during the Jurassic and been trapped until redistributed during the Laramide orogeny and augmented by locally produced hydrocarbons.

Burial during Laramide also was sufficient to cause petroleum source rocks of Early and Late Cretaceous age to begin expelling oil in early Eocene time to structures which were developing around the basin margins.

The first production in the Rocky Mountains from beneath Precambrian was at the southern end of the Powder River basin where the Muddy Sandstone oil reservoir at South Glenrock Field extended beneath a thrust wedge on the north flank of the Laramie Range (Gries, 1983). Similarly, Tepee Flats field produces from Cretaceous sandstones in a subthrust trap on the west flank of the Casper arch in the adjoining Wind River basin. Geologic data are very limited and do not allow accurate prediction of future reserves or field sizes in this play.

Stratigraphic Plays

Middle Minnelusa ("Leo") Sandstone Play (fig. 17).--The Leo play encompasses the occurrence of oil in stratigraphic traps within the quartzose sandstones of the "Leo", or middle member of the Minnelusa Formation in the southern part of the basin. The Leo consists of sandstone, carbonate, shale and evaporite, which were deposited in a suite of

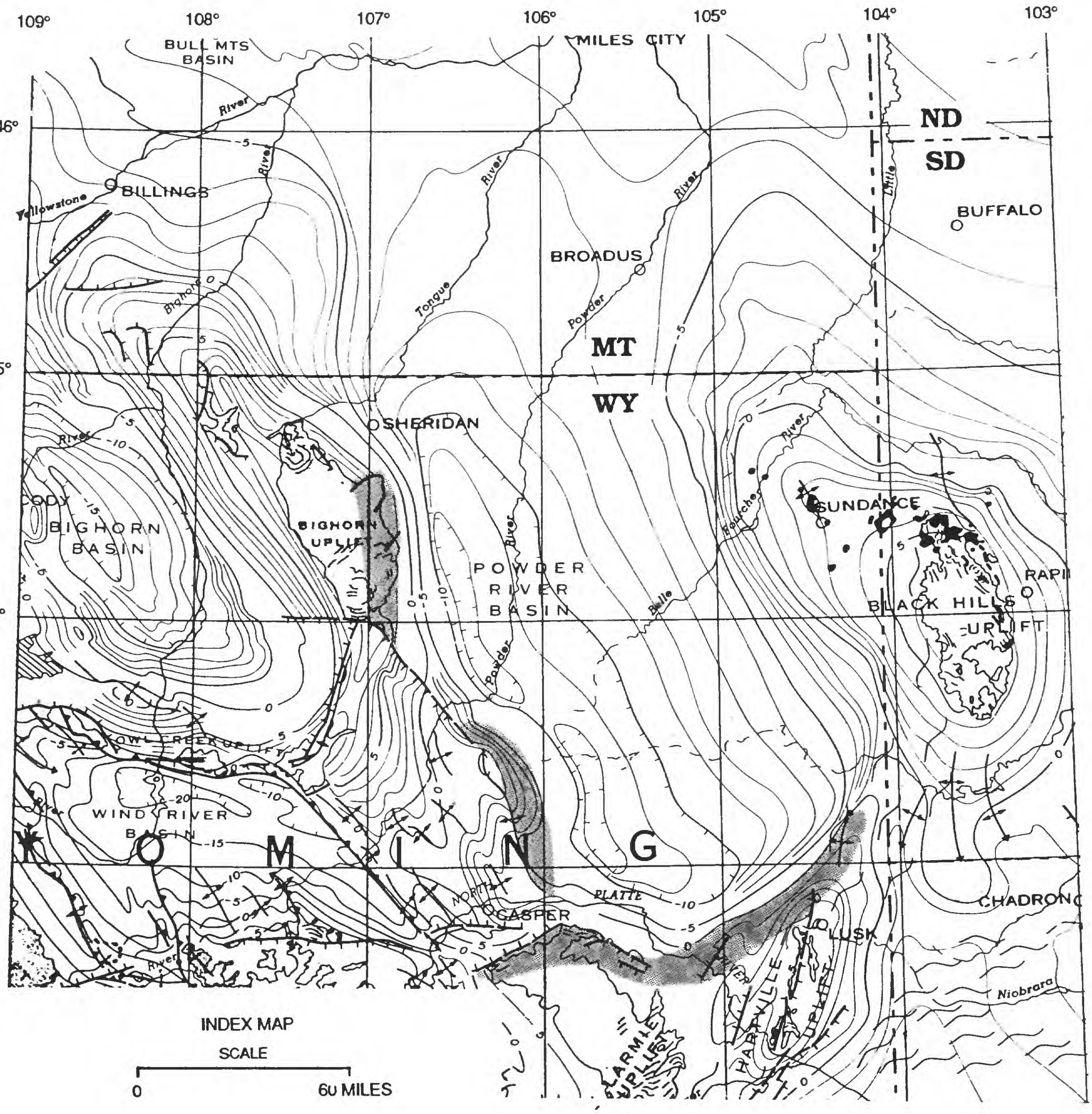

Figure 16.--Map showing area of Basin margin subthrust play (shaded). Structural contours on top Precambrian, in feet (after Bayley and Muehlberger, 1968).

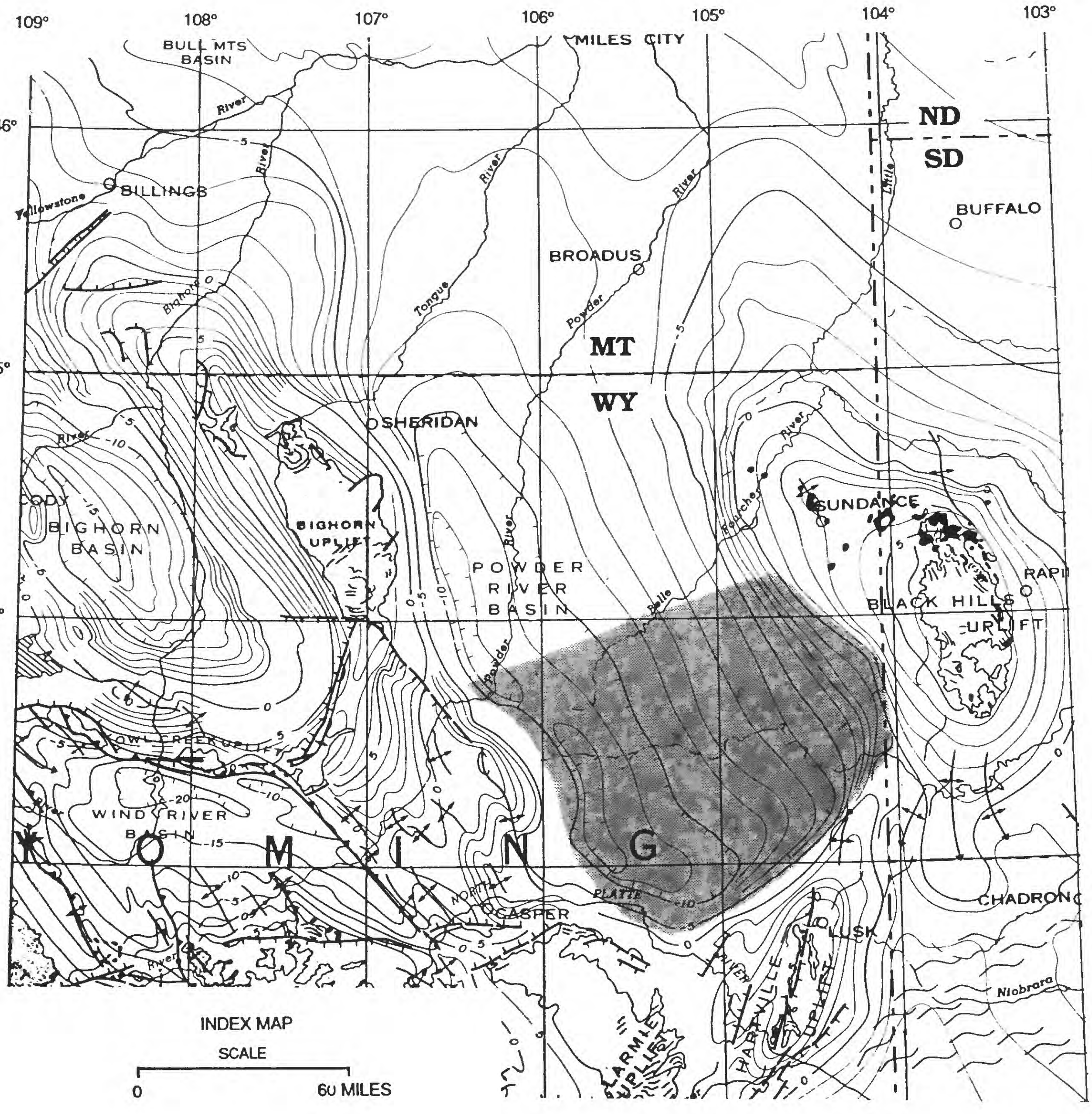

Figure 17.--Map showing area of Middle Minnelusa ("Leo") Sandstone play (shaded). Structural contours on top Precambrian, in feet (after Bayley and Muehlberger, 1968).

environments associated with offshore-prograding eolian sand dunes (Tromp and others, 1981; Fryberger and others, 1983, Fryberger, 1984; George, 1984; and Motes, 1984). Traps are subtle and include sandstone pinchouts or gradations into impermeable facies.

Desmoinesian black shale source rocks associated with this reservoir sequence are believed to be the principal source for the oil in the "Leo". Organic carbon content ranges from less than 1 to 26 weight percent and averages 5.4 percent. They have reached sufficient thermal maturity during Laramide to have generated substantial quantities of liquid hydrocarbons. More speculative migration models also propose long distance pre-Laramide migration through Tensleep-Minnelusa reservoirs from Phosphoria source beds, west of the present basin formation. Gravity of hydrocarbons generally ranges from 20 to 35° API., increasing with depth.

The "Leo" play is lightly explored and accumulation sizes are anticipated to be similar to fields in the more important Upper Minnelusa sandstone play discussed below. Depths to the reservoir sandstones in this play extend to about 4,575 m (15,000 ft).

