POWDER RIVER BASIN PROVINCE (033)

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With a section on coalbed gas plays by Dudley D. Rice and Thomas M. Finn

INTRODUCTION

The Powder River Basin is a major intermontane basin of Laramide origin in the northern Rocky Mountains and occupies northeastern Wyoming and a small part of southeastern Montana. It constitutes the major part of the encompassing province, and together with portions of adjoining uplifts, comprises more than 34,000 sq mi.

The basin is a deep, northerly trending, asymmetric, mildly deformed trough, approximately 250 mi long and 100 mi wide. Its structural axis is close to its western margin, which is defined by reverse and thrust faults and by hogbacks of steeply dipping and overturned strata along the Bighorn Mountains uplift and by the Casper Arch. It is bounded on the south by reverse or thrust faults along the Laramie and Hartville Uplifts, 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 described by the structurally subtle northwest-trending Miles City Arch.

The Powder River Basin is filled with a thick sequence of Phanerozoic strata, which exceed 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, which rarely exceeds 2,200 ft, followed by a very 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 the local uplifts and the present basin.

The basin is one of the richest petroleum provinces in the Rocky Mountains. More than 2.7 billion barrels of recoverable oil and over 2.3 TCF gas have been discovered in about 700 fields since the discovery of the giant Salt Creek field in 1908, of which about 225 are greater than 1 MMBOE in size. Exploration began in the late 1800's, and the first discovery was in the Lower Cretaceous Newcastle Sandstone on the east flank of the basin about 1887. Hydrocarbons occur in reservoirs ranging in age from Mississippian to Late Cretaceous in both structural and stratigraphic traps. Plays in this basin are of both structural and stratigraphic types and occur in three major petroleum source rock and reservoir systems--Pennsylvanian-Permian, Lower Cretaceous, and Upper Cretaceous. Plays that are individually assessed are listed below.

CONVENTIONAL PLAYS

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3302	Basin Margin Anticline
3303	Leo Sandstone
3304	Upper Minnelusa Sandstone
3305	Lakota Sandstone
3306	Fall River Sandstone
3307	Muddy Sandstone
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3310	Turner Sandstone
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3315	Biogenic Gas

UNCONVENTIONAL PLAYS

3308 *Mowry Fractured Shale*

3311 *Niobrara Fractured Shale*

3350 *Powder River Basin–Shallow Mining-Related*

3351 *Powder River Basin–Central Basin*

Unconventional coalbed gas plays are Powder River Basin–Shallow Mining-Related Play (3350) and Powder River Basin–Central Basin Play (3351); these are described by Dudley D. Rice and Thomas M. Finn. Further discussion of coalbed gas plays, with references, may be found in the chapter by Rice, "Geologic framework and description of coalbed gas plays" elsewhere in this CD-ROM.

Other associations having trapping potential are present and in a few cases have yielded small amounts of oil or gas. They include sandstone pinchouts or truncations in the Sundance and Morrison Formations, "stray" marine Upper Cretaceous sandstones, and in sandstones of the Triassic, Pennsylvanian Amsden, Ordovician Lander, and Cambrian Flathead. Stratigraphic entrapment is also possible in various carbonate rocks, including Madison, Forelle, Minnekahta, Sundance and Alcova, due to local porosity development, erosion, or relief. None of these associations are considered likely to contain accumulations larger than the minimum sizes considered and were not quantitatively assessed.

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CONVENTIONAL PLAYS

3301 BASIN MARGIN SUBTHRUST PLAY

This subthrust play encompasses the occurrence of petroleum trapped in deformed strata below major thrusts located along the basin margins. The overthrust wedge of Precambrian rocks may act as a trap and seal of fluids in the underlying sedimentary wedge, or may simply conceal traps which have formed in underlying folds or faults. This is a hypothetical play, although productive in the adjacent Wind River Basin. Reservoirs range in age from Mississippian to Late Cretaceous and include sandstones, carbonates and possibly fractured shales. The play occupies approximately 1,400 m^2 on the western and southern margins of the basin.

Reservoirs: Reservoir lithotypes include sandstones and carbonates and range in age from Mississippian to Upper Cretaceous. Principal reservoirs are the Cretaceous Frontier, Muddy, and Dakota sandstones, Jurassic sandstones, and the Pennsylvanian-Permian Tensleep-Minnelusa sandstone.

Source rocks: Principal source rocks for Paleozoic reservoirs include Pennsylvanian Desmoinesian black shales and, possibly, organic-rich rocks of the Permian Park City (Phosphoria) Formation 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 reservoirs have been juxtaposed by faults. Cretaceous and Paleozoic reservoirs generally have distinct oil types related to their different sources.

Timing and migration: Principal generation and migration of hydrocarbons took place in the Laramide during development of the structural traps. Speculative migration models also propose long-distance pre-Laramide migration through Tensleep-Minnelusa reservoirs from Phosphoria source beds, far to the west, prior to present basin formation. Permian black shales in the area of western Wyoming and eastern Idaho, however, probably would have been buried deeply enough to generate hydrocarbons by Jurassic time. If petroleum was supplied from these distant sources, some of it could have moved into the area of the present basin during the Jurassic and been redistributed during the Laramide orogeny, when augmented by locally generated hydrocarbons.

Traps: Traps are structural closures, caused variously by the overlying Precambrian wedge or by folds or faults within the underlying sediment rock column. Seals are generally fine grained clastic rocks, primarily Cretaceous, and Triassic and Permian shales. Drilling depths generally range from 4,000 to 14,000 feet.

Exploration status and resource potential: The first production in the Rocky Mountains from beneath Precambrian basement rocks was at the southern end of the Powder River Basin where the Muddy

Sandstone reservoir at South Glenrock field extended beneath a thrust wedge of the Laramie Range, which overrides the edge of a large basin margin anticline. Subthrust traps are not certainly identified, and geologic data are very limited and do not allow easy exploration of this play.

This play, although carrying a considerable risk and modest overall potential, also has the possibility for accumulations of substantial size.

3302. BASIN MARGIN ANTICLINE PLAY

This play is characterized by oil and gas accumulations trapped in large and small anticlines along the southern and western margins of the basin. The majority of the anticlines are relatively simple folds which are reverse-faulted at depth but with extensional faults on their crests. Fault closures, particularly on plunging anticlinal noses, also produce, as do combination traps. Reservoirs range in age from Mississippian to Late Cretaceous and include sandstones, carbonates and occasional fractured shales. The play covers approximately 9,000 m^2.

