Chapter 5

Geologic Assessment of Undiscovered Petroleum Resources in the Waltman Shale Total Petroleum System, Wind River Basin Province, Wyoming

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By Steve Roberts, Laura N.R. Roberts, and Troy Cook

Chapter 5 of
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Geologic Assessment of Undiscovered Petroleum Resources in the Waltman Shale Total Petroleum System, Wind River Basin Province, Wyoming

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Abstract

The Waltman Shale Total Petroleum System encompasses about 3,400 square miles in the Wind River Basin Province, Wyoming, and includes accumulations of oil and associated gas that were generated and expelled from oil-prone, lacustrine shale source rocks in the Waltman Shale Member of the Paleocene Fort Union Formation. Much of the petroleum migrated and accumulated in marginal lacustrine (deltaic) and fluvial sandstone reservoirs in the Shotgun Member of the Fort Union, which overlies and intertongues with the Waltman Shale Member. Additional petroleum accumulations derived from Waltman source rocks are present in fluvial deposits in the Eocene Wind River Formation overlying the Shotgun Member, and also might be present within fan-delta deposits included in the Waltman Shale Member, and in fluvial sandstone reservoirs in the uppermost part of the lower member of the Fort Union Formation immediately underlying the Waltman. To date, cumulative production from 53 wells producing Waltman-sourced petroleum exceeds 2.8 million barrels of oil and 5.8 billion cubic feet of gas. Productive horizons range from about 1,770 feet to 5,800 feet in depth, and average about 3,400 to 3,500 feet in depth.

Formations in the Waltman Shale Total Petroleum System (Fort Union and Wind River Formations) reflect synorogenic deposition closely related to Laramide structural development of the Wind River Basin. In much of the basin, the Fort Union Formation is divided into three members (ascending order): the lower unnamed member, the Waltman Shale Member, and the Shotgun Member. These members record the transition from deposition in dominantly fluvial, floodplain, and mire environments in the early Paleocene (lower member) to a depositional setting characterized by substantial lacustrine development (Waltman Shale Member) and contemporaneous fluvial, and marginal lacustrine (deltaic) deposition (Shotgun Member) during the middle and late Paleocene.

Waltman Shale Member source rocks have total organic carbon values ranging from 0.93 to 6.21 weight percent, averaging about 2.71 weight percent. The hydrocarbon generative potential of the source rocks typically exceeds 2.5 milligrams of hydrocarbon per gram of rock and numerous samples had generative potentials exceeding 6.0 milligrams of hydrocarbon per gram of rock. Waltman source rocks are oil prone, and contain a mix of Type-II and Type-III kerogen, indicating organic input from a mix of algal and terrestrial plant matter, or a mix of algal and reworked or recycled material. Thermal maturity at the base of the Waltman Shale Member ranges from a vitrinite reflectance value of less than 0.60 percent along the south basin margin to projected values exceeding 1.10 percent in the deep basin west of Madden anticline. Burial history reconstructions for three wells in the northern part of the Wind River Basin indicate that the Waltman Shale Member was well within the oil window (R_o equal to or greater than 0.65 percent) by the time of maximum burial about 15 million years ago; maximum burial depths exceeded 10,000 feet. Onset of oil generation calculated for the base of the Waltman Shale member took place from about 49 million years ago to about 20 million years ago. Peak oil generation occurred from about 31 million years ago to 26 million years ago in the deep basin west of Madden anticline.

Two assessment units were defined in the Waltman Shale Total Petroleum System: the Upper Fort Union Sandstones Conventional Oil and Gas Assessment Unit (50350301) and the Waltman Fractured Shale Continuous Oil Assessment Unit (50350361). The conventional assessment unit primarily relates to the potential for undiscovered petroleum accumulations that are derived from source rocks in the Waltman Shale Member and trapped within sandstone reservoirs in the Shotgun Member (Fort Union Formation) and in the lower part of the overlying Wind River Formation. The potential for Waltman-sourced oil accumulations in fan-delta deposits within the Waltman Shale Member, and in fluvial sandstone deposits in the uppermost part of the lower member of the Fort Union also is considered in the assessment of this assessment unit. Definition of the Waltman Fractured Shale Continuous Oil Assessment Unit is based on previous studies indicating a potential for hydrocarbon (oil) saturation and entrapment within the Waltman Shale Member in areas near

Madden anticline. This assessment unit is hypothetical and was not quantitatively assessed.

Mean estimates of the total undiscovered petroleum resources in the Upper Fort Union Sandstones Conventional Oil and Gas AU are 12 million barrels of oil, 24 billion cubic feet of gas, and 1.4 million barrels of natural gas liquids.