Upper Minnelusa Sandstone Play (fig. 18).--This play encompasses the occurrence of oil in stratigraphic accumulations which are largely related to paleotopography and reservoir truncation at the top of the Minnelusa Formation. The play is located on the broad, gently sloping eastern flank of the Powder River basin in areas containing well-developed eolian sandstone reservoirs of Permian age in the upper part of the formation. The play appears to be somewhat limited to the south by the widespread occurrence of evaporites which adversely affect hydrocarbon migration and reservoir quality. The significance of subtle paleotectonic features, such as the Belle Fourche Arch of Slack (1981), remains problematic.

Reservoirs are principally eolian dune sandstones of Wolfcampian age within a complex cyclic sequence of carbonates and sandstones of marine and non-marine origin dominated by erg and sabkha environments (Van West, 1972; George, 1984; Fryberger, 1984). Vuggy dolomite contributes to production in several fields but rarely as a primary reservoir. Sandstones are generally very mature, typically fine to medium grained orthoquartzites, with a varying carbonate component. Average reservoir porosities typically range from 15 to 24 percent.

As discussed by Van West (1972), the largest portion of Upper Minnelusa oil has been trapped in paleo-topographic highs or erosional remnants at the top of the Minnelusa, overlain by the Opeche Shale. Other significant traps include preserved dune forms, permeability pinchouts of both depositional and diagenetic origin within the cyclothem sequence, and low relief structural closures. Seals are provided by overlying impermeable rocks of the Goose Egg Formation, generally the Opeche Shale, and by internal lithologic variation and cementation. Most oil found to date is in areas with maximum paleo-topographic relief (Moore, 1983).

Oil is believed to have been derived from dark marine shales of Desmoinesian age below the Upper Minnelusa sandstone. These shales are present within the play area and mature in the deeper parts of the basin (Clayton and Ryder, 1984). Speculative migration models propose long distance migration

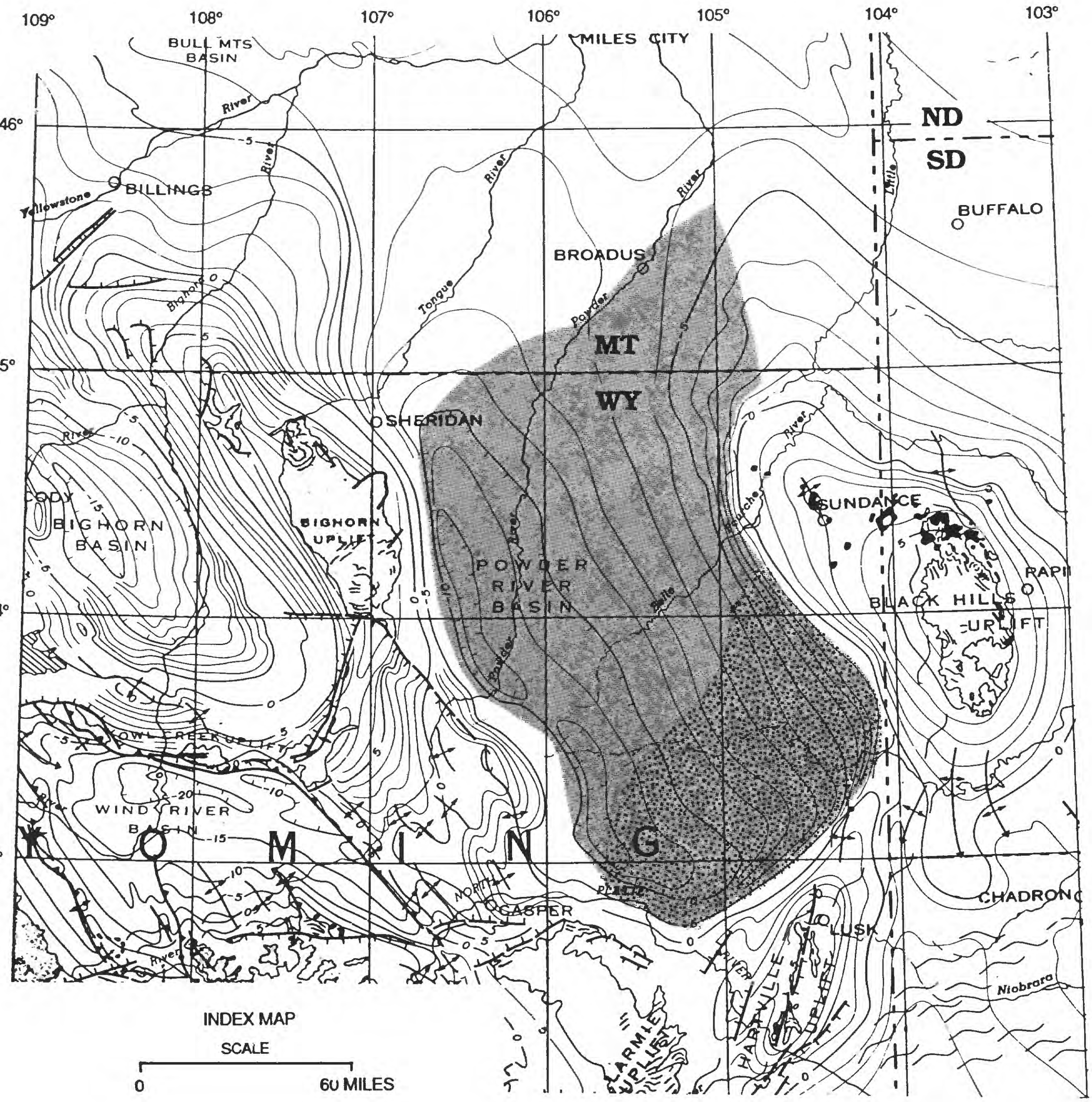

Figure 18.--Map showing area of Upper Minnelusa Sandstone play (shaded). Speculative and less prospective area shown with stipple. Structural contours on top Precambrian, in feet (after Bayley and Muehlberger, 1968).

through Tensleep-Minnelusa reservoirs from Phosphoria source beds, far to the west, prior to present basin formation (Sheldon, 1967; Claypool and others, 1978). Gravity of hydrocarbons generally range from 20 to 35° API., increasing with depth. Oils are typically undersaturated with reference to gas.

Permian black shales in the area of western Wyoming and eastern Idaho were probably buried deeply enough to generate hydrocarbons by Jurassic time. If petroleum was supplied from both distant and local sources, some of it could have moved into the area of the present basin during the Jurassic. During the Laramide orogeny the oil may have been partially redistributed, augmented by Laramide generation from local source beds.

The play is well established, with an active exploration history exceeding 30 years. Status ranges from well-explored over a significant part of the shallow eastern flank of the basin to very lightly explored in the deeper parts. More than 160 fields have been discovered through 1983 and contain more than 380 million barrels of recoverable oil. Those larger than 1 MMBO are shown in Appendix table B. The largest field discovered, Raven Creek Field, is larger than 50 million barrels recoverable, and mean accumulation size is approximately 2.5 million barrels.

For assessment purposes, the play was divided into a relatively well-explored "mature" area, and a less well explored area. Undiscovered resources are expected to consist primarily of oil and may exceed what has already been discovered. Sizes of undiscovered accumulations in the relatively unexplored areas are expected to be similar to existing fields.

Depths to prospective traps in the play are from about 1,050 to 4,550 m (3,500 to 15,000 feet); most are in the 2,450 to 4,250 m (8,000 to 14,000 foot) range.

<u>Lakota Play (fig. 19)</u>.--This play encompasses the occurrence of oil in stratigraphic traps of the basal Inyan Kara Group ("Lakota") sandstones in the structurally uncomplicated portions of the Powder River basin. Traps are invariably discrete or composite channel sandstones of alluvial or deltaic origin sealed by fine-grained alluvial deposits. Traps occur in combination with structural noses and on anticlinal closures, but within the play area, such structural closures are not significant and the essential mechanism is considered to be stratigraphic. Seals are fine-grained alluvial and deltaic rocks of the Fuson and the overlying Fall River and Skull Creek shales. The underlying Jurassic Morrison Formation may also provide lateral seals where the sandstones are entrenched into it.

Reservoirs are fine to coarse grained sandstones which are locally pebbly or conglomeratic. Most contain chert and lithic fragments. Average porosities range from 13 to 25 percent, though typically 14 to 17 percent, and decrease with depth.

Source rocks are presumed to be the overlying Mowry Shale, the Lower Cretaceous Skull Creek-Thermopolis Shale and, possibly, the Fall River or Fuson shales, although reservoirs in trapping configurations may not be charged due to isolation from the source rock units.