Reservoirs: Major reservoirs are sandstones and most important are the Cretaceous Frontier, Muddy and Dakota sandstones and the Pennsylvanian-Permian Tensleep-Minnelusa sandstone. In some places fractured shales of Cretaceous age are productive. Few Mississippian rocks are productive and older producing reservoirs are unknown. Multiple pay zones are common; fine-grained rocks intercalated with the reservoirs provide seals. A regional seal is the Permian-Triassic redbed sequence, which separates Paleozoic and Mesozoic reservoirs in most fields. Individual reservoir average thicknesses range from less than 10 to greater than 100 and average porosities range from 10 to 27 percent.

Source rocks: Principal source rocks for Paleozoic reservoirs include Pennsylvanian Desmoinesian black shales and, possibly, organic-rich rocks of the Permian Phosphoria Formation 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 reservoirs have been juxtaposed by faults. Cretaceous and Paleozoic reservoirs generally have distinct oil types related to their different sources. Gravities of oils in Mesozoic rocks are typically 32û–44û API, with low sulfur - generally between 0.1 and 0.2 percent, whereas the Paleozoic crudes are typically 22û–35û degrees API, with 1 to 4 percent sulfur.

Timing and migration: Source rocks of Cretaceous age probably began expelling oil into structures which were developing around the basin margins in Paleocene time. Principal among these are the Mowry Shale 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 shales of the Upper Cretaceous Frontier and Steele Formations have expelled oil in amounts secondary to those of other Cretaceous source beds. Speculative migration models also propose long-distance pre-Laramide migration through Tensleep-Minnelusa reservoirs from Phosphoria source beds, far to the west, prior to present basin formation. If petroleum was supplied from these distant sources, some of it could have moved into the area of the present basin during the Jurassic and been redistributed during the Laramide orogeny, when augmented by locally generated hydrocarbons. Oil gravities range from 20û–50û API, with heavier crudes generally in the Paleozoics. GOR generally ranges from 10 to 2,000 CFG/bbl and average approximately 300 CFG/bbl. NGL/gas ratios average around 30 bbl/MMCFG.

Traps: Traps are anticlines along the southern and western margins of the basin. The majority are relatively simple folds which are reverse-faulted at depth but with extensional faults on their crests. Fault closures, particularly on plunging anticlinal noses, also produce, as do combination traps in this play. Drilling depths generally range from 3,000 to 10,000 ft.

Exploration status and resource potential:: Exploration of the play has proceeded for approximately 100 years with discovery of a series of major fields, including Salt Creek, Teapot Dome, Big Muddy and Lance Creek. Most were found early in the exploration history of the basin. Salt Creek alone has produced almost 0.75 BBO. Total discovered known recoverable resource exceeds 1 BBO and 1 TCF associated-dissolved gas.

Exploration in the play is nearing its conclusion and little potential remains; future discoveries will probably be made in small and subtle traps.

3303. LEO SANDSTONE PLAY

The Leo Sandstone Play is characterized by the occurrence of oil in stratigraphic traps in quartzose sandstones of the Leo Sandstone Member of the Minnelusa Formation, in the southern part of the basin. Traps are subtle and include primarily sandstone pinchouts or gradations into impermeable facies. The play covers approximately 8,300 sq mi.

Reservoirs: The Leo consists of sandstone, carbonate, shale and evaporite, which were deposited in a suite of environments associated with offshore-prograding eolian sand dunes. Reservoirs range from a few feet in thickness to more than 50 ft, and are highly variable in quality. In general character, they are believed to be similar to Upper Minnelusa reservoirs.

Source rocks: Desmoinesian black shale source rocks associated with the reservoir sequence are thought to be the principal source for oil in the "Leo". 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 and are probably the principal source of the oil in reservoirs of the Leo.

Timing and migration: Oil is believed to have been derived from dark marine shales of Desmoinesian age, which are associated with the reservoirs. These shales are present within the play area and matured in the deeper parts of the basin during the Laramide orogeny. Speculative migration models propose long-distance pre-Laramide migration through Tensleep-Minnelusa reservoirs. Gravities of oil generally range from 20û-35û API, increasing with depth. Oils are typically undersaturated with reference to gas.

Traps: Traps are subtle and include primarily sandstone pinchouts or gradations into impermeable facies. Drilling depths range form 6,000 to as deep as 17,000 ft.

Exploration status and resource potential: Although a few fields have been found in the Leo in structural traps, the Leo stratigraphic play is only lightly explored. The future potential is good; however, accumulation sizes are anticipated to be small.

3304. UPPER MINNELUSA SANDSTONE PLAY

This play is based on the occurrence of oil in stratigraphic accumulations which are largely related to paleotopography, reservoir truncation, and sandstone pinchouts at the top of the Minnelusa Formation on the broad, gently sloping eastern flank of the Powder River Basin. The play is located in areas containing well-developed eolian sandstone and is limited on the south by the widespread occurrence of evaporites which adversely affect hydrocarbon migration and reservoir quality. The play covers approximately 10,000 sq mi and is located on the eastern flank and central portions of the Powder River Basin.

Reservoirs: Reservoirs are principally eolian dune sandstones of Wolfcampian age within a complex cyclic sequence of carbonates and sandstones of marine and nonmarine origin dominated by erg and sabkha environments. Vuggy dolomite contributes to production in several fields but is rarely 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 12 to 24 percent in producing fields but are expected to be generally less in downdip areas of the play.

Source rocks: Oil is believed to have been derived from dark marine shales of Desmoinesian age, which lie below the Upper Minnelusa sandstone. Organic carbon content of the shales ranges from less than 1 to 26 weight percent and averages 5.4 percent. These shales are present within the play area and matured in the deeper parts of the basin during Laramide time.

Timing and migration: Hydrocarbon generation and migration from local Desmoinesian source rocks into nearby traps occurred during Laramide time. The significance of local subtle paleotectonic features, such as the Belle Fourche Arch, on hydrocarbon accumulation is problematic. Speculative migration models propose long-distance migration through Tensleep-Minnelusa reservoirs from Phosphoria source beds, far to the west, prior to present basin formation. In those areas, the Phosphoria would probably have been buried deeply enough to generate hydrocarbons, possibly allowing some migration into the area of the present basin during the Jurassic, followed by partial redistribution during the subsequent Laramide orogeny. Gravities of oil generally range from 18û–40û API, increasing with depth. Oils are typically undersaturated with reference to gas, and GOR averages around 60 CFG/bbl. Natural gas liquids generally are not reported.

