BIGHORN BASIN PROVINCE (034)

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INTRODUCTION

The Bighorn Basin is an asymmetric heart-shaped intermontane basin of the Rocky Mountain foreland, located in north-central Wyoming and south-central Montana. Province boundaries are defined by fault-bounded Laramide uplifts that surround it. These include the Owl Creeks to the south, Absaroka Volcanic Plateau and Beartooths to the west, Big Horns to the east, and the Nye-Bowler Lineament to the north in Montana. The province is about 175 miles long and 100 miles wide encompassing an area of about 13,200 sq mi.

Approximately 2.7 BBO and 1.8 TCFG have been discovered (as of year-end 1990) since the first fields, Garland and Greybull, were discovered in 1906 and 1907, respectively. The vast majority of production has been from basin margin anticlinal structures such as Oregon Basin (475 MMBO, and 206 BCFG), Elk Basin (557 MMBO, and 368 BCFG), Hamilton Dome (261 MMBO), Grass Creek (212 MMBO) and Garland (200 MMBO and 142 BCFG). The largest stratigraphically trapped field is Cottonwood Creek (discovered in 1953) with 59 MMBO and 42 BCFG from the Phosphoria Formation.

Plays in this basin result from both structural and stratigraphic traps and occur in primarily Permian and Cretaceous source rock and reservoir systems. Plays individually assessed or considered are treated in the following discussion. Conventional plays include Basin Margin Subthrust Play (3401), Basin Margin Anticline Play (3402), Deep Basin Structure Play (3403), Sub-Absaroka Play (3405), Phosphoria Stratigraphic Play (3406), Tensleep Paleotopography Play (3407), Greybull-Cloverly-Muddy Sandstone Stratigraphic Play (3408), Bighorn-Darby Wedge-Edge Pinchout Play (3410), Flathead-Lander and Equivalent Sandstone Stratigraphic Play (3411), Madison Limestone Stratigraphic Play (3412), Darwin-Amsden Sandstone Stratigraphic Play (3413), Triassic-Jurassic Stratigraphic Play (3414), Cody and Frontier Stratigraphic Play (3416), and Shallow Tertiary-Upper Cretaceous Stratigraphic Play (3417). One unconventional play, Basin-Center Gas Play (3404), was defined but not formally assessed. Only the Basin Margin Anticline Play (3402), Deep Basin Structure Play (3403), and Phosphoria Stratigraphic Play (3406) have significant production. Basin-Center Gas Play (3404, unconventional) is described, but was not assessed.

Not included in the assessment of resources is coalbed methane. Discussion of coalbed gas plays, with references, may be found in the chapter by D.D. Rice, "Geologic framework and description of coalbed gas plays" elsewhere in this CD-ROM.

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CONVENTIONAL PLAYS

3401. BASIN MARGIN SUBTHRUST PLAY (HYPOTHETICAL)

Laramide basin-margin thrusting may have trapped oil and gas in upturned, overturned, folded, and faulted Phanerozoic strata below the overthrust wedge. The limits of this play are defined by the leading edge of basin margin thrust faults and an approximate displacement of 6 mi. The play boundary includes portions of the play that are contiguous but occur in the Wind River Basin and Southwestern Wyoming Provinces (Provinces 035 and 037 respectively).

Reservoirs: Reservoir type and quality are highly variable. Porous and permeable sandstone and carbonate facies may have good reservoir quality. Also, some less conventional lithotypes may have good reservoir quality due to extensive fracturing associated with thrusting. Reservoirs can be any age but principal reservoirs are the Pennsylvanian Tensleep Sandstone, Permian Phosphoria carbonates, and Upper Cretaceous Frontier sandstones.

Source rocks: Hydrocarbons in the Bighorn Basin are of two geochemical source rock classes, Permian (Phosphoria Formation) and Cretaceous (Mowry, Frontier, Mesaverde, Meeteetse).

Timing and migration: Because Laramide thrust faults have thrust thick wedges of Precambrian rocks over Phanerozoic rocks, the depth of the source rocks is usually great enough that they could have generated hydrocarbons locally or that hydrocarbons could have migrated from mature areas in deeper parts of the basin during and after Laramide deformation. Some pre-Laramide migration may have taken place from the Phosphoria Formation, moving hydrocarbons into reservoirs before tectonic development of the basin margin folds and faults. In this situation, stratigraphic traps could have formed prior to basin margin thrusting and subsequent development of basin margin folds and faults. Faulting could then have superimposed structural control on these stratigraphic traps.

Traps: Petroleum is trapped where structures with closure occur beneath the thrust or are concealed by the thrust fault and may be sealed by impermeable rocks of the hanging wall of the fault. In the thrusting process the underlying beds are folded and often upturned or overturned; fault slivers are typically present. Oil and gas may be trapped in these upturned, overturned, folded, and faulted strata. Depth to potential

production is highly variable, ranging up to 20,000 ft on the structurally steepest side of the asymmetrical basin and to less than 10,000 ft in other basin-margin areas.

Exploration Status: This is a conceptual play based on an analog model in the Wind River Basin, where one field, Tepee Flats, is currently producing gas from the Frontier Formation at a depth of about 12,200 ft (9 BCFG).

Resource potential: Fields in this play will be gas fields in deeper parts of the basin and oil fields in areas where entrapment is shallower. Anticipated size of fields is small, and number is limited.

3402. BASIN MARGIN ANTICLINE PLAY

This demonstrated play is defined by the occurrence of oil and gas trapped in anticlines and domes, in many cases faulted, and in faulted fold noses that formed during the Laramide orogeny. These structures are best developed along the shallow margins of the basin, with production from a few hundred feet to about 12,000 ft. The inner boundary of the play is drawn at the approximate basinward limit of basin-margin anticlines. The outer boundary is drawn at the top of the Tensleep on outcrop, except on the west side of the basin where it is coincident with the east edge of Eocene Absaroka volcanic rocks.