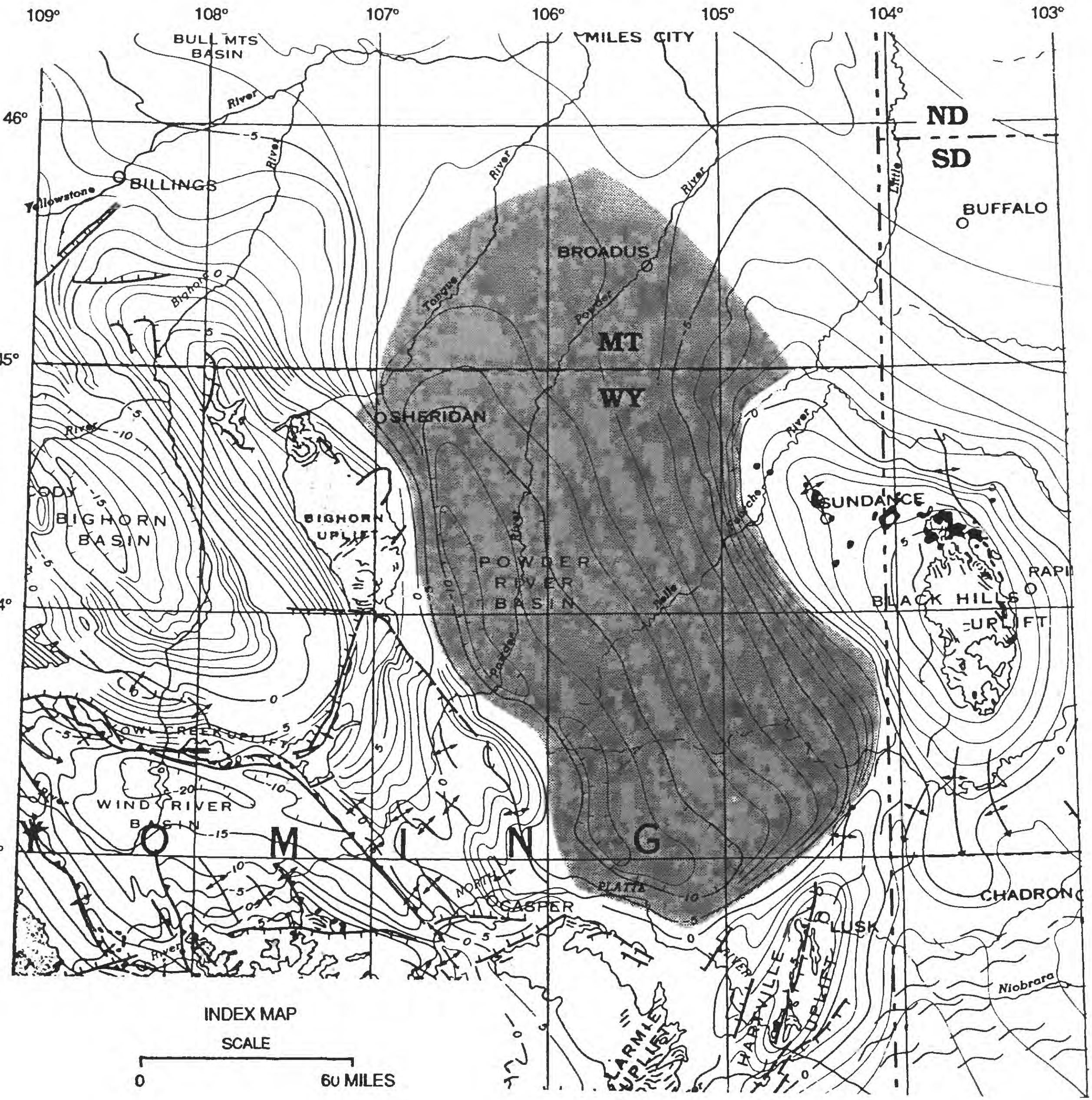

Figure 19.--Map showing area of Lakota Sandstone play (shaded). Structural contours on top Precambrian, in feet (after Bayley and Muehlberger, 1968).

The Lakota Sandstone play is generally lightly explored due to the small size, unpredictability, and difficulty of detection of accumulations in channel sandstones. Through 1982, about 12 fields had been discovered, accounting for about 10 million barrels of oil. Sizes of undiscovered accumulations are estimated to be generally small, although a few larger traps in the 5 to 20 million barrels range may exist. Lakota pools in large Laramide structures peripheral to the play area suggest the potential of these reservoirs. Depth range for the play is from about 1,200 m to about 3,950 m (4,000 to 13,000 feet); generally 2,300-3,650 m (7,500 to 12,000 feet) in the more prospective areas. Estimated undiscovered resources are believed to be modest and the petroleum resources of the play were assessed in aggregate with other plays of small resource potential.

Fall River ("Dakota") Sandstone Play (fig. 20).--This play encompasses the occurrence of oil and gas in stratigraphic traps within the regressive clastic wedge of the Fall River formation. This widespread clastic wedge prograded into the Cordilleran seaway or Western Interior Seaway from the south and east following the initial transgression of Cretaceous seas into the western interior region (MacKenzie and Poole, 1962; MacKenzie and Ryan, 1962; Dondanville, 1963). In the area of the Powder River basin it is composed of a marine, deltaic and alluvial complex that was situated along the eastern margin of the seaway. These strata become progressively more marine to the west, consisting entirely of marine shales and siltstones of the Thermopolis Shale on the west side of the basin (fig. 7).

Most oil and gas occurs on the structurally uncomplicated east flank of the basin. Individual point-bar deposits or point-bar complexes have cut into older marine, deltaic, estuarine, and strandline sediments and are typically sealed updip by fine grained abandoned channel deposits (Mettler, 1968; Berg, 1968; Harris, 1976). Marine bar sandstone traps resulting from pinchouts are also considered prospective, although not well documented. In a few instances structure plays a role in providing additional closure. For example, near the western edge of the Dakota regressive wedge, several accumulations have been discovered in combination with large structural closures or plunging anticlinal noses, as South Glenrock and Sage Spring Creek fields.

Fall River reservoirs are mature quartzose sandstones, generally fine grained. Average reservoir porosity typically varies from 12 to 23 percent and is usually in the range of 13 to 18 percent. The Fall River sandstone is sealed top and bottom by enclosing shales of the Fall River and Skull Creek Formations. Lateral and vertical seals for individual traps within the unit are provided by fine grained rocks, such as those found in abandoned channel oxbow fills and low energy marine sequences.

Most of the oil is probably derived from the rich overlying Mowry shale, which is separated by several hundred feet from the reservoir sequence. Possible source rocks include the associated Skull Creek and Fall River marine shales. Mowry and Skull Creek Shales were found to contain a mixture of types II and III organic matter. Because of a generally higher proportion of type II material, the Mowry is a better petroleum source than the Skull Creek Shale. All of these rocks are thermally mature in the deeper parts of the basin.

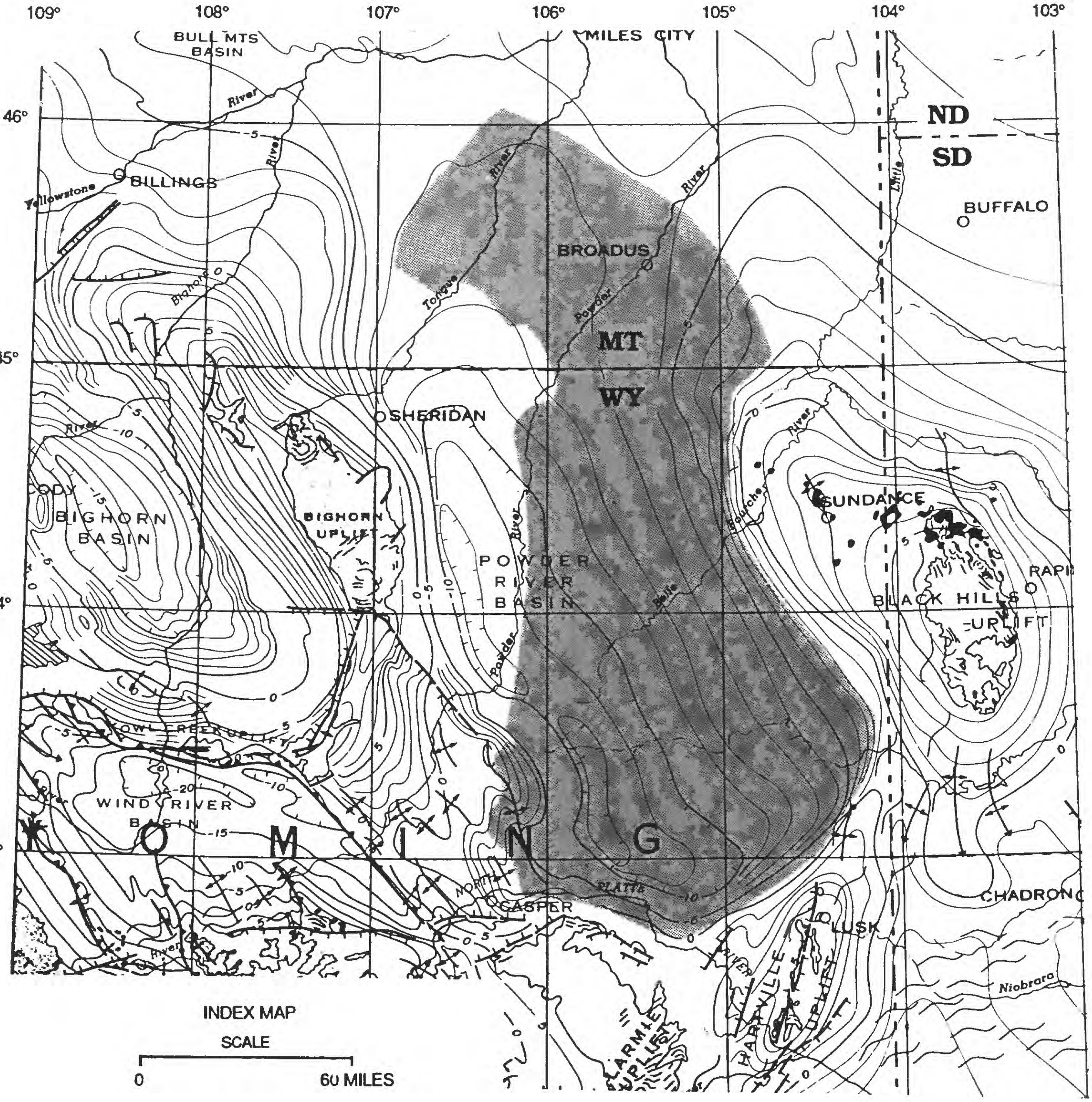

Figure 20.--Map of area of Fall River ("Dakota") Sandstone play (shaded). Structural contours on top Precambrian, in feet (after Bayley and Muehlberger, 1968).

Exploration in the Fall River Sandstone play has continued for approximately 30 years and has resulted in discovery of more than 30 individual accumulations, aggregating between 60 and 100 million barrels of oil. The largest accumulation, Coyote Creek Field, is approximately 20 million barrels (Appendix Table C). Pool sizes remaining to be discovered will probably be similar to those found, that is, mostly less than 10 million barrels. Exploration is currently expanding into deeper parts of the basin. Depth range of this play is from about 1,200 m to 3,950 m (4,000 to 13,000 feet), and generally from 2,300 to 3,650 m (7,500 to 12,000 feet) in the more prospective areas.

Muddy-Newcastle Play (Lower Cretaceous) (fig. 21).--This play encompasses the occurrence of oil and gas in stratigraphic traps of the Lower Cretaceous Muddy-Newcastle sandstone complex of the Powder River basin. It is characterized by a suite of trap types related to depositional environments of the involved reservoirs.