Traps: The largest portion of Upper Minnelusa oil has been trapped in paleotopographic 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 and by internal lithologic variation and cementation. The majority of oil found to 1994 is in areas with maximum paleotopographic relief. Depth to prospective traps is from about 5,000 to 15,000 feet, most in the 8,000 - 14,000 ft range.

Exploration status: The play is well established, with an active exploration history exceeding 30 years, and covers a significant part of the eastern flank of the basin. More than 160 fields had been discovered through 1990, and they contain approximately 500 MMBO (known recoverable oil). The largest field discovered, Raven Creek, is approximately 47 MMBO.

Resource potential: For assessment purposes, the relatively well explored "mature" area of the shallow eastern flank of the basin is considered an approximate analog for deeper parts of the play to the west. Undiscovered resources are expected to consist primarily of oil and are believed to be substantial. Sizes of undiscovered accumulations in the relatively unexplored areas are expected to be similar to those of the heavily explored analog area.

3305. LAKOTA SANDSTONE PLAY

This play is characterized by the occurrence of oil in stratigraphic traps of the basal Inyan Kara Group in the structurally uncomplicated portions of the basin. The traps are invariably within descrete or composite channel sandstones of alluvial or deltaic origin and are sealed by fine-grained alluvial nonmarine sediments. These traps also occur in combination with structural noses or anticlinal closures outside of the play area. The area of the play is approximately 21,000 sq mi.

Reservoirs: Reservoirs are fine-to coarse-grained sandstones, locally pebbly or conglomeratic. Producing reservoir thicknesses are reported to range from 6 to 13 ft but are locally expected to exceed these values. Porosities of up to 25 percent are reported.

Source rocks: Most of the oil is probably derived from the organic-rich, overlying Mowry Shale, which is separated by several hundred feet from the reservoir sequence. Other possible source rocks include the more closely associated marine Skull Creek Shale and shale of the Fall River sequence. The Mowry and

Skull Creek Shales contain a mixture of types II and III organic matter. Because of richness and 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 deep parts of the basin. Hydrocarbon type is principally oil.

Timing and migration: Hydrocarbon generation and migration from local Cretaceous source rocks into preexisting stratigraphic traps occurred during the Laramide orogeny. Because potential source beds lie separated and above the reservoir sequence, particularly in the case of the Mowry, vertical migration is required and may limit the charge to potential traps. Gravity of reported oils ranges from 26û to 45û API.

Traps: Traps are stratigraphic, sandstone pinchouts within discrete or composite channel sandstones of alluvial origin. Similar traps occur within structural noses or anticlinal closures outside the play area. Lateral seals are fine-grained alluvial nonmarine sediments within the formation (Fuson Shale), and in the entrenched Jurassic Morrison Formation. Vertical seals are provided by overlying Fall River and Skull Creek Shales. Depth range for traps is about 2,000- 13,000 ft in the more prospective areas.

Exploration status and resource potential: The play is generally lightly explored due to the small size, unpredictability, and difficulty of finding accumulations.

This play is of modest potential and probably contains a substantial number of small accumulations.

3306. FALL RIVER SANDSTONE PLAY

This play is characterized by oil and gas occurrence in stratigraphic traps within the regressive clastic wedge of the Fall River Formation (Dakota Sandstone) of the Lower Cretaceous Inyan Kara Group. This widespread clastic wedge prograded into the Western Interior Seaway from the south and east. It is composed of a marine, deltaic, and alluvial complex which becomes progressively more marine to the west, where it consists entirely of marine shale and siltstone of the Thermopolis Shale. The play covers an area of about 14,000 sq mi, largely in the east and central part of the basin.

Reservoirs : Reservoir rocks are generally fine grained, mature quartzose sandstones. Average reservoir porosity generally ranges from 8 to 23 percent and is usually on the order of 13-18 percent. The unit is sealed at the top and bottom by enclosing shales of the Fall River and Skull Creek Formations.

Source rocks: Most of the oil is probably derived from the organic-rich, overlying Mowry Shale, which is separated by several hundred feet from the reservoir sequence. Other possible source rocks include the more closely associated marine Skull Creek and Fall River Shales. The Mowry and Skull Creek Shales 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. All these rocks are thermally mature in the deeper parts of the basin.

Timing and migration: Hydrocarbon generation and migration from associated Cretaceous source rocks into preexisting traps occurred during the Laramide orogeny. Sources matured in the deep parts of the basin and are locally present within the play area. Some lateral migration out of the area of mature source rocks through Fall River carrier beds also appears to have taken place. Oil gravity ranges from 28û to 46û API. GOR generally ranges from 40 to 1,100 CFG/bbl and averages about 400 CFG/bbl, increasing with depth to about 2,000 CFG/bbl at 12,000 ft. NGL/gas ratios generally average around 70 bbl/MMCFG.

Traps: Traps are principally those associated with distributary and estuarine channel sandstones. Within the depositional complex, individual point-bar deposits or point-bar complexes have cut into older marine, deltaic, and strandline sediments and are typically sealed updip by fine-grained abandoned channel deposits and low-energy marine sequences. Marine bar sandstone traps resulting from pinchouts are also considered prospective, although they are not well documented. The unit is sealed at the top and bottom by enclosing shales of the Fall River and Skull Creek Formations. In a few instances structure plays a role in providing additional closure. For example, near the western edge of the Dakota regressive wedge, several stratigraphic accumulations have been discovered in combination with large structural closures or plunging anticlinal noses. Drilling depths range from 4,000 to 14,500 ft, mostly 6,000-12,500 ft in the more prospective areas.

Exploration status and resource potential: Other than production at the western margins of the Dakota wedge from combination traps, such as South Glenrock, most of the oil and gas accumulations in the play occur on the structurally uncomplicated east flank of the basin. Exploration in the play has continued for approximately 30 years and has resulted in the discovery of more than 30 individual pools or fields, aggregating about 170 MMBO (known recoverable oil) and 110 BCFG. The largest accumulation, South Glenrock Creek field, contains approximately 38 MMBO (known recoverable oil).

Undiscovered resources in this play are estimated to be modest, and undiscovered pools will probably be similar in size to those found, that is, mostly less than 10 MMBO. Exploration is currently expanding into deeper parts of the basin.