Reservoirs: Producing formations range in age from Cambrian to Late Cretaceous and include Flathead, Bighorn, Jefferson, Madison, Amsden, Tensleep, Phosphoria and Ervay, Dinwoody, Crow Mountain, Chugwater, Cloverly, Dakota, Greybull, Lakota, Muddy, Frontier, and Mesaverde Formations. Primary production has been from the Madison, Tensleep, Phosphoria, and Frontier, often occurring as multiple pay zones in single fields. Many of the fields with multiple pay zones show common oil-water contacts for the Paleozoic reservoirs, particularly the Phosphoria and Tensleep. Sandstone is the dominant reservoir lithology, in most cases relatively homogeneous and of good quality. Substantial hydrocarbons have also been produced from heterogeneous carbonate reservoir rocks of the Jefferson, Madison, and Phosphoria Formations. Reservoir thickness is highly variable, with individual reservoirs as thick as several hundred feet. Most reservoirs, however, are less than 50 ft. thick.

Source rocks: Within the thick sequence of hydrocarbon-bearing strata are numerous organic-rich argillaceous sedimentary rocks. Hydrocarbons are derived from two distinct geochemical source rock classes, Permian (Phosphoria Formation) and Cretaceous (Mowry, Frontier, Mesaverde, Meeteetse). Oil and gas in the Cretaceous

reservoirs appear to be have their source in associated Cretaceous organic-rich beds, whereas Paleozoic oil and gas appear to be derived primarily from a distinct Phosphoria source. The thermal maturity is high in many areas of the basin, especially where source beds are very deeply buried, and in these areas gas predominates.

Timing and migration: Local generation of oil without long-distance migration occurred during the Laramide orogeny; however, pre-Laramide generation and long-distance migration from western Wyoming prior to basin formation, followed by remigration during the Laramide, is an additional scenario. Cretaceous source rocks are known to have reached maturity by early Paleocene time in deep parts of the basin, followed by younger rocks . Structural growth of traps apparently coincided with this Laramide stage of maturation and was the final concentrating process in a long and complex history of generation, migration, and accumulation of hydrocarbons.

Traps: Trapping mechanism is closure in both anticlines and domes, in many cases faulted, and in faulted fold noses that formed during the Laramide orogeny. These structures are best developed around the shallow margins of the basin, with production from a few hundred feet to about 12,000 ft. Within these structures, interbedded impermeable beds act as seals, particularly separating Paleozoic and Mesozoic reservoirs.

Exploration status: Approximately 2.5 BBO and 1.8 TCFG have been discovered (cumulative production plus proved reserves as of year-end 1990) since the first fields, Garland and Greybull, were discovered in 1906 and 1907, respectively. Most traps had been explored by about 1950, by which time several giant fields had been discovered, which account for most of the basin's hydrocarbon production. In fact, by 1950, about 50 fields greater than 1 MMBOE had been discovered in this play. The vast majority of production has been from basin margin anticlinal structures such as Oregon Basin (475 MMBO and 206 BCFG), Elk Basin (557 MMBO and 368 BCFG), Hamilton Dome (261 MMBO), Grass Creek (212 MMBO) and Garland (200 MMBO and 142 BCFG). Depth to production ranges from several hundred feet to about 10,000 ft.

Resource potential: This is a well-explored play. Prospects for significant new discoveries are not good, although new production could occur as extensions and secondary features related to larger structural trends. Small fields are likely. The mix of oil and gas should be in about the same proportion as historic.

3403. DEEP BASIN STRUCTURE PLAY

This is a demonstrated primarily gas and NGL play with entrapment in large intrabasin anticlinal and fold nose structures within the central portion of the basin, such as Five Mile-Dobie Creek field. The play area cuts diagonally across the deep axial part of the basin. Play limits are defined by the approximate boundaries of recognized structural trends.

Reservoirs: Reservoir rocks range in age from Permian to Cretaceous and include the Phosphoria, Tensleep, Muddy, and Frontier Formations. Frontier and Muddy sandstone reservoirs have porosity between 8 and 12 percent at Five Mile-Dobie Creek fields, porosity limited by burial diagenesis. Heterogeneous carbonate reservoirs in the Phosphoria are productive (about 7 percent). No commercial hydrocarbon production has been established from the Tensleep Sandstone, but hydrocarbon shows indicate potential. However, its potential is limited due to deep burial. Reservoir thickness ranges from 25 to 100 ft.

Source rocks: Indigenous source rocks occur primarily in marine Phosphoria shales and marine and paludal shales of the Cretaceous Thermopolis, Mowry, Frontier, Cody and Mesaverde Formations. Most of these formations are very deeply buried in this play area and may be beyond the maturity range of oil generation and into the gas zone.

Timing and migration: Some of the stratigraphically lowest Cretaceous shale formations and the Phosphoria Formation may have been buried deeply enough in the area to the west for hydrocarbon migration to begin even before the onset of the Laramide orogeny in Late Cretaceous time and extend into this area. Permian and Cretaceous source beds in the deep axial part of the basin may be as deep as 15,000 ft or more on the northwest end of the play trend. Here, Cretaceous source rocks reached maturity by early Paleocene time. Reservoir sandstones in the Frontier and Mesaverde Formations are interbedded with marine source rocks, favoring easy migration from source to reservoir rock.

Traps: The primary trapping mechanism in this play is a Laramide intrabasin "anticlinal" structural feature, fault bounded on the north side and often referred to as the "Five Mile Trend." It extends northwest diagonally across the center of the basin and is the only large structure in the play. It plunges northwesterly with depth to the top of the Tensleep in excess of 25,000 ft at the northwest end. At the southeast end, close to the Cottonwood Creek, Worland, and Rattlesnake fields, the depth to the

Tensleep is about 11,000 ft. Petroleum may be sealed in reservoirs by fine-grained beds that are interbedded with the reservoirs and that may also have been source rocks. Entrapment is in anticlinal and fold nose structures. Depth of potential production ranges from about 10,000 ft on the southeast to in excess of 20,000 ft on the northwest.