Lower Cretaceous Muddy and Newcastle Sandstones are composed of sediment transported into the Cretaceous seaway from the east, accompanying or following subareal erosion over much of the area (Stone, 1972; Mitchell, 1976; Gustason and others, 1988). Erosion was succeeded by a gradual transgressive phase interrupted by periodic regressive pulses in which appreciable sand was deposited, although the unit also contains abundant shale. The result is a compound wedge consisting of deposits from a variety of depositional environments and a variety of stratigraphic traps. Reservoirs include marine bar and strandline, channel, estuarine, alluvial and lower delta plain sandstones bodies (Haun and Barlow, 1962; Stone, 1972; Waring, 1976).

In many cases, thicker sandstones accumulated within the more deeply dissected troughs or valleys of the unconformity cut into the Thermopolis-Skull Creek Shale. The approximately northeast-striking estuarine and alluvial Fiddler Creek and Clareton trends are examples. The dominantly marine bar facies traps, such as Hilight, Kitty, and Recluse Fields, are generally nearly north-trending, except for Bell Creek Field. They may represent still-stands during the transgressive phase of Muddy deposition, when extensive high-energy marine bar or barrier sandstone deposits accumulated. Often a single field is a composite of overlapping separate traps and oil pools as documented by Berg (1976). Seals for the various traps are provided by the enclosing Skull Creek, Muddy, and Mowry shales.

Muddy-Newcastle reservoirs are generally fine to very fine grained sandstones. They contain scattered lithic fragments and chert; interstitial clay is occasionally abundant. Average reservoir porosities are variable but usually range between 10 and 25 percent, with a mean of about 15 percent. Porosity generally decreases with depth.

Primary source of the abundant hydrocarbons in the formation is the overlying organic-rich Mowry shale. Secondary sources are "black" shales of the Skull Creek, whose source rock quality is sufficient to have provided some petroleum (Burtner and Warner, 1984). Distribution of fields is generally limited to an area which overlies or is peripheral to mature source rocks in these formations (Momper and Williams, 1979, 1984). Gravity

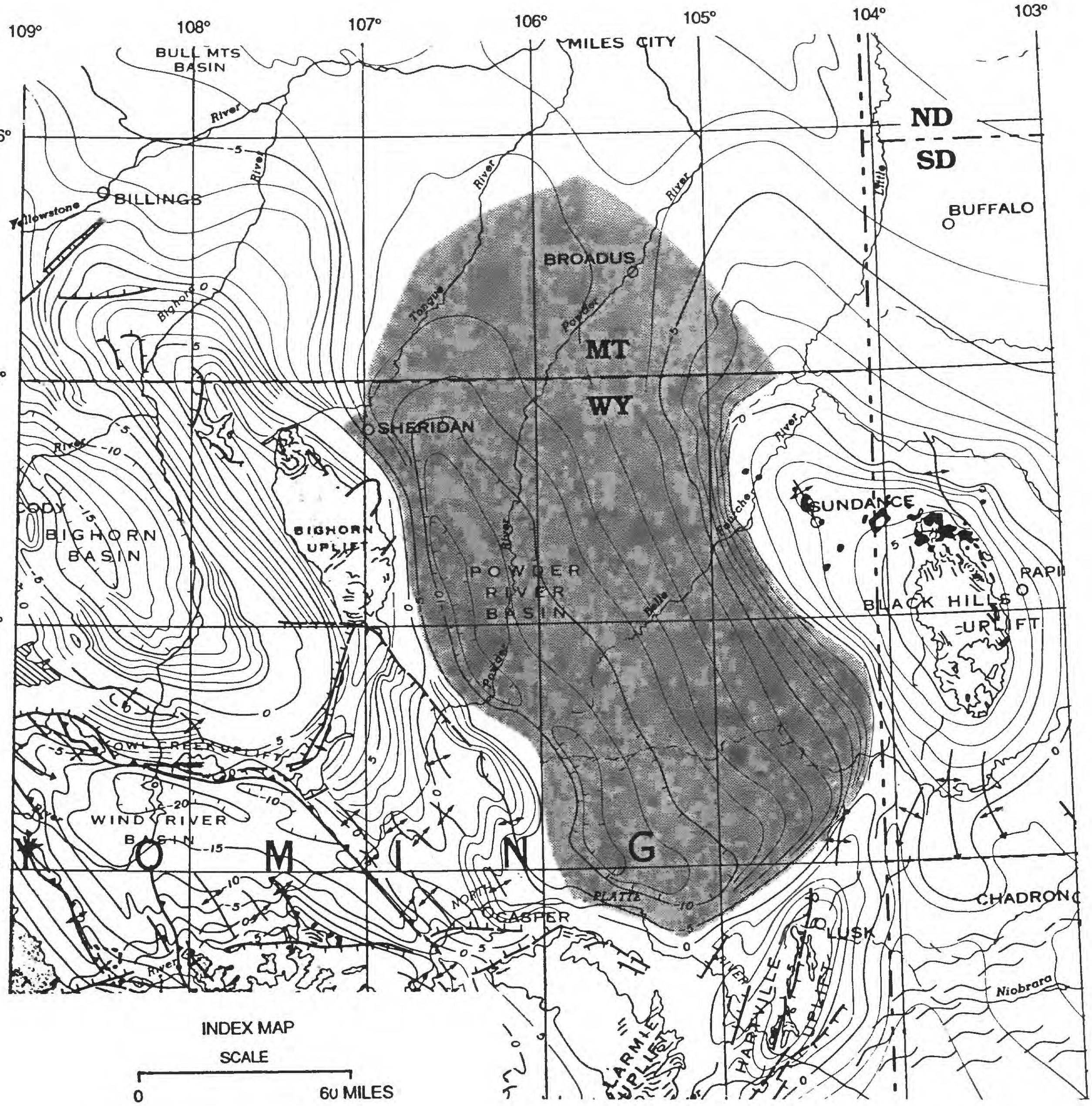

Figure 21.--Map showing area of Muddy-Newcastle Sandstone play (shaded). Structural contours on top Precambrian, in feet (after Bayley and Muehlberger, 1968).

of the hydrocarbons in the fields is generally high, typically ranging from 35 to 45° API, and the oils are rich in dissolved gas.

The play is well established, with a history of more than 40 years of production. Exploration ranges from intensive over the shallower parts of the basin to lightly explored in the deeper parts. Over 170 recognized accumulations have been discovered through 1983, accounting for more than 580 million barrels of recoverable oil; 39 accumulations exceed one million barrels (Appendix). The largest field, Bell Creek Field in Montana (fig. 13, no. 2), is estimated to exceed 139 million barrels. Mean pool size is approximately 3 million barrels. Sizes of undiscovered accumulations are expected to be smaller than those already discovered, with an abundance of small accumulations and a few of substantial size. Undiscovered resources are estimated to be large, and mostly situated in deeper parts of the basin. Depth of prospective traps is generally from 1,050 to 3,650 m (3,500 to 12,000 feet), with the greatest potential in the deeper parts.

Mowry Shale Play (fig. 22).--This play encompasses the occurrence of oil and gas in fractured Mowry shale reservoirs in the deeper parts of the basin. Controls on the origin and distribution of fracturing in the Mowry shale remain obscure. Some workers have proposed geopressuring associated with thermal maturation of organic matter and concurrent phase and volume changes as the causative factor, while others have proposed tectonic controls. The highly organic Mowry Shale is considered both reservoir and source. Seals appear to be provided by ductile shales overlying and associated with the Mowry. The Mowry Shale contains a mixture of types II and III organic matter and appears to have generated a very large quantity of oil in the deeper parts of the basin.

There has been no known purposeful exploration in this play, however, at least six fields in the deeper parts of the basin have shown production from fractured Mowry Shale, usually in conjunction with the Muddy Sandstone. Resource potential is essentially unknown, but probably small in terms of present recoverablity. Although not assessed, a large resource of a relatively diffuse, non-conventional sort may exist.

Deep Frontier Sandstone Play (Upper Cretaceous) (fig. 23).--This play encompasses the occurrence of oil and gas in stratigraphic traps in offshore marine shelf sandstones of the Frontier Formation. These traps are generally in large, high-energy bar complexes, located in the deeper parts of the basin.

Sandstones, known as "First Wall Creek", "First Frontier" or "Turner sandstone", are the principal objectives in this play. Genetically similar sandstones lower in the formation are also prospective in the western part of the basin and most of these sandstones represent a depositional setting similar to the overlying Sussex and Shannon Sandstone Members. They are a part of a regressive clastic sequence derived from the west (Haun, 1958; Barlow and Haun, 1970; Goodell, 1962). Deltaic facies of equivalent age have been identified west of these shelf sandstones and, to the east, they thin and grade into offshore sandstones of the Turner Sandy Member of the Carlile Shale (Merewether and others, 1979).