Introduction

The Waltman Shale Total Petroleum System (TPS) in the Wind River Basin, Wyoming (fig. 1), includes strata in the Fort Union Formation (Paleocene) and in the lower part of Wind River Formation (Eocene) (fig. 2). The Waltman Shale TPS is an oil-prone system, based on the concept that oil and associated gas was generated and expelled from thick, organic-rich lacustrine shale beds in the Waltman Shale Member of the Fort Union Formation. Much of the petroleum migrated and accumulated in marginal lacustrine (deltaic) and fluvial sandstone reservoirs in the Shotgun Member of the Fort Union, which overlies and intertongues with the Waltman Shale Member (fig. 1). Additional petroleum accumulations derived from Waltman source rocks are in fluvial deposits in the Wind River Formation overlying the Shotgun Member, and also might be present within fan-delta deposits in the Waltman Shale Member, and in fluvial sandstone reservoirs in the uppermost part of the lower unnamed member of the Fort Union Formation immediately underlying the Waltman Shale Member. In areas of the basin where individual members of the Fort Union are not present or recognized, a potential for hydrocarbon accumulation might exist in fluvial deposits in the undifferentiated Fort Union Formation. However, undiscovered petroleum accumulations in Fort Union strata in areas where the Waltman Shale Member is absent or only represented by thin shale intervals (for example, Johnson, Chapter 10, this CD-ROM) are assessed as part of the Cretaceous–Tertiary Lower Composite TPS (Johnson and others, Chapter 4, this CD–ROM) because of the possibility of mixing hydrocarbons (especially gas) that have migrated from deeper source rocks with hydrocarbons sourced by the Waltman.

The TPS encompasses about 3,400 square miles (mi^2) and the boundary is generally defined by the outcrop limits of the Fort Union Formation, or the inferred limits where overlapped by the Wind River Formation (fig. 1). Adjacent to the Owl Creek Mountains and Casper arch on the north and east margins of the basin, respectively, the TPS extends to the estimated subthrust limits of the Waltman Shale Member.

The stratigraphic top and base of the petroleum system is difficult to pinpoint because both horizons essentially represent the uppermost and lowermost limits for migration of hydrocarbons derived from the Waltman. Downward migration of Waltman-sourced oil into lower Fort Union rocks might be inhibited by the counteractive effects of buoyancy or capillary pressure if underlying rocks are tight (having low permeability). Additionally, throughout most of the basin gas-prone source rocks (coal and carbonaceous shale) in the lower unnamed member of the Fort Union and deeper formations reached peak gas generation well before onset of oil generation from the Waltman Shale Member (Roberts and others, Chapter 6, this CD-ROM). Potential overpressure induced by gas generation, migration, and accumulation in strata sealed below the thick Waltman also might have impeded any significant downward migration of Waltman-sourced oil into underlying, overpressured units. For these reasons, potential reservoirs for Waltman-sourced oil accumulations in the lower part of the Fort Union are most likely to be in close proximity (a few hundred feet or less?) to the base of the Waltman Shale Member.

The upper limit of the TPS also is problematic as there is no identifiable, regionally pervasive seal that would inhibit the upward migration of hydrocarbons derived from the Waltman. Interbedded shale or mudstone in fluvial strata of the Fort Union (Shotgun Member) and Wind River Formations overlying the Waltman might form seals locally, but the stratigraphic position of such seals could vary greatly throughout the basin. Additionally, potential faults or fractures in units overlying major structures in the basin (for example, Madden anticline; fig. 3) could allow for upward migration of petroleum into shallow horizons well above the Waltman Shale Member. However, current oil production is mainly from reservoirs within 1,000 to 1,500 feet (ft) above the top of the Waltman and most production and tests for oil typically target sandstone units bounded by lacustrine shale in the uppermost part of the Waltman, or target the lowermost, coarsening upward sandstone successions in the Shotgun Member immediately overlying the shale. Because of the oil production and exploration trends to date, the authors restrict the top of the TPS to the lower part of the Wind River Formation, arbitrarily suggesting a horizon within about 1,500 ft of the top of the Waltman Shale Member. However, upward migration of petroleum from the Waltman could exceed this designated limit in some areas.

Several fields in the Wind River Basin are producing oil sourced by the Waltman Shale Member (fig. 4), although Katz and Liro (1993) suggested that oil produced from Shotgun Member reservoirs in Fuller Reservoir field is not solely derived from the Waltman. Based on data from the Wyoming Oil and Gas Conservation Commission (2005), most of the historic production has taken place in the Fuller Reservoir field where cumulative production from 33 wells has totaled more than 2.3 million barrels of oil (MMBO) and 4.4 billion cubic feet (BCF) of gas; cumulative production from 8 wells in Haybarn field is more than 330,000 barrels of oil and about 1.4 BCF of gas, and in the greater Madden area (Madden, Lost Cabin, and Lysite fields) 11 wells have produced some 183,000 barrels of oil and 0.36 BCF of gas. One well in the Carvner Field produced about 5,600 barrels of oil and 5 million cubic feet (MMCF) of gas (Wyoming Oil and Gas Conservation Commission, 2005).

Two assessment units (AUs) were defined in the Waltman Shale TPS: the Upper Fort Union Sandstones Conventional