Exploration status: The level of exploration is minimal. One field, Five Mile-Dobie Creek (discovered in 1952), is in the category of greater than 1 MMBOE ultimately recoverable. Two fields are in the category of less than 1 MMBOE ultimately recoverable. To date, approximately 2.25 MMBNGL and 57 BCFG have been discovered.

Resource potential: This play is not very well demonstrated. The level of exploration is minimal and the potential for future discoveries is uncertain; structures at equivalent depths in the Wind River Basin are gas-productive.

3405. SUB-ABSAROKA PLAY

In this demonstrated play, oil occurs beneath Eocene-age volcanic rocks, trapped in Laramide anticlines and domes, in many cases faulted and eroded prior to being covered by volcanics. Play limits are as follows: the eastern limit is defined by the eastern extent of the overlying volcanics, exclusive of the Beartooth Uplift; the northern limit by the approximate Precambrian contact; the western limit by the approximate position of truncated subcropping strata (near the Yellowstone Park boundary); and the southern limit by the southern extent of Eocene volcanics.

Reservoirs: Based on nearby production from structural traps, quartzose sandstone of the Pennsylvanian Tensleep Sandstone is the primary objective. Secondary objective's include carbonates of the Mississippian Madison Limestone, Permian Phosphoria and Dinwoody Formations, and sandstones of the Pennsylvanian Darwin, Triassic Chugwater, Jurassic Curtis, and the Lower and Upper Cretaceous. The degree to which secondary cementation has destroyed the primary porosity is highly variable. At shallow depths, as is the case here, reservoir quality of the Tensleep is very good–porosity is as high as 20 percent. Porosity of the Madison, Amsden, Phosphoria, and Dinwoody is anticipated to be in the range of 6–12 percent, based on well log calculations. Net pay reservoir thickness estimates include: Phosphoria Formation,. 35 ft; Tensleep Sandstone, 75 ft; Chugwater Formation, 50 ft; and Frontier Formation, 40 ft.

Source rocks: Abundant carbon-rich source rocks exist in Paleozoic and Mesozoic formations within the basin, and many of them were buried deeply enough to generate hydrocarbons even before the Laramide orogeny.

Timing and migration: The eastern side of the play is near the basin axis where hydrocarbons were most likely being formed earliest. A considerable amount of faulting resulted from the Laramide on this western side of the basin, and these faults could easily have been conduits for the migration of hydrocarbons upward until they reached porous and permeable reservoir beds and a trap. Long-distance migration of Phosphoria-sourced oil from the west prior to basin formation, followed by remigration during the Laramide, is also possible.

Traps: Domes and plunging anticlines provide the trapping mechanism for hydrocarbons. In some cases they may be combined with faults and possibly fault traps within the anticlines. Structures in the eastern play area are on trend with producing structures of the basin-margin anticline play, which may be representative of structural style and productivity. Interbedded impermeable beds within these structures form seals. Fields may have multiple pay zones, especially considering the extensive faulting of the area. Oil seeps are numerous along fractures in the overlying volcanics. The depth range of the objective interval is difficult to predict considering the rugged topography of the Absaroka Mountains.

Exploration status: This play has not been extensively explored because of the difficulty of exploring beneath the volcanic rocks. Six small fields (less than 1 MMBOE) have produced oil from small structures beneath the volcanics. They include Aspen Creek, Baird Peak, Dickie, Prospect Creek, Prospect Creek South, and Skelton Dome fields.

Resource potential: The potential for significant large new field discoveries (greater than 1 MMBOE) is good. Several of the basin-margin anticlinal fields on trend with this play area have large reserves. For example, Fourbear field has 31.2 MMBO ultimate recoverable and Pitchfork has 68 MMBO ultimate recoverable.

3406. PHOSPHORIA STRATIGRAPHIC PLAY

High-sulfur oil (to 30_ API gravity) is stratigraphically trapped in the Ervay Member of the Phosphoria Formation along a generally north-south trend or transition zone from Phosphoria carbonates on the west to red shale and evaporites of the Goose Egg Formation on the east. The play area is located in the eastern Bighorn Basin; limits of

the play are defined on the east by the eastern limit of the Ervay Tongue, on the west by the estimated downdip limit of perceived oil accumulations, on the north and south by Phosphoria outcrops.

Reservoirs: Reservoirs occur in the Permian Ervay Member of the Phosphoria Formation. They are typically dolomitized grainstones and packstones, although algal rocks containing fenestrate porosity contribute locally. These reservoirs formed in high-energy tidal and associated environments. At Cottonwood Creek field, oil in high-energy tidal channels is sealed updip by tight fine-grained intertidal and supratidal carbonates. Reservoir matrix porosities average about 10 percent, but are often fracture enhanced. Reservoir thickness ranges from about 25 to 75 ft.

Source rocks: Oil was generated from organic-rich Permian Phosphoria shale source rocks to the west where burial depth was sufficient to generate hydrocarbons.

Timing and migration: Both Laramide-related and pre-Laramide generation and migration of hydrocarbons may have occurred. Generation of oil from Phosphoria source rocks may have begun as early as the Jurassic in western Wyoming and eastern Idaho.

Traps: Stratigraphic traps lie near the edge of the carbonate tongue of the Ervay Member in porous detrital reservoirs which were deposited within high-energy regimes of tidal channels on a coastal flat, sealed updip by tight, fine-grained carbonates and red shales of intertidal and supratidal origin. Lateral seals for traps are the mud-supported carbonates of the Ervay Member, although the regional trap can be viewed as the facies change from carbonate into redbeds. Vertical seals are the fine-grained rocks of the overlying Triassic Dinwoody and Chugwater Formations and internal footseals are provided by fine grained redbeds or carbonates. Depth to production is not estimated to exceed 12,000 ft.