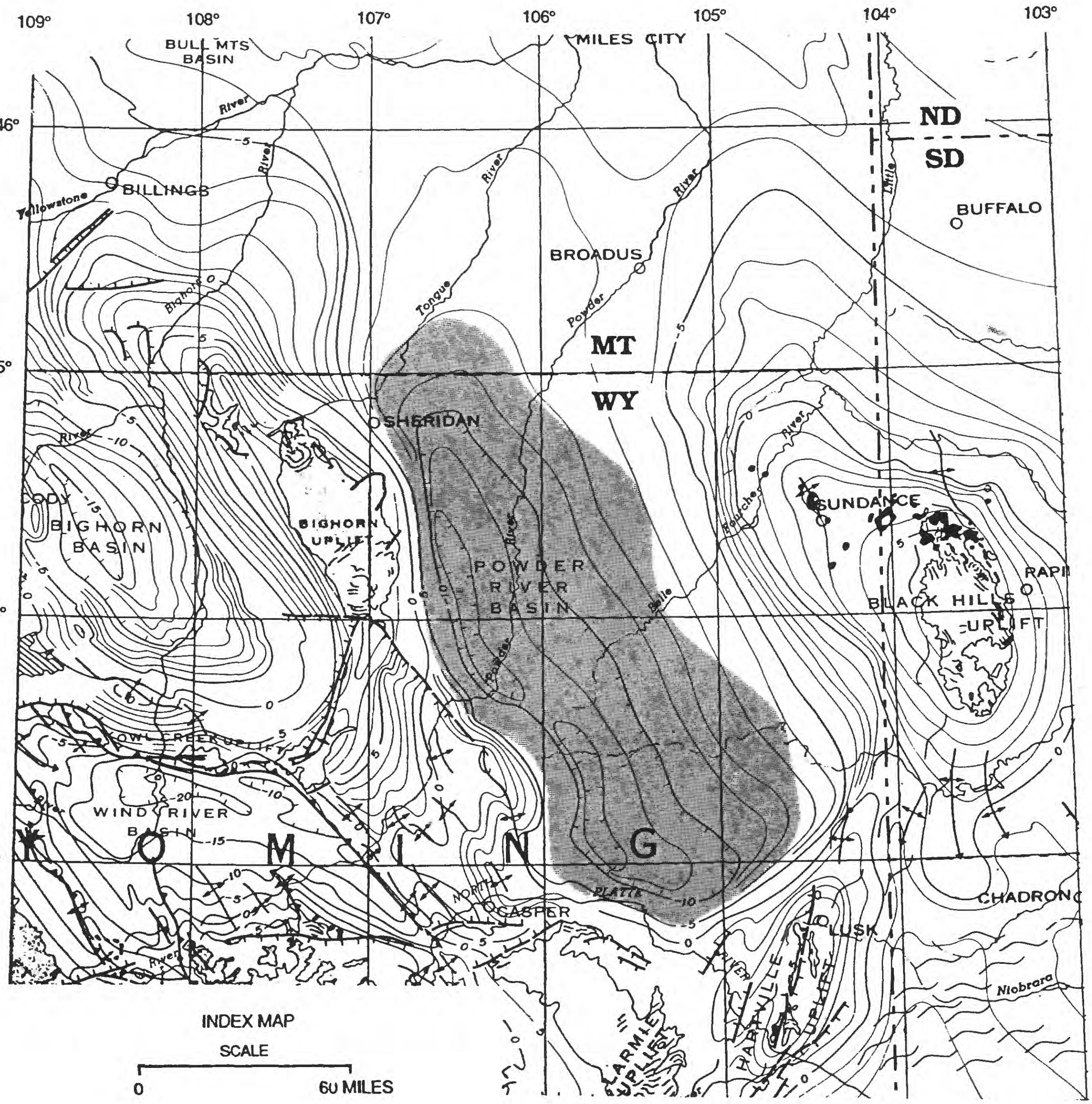

Figure 22.--Map showing area of Mowry Shale play (shaded). Structural contours on top Precambrian, in feet (after Bayley and Muehlberger, 1968).

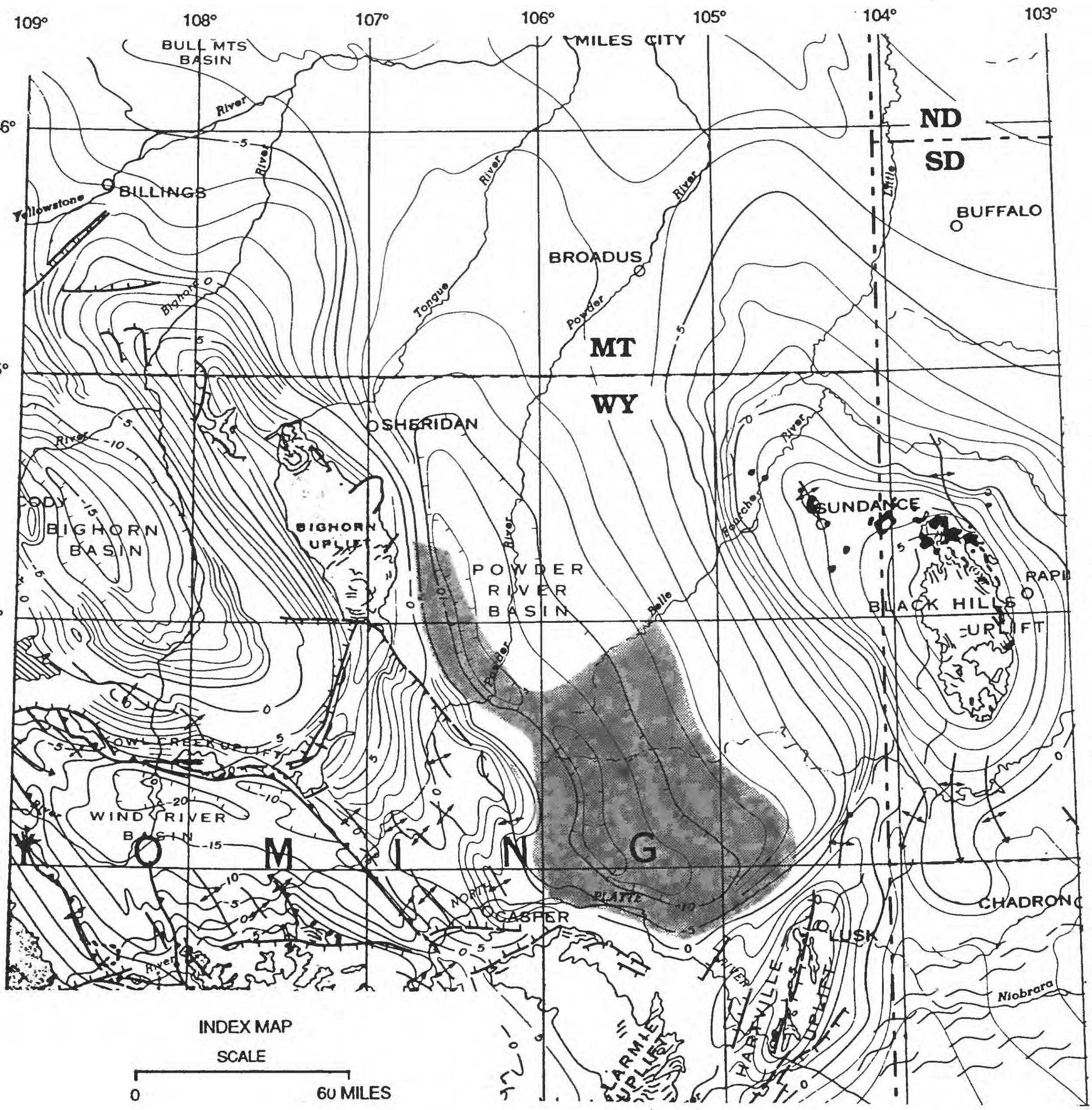

Figure 23.--Map showing area of Deep Frontier Sandstone play (shaded). Structural contours on top Precambrian, in feet (after Bayley and Muehlberger, 1968).

Accumulations result from pinchouts at the margins of individual bars or bar complexes, and from porosity loss within the sandstone bodies. Barlow and Haun (1970) have attributed the giant oil pool in the "2nd Wall Creek" ("Second Frontier sandstone") at Salt Creek Field (over 300 million barrels recoverable oil) to remigration of oil from pre-existent stratigraphic traps. The sandstones generally trend NW-SE although they locally coalesce into less regular configurations (Winn and others, 1983). Shales and siltstones of Frontier and overlying Carlile and Niobrara Formations form seals.

Reservoir sandstones contain abundant quartz, chert, lithic fragments, and appreciable interstitial clay. Average porosities generally range from 10 to 16 percent and some reservoirs are fracture-enhanced.

Source rocks include the organic-rich rocks of the Upper Cretaceous Carlile, Niobrara and Frontier Formations and the Mowry Shale. All achieve maturity in the deeper parts of the basin. The Mowry Shale contains a mixture of types II and III organic matter and is estimated to have generated a very large amount of oil. The Niobrara Formation and Carlile Shale, collectively, are, overall, a major source of oil found in Upper Cretaceous reservoirs. However, the areal extent of effective source rocks in these formations is less extensive than the deeper Mowry Shale. Upper Cretaceous shale in the Frontier Formation has also expelled oil in amounts secondary to the major Cretaceous source rocks. Oil in this play tends to be high API gravity and rich in dissolved gas.

Although the Frontier Formation is the major producing formation of the Powder River basin, simple stratigraphic traps have accounted for little more than 30 million barrels of oil and a modest amount of gas. This exploration play began in the early 1970's, stimulated by discovery of Spearhead Ranch Field. Field sizes are not well documented, but the largest to date is probably Powell-Ross Field with more than 10 million barrels (Appendix). Several of the approximately 20 individual pools in this play may eventually be found to coalesce. Accumulations remaining to be discovered are very likely to be modest in size. Depth for future activity in the play will generally range from 2,450-3,950 m (8,000 to 13,000 feet).

Turner Sandstone Play (fig. 24).--This play encompasses the occurrence of oil in stratigraphic traps of the Turner Sandstone Member of the Carlile Shale (Upper Cretaceous) on the shallow east flank of the basin. Sandstones are marine and appear to represent outer shelf equivalents of the "First Wall Creek sand" of the Frontier Formation. Traps result from sandstone or porosity pinchouts. Reservoir bodies are very thin and show irregular configurations, as at Shurley Field, and E-W linear trends, as at South Coyote Creek and Todd Fields, the latter appearing to be either transverse bars or lag deposits in subtle swales (Rice and Keighin, 1988). Reservoir sandstones are typically of poor quality and contain abundant clay, chert and lithic fragments. Secondary porosity is a major factor in reservoir development at Todd Field (Charoen-pakdi and Fox, 1989).