3307. MUDDY SANDSTONE PLAY

This play describes the occurrence of oil and gas in stratigraphic traps of the Lower Cretaceous Muddy-Newcastle Sandstone complex of the Powder River Basin and is characterized by a suite of trap types related to a variety of depositional environments. Muddy and Newcastle Sandstones are composed of sediment transported into the Cretaceous seaway from the east, accompanying or following subaerial erosion over much of the area. Erosion was succeeded by a gradual transgressive phase interrupted by periodic regressive pulses in which appreciable sand was supplied. The result is a compound clastic wedge consisting of deposits from a variety of depositional environments and having a variety of stratigraphic traps. These include marine bar, strandline, distributary channel, estuarine, alluvial and lower delta plain sandstone bodies. The play area is approximately 21,000 sq mi and covers much of the Powder River Basin.

Reservoirs: Reservoirs are highly variable. 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 dominantly marine bar facies traps are generally nearly north trending. They may represent still-stands during transgression, when high-energy marine bar or barrier sandstone deposits accumulated. Often a single field is a composite of overlapping separate traps and oil pools. Reservoirs are generally fine to very fine grained sandstones. They contain scattered lithic fragments and chert; interstitial clay is in some places abundant. Average reservoir porosities are variable but usually range between 9 and 22 percent, with a mean of about 15 percent. They decrease in quality with depth; average permeabilities range from 1 to more than 1,000 mD. Reservoir thicknesses generally average between 10 and 25 ft.

Source rocks: Most of the oil is probably derived from the organic-rich, overlying Mowry Shale. Other possible source rocks include the associated marine Skull Creek shale. The Mowry and Skull Creek Shales contain a mixture of types II and III organic matter. Because of its richness and generally higher proportion of type II material, the Mowry is a better petroleum source than the Skull Creek, although the latter is adequate to have provided some petroleum. All these rocks are thermally mature in the deep parts of the basin. Distribution of fields is generally limited to an area that overlies or is peripheral to mature source rocks.

Timing and migration: Hydrocarbon generation and migration from local Cretaceous source rocks into available Muddy sandstone stratigraphic traps and carrier beds occurred during the Laramide orogeny. Significant updip lateral migration of oil from the area of mature source rocks in the deeper parts of the basin into peripheral areas took place, extending to the Black Hills. Other than near the outcrop, gravity of the oil in the accumulations is generally high, typically ranging from 35û to 50û API, and rich in dissolved gas. GOR ranges from around 100 to 10,000 CFG/bbl and averages about 1,000 CFG/bbl. GOR increases with depth, averaging about 3,000 CFG/bbl at 10,000 ft. NGL/Gas ratios average around 70 bbl/MMCF.

Traps: The interval is composed of sediment transported into the Cretaceous seaway from the east, accompanying or following subaerial erosion over much of the area. Erosion was succeeded by a gradual transgressive phase interrupted by periodic regressive pulses in which appreciable sand was supplied. The result is a compound wedge consisting of deposits from a variety of depositional environments and having a variety of stratigraphic traps. These include marine bar, strandline, distributary channel, estuarine, alluvial, and lower delta plain sandstone bodies. Seals are provided by the enclosing Skull

Creek, Muddy, and Mowry shales. Depth of prospective traps is generally from 3,000 to 14,000 ft, with the greatest potential in the deeper parts of the basin.

Exploration status: The play is well established, with a history of more than 40 years. Exploration ranges from intensive over the shallow parts of the basin to lightly in the deep parts. For assessment purposes, the relatively well explored "mature" area of the basin is considered an approximate analog for unexplored areas. More than 170 individual accumulations have been discovered and account for more than 550 MMBO of recoverable oil and 940 BCFG (known recoverable gas); 39 accumulations exceed 1 MMBO in size. The largest field, Bell Creek field, is approximately 134 MMBO known recoverable.

Resource potential: Undiscovered accumulations are expected to be smaller on average than those found to 1994 and represent a population containing an abundance of small accumulations and a few of substantial size. Overall, undiscovered resources are estimated to be modest and located mostly in deep parts of the basin.

3309. DEEP FRONTIER SANDSTONE PLAY

In this play, oil and gas occur in stratigraphic traps in offshore marine shelf sandstones of the Upper Cretaceous Frontier Formation in large, high-energy bar complexes, located in the deeper parts of the present basin. The play covers an area of about 4,400 sq mi in the central and southern parts of the Powder River Basin.

Reservoirs: Discrete sandstone reservoirs, known as "First Wall Creek,“ "First Frontier," or Turner sandstones, are the principal objectives in this play. Similar sandstones lower in the formation are prospective in the western part of the basin and are included within the play. The Frontier is part of a prograding clastic sequence derived from the west. Deltaic facies of equivalent age have been identified to the west and, to the east, the marine sandstones thin and grade into offshore shelf sandstones of the Turner Sandy Member of the Carlile Shale. Individual reservoirs are discontinuous. Reservoirs contain abundant quartz, chert, lithic fragments, and appreciable interstitial clay. Average porosities generally range from 10 to 15 percent, and some of the reservoirs are fracture enhanced; reservoir thicknesses range between 4 and 130 ft.

Source rocks: 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 deep parts of the basin. The Mowry Shale contains a mixture of types II and III organic matter and is estimated to have generated a great amount of oil. The Niobrara Formation and Carlile Shale together are a primary source of oil found in Upper Cretaceous reservoirs. However, the areal extent of effective source rocks in these formations is less than the deeper Mowry Shale. Shale in the Frontier Formation has also expelled oil in amounts secondary to the major Cretaceous source rocks.

Timing and migration: Hydrocarbon generation and migration from local Cretaceous source rocks into traps occurred during the Laramide orogeny. Oil is believed to have been derived from Upper Cretaceous dark marine shales, which are closely associated with the reservoirs. These source rocks are present within the play area and matured in the deep parts of the basin during the Laramide orogeny. Oil in this play tends to be high API gravity, ranging from 34û to 47û API, rich in dissolved gas. GOR ranges between 1,000 and 13,000 CFG/bbl and averages about 4,000 CFG/bbl. NGL/Gas ratios average about 50 bbl/MMCFG.