Exploration status: Exploration of the Phosphoria Stratigraphic Play was stimulated by the discovery of Cottonwood Creek field in the Bighorn Basin in 1953. This field, the largest in the play, has 59 MMBO and 42 BCFG known recoverable. Subsequent discoveries have been infrequent and smaller in size, approximately 10 in number. Of note are Frisby, South-Rattlesnake (discovered 1949) (14 MMBO, and 11 BCFG), Manderson (discovered 1951) (1.35 MMBO and 1.26 BCFG), and Slick Creek-No Water Creek (discovered 1951) (9.9 MMBO and 8.2 BCFG). Depth to objective ranges from about 3,000 ft to about 12,000 ft.

Resource potential: Undiscovered pools are estimated to be of small size.

3407. TENSLEEP PALEOTOPOGRAPHY PLAY (HYPOTHETICAL)

In this hypothetical play, oil and gas accumulations are controlled by erosional paleotopography at the top of the Tensleep Sandstone in areas of low structural relief in the basin.

Reservoirs: Reservoirs are fine-to medium grained orthoquartzites of eolian and beach facies with average porosities in the range of 10 to 24 percent, decreasing with depth. Early migration of hydrocarbons may inhibit substantial porosity loss in filled reservoirs.

Source rocks: Source rocks are considered to be the organic-rich shales of the Phosphoria Formation.

Timing and migration: Initial migration is believed to have occurred prior to the Laramide deformation.

Traps: A regional unconformity truncates the top of the Tensleep and paleotopographic relief on the order of 100-150 ft is widespread. In those places where the magnitude of associated structural dip does not exceed paleoslopes to allow remigration of hydrocarbons, stratigraphic traps remain potential sites of hydrocarbon accumulation. Traps are modified by internal diagenetic and primary depositional characteristics of the sandstones and associated dolomites. Seals are impermeable Phosphoria dolomites and shales, or Goose Egg shales and evaporites of Permian age, which overlies the Tensleep Sandstone. Depth to traps is anticipated to range from about 4000 to 13,000 ft, below which the reservoir is anticipated to be tight.

Exploration status: Exploration in this play has not occurred other than incidentally. However, paleotopographic trapping configurations have been documented within some of the structural traps. No purely stratigraphic traps have been found.

Resource potential: Resource potential is moderate, and accumulations will be small. Production from the upper Minnelusa in the northern Powder River basin may be an acceptable analog. There, fields are small but numerous.

3408. GREYBULL-CLOVERLY-MUDDY SANDSTONE STRATIGRAPHIC PLAY (HYPOTHETICAL)

This play is hypothetical. Oil occurs in stratigraphic traps of the basal Dakota Group (Greybull and Lakota) sandstones. Production from Lakota pools in Laramide structures peripheral to or within the play area suggest reservoir potential, even though not representative of sizes of stratigraphic traps in the play.

Reservoirs: Reservoirs are fine- to coarse-grained sandstones that are locally pebbly or conglomeratic, and contains abundant chert. Oil occurs within discrete channels or composite channel sandstones of alluvial origin. Depths of the play range from about 4,000 to 13,000 ft, below which reservoirs are anticipated to be tight.

Source rocks: Source rocks for the play are presumed to be Cretaceous marine shales in the Mowry and Thermopolis. Kerogen occurs as Types II and III.

Timing and migration: Mowry source rocks in some parts of the basin entered the thermal zone or liquid hydrocarbon generation during the Paleocene and exited it during the Miocene.

Traps: Traps occur in alluvial channels that commonly occur in combination with structural noses or anticlinal closures but major structural closures are not considered part of the play. The essential trapping mechanisms are stratigraphic. Seals are associated fine-grained alluvial and delta plain rocks, usually the Fuson Shale or Jurassic Morrison. Principal vertical seals are overlying Thermopolis and Fuson shales, or Dakota siltstones. The underlying Jurassic Morrison provides a lateral seal where it is entrenched by sandstone reservoirs.

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

Resource potential: The number of undiscovered accumulations is estimated to be substantial; a few are probably of appreciable size. Although a number of these reservoirs are productive in structural or combination traps, no pure stratigraphic accumulations have been found to 1993. A large number of pools are estimated, a few of which may be of appreciable size (5-10 MMBO). Most accumulations, however, will average less than 1 MMBOE.

3410. BIGHORN-DARBY WEDGE-EDGE PINCHOUT PLAY (HYPOTHETICAL)

This hypothetical play encompasses hydrocarbon occurrence in the wedge-edge or beveled-edge pinchouts of the Ordovician Bighorn Dolomite which abut against the base of the Madison Limestone, providing potential traps. No hydrocarbon occurrences or source rocks are known.

Reservoirs: Reservoirs in the Bighorn Dolomite exhibit intergranular porosity and are anticipated to be present over most of the play area.

Source rocks: Source rocks have not been identified associated with the objective sequence. Their absence attributes great risk to the play.

Timing and migration: Unknown.

Traps: Although regional truncation is demonstrated, the presence of traps at this unconformity is undocumented and internal traps are not demonstrated.

Exploration status: No production exists within this play and exploration is incidental to other activity.

Resource potential: This play bears very high risk (probability of success is less than 0.1) owing to poor charge and trap potential. It is considered to have little likelihood of significant hydrocarbons. No quantitative estimate of resources was made.

3411. FLATHEAD-LANDER AND EQUIVALENT SANDSTONE STRATIGRAPHIC PLAY (HYPOTHETICAL)

This hypothetical play includes hydrocarbons trapped in stratigraphic pinchouts of the Cambrian Flathead and Ordovician Lander Sandstones. No hydrocarbon occurrences or source rocks are known.

Reservoirs: Reservoirs are sandstones anticipated to be present over much of the play area and they exhibit considerable variability. Quality of reservoirs may be poor owing to diagenesis.

Source rocks: Source rocks have not been identified associated with the objective sequence. Their absence attributes great risk to the play.

Timing and migration: Unknown.

Traps: Although stratigraphic pinchouts are anticipated, no traps have been recognized.

Exploration status: No production exists within this play.

Resource potential: This play bears very high risk (probability of success is less than 0.1) owing to poor charge and trap potential. It is considered to have little likelihood of significant hydrocarbons. No quantitative estimate of resources was made.