Source for the oil is probably the associated organic-rich rocks of the Frontier, Carlile, and Niobrara Formations, although contribution from the

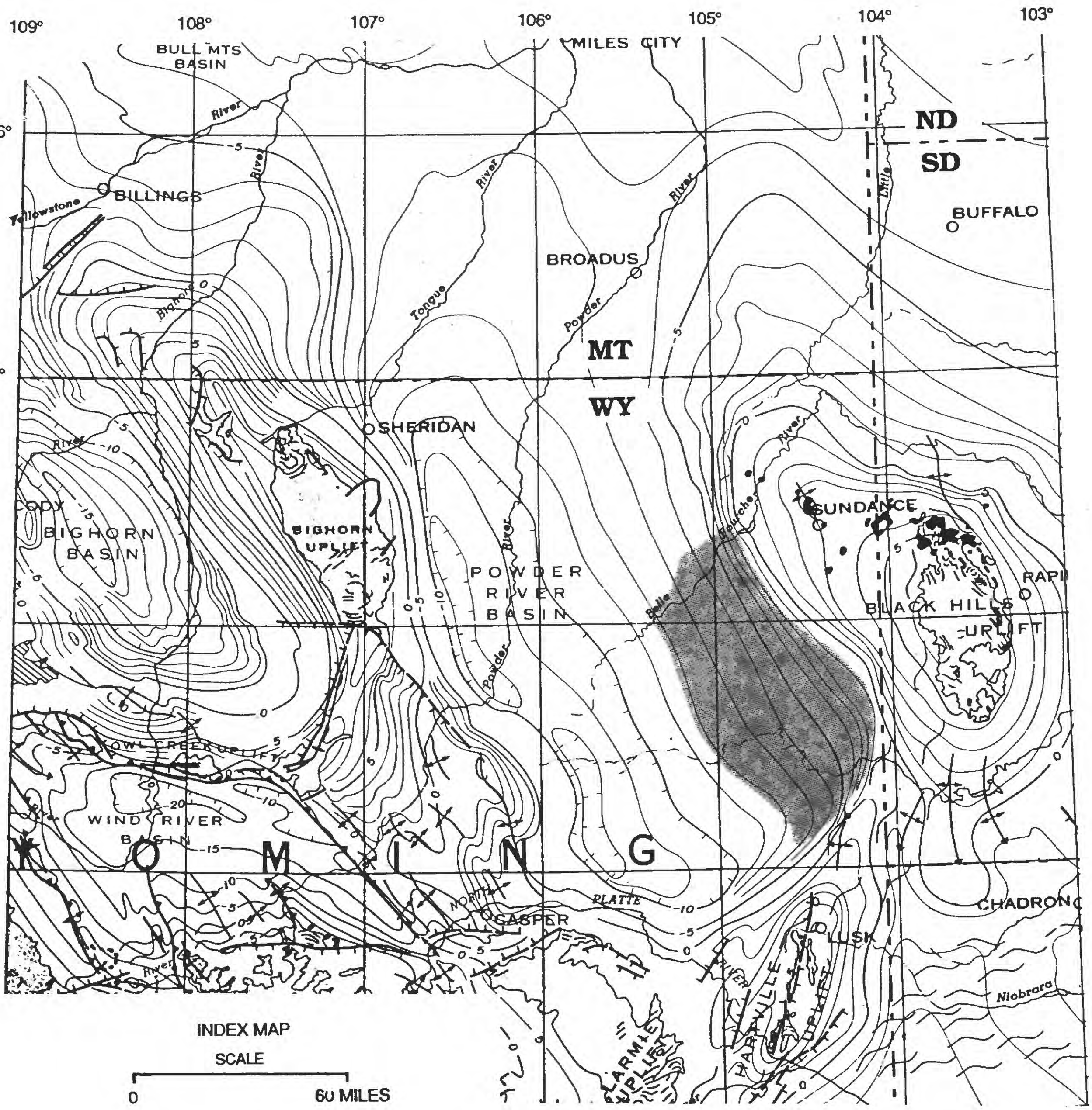

Figure 24.--Map showing area of Turner Sandstone play (shaded). Structural contours on top Precambrian, in feet (after Bayley and Muehlberger, 1968).

rich Mowry Shale is also likely. The areal extent of effective source rocks is greater for the older formations. Data also indicate that the Upper Cretaceous Belle Fourche Shale may have expelled oil in amounts secondary to the major Cretaceous source rocks.

Incidental exploration of the Turner Sandstone on the shallow east flank of the basin occurred as early as 1915 as an adjunct to other exploration activity. Pools have been small and mostly marginally economic, the largest being approximately 12 million barrels (Appendix). Potential for large undiscovered resources in this play is slight and the petroleum resources of the play were assessed in aggregate with other plays of small resource potential.

Shannon and Sussex Marine Shelf Sandstone Play (fig. 25).--This play includes stratigraphic traps in the Shannon and Sussex Sandstone Members of the Steele Shale. These sandstones are interpreted as having been deposited on a broad shelf seaward from the marine shoreline:

Shannon Sandstone Member - Facies of the Shannon have characteristics of a "wide-shelf model" of deposition (Asquith, 1974). Asquith has reconstructed the shelf, slope, and basin topography using electric log correlations of bentonite marker beds in the Cody Shale and has shown the Shannon to be situated at the top of this progradational shelf sequence of predominantly offshore muds. Tillman and Martinsen (1984) and Spearing (1976) presented evidence from outcrops and subsurface strata to support the interpretation of the Shannon as an offshore shallow-marine sand transported by marine currents in a longshore direction. Detailed subsurface facies analysis by Crews and others (1976) has indicated that the shales underlying the Shannon have been scoured locally and beveled regionally, suggesting that the same pattern of marine currents that transported the Shannon sands may also have shaped the pre-Shannon surface.

Sussex Sandstone Member - Hobson and others (1982) interpreted the Sussex at House Creek Field to have been deposited as part of an offshore bar complex many tens of kilometers from the shoreline in an outer shelf location. They invoke a mechanism whereby, as a rapid transgression took place, rapid shoreface retreat left residual sand sheets on the shelf. These were later transported and formed into broad elongate sand complexes or offshore bars by marine currents. The productive limits of oil fields suggest a relatively narrow and sinuous sandstone distribution. However, the sand bodies are much broader with relief on the order of tens of meters over tens of kilometers. Brenner (1978) attributes the lobate lateral edges characteristic of the sand bodies to periodic breaching by storm-generated currents. Detailed mapping by Crews and others (1976) revealed at least 12 well-sorted sandstone bodies, imbricated, with the youngest to the east. They trend generally N 30°-40°W and are separated by areas of siltstone and mudstone. These sandstone bodies are about 1 to 3 km (.6 to 2 mi) wide, 8 to 48 km (5 to 30 mi) long, and up to 10 m (33 ft) thick.

The Sussex-Shannon play is limited in distribution to the deeper parts of the basin. According to Brenner (1978), petroleum in the Sussex Sandstone Member accumulated in classic updip pinchout traps where porous and permeable shelf sandstone bars pinch out into shale. House Creek Field in the south-central part of the basin produces from the Sussex. It trends

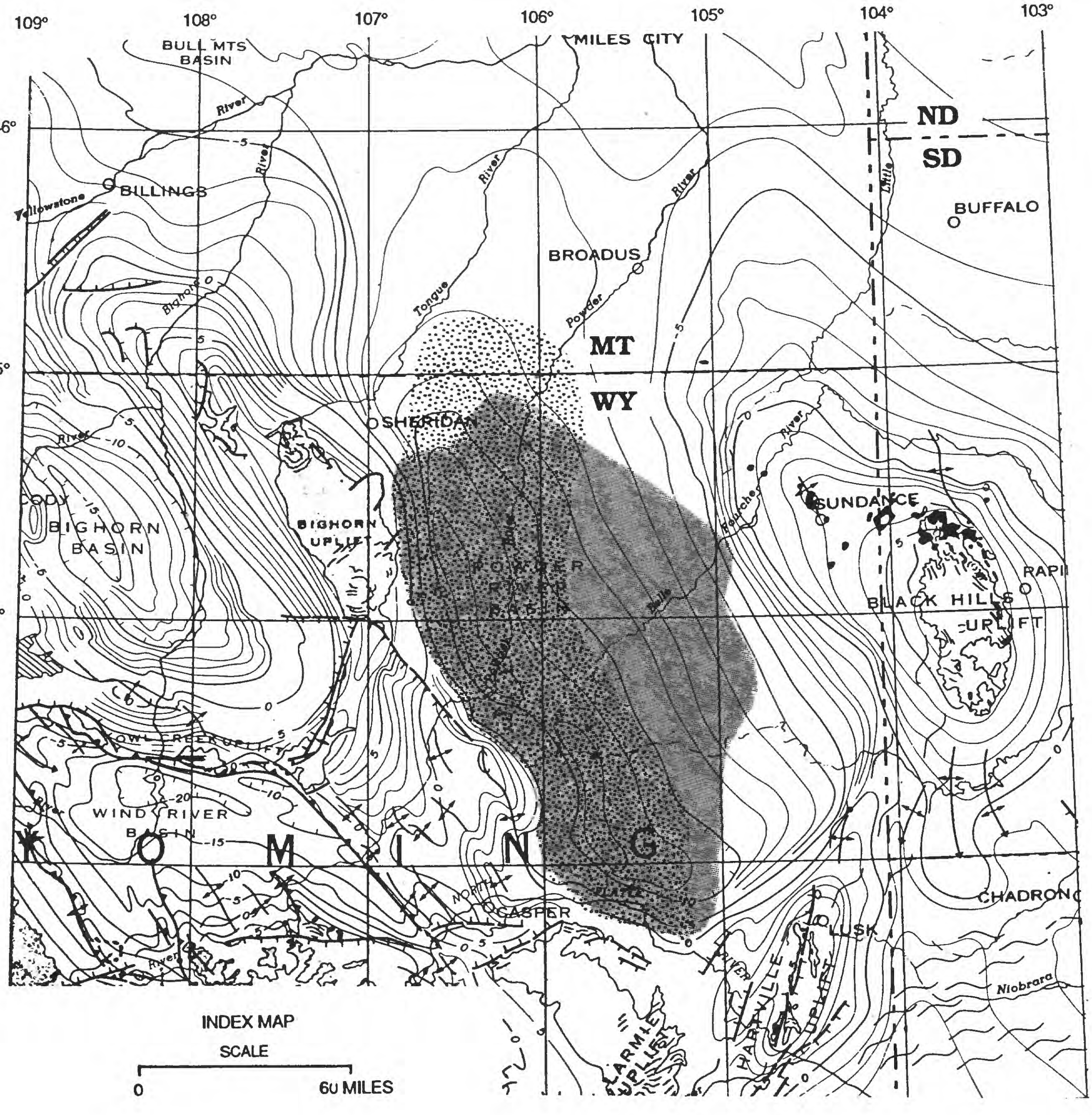

Figure 25.--Map showing area of Shannon and Sussex Marine Shelf Sandstone plays (stippled and shaded, respectively). Structural contours on top Precambrian, in feet (after Bayley and Muehlberger, 1968).