Traps: Accumulations are in traps resulting from pinchouts at the margins of individual bars or bar complexes, and from porosity loss within the sandstone bodies. The giant oil pool in the "Second Frontier sandstone" (more than 300 MMBO known recoverable) at Salt Creek field has been attributed to remigration of oil from a preexisting stratigraphic trap. Most of these sandstone bodies trend NW-SE, although they coalesce locally into less regular configurations. Shales and siltstones of the Frontier and overlying Carlile and Niobrara Formations form seals. Drilling depths to prospective future traps will range from 8,000 to 13,000 ft.

Exploration status and resource potential: Exploration in the play began in the early 1970's. Field sizes are not well documented and the largest to 1994 is over 20 MMBO known recoverable. More than 40 MMBO and 200 BCFG have been discovered. Several of the approximately 20 individual pools in the play may eventually coalesce; currently only 8 appear to exceed 1 MMBO or 6 BCFG.

Undiscovered accumulations are probably modest in size.

3310. TURNER SANDSTONE PLAY

This play is defined by the occurrence of oil and gas in stratigraphic traps in offshore marine shelf sandstones of the Turner Sandstone Member of the Carlile Shale on the shallow east flank of the basin. The play covers approximately 3,000 sq mi.

Reservoirs: Reservoirs are marine Turner sandstones, many with often poor porosity and permeability, and in some areas classified as "tight." Reservoirs contain abundant quartz, chert, lithic fragments, and appreciable interstitial clay. Producing reservoirs range from 5 to 35 ft in thickness.

Source rocks: Source rocks are considered to be the underlying Mowry Shale and associated organic-rich Upper Cretaceous shales of the Belle Fourche, Greenhorn, Niobrara, and Carlile formations. Timing is favorable; stratigraphic traps had formed prior to hydrocarbon generation and migration. Primary hydrocarbon type is oil.

Timing and migration: Hydrocarbon generation and migration from local Cretaceous source rocks into available traps occurred during the Laramide orogeny. Oil is believed to have been derived from dark marine shales of Cretaceous age, which are associated with the reservoirs. These shales are present in the deeper parts of the basin and matured during the Laramide orogeny. Some lateral migration of oil is required for known accumulations within this play. Oil gravity ranges from 39û to 43û API. GOR ranges from about 500 to 2,400 CFG/bbl and averages about 1,500 CFG/bbl. NGL/Gas ratio is probably around 50-200 bbl/MMCFG.

Traps: Traps occur both as transverse bars and as less well defined, generally thin bar complexes of irregular shape. These sandstones are the general equivalent of the "First Frontier" or "1st Wall Creek" sandstones of the western flank of the basin. Seals are associated fine-grained marine rocks of the Carlile Shale and Frontier Formation. Drilling depths for prospective traps generally range from 500 to 8,000 ft.

Exploration status and resource potential: The first discovery in the play was in 1915, and the sandstones are currently productive at several places. About 20 MMBO known recoverable has been discovered. Existing fields are small, and potential exists for additional, generally small accumulations. The largest field is Finn-Shirley with about 13 MMBO known recoverable.

The potential for large undiscovered resources in this play is slight, and individual accumulations are expected to be generally small.

3312. SUSSEX-SHANNON SANDSTONE PLAY

This play encompasses hydrocarbon accumulations in stratigraphic traps in the Sussex and Shannon Sandstone Members of the Cody Shale. These two units are interpreted to have been deposited as offshore bar complexes. They formed as a result of residual sand sheets on the shelf being transported and formed into broad, elongate sandstone bodies or offshore bars by marine currents. The play covers an area of approximately 15, 000 sq mi in the deep part of the basin.

Reservoirs: Marine shelf sandstones provide reservoirs for the play. Limits of known fields suggest that sandstone reservoirs have a relatively narrow and sinuous distribution, although the overall sand bodies are much broader, having relief on the order of tens of feet over several miles. Local mapping in the Sussex has identified at least 12 well-sorted imbricated sandstone bodies that trend generally N. 30û-40û W., being separated by areas of siltstone and mudstone. Areal extent of larger units is about 0.5-12 mi wide, 5-30 mi long, and as much as 33 ft thick. Sandstones of good reservoir quality are as much as 30 feet thick and may extend 20 or more mil along strike and about 3 mi across. Reservoir thickness ranges from 5 to 32 ft. Average porosity ranges from 10 to 15 percent and permeability, 1 to 20 mD.

Source rocks: The Niobrara Formation and Carlile Shale are major sources of oil in Upper Cretaceous reservoirs, and shale in the Upper Cretaceous Frontier and Steele Formations have also expelled oil but in amounts secondary to the primary source beds. However, the areal extent of effective source rocks is far less extensive than in the deeper but richer Mowry Shale.

Timing and migration: In most of the play, vertical migration of oil and gas allowed reservoirs of both the Sussex and Shannon to be charged from deeper source rocks. Oil gravities range from 35û to 39û API. GOR ranges from 300 to 2,100 CFG/bbl and averages around 800 CFG/bbl. NGL/Gas ratios average about 80 bbl/MMCFG.

Traps: Traps are stratigraphic in a series of relatively narrow and sinuous sandstone reservoirs within overall sand bodies which are much broader and have relief on the order of tens of feet over several miles. Detailed subsurface studies have indicated that the shales underlying the Shannon have been scoured locally and beveled regionally. Lobate lateral edges characteristic of the sand bodies are attributed to periodic breaching by storm-generated currents. Local mapping in the Sussex has identified at least 12 well-sorted imbricated sandstone bodies that trend generally N. 30û-40û W., being separated by areas of siltstone and mudstone. Areal extent of larger units is about 0.5-12 mi wide, 5-30 mi long, and as much as 33 ft thick. Individual sandstones of good reservoir quality are as much as 30 feet thick and may extend 20 or more mi along strike and about 3 mi across. Traps are classic updip pinchouts of porous and permeable shelf sandstone bars into shale. Drilling depths range from 7,000 to 11,000 ft.

Exploration status and resource potential: Exploration in the play has resulted in the discovery of about 180 MMBO and 90 BCFG. About 12 fields are in the category of greater than 1 MMBOE along with 10 smaller fields. The largest producing Sussex field is House Creek, approximately 24 MMBO known recoverable, and the largest Shannon field, Hartzog Draw, is about 120 MMBO with 35 BCFG.

The southern part of the basin is well explored, whereas the northern part is lightly explored. The size of fields remaining to be discovered is thought to be similar to those discovered.