3412. MADISON LIMESTONE STRATIGRAPHIC PLAY (HYPOTHETICAL)

This hypothetical play encompasses oil entrapment within or at the top of the Mississippian Madison Limestone caused by porosity variation and topography related to karst development.

Reservoirs: Karstic vuggy reservoirs in the upper part of the Madison Limestone are expected throughout the play area.

Source rocks: Source rocks have not been identified associated with the objective sequence. Their absence attributes great risk to the play.

Timing and migration: Unknown.

Traps: No traps have been recognized.

Exploration status: No production exists within this play.

Resource potential: This play bears very high risk (probability of success is less than 0.1) owing to poor charge and trap potential. It is considered to have little likelihood of significant hydrocarbons. No quantitative estimate of resources was made.

3413. DARWIN-AMSDEN SANDSTONE STRATIGRAPHIC PLAY (HYPOTHETICAL)

This hypothetical play consists of stratigraphic entrapment of oil in discontinuous sandstones of the Pennsylvanian Darwin and Amsden Formations. Although no occurrence of oil in such traps is known, these formations may possibly be productive in structural settings.

Reservoirs: Reservoirs are sandstones anticipated to be present over most of the play area in the Darwin and Amsden Formations. Quality of reservoirs may be poor owing to diagenesis.

Source rocks: Source rocks have not been identified with certainty associated with the objective sequence. Their absence attributes great risk to the play.

Timing and migration: Unknown.

Traps: Considerable variability of sandstone distribution exists within the Amsden, and traps are anticipated to be enhanced by structural pinchouts.

Exploration status: No production exists within this play.

Resource potential: This play bears very high risk (probability of success is less than 0.1) owing to poor charge and trap potential. It is considered to have little likelihood of significant hydrocarbons. No quantitative estimate of resources was made.

3414. TRIASSIC AND JURASSIC STRATIGRAPHIC PLAY (HYPOTHETICAL)

This hypothetical play encompasses stratigraphic traps in the Crow Mountain Sandstone and equivalent(?) Jelm Formation of the Chugwater Group, Sundance Formation, and Morrison Formation. It also includes wedge-edge pinchouts and truncations of the Nugget Sandstone.

Reservoirs: Reservoirs are sandstones anticipated to be present over most of the play area in the formations named. These reservoirs often have good properties where penetrated in the basin.

Source rocks: Source rocks associated with the objective sequence have not been identified with certainty. Charging of traps appears to require migration from source beds well above or below the objectives such as from the Phosphoria Formation.

Timing and migration: Unknown.

Traps: No traps have been recognized.

Exploration status: No production exists within this play.

Resource potential: This play bears very high risk (probability of success is less than 0.1) owing to poor charge and trap potential. It is considered to have little likelihood of significant hydrocarbons. No quantitative estimate of resources was made.

3416. CODY AND FRONTIER STRATIGRAPHIC PLAY (HYPOTHETICAL)

This hypothetical play includes deep oil and gas accumulations in stratigraphic traps in the Cody and Frontier (Torchlight and Peay) Formations in a thick sequence of marine shale and fine-grained sandstone.

Reservoirs: Reservoirs of fine-grained lithic sandstone are distributed throughout the play area in the Cody and Frontier Formation. Reservoir quality is anticipated to rapidly decrease with depth. Although equivalent reservoirs are productive in

structural settings, reservoir quality in deeper, off-structural setting of this play remains problematic.

Source rocks: Cretaceous source rocks are present, associated with the objective sequence, particularly the Mowry Shale.

Timing and migration: Unknown, although potential traps existed at the time of primary migration.

Traps: Stratigraphic pinchout traps may be distributed throughout the play area, but the presence of traps of significant size is not demonstrated.

Exploration status: No production exists within this play.

Resource potential: This play bears very high risk (probability of success is less than 0.1) owing primarily to poor reservoir and trap potential. It is considered to have little likelihood of significant hydrocarbons. No quantitative estimate of resources was made.

3417. SHALLOW TERTIARY-UPPER CRETACEOUS STRATIGRAPHIC PLAY

This play, in the central portion of the basin, traps primarily gas and some liquids in stratigraphic and combination traps.

Reservoirs: Reservoirs are sandstones, generally arkosic and lithic, with good porosity and permeability at shallow depths. Principal reservoirs are in the Fort Union, Lance, Meeteetse and Mesaverde Formations.

Source rocks: Source rocks are associated humic-rich rocks, with some contribution from underlying Cretaceous rocks. Gas appears to be thermogenic with some mixing of biogenic gas. Some vertical migration may have occurred.

Timing and migration: Timing of generation and migration are favorable in that traps had been formed by the time of generation and migration.

Traps: Traps are stratigraphic, caused by facies changes. They are typically alluvial sandstones that occur as localized channel bodies of limited extent. Traps are small and sometimes occur in combination with structures. Seals are provided by associated fine-grained rocks, variously, Eocene, Paleocene, and uppermost Cretaceous in latest age.

Exploration status: This play has seen exploration for many years, with discovery of a number of small accumulations of less than 6 BCFG or 1 MMBO.

Resource potential: Small accumulations (less than 1 MMBOE) are anticipated, and a very high risk was assigned to occurrence of larger accumulations.

UNCONVENTIONAL PLAY

Continuous-Type Gas

3404. BASIN CENTER GAS PLAY (HYPOTHETICAL)

This play is characterized by gas trapped in an extensive basin center accumulation in sandstones of Paleocene and uppermost Cretaceous age in deep parts of the basin. The play is characterized by overpressuring due to active generation of gas. Older Cretaceous rocks, which may also be geopressured, were not considered because of their generally thin reservoir development and limited reservoir volume. This play is defined vertically by the approximate R_O=1.0 occurrence at the top of the involved section, which is approximately at 12,000 ft, and encompasses underlying Paleocene and Upper Cretaceous rocks to the base of the Mesaverde Formation.

Reservoirs: Reservoirs are generally lenticular arkosic or lithic sandstones of alluvial origin with poor to modest porosity and low permeability. Some more blanket-like marine sandstones also are present. The Fort Union, Lance, Meeteetsee, and Mesaverde contain reservoirs. Internal compartmentalization of the sequence is important.