N 40° to 45°W which is nearly perpendicular to the shelf trend and is an updip stratigraphic trap surrounded by Steele Shale. Reservoir-quality rocks do not generally exceed about 10 m (33 ft) in thickness and may extend 30 or more km (19 mi) along strike and up to 5 km (3 mi) down-dip (Sabel, 1985). Similar traps are identified in the Shannon.

The Niobrara Formation and Carlile Shale are major sources of oil in Upper Cretaceous reservoirs, although, the areal extent of effective source rocks in these formations is less extensive than the deeper Mowry Shale. The Upper Cretaceous shales in the Frontier and Steele Formations also have expelled oil in amounts secondary to the major Cretaceous source rocks. In most of this play, vertical migration of hydrocarbons is required to charge Sussex and Shannon reservoirs.

About 120 million barrels of recoverable oil and 70 billion cubic feet of gas have been discovered in the Shannon and Sussex Sandstone Members. About 10 fields are in the category of greater than 1 million barrels of oil (Appendix), and another 10 fields are less than 1 million barrels of oil or equivalent. House Creek Field has produced about 19 million barrels of oil from an estimated 160 million barrels of oil originally in place in the Sussex Member. In the analogous Shannon Member, Hartzog Draw Field is the largest field, having produced about 33 million barrels of oil and about 14 billion cubic feet of gas. The southern part of the basin is well explored but the northern part is lightly explored. The size of fields remaining to be discovered is thought to be in the same range as those discovered.

Mesaverde and Lewis Stratigraphic Play (fig. 26).--This play encompasses the occurrence of oil and gas in sandstone stratigraphic traps in the Upper Cretaceous Mesaverde and Lewis Formations. Strata involved in these plays are part of a large western-derived regressive clastic sequence. They include deltaic and marine shelf sandstones that grade into siltstone or shale, resulting in stratigraphic petroleum entrapment. Deltaic sands were deposited in a wave-dominated high-destructive shoreline and were locally modified into offshore bars. These bars include porous sands that pinch out eastward forming traps for hydrocarbons and occur in the Teapot and Parkman Members of the Mesaverde Formation and the Teckla Sandstone Member of the Lewis Shale. Stratigraphic studies that have led to current sedimentological interpretations of these Upper Cretaceous strata in the Powder River basin are highlighted by Curry (1976) and include particularly those of Gill and Cobban (1966), Weimer (1961), and Asquith (1970).

The oldest of the Mesaverde cycles of deposition in the Powder River basin is the upward-coarsening progradational Parkman Sandstone Member. Sandstone was derived from the Cretaceous cordillera in eastern Idaho and southeastern Montana (Hubert and others, 1972). Deposition took place on a southeasterly prograding, wave-dominated, high-destructive, delta. The Parkman delta prograded over upper prodelta slope deposits of the Cody Shale. As indicated by the orientation of pillow structures at the base of delta front sandstone beds, subaqueous parts of the delta surface sloped to the southeast. Upper delta plain facies that comprise the upper part of the Parkman include carbonaceous mudstone, lenses of channel sandstone, and a few thin lignite beds deposited in floodplains, meandering streams, lakes, swamps, coastal marshes and tidal creeks. During the subsequent destructional phase, caused by compaction of thick prodelta mud over which

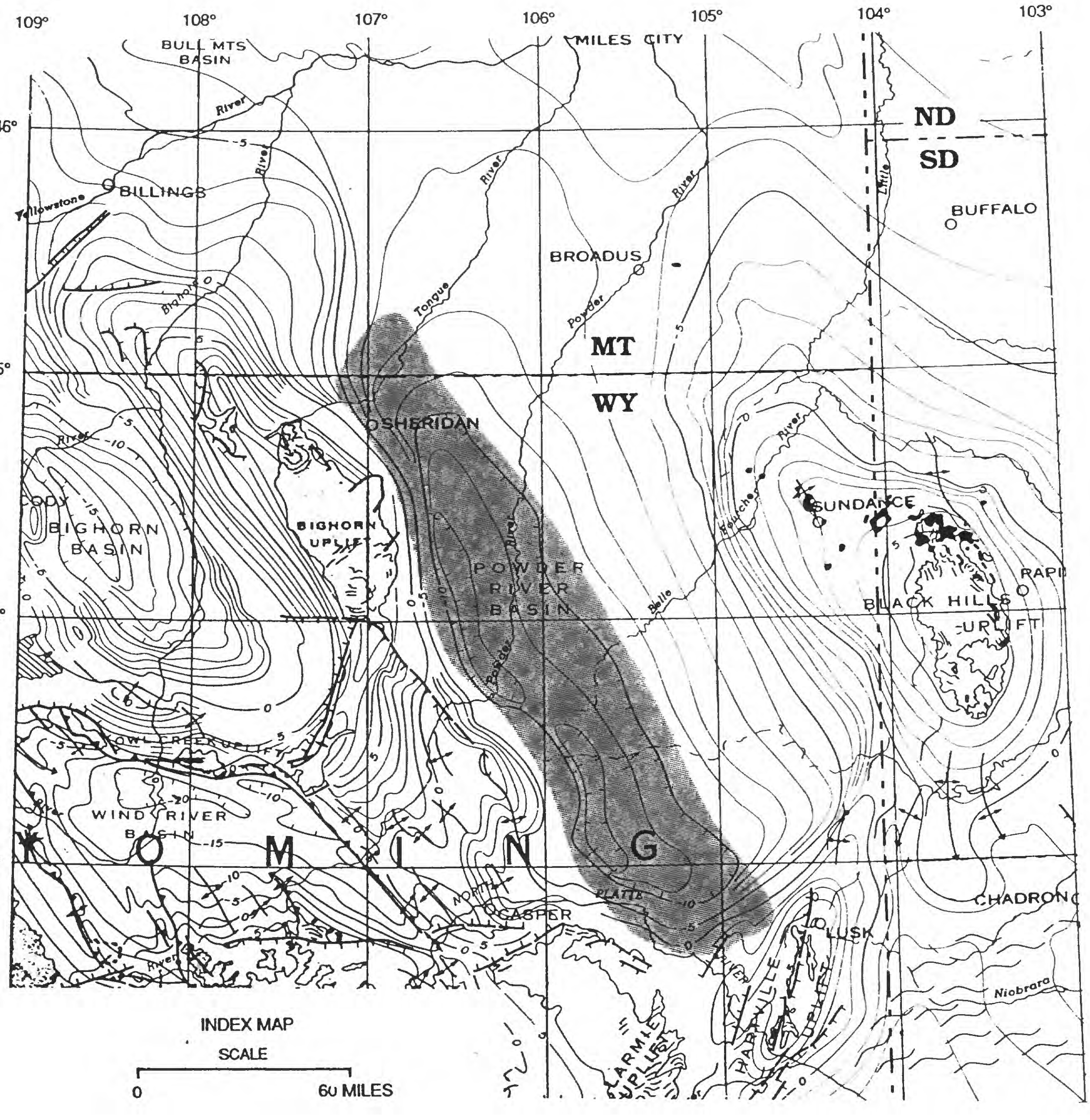

Figure 26.--Map showing area of Mesaverde and Lewis stratigraphic play (shaded). Structural contours on top Precambrian, in feet (after Bayley and Muehlberger, 1968).

the deltas prograded, marine shoreline sandstone was deposited, followed by marine shale deposition. This marked the termination of delta growth. Curry (1973) has correlated outcrops with nearby subsurface well logs and has interpreted facies changes into the subsurface. Barrier island sandstone is thought to be present seaward of the delta plain sandstones. Still farther to the east these barrier island sandstones grade into finer-grained marine sandstones, siltstones, and shale.

During a second progradational event, the Teapot Sandstone Member was deposited in a fashion similar to that of the Parkman. Curry (1976) mapped six stages of imbricate prodelta slope deposition. As these prodelta facies were being deposited to the east, sandstones of the Teapot were being deposited in a variety of deltaic environments. These included subaerial delta plains, marine bars seaward from the delta plain, as well as deeper marine slopes. A destructive deltaic phase followed, ended by deposition of the marine Lewis Shale.

During deposition of the Lewis Shale, a third and more local deltaic progradation resulted in deposition of the Teckla Sandstone Member. The locations of the Teckla delta systems, inferred from subsurface mapping, approximately coincide with similar systems in the Teapot Sandstone Member. Deposition of deltaic strata was followed by transgression of the Lewis sea once again and renewed deposition of finer-grained marine clastics.

Traps in these sequences are produced primarily by updip pinchouts of shallow marine sandstones into finer-grained facies which act as seals. As an example, Runge and others (1973) have described the occurrence of oil at Poison Draw Field, the largest oil field with Teckla production. Here, the reservoirs are a complex of strandline sandstones in which oil is trapped by updip loss of porosity due to increasing siltstone and shale content. The complexity of the sandstone bodies is attested to by the presence of multiple oil-water contacts within the field. Isbell and others (1976) reported on the petroleum geology of the Well Draw Field. In this field, production is from marine sandstones in the Teapot representing a large northwest-trending stratigraphic trap formed by an updip facies change from porous shallow-water marine sandstone into tight, offshore siltstone and shale; they note that the productive Teapot trend continues northward to include Mikes Draw and Don Draw Fields. At Dead Horse Creek and Barber Creek Fields (fig. 14, no. 28), oil is similarly trapped in a marine bar of the Parkman Sandstone.

The Niobrara Formation and Carlile Shale are probably contributing sources for oil in these reservoirs, although the areal extent of effective source rocks in these formations is less extensive than the deeper Mowry Shale. Shales in the Frontier and Steele Formations also have expelled oil in amounts secondary to the major Cretaceous source rocks. In this play, it appears that vertical migration of hydrocarbons is required to charge the reservoirs.