3313. MESAVERDE-LEWIS PLAY

This play involves oil and gas occurrence in stratigraphic traps in marine sandstones of the Upper Cretaceous Mesaverde Formation and Lewis Shale. Strata involved in this play are part of a large western-derived regressive clastic sequence and include deltaic and marine shelf sandstone members that grade into siltstone or shale. Deltaic sands deposited in a wave-dominated high-destructive phase and locally modified into offshore bars produce the primary reservoirs and traps for hydrocarbons. The play area is an elongate, northwesterly trend in the deep, central part of the basin and covers about 9,400 sq mi.

Reservoirs: Reservoirs are porous feldspathic sandstones within the Teapot and Parkman Sandstone Members of the Mesaverde, and the Teckla Sandstone Member of the Lewis Shale. Sandstones are quite variable in development. Average reservoir thickness typically ranges from 10 to 150 ft, and average porosity and permeability generally range from 12 to 18 percent and 2 to 34 mD, respectively. Average porosity is about 15 percent.

Source rocks: The Niobrara Formation and Carlile Shale are probably the primary sources of oil for Mesaverde and Lewis reservoirs, although the areal extent of effective source rocks in these formations is less than in deeper Mowry Shale source beds. The Frontier Formation and Steele Shale probably have expelled oil in secondary amounts.

Timing and migration: Vertical migration of oil from one or more of these units appears to have charged reservoirs in this play. Oil gravities range from 35û to 47û API and average about 41û API. GOR ranges from about 100 to 10,000 CFG/bbl and averages about 1,000 CFG/bbl. NGL/Gas ratios range from about 30 to 100 bbl/MMCFG and average about 70 bbl/MMCFG.

Traps: Traps are created by updip pinchout of shallow marine sandstones into finer grained prodelta and open-shelf facies. Deltaic sands were deposited in a wave-dominated high-destructive shoreline phase, locally modified into offshore bars that pinch out eastward. In the largest oil field that produces from Teckla Sandstone, Poison Draw, the reservoirs are a complex of deltaic 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. One of the largest Teapot Sandstone producing fields, Well Draw, is a large northwest-trending stratigraphic trap formed by an updip facies change from porous shallow-water marine sandstone into tight, offshore siltstone and shale. The Parkman Sandstone characteristically produces from accumulations trapped within northwest-trending marine bar sandstones, as at Dead Horse Creek-Barber Creek. Depth to objective traps ranges from 5,000 ft to about 9500 ft in the axial parts of the basin.

Exploration status and resource potential: Approximately 110 MMBO and 180 BCFG have been discovered in this play. About 15 fields are in the category of greater than 1 MMBOE, and 45 fields with less than 1 MMBOE have been discovered. The largest field, Well Draw field, is about 46 MMBO and 98 BCFG known recoverable.

A very large area in the northern part of the basin remains to be evaluated. Undiscovered accumulations will probably be of similar size to those discovered to date, generally with ultimate recoverable resources of less than 10 MMBO and less than 5 BCFG.

3315. BIOGENIC GAS PLAY (HYPOTHETICAL)

This play encompasses biogenically generated gas trapped in conventional stratigraphic and structural traps in the Tertiary and Cretaceous sequence. It resides generally above and beyond the limits of thermally mature source beds and their migrated hydrocarbons. It involves virtually the entire Cretaceous and Fort Union sequence in Montana, rising stratigraphically southward to include principally uppermost Cretaceous rocks and overlying Tertiary beds. The play covers approximately 23,000 sq mi.

Reservoirs: Reservoirs are sandstones, ranging in age from Early Cretaceous to Eocene, but primarily of latest Cretaceous and Paleocene age, including sandstones in the Frontier, Sussex, Mesaverde, Bearpaw, Lance, and Fort Union.

Source rocks, timing and migration: Source rocks are Tertiary and Cretaceous coals and fine-grained humic-rich rocks within the sequence.

Initial generation and migration into available traps probably occurred very soon after burial, although in some instances accumulations have now been buried to depths below biogenic environments.

Traps: Traps are primarily stratigraphic traps, but also include combination traps and small structural closures. Most traps are produced by pinchouts of marine and alluvial sandstones. Seals are fine-grained clastic rocks within the Cretaceous and Tertiary sequence. Drilling depths generally range from about 700 to 3,000 ft.

Exploration status and resource potential: This is a demonstrated play, but known accumulations are very small. These include East Bell Creek, Hammond, Pumkin Creek, Hardin, and Toluca fields. None is larger than 6 BCFG. In adjoining provinces in Montana, similar plays produce large amounts of gas.

This play is considered to have slight potential for undiscovered accumulations greater than 6 BCFG, and because of that high risk was not quantitatively estimated.

UNCONVENTIONAL PLAYS

Continuous-Type Plays

3308. MOWRY FRACTURED SHALE PLAY

This unconventional play is defined by the occurrence of oil and gas in highly fractured Mowry shale reservoirs in the deep parts of the basin. The shale is considered both a reservoir and a source. The play occupies an area of thermally matured Mowry Shale in the central part of the basin, occupying approximately 10,000 sq mi.

Reservoirs: The highly fractured shale constitutes the reservoir. Controls on the origin and distribution of fracturing in the shale are not certain but appear to be related to geopressuring associated with thermal maturation of the organic matter and attendant phase and volume changes. Tectonic controls play a secondary role.

Source rocks , timing and migration: The organic-rich Mowry Shale contains a mixture of types II and III organic matter, is thermally mature in the deep parts of the basin, and is self-sourced. Hydrocarbons accumulated contemporaneously with fracture development which is associated with overpressuring and thermal maturation of the organic matter.

Traps: The trap consists of intensive fracturing in the Mowry Shale contained by overlying ductile Cretaceous shale and laterally unfractured Mowry Shale.

Exploration status and resource potential: No known purposeful exploration has taken place 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 productive Muddy sandstone.

A large quantity of in-place hydrocarbons may exist of a relatively dispersed, nonconventional sort. The play is basically hypothetical and data are insufficient to permit a satisfactory assessment of recoverable resources.

3311. NIOBRARA FRACTURED SHALE PLAY

This unconventional play is defined by the occurrence of oil and associated gas principally in fractured shale reservoirs of the Niobrara Formation. Reservoirs are fractured shale within the formation, but include some fracture reservoirs of underlying formations. Controls on fracturing are not well understood. In some instances, fractures appear localized or enhanced on structural flexures and faults. Geopressuring associated with thermal maturation of the organic matter and attendant phase and volume change have been proposed as a causative factor.