Source rocks: Source rocks include associated humic-rich rocks and coals. Some contribution may have come from underlying Cretaceous rocks. Gas appears to be thermogenic, with some vertical migration possible.

Timing and migration: Timing of generation and migration of hydrocarbons was favorable in that it took place after traps had formed. Overpressuring due to active generation of gas generally coincides with R_O of 1.0 percent or more.

Traps: Accumulation appears to result from a regional stratigraphic trap caused by low reservoir permeability combined with active gas generation. Alluvial sandstones, particularly localized channel bodies of limited extent, provide internal compartmentalization. Local structures may enhance trapping. Seals are provided within the low-permeability reservoirs and by associated fine-grained rocks, variously Paleocene and uppermost Cretaceous. Ground-water influx and hydrodynamic enhancement may contribute to trapping.

Exploration status: This play has seen virtually no meaningful exploration and is speculative in nature. Field development has not yet taken place.

Resource potential: Potential for gas accumulations is good. Due to lack of data and tentative characterization of the play, no quantitative assessment was made.

REFERENCES

Andrews, S., and Higgins, L. S., 1984, Influence of depositional facies on hydrocarbon production in the Tensleep Sandstone, Big Horn basin, Wyoming--A working hypothesis: Wyoming Geological Association, 35th Annual Field Conference, Guidebook, p. 183-198.

Bailey, M.H., and Sundell, K.A., 1986, Preliminary results of wildcat drilling in Absaroka volcanic rocks, Hot Springs County, Wyoming [abs]: The Outcrop, Rocky Mountain Association of Geologists, v. 35, p. 3-4.

Berg, R.R., 1962, Mountain flank thrusting in Rocky Mountain foreland, Wyoming and Colorado: American Association of Petroleum Geologists Bulletin, v. 46, p. 2019-2032.

Blackstone, D.L., Jr., 1990, Rocky Mountain foreland structure exemplified by the Owl Creek Mountains, Bridger Range and Casper Arch, Central Wyoming: Wyoming Geological Association, 41st Annual Field Conference, 1990, Guidebook, p. 151-166.

Bown, T.M., 1980, Summary of latest Cretaceous and Cenozoic sedimentary, tectonic, and erosional events, Bighorn Basin, Wyoming, *in* Gingerich, P.D., ed., Early Cenozoic paleontology and stratigraphy of the Bighorn Basin: University of Michigan Papers on Paleontology No. 24, p. 25-32.

Bredehoeft, J.D., Belitz, K., and Sharp-Hansen, S., 1992, The hydrodynamics of the Big Horn basin--A study of the role of faults: American Association of Petroleum Geologists Bulletin, v. 76, no. 4, p. 530-546.

Brittenham, M.D., and Tadewald, B.H., 1985, Detachment and basement involved structures beneath the Absaroka Range volcanics, *in* Gries, R.R. and Dyer, R.C., eds., Seismic exploration of the Rocky Mountain Region: Rocky Mountain Association of Geologists, p. 31-43.

Burtner, R.L. and Warner, M.A., 1984, Hydrocarbon generation in Lower Cretaceous Mowry and Skull Creek Shales of the northern Rocky Mountain area, *in* Woodward, Jane, Meissner, F.F., and Clayton, J.L., eds., Hydrocarbon source rocks of the greater Rocky Mountain region: Rocky Mountain Association of Geologists, p. 449-467.

Claypool, G.E., Love, A.H., and Maughan, E.K., 1978, Organic geochemistry, incipient metamorphism, and oil generation in black shale members of Phosphoria Formation, Western Interior United States: American Association of Petroleum Geologists Bulletin, v. 62, p. 98-120.

Curry, W.H., III, 1962, Depositional environments in central Wyoming during the Early Cretaceous: Wyoming Geological Association, 17th Annual Field Conference, 1962, Guidebook, p. 118-123.

Curry, W.H., III, 1984, Paleotopography at the top of the Tensleep Formation, Bighorn Basin, Wyoming: Wyoming Geological Association, 36th Annual Field Conference, 1984, Guidebook, p. 199-212.

De Bruin, R.H., and Hostetler, S.D., 1993, Oil and gas fields map of the Bighorn basin, Wyoming: Geological Survey of Wyoming, Map Series 40, Scale 1:316,800.

Dolson, J., Muller, D., Evetts, M.J., and Stein, J.A., 1991, Regional paleotopographic trends and production, Muddy Sandstone (Lower Cretaceous), Central and Northern Rocky Mountains: American Association of Petroleum Geologists Bulletin, v. 75, no. 3, p. 409-435.

Erslev, E.A., 1993, Thrusts, back-thrusts, and detachment of Rocky Mountain foreland arches, *in* Schmidt, C.J., Chase, R.B., and Ersley, E.A., eds., Laramide basement deformation in the Rocky Mountain Foreland of the Western United States: Geological Society of America Special Paper 280, p. 339-358.

Evans, J.P., 1993, Deformation mechanisms and kinematics of a crystalline-cored thrust sheet--The EA thrust system, *in* Schmidt, C.J., Chase, R.B., and Ersley, E.A., eds., Laramide basement deformation in the Rocky Mountain Foreland of the Western United States: Geological Society of America Special Paper 280, p. 147-161.

Fanshawe, J.R., 1971, Structural evolution of Bighorn Basin: Wyoming Geological Association, 23rd Annual Field Conference, 23rd, Guidebook, p. 35-37.

Fox, J.E., Lambert, P.W., Mast, R.F., Nuss, N.W., and Rein, R.D., 1975, Porosity variation in the Tensleep and its equivalent, the Weber Sandstone, western Wyoming--A log and petrographic analysis: Rocky Mountain Association of Geologists Field Trip Symposium, Guidebook, p. 185-216.