Approximately 100 million barrels of oil and 150 billion cubic feet of gas have been discovered in these traps. About 13 fields are in the category of greater than 1 million barrels of oil (Appendix) and 45 are fields with less than 1 million barrels of oil. The largest field is Well Draw estimated at about 45 million barrels of oil and 85 billion cubic feet of gas.

A very large area in the northern part of the basin remains to be evaluated. Fields discovered in the future will probably be of the size range of those discovered to date, typically with ultimate recoverable reserves of less than 10 million barrels of oil and less than 5 billion cubic feet of gas. The depth of objective sandstones is about 3,050 m (10,000 feet) in the axial part of the basin.

Other Plays

Other associations having trapping potential are present and in some cases have yielded small amounts of oil or gas. They include sandstone pinchouts, truncations and onlaps in the Sundance and Morrison Formations, the Lance and Fort Union Formations, in "stray" Upper Cretaceous sandstones, and in sandstones of the Triassic, Pennsylvanian Amsden, Ordovician Lander and Cambrian Flathead. Stratigraphic entrapment also may occur in various carbonate intervals, including Madison, Forelle, Minnekahta, Niobrara, Sundance and Alcova formations. These associations were treated collectively for purposes of assessment. Not included in the assessment are such unconventional resources as coal bed methane and fractured shale reservoirs as may be found in parts of the Upper Cretaceous.

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APPENDIX

Tables of accumulations larger than 1 MMBO or 6 BCF, by play
[Data in part from NRG Associates, 1986; Wyoming O&G CC, 1986; and Montana O&G CC 1986]

Field name	Discovery date	Estimated size (ult. rec.) Oil (MMBO)	Gas (BCFG)
A. Basin margin anticline play (through 1983)			
Salt Creek-Teapot Dome	1908	675.0	708.0
Meadow Creek-Sussex	1948	113.0	118.8
Lance Creek	1918	106.5	139.8
Glenrock, South	1950	78.5	28.6
Big Muddy	1916	54.1	<0.1
North Fork-Cellars Ranch	1951	27.5	<0.1
Sussex, West	1951	18.8	8.8
Cole Creek	1938	17.3	0.5
Cole Creek, South	1948	16.5	0.1
Sage Spring Creek	1949	15.7	4.3
Salt Creek, East	1951	12.8	0.8
Ash Creek, South	1954	9.0	0.2
Little Buck Creek	1944	7.9	3.8
Ash Creek, MT & WY	1952	6.9	0.2
Lance Creek, East	1919	6.7	1.9
Buck Creek	1952	6.7	3.3
Mule Creek	1919	3.9	0.1
Tisdale, North	1952	3.8	<0.1
Lightning Creek	1949	2.9	1.0
Soap Creek, MT	1921	2.7	0
Brooks Ranch	1957	2.7	0
Tisdale, East	1959	2.7	0.1
Glenrock	1949	2.6	0.2
Salt Creek, West	1917	1.8	<0.1
Sherwood	1954	1.7	21.5
Twenty Mile Hill	1960	1.5	0.1

B. Minnelusa play (through 1981)

Field name	Discovery date	Oil (MMBO)	Gas (BCFG)
Raven Creek	1960	51.7	
Timber Creek	1958	18.2	
Stewart	1965	17.1	
Dillinger Ranch	1964	16.5	
Duvall Ranch	1964	14.8	
Halverson	1962	14.6	
Reno	1965	11.5	
Reel	1962	11.0	

Field name	Discovery date	Estimated size (ult. recov.) Oil (MMBO)	Gas (BCFG)
B. Minnelusa play (through 1981)--continued			
Hamm	1967	10.3	
Little Mitchell Creek	1966	9.7	
Rozet, West	1967	8.0	
Robinson Ranch	1958	7.5	
Semlek, West	1963	7.5	
Slattery	1963	7.5	
Wallace	1966	7.1	
Semlek	1962	6.8	
CH	1967	6.7	
Mellott Ranch	1961	6.5	
Rozet, South	1965	6.1	
Camp Creek	1962	5.0	
Rourke Gap	1973	5.0	
MD	1967	4.7	
Kummerfeld	1969	4.3	
Rocky Point	1961	4.1	
Guthery	1960	4.0	
Prong Creek	1959	3.9	
Windmill	1967	3.8	
Bone Pile	1972	3.8	
OK	1973	3.6	
Bishop Ranch, South	1968	3.6	
Kuehne Ranch	1965	3.5	
Rozet, East	1965	3.4	
Big Hand	1975	3.4	
Wagon Spoke	1972	3.2	
Tholson Ranch	1969	3.2	
Donkey Creek	1957	3.0	
Rainbow Ranch	1960	2.7	
Maysdorf	1976	2.5	
Dutch	1975	2.5	
Pownall Ranch	1960	2.5	
Edsel	1981	2.5	
Kuehne Ranch, Southeast	1966	2.2	
Reno, East	1966	2.1	
Robinson Ranch, East	1961	2.1	
Sharp	1975	1.8	
Robinson, Ranch, South	1961	1.6	
Am Kirk	1962	1.6	
Kane	1966	1.5	
Reynolds Ranch	1972	1.5	
Pickrell Ranch	1965	1.5	

Field name	Discovery Date	Estimated size (ult. recov.) Oil (MMBO)	Gas (BCFG)
B. Minnelusa play (through 1981)--continued			
Deadman Creek	1973	1.5	
Wolff	1974	1.5	
Jewel, South	1978	1.5	
Haight	1978	1.5	
Basin, Northwest	1965	1.4	
Texas Trail	1974	1.3	
Gibbs & South Gibbs	1970	1.3	
County Line	1974	1.3	
Eitel	1977	1.3	
Breaks	1976	1.2	
Roehrs	1966	1.2	
Stewart, East	1980	1.2	
Brennan	1980	1.2	
Breen	1966	1.2	
Kiehl	1972	1.0	
Swartz Draw	1981	1.0	
Pleasant Valley	1963	1.0	
Rozet, Northeast	1966	1.0	
C. Dakota sandstone play (through 1983)			
Coyote Creek	1958	21.7	25.4
Buck Draw	1983	12.0	22.5
Donkey Creek	1953	11.6	1.4
Kummerfeld	1960	7.4	0.8
Moorcroft, West	1964	7.0	9.7
Burke Ranch	1953	6.8	0.3
Miller Creek	1959	6.4	4.8
Wood	1967	4.8	0.1
Coyote Creek, South	1963	1.0	0.3
Included as part of Basin Margin anticline play:			
South Glenrock	1950	39.3	8.5
Sage Spring Creek	1949	15.7	4.3
Big Muddy	1922	8.7	

Field name	Discovery date	Estimated size (ult. recov.) Oil (MMBO)	Gas (BCFG)
		D. Muddy-Newcastle sandstone play (through 1983)	
Bell Creek, MT	1967	139	23.1
Clareton Trend	1950	90	29.0
Hilight	1969	75	231.0
Fiddler Creek Trend	1948	56.4	>7.0
Gas Draw	1968	26.6	10.9
Recluse	1967	22.4	84.6
Kitty	1965	20.0	110.0
Amos Draw	1982	20.0	50.0
Rozet	1959	19.1	9.2
Raven Creek	1956	11.7	12.3
Springen Ranch	1968	10.6	11.7
Ute	1967	9.8	21.9
Rocky Point	1963	7.0	16.1
Whitetail	1968	6.6	1.8
Collums, South	1969	5.9	6.1
Mill-Gillette	1962	4.3	9.9
Steinle Ranch	1973	4.2	8.2
Chan	1968	4.2	4.9
Sandbar, East	1968	3.8	5.3
Sandbar, West	1968	3.5	6.8
Oedekoven	1968	3.4	5.8
Rozet, East & Northeast	1961	3.3	.2
Donkey Creek, South	1956	3.2	1.3
Porcupine	1969	3.2	45.6
Lazy B	1969	3.0	4.8
Fence Creek	1968	3.0	1.7
HA Creek-Thunder Creek	1974	2.8	39.0
Moorcroft, West	1956	1.8	0.6
School Creek	1960	1.8	12.0
Carson	1969	1.6	3.2
Felix	1982	1.6	20.9
Joe Creek	1969	1.4	2.7
Andy	1983	1.1	9.0
Hunter Ranch	1968	1.1	0.8
Prairie Creek	1960	1.1	0.4
Big Hand	1969	1.1	1.0
Frog Creek	1972	1.1	2.6
Soda Well, East	1964	1.0	0

Field name	Discovery date	Estimated size (ult. recov.) Oil (MMBO)	Gas (BCFG)
E. Deep Frontier sandstone play (through 1983)			
Powell-Ross	1954	10.5	30.0
Spearhead Ranch, South	1973	5.8	49.2
Trabing	1975	1.0	1.2
F. Shallow Turner sandstone play (through 1983)			
Finn-Shurley	1963	12.0	7.0
Coyote Creek, South	1963	3.7	1.5
Todd	1974	1.4	3.6
G. Sussex sandstone and Shannon sandstone plays (through 1983)			
Hartzog Draw	1975	60.0	25.8
House Creek	1968	22.4	18.6
Pine Tree	1976	9.0	6.1
Heldt Draw-Culp Draw	1973	6.3	6.3
Holler Draw	1974	3.0	1.5
Triangle U	1974	2.5	0.7
Jepsen Draw-Nipple	1974	2.5	0.6
Payne	1969	2.0	3.2
Table Mountain	1977	2.0	2.4
Indian Creek	1974	1.8	2.9
H. Mesaverde and Lewis stratigraphic plays (through 1983)			
Well Draw	1972	43.5	84.0
Dead Horse Creek-Barber Creek	1957	16.0	3.7
Scott	1978	15.0	13.2
Kaye	1969	7.5	6.1
Poison Draw	1972	7.2	10.8
Flat Top	1959	2.8	29.1
Manning	1970	2.4	5.1
Bridge Draw	1980	2.2	0.3
Martin Spring	1975	1.9	0.6
Dry Fork	1970	1.3	1.0
Empire	1974	1.2	0.4
Brush Creek	1976	1.1	0.3
Dead Horse Creek, South	1961	1.0	0.5