Reservoirs: Reservoirs are fractured shale within the formation. Fracturing appears localized or enhanced in association with structural flexures and faults; however, primary fracturing for the play is considered to be caused by geopressuring associated with thermal maturation of the organic matter and attendant phase and volume changes. Distribution of mature Niobrara Shale and fracturing is not well known.

Source rocks: The highly organic Niobrara Shale is considered both a reservoir and source. Organic material is largely type II. Hydrocarbons released produce high-gravity oil.

Timing and migration: The shale is thermally mature in deep parts of the basin. Although primarily self-sourced, some lateral or vertical migration of hydrocarbons into immature areas, such as at Salt Creek field, where oil has been produced from fractured shales, appears to have occurred. Timing is favorable with reference to trap formation.

Traps: Trapping is the product of fractures in the Niobrara Shale being contained by overlying Cretaceous shales of the Steele Shale and laterally unfractured Niobrara. Silo field, in the nearby Denver Basin, is considered a geologic analog.

Exploration status and resource potential: The Niobrara is amenable to horizontal drilling and completion techniques, for which Silo field, in the northern Denver Basin, is considered a development analog. Conventional drilling has produced modest amounts of oil at West Salt Creek and Smokey Gap in the Powder River Basin, and a small amount of production from Niobrara exists in deep parts of the basin; however, the play remains virtually unexplored.

The play is basically hypothetical, and data are insufficient to permit a satisfactory assessment of recoverable resources, which may be large.

Coalbed Gas Plays

By Dudley D. Rice and Thomas M. Finn

Two plays are identified in the Powder River Basin, Powder River Basin–Shallow Mining-Related Play (3350) and Powder River Basin–Central Basin Play (3351).

The coalbed gas potential of the Powder River Basin of northeastern Wyoming and southeastern Montana is evaluated by Law and others (1991) and Tyler and others (1991). The hydrologic effects of surface coal mining, which might affect coalbed gas production, are given by Martin and others (1988).

The Tongue River, the upper member of the Paleocene Fort Union Formation, is the main coal-bearing unit in the Powder River Basin. The Tongue River, which was deposited in fluvial and lacustrine environments, is as much as 1,700 ft thick and contains 8 to 10 coal beds. The coal beds can be anomalously thick and range from less than 5 ft to more than 190 ft in thickness. Some of the thicker, more laterally continuous coal beds are commonly 20 to 90 ft thick. Because of the size of the basin and the thickness of the coal beds, the basin contains large resources of coal (as much as 1.3 trillion short tons). Some of the thicker seams are correlatable over large areas and are referred to as the Anderson-Dietz, Wyodak-Anderson, and Big George-Sussex. They were deposited in mires associated with meandering and anastomosing rivers. The coals in the basin occur at depths less than 2,500 ft.

The rank of coal in the Fort Union Formation is low over the entire basin, ranging from lignite to subbituminous B. These are the lowest rank coals in the United States from which commercial production has been established. The level of thermal maturity is also low in the underlying Upper Cretaceous shales indicating a relatively low geothermal gradient for the basin. As much as 2,000 ft of overburden was probably removed about 10 Ma, so that the Tertiary coals were never buried deeper than 4,500 ft.

Natural gas produced from the Fort Union coals is composed mostly of methane with minor amounts of ethane (average 0.2 percent) and carbon dioxide (average 0.5 percent). The gases are interpreted to be biogenic based on carbon isotope analyses, but the timing of the gas generation is questionable. Biogenic gas was undoubtedly generated and accumulated shortly after deposition of the peat during a time of rapid subsidence and deposition. However, some of this early-formed gas probably degassed following uplift and erosion about 10 Ma and earlier along the flanks as the basin was forming. Relatively recent groundwater flow in the basin also probably lead to generation of biogenic gas, particularly along the flanks of the basin. However, the widespread generation of late-stage biogenic gas generation in association with groundwater flow is uncertain because of the discontinuous nature of the coal beds.

The Powder River is a very large intermontane structural basin; the axis is along the west side. Dips of Tertiary strata on the broad eastern flank are gentle (average 1 to 2¡), whereas those on the western flank are steeper (average 5 to 25¡). Along the shallow eastern flank of the basin, the coals are deformed in an area where the structure, as indicated by deeper Cretaceous units, is a gently dipping, homoclinal slope. These structural features, which are small-scale folds and faults, are interpreted to be penecontemporaneous compaction structures that formed in response to rapid facies changes associated with the fluvial and lacustrine depositional environments. Although these compaction structures have only been identified on the shallow eastern flank, they should be widespread in the basin.

Face cleats in the Tongue River coals are generally normal to bedding and generally strike in an easterly direction. The average spacing of the cleats as measured in a mine ranges from about 3 to 5 in. This spacing would probably be closer in higher rank coals. Because of the different stress fields associated with compaction folding and faulting, the orientation and spacing of the cleats may vary over short distances.

The Tongue River coals are major aquifers in the Powder River Basin. In general, groundwater flows to the northwest from the east side of the basin. Artesian conditions are developed within the basin where the coal beds are discontinuous and confined by shales. Flowing water wells resulting from these artesian conditions are common in the Tongue and Powder Rivers valleys. The water from both shallow producing wells and several mines is relatively fresh (TDS less than 1,300 ppm) and can be surface discharged. However, the large volume of water from the thick, permeable coal beds may create erosional problems. In addition, possible depletion of shallow aquifers and (or) contamination by gas escaping from dewatered coal seams are concerns. Sandstones overlying the coal beds are used as aquifers. If communication does exist, the sandstone aquifers may be depleted by coal dewatering associated with coalbed gas production.

As a result of low rank and shallow depths, gas contents of the Tertiary are low (less than 75 Scf/t), and the coals may be undersaturated with respect to gas. However, because of the large resources of coal, the in-place gas resources in the basin have been estimated to be as much as 30 TCF using an average gas content of 25 Scf/t.

The Powder River Basin is a major coal-producing province because of the occurrence of relatively thick, low-sulfur coals at shallow depths. The coal is mined entirely on the surface in both Wyoming and Montana. On the basis of 1991 tonnage figures, Campbell County, Wyoming, which is on the shallow eastern flank, is first in the country for both total coal production and coal production from surface mining. Because of the low gas contents and the fact that all coal is mined on the surface, methane emissions are considered to be minimal in the basin.