Garfield, T.R., Hurley, N.F., and Budd, D.A., 1992, Little Sand Draw Field, Big Horn Basin, Wyoming: A hybrid dual-porosity and single-porosity reservoir in the Phosphoria Formation: American Association of Petroleum Geologists Bulletin, v. 76, no. 3, p. 371-391.

Gill, J.R., and Cobban, W.A., 1966, Regional unconformity in Late Cretaceous, Wyoming, *in* Geological Survey research, 1966: U. S. Geological Survey Professional Paper 550-B, p. B20-B27.

Gries, R.R., 1981, Oil and gas prospecting beneath the Precambrian of foreland thrust plates in the Rocky Mountains: The Mountain Geologist, v. 18, p. 1-18.

Goodell, H.G., 1962, The stratigraphy and petrology of the Frontier Formation of Wyoming: Wyoming Geological Association, 17th Annual Field Conference, 1962, Guidebook, p. 173-210.

Hagen, E.S., and Surdam, R.C., 1984, Maturation history and thermal evolution of Cretaceous source rocks of the Bighorn Basin, Wyoming and Montana, *in* Woodward, Jane, Meissner, F.F., and Clayton, J.L., eds., Hydrocarbon source rocks of the greater Rocky Mountain region: Rocky Mountain Association of Geologists, p. 321-338.

Keefer, W.R., 1972, Frontier, Cody, and Mesaverde Formations in the Wind River and southern Bighorn Basin, Wyoming: U. S. Geological Survey Professional Paper 495-E, 26 p.

Lawson, D.E., and Smith, J.R., 1966, Tensleep, Bighorn Basin: American Association of Petroleum Geologists Bulletin, v. 50, p. 2197-2220.

Mankiewicz, D., and Steidtmann, J.R., 1979, Depositional environments and diagenesis of the Tensleep Sandstone, eastern Bighorn Basin, Wyoming: Society of Economic Paleontologists and Mineralogists Special Publication 26, p. 319-336.

Maughan, E.K., 1984, Geological setting and some geochemistry of petroleum source rocks in the Permian Phosphoria Formation, *in* Woodward, Jane, Meissner, F.F., and Clayton, J.L., eds., Hydrocarbon source rocks of the greater Rocky Mountain region: Rocky Mountain Association of Geologists, p. 281-294.

McCaleb, J.A., and Willingham, R.W., 1967, Cottonwood Creek field, Wyoming: American Association of Petroleum Geologists Bulletin, v. 51, p. 2122-2132.

Meissner, F.F., 1978, Patterns of source-rock maturity in nonmarine source rocks of some typical Western Interior basins, *in* Nonmarine Tertiary and Upper Cretaceous source rocks and the occurrence of oil and gas in west-central U.S.: Rocky Mountain Association of Geologists Continuing Education Lecture Series, p. 1-37.

Meissner, F.F., Woodward, J., and Clayton, J.L., 1984, Stratigraphic relationships and distribution of source rocks in the greater Rocky Mountain region, *in* Woodward, Jane, Meissner, F.F., and Clayton, J.L., eds., Hydrocarbon source rocks of the greater Rocky Mountain region: Rocky Mountain Association of Geologists, p. 1-34.

Merewether, E.A. and Cobban, W.A., 1986, Biostratigraphic units and tectonism in the mid-Cretaceous foreland of Wyoming, Colorado, and adjoining areas, *in* Peterson, J.A., ed., Paleotectonics and sedimentation in the Rocky Mountain region, United States: American Association of Petroleum Geologists Memoir 41, p. 443-468.

Merewether, E.A., Cobban, W.A., and Ryder, R.T., 1975, Lower Upper Cretaceous strata, Bighorn Basin, Wyoming and Montana, *in* Exum, F.A., and George, G.R., eds., Geology and Mineral Resources of the Bighorn Basin: Wyoming Geological Association, 27th Annual Field Conference, 1975, Guidebook, p. 73-84.

Miller, D.N., Jr., Barlow, J.A, Jr., and Haun, J.D., 1965, Stratigraphy and petroleum potential of latest Cretaceous rocks, Bighorn Basin, Wyoming: American Association of Petroleum Geologists Bulletin, v. 49, p. 277-285.

Mitchell, G., 1978, Grieve oil field--A Lower Cretaceous estuarine deposit: Wyoming Geological Association, 30th Annual Field Conference, 1978, Guidebook, p. 147-165.

Montana Oil and Gas Conservation Division, 1986, Annual review for the year 1985 relating to oil and gas: Montana Department of Natural Resources and Conservation, v. 29, 67 p.

Mullen, D.M., and Barlow & Haun, Inc., 1993, FS-2. Bighorn basin *in* Atlas of Rocky Mountain gas reservoirs: New Mexico Bureau of Mines and Mineral Resources, p. 71.

Orr, W.L., 1974, Changes in sulfur content and isotopic ratios of sulfur during petroleum maturation--Study of Big Horn Basin Paleozoic oils: American Association of Petroleum Geologists Bulletin, v. 58, no. 11, p. 2295-2318.

Paull, R.A., and Paull, R.K., 1990, Persistent myth about the Lower Triassic Little Medicine Member of the Goose Egg Formation and the Lower Triassic Dinwoody Formation, central Wyoming: Wyoming Geological Association, 41stAnnual Field Conference, 1990, Guidebook, p. 31-49.

Parker, S.E., 1986, Structure contour map on top of the Upper Cretaceous Cody Shale, Bighorn Basin, Wyoming: Wyoming Geological Survey Open-File Report 86-9.

Paylor, E.D., II, and Yin, A., 1993, Left-slip evolution of the North Owl Creek fault system, Wyoming, during Laramide shortening, *in* Schmidt, C.J., Chase, R.B., and Ersley, E.A., eds., Laramide basement deformation in the Rocky Mountain Foreland of the Western United States: Geological Society of America Special Paper 280, p. 229-242.

Pedry, J.J., 1975, Tensleep fault trap, Cottonwood Creek field, Washakie County, Wyoming: Wyoming Geological Association, 27th Annual Field Conference, 1975, Guidebook, p. 211-219.