More than 250 coalbed gas wells have been drilled in the basin. Although some wells have been drilled in the deeper part (greater than 1,000 ft) of the basin, most of the wells are located on the shallow eastern flank and close to active surface mines. The dewatering operation at the mine has probably lowered the water table of coal beds in the nearby wells. In 1992, 29 wells produced about 1 BCF of coalbed gas from the Rawhide Butte and Maysdorf fields. The average depth of production in these fields is about 500 ft and daily production from individual wells is less than 100 MCF/D. In the Rawhide Butte field, pressure gradients range from 0.26 to 0.29 psi/ft. These values indicate underpressuring that might be the result of dewatering in adjacent coal mines. In addition, there has been development of gas from adjoining sandstones where gas was generated in and migrated from adjoining coal beds.

In the Hartzog oil field, several shallow coalbed gas wells have been drilled. The produced water will be used for waterflooding and the coalbed gas will be utilized for lease operations.

The Powder River Basin is primarily an oil-prone basin with an extensive infrastructure for oil development. The coalbed gas development to date has partially been controlled by the proximity of low-pressure gas pipelines and future development will depend on an expanded infrastructure for natural gas.

The target area for coalbed gas in the Powder River Basin is where the Tertiary coal beds are generally deeper than 500 ft and covers the whole basin. Within the target area, two plays have been identified: Powder River Basin–Shallow Mining-Related Play (3350) and Powder River Basin–Central Basin Play (3351).

3350. POWDER RIVER BASIN–SHALLOW MINING-RELATED PLAY

The Powder River Basin–Shallow Mining-Related Play (3350) is adjacent to active or anticipated coal mines. One large area extends along the eastern flank, and another smaller area is in the northwestern part of basin. This play extends from the downdip limits of active or anticipated mines to the boundary where 5 ft or more of water level decline in the Fort Union coal beds is expected because of surface coal mining. The two currently producing fields (Rawhide Butte and Maysdorf) are located within this play. The potential for additional reserves from this play is regarded as good to fair and is limited by low gas contents. The best potential is on structural highs where a free gas cap probably occurs. Off structure, the gas will probably be produced in conjunction with large amounts of water.

3351. POWDER RIVER BASIN–CENTRAL BASIN PLAY

The Powder River Basin–Central Basin Play (3351) coincides with the rest of the basin where the Fort Union coal beds are deeper than 500 ft. Sparse data indicate that the gas contents, because of low rank, may not be significantly higher with increasing depth. Although some wells have been drilled in this play, no commercial production has been established. The potential for reserves from this play is assessed to be fair to poor.   The coals may be undersaturated with respect to gas, and large amounts of groundwater are present in the cleat systems.

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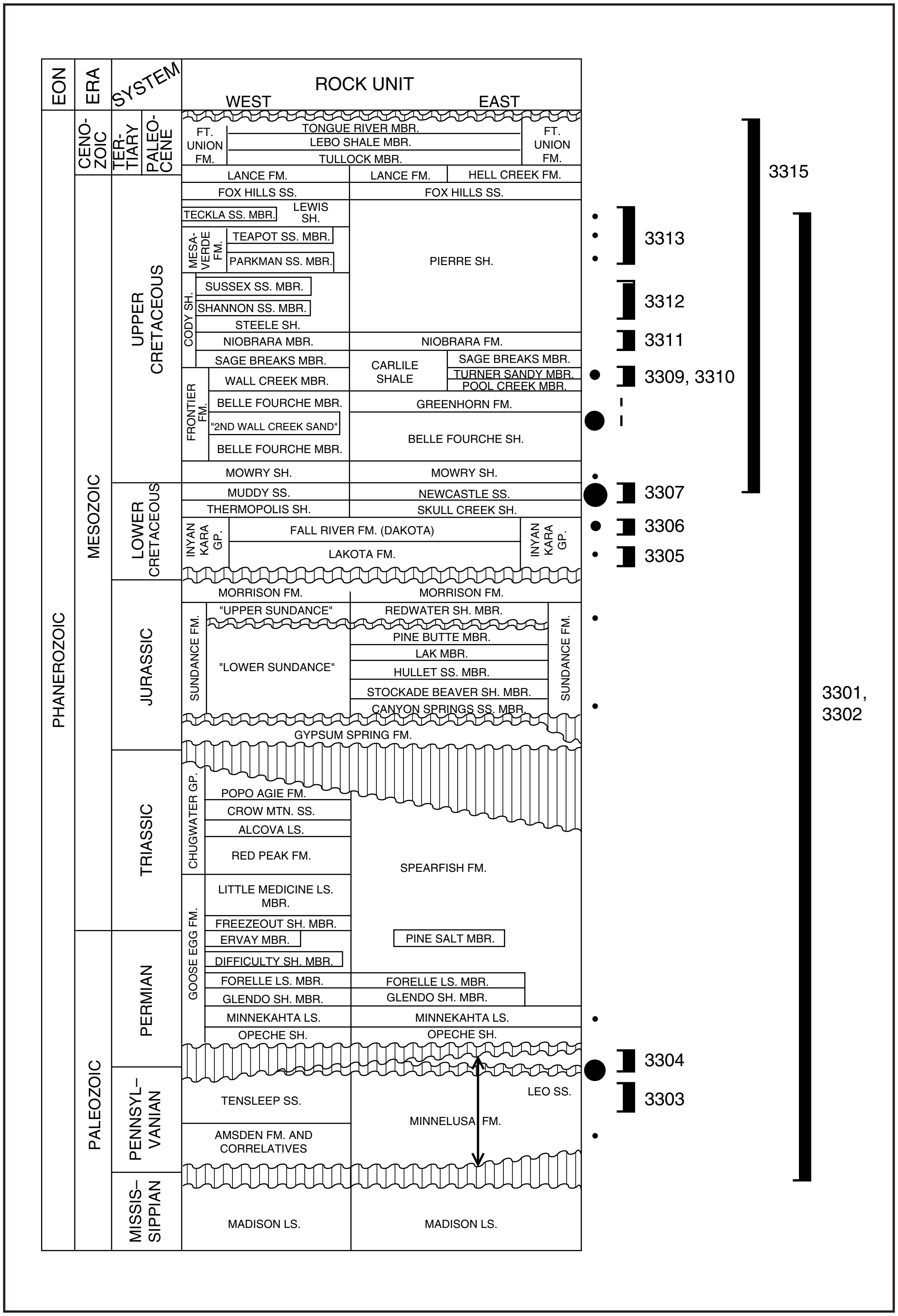
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