Peterson, J.A., 1984, Permian stratigraphy, sedimentary facies, and petroleum geology, Wyoming and adjacent area, *in* Goolsby, J., and Morton, D., eds., The Permian and

Pennsylvanian geology of Wyoming: Wyoming Geological Association, 35th Annual Field Conference, Guidebook, p. 25-64.

Ray, R.R., and Berg, C.R., 1985, Seismic interpretation of the Casper Arch Thrust, Teepee Flats field, Wyoming, *in* Gries, R.R., and Dyer, R.C., eds., Seismic exploration of the Rocky Mountain Region: Rocky Mountain Association of Geologists, p. 51-58.

Rogers, J.P., 1971, Tidal sedimentation and its bearing on reservoir and traps in Permian Phosphoria strata, Cottonwood Creek field, Bighorn Basin, Wyoming: The Mountain Geologist, v. 8, p. 71-80.

Severn, W.P., 1961, General stratigraphy of the Mesaverde Group, Bighorn Basin, Wyoming, *in* Wyoming Geological Association, 16th Annual Field Conference, 1961, Guidebook, p. 195-199.

Sheldon, R.P., 1967, Long-distance migration of oil in Wyoming: The Mountain Geologist, v. 4, p. 53-65.

Siemers, C.T., 1975, Paleoenvironmental analysis of the Upper Cretaceous Frontier Formation, northwestern Bighorn Basin, Wyoming, *in* Exum, F.A., and George, G.R., eds., Geology and mineral resources of the Bighorn Basin: Wyoming Geological Association, 27th, Annual Field Conference, 1975, Guidebook, p. 85-100.

Skeen, R.C., and Ray, R.R., 1983, Seismic models and interpretation of the Casper Arch Thrust--Application to Rocky Mountain foreland structure, *in* Lowell, J.D., ed., Rocky Mountain foreland basins and uplifts: Rocky Mountain Association of Geologists, p. 99-124.

Stauffer, J.E., 1971, Petroleum potential of Bighorn Basin and Wind River basin, Casper arch area, Wyoming, and Crazy Mountain basin-Bull Mountains basin area, Montana: American Association of Petroleum Geologists Memoir 15, p. 613-655.

Stearns, D.W., 1975, Laramide basement deformation in the Bighorn Basin--The controlling factor for structures in the layered rocks: Wyoming Geological Association, 27th Annual Field Conference, Guidebook, p. 149 - 158.

Stephenson, T.R., VerPloeg, A.J., and Chamberlain, L.S., 1984, Oil and gas map of Wyoming: Geological Survey of Wyoming Map Series 12.

Stone, D.S., 1967, Theory of Paleozoic oil and gas accumulation in Bighorn Basin, Wyoming: American Association of Petroleum Geologists Bulletin, v. 51, p. 2056-2114.

Stone, D.S., 1983, Seismic profile: South Elk Basin, *in* Bally, A. W., ed., Seismic expression of structural styles: American Association of Petroleum Geologists Studies *in* Geology Series No. 15, v. 3, p. 3.2.2-20 - 3.2.2-24.

Stone, D.S., 1985, Geologic interpretation of seismic profiles, Bighorn Basin, Wyoming, part 1--East flank, *in* Gries, R.R. and Dyer, R.C., eds., Seismic exploration of the Rocky Mountain region: Rocky Mountain Association of Geologists and the Denver Geophysical Society, p. 165-174.

Stone, D.S., 1985, Geologic interpretation of seismic profiles, Bighorn Basin, Wyoming, part II--West flank, *in* Gries, R.R. and Dyer, R.C., eds., Seismic exploration of the Rocky Mountain region: Rocky Mountain Association of Geologists and the Denver Geophysical Society, p. 175-187.

Stone, D.S., 1993, Basement-involved thrust-generated folds as seismically imaged in the subsurface of the central Rocky Mountain foreland, *in* Schmidt, C.J., Chase, R.B., and Ersley, E.A., eds., Laramide basement deformation in the Rocky Mountain Foreland of the Western United States: Geological Society of America Special Paper 280, p. 271-318.

Sundell, K.A., 1990, Sedimentation and tectonics of the Absaroka basin of northwestern Wyoming: Wyoming Geological Association, 41st Annual Field Conference, 1990, Guidebook, p. 105-122.

Sundell, K.A., 1983, Volcanic stratigraphy, timing, and petroleum exploration in southeastern Absaroka Range, Bighorn Basin, Wyoming [abs.]: American Association of Petroleum Geologists Bulletin, v. 67, p. 1357-1358.

Thomas, H.D., 1957, Geologic history and structure of Wyoming: Wyoming Geological Association, Wyoming Oil and Gas Fields Symposium, p. 15-23.

Thomas, L.E., 1965, Sedimentation and structural development of Bighorn Basin: American Association of Petroleum Geologists Bulletin, v. 49, p. 1867-1877.

Tonnsen, J.J., 1980, The Frontier Formation in northwestern Wyoming and adjacent areas: Wyoming Geological Association, 31st Annual Field Conference, 1980, Guidebook, p. 173-184.

Tonnsen, J.J., ed., 1985, Montana oil and gas fields symposium: Montana Geological Society, 2 volumes, 1217 p.

U. S. Geological Survey and Minerals Management Service, 1988, National assessment of undiscovered conventional oil and gas resources: U.S. Geological Survey/Minerals Management Working Paper, Open-File Report 88-373, 511 p.

Wyoming Geological Association, 1957, Wyoming oil and gas fields symposium: Wyoming Geological Association, Casper, Wyoming, 484 p.; with supplements: 1961; 1969-73 (in Earth Science Bulletin); variously paged and unpaged.

Wyoming Geological Association, 1983, Wyoming stratigraphic nomenclature chart: Wyoming Geological Association, 34th Annual Field Conference, 1983, Guidebook, p. 12.

Wyoming Oil and Gas Conservation Commission, compiler, 1986, Wyoming oil and gas statistics, 1985: Wyoming Oil and Gas Conservation Commission, Casper, Wyo., 137 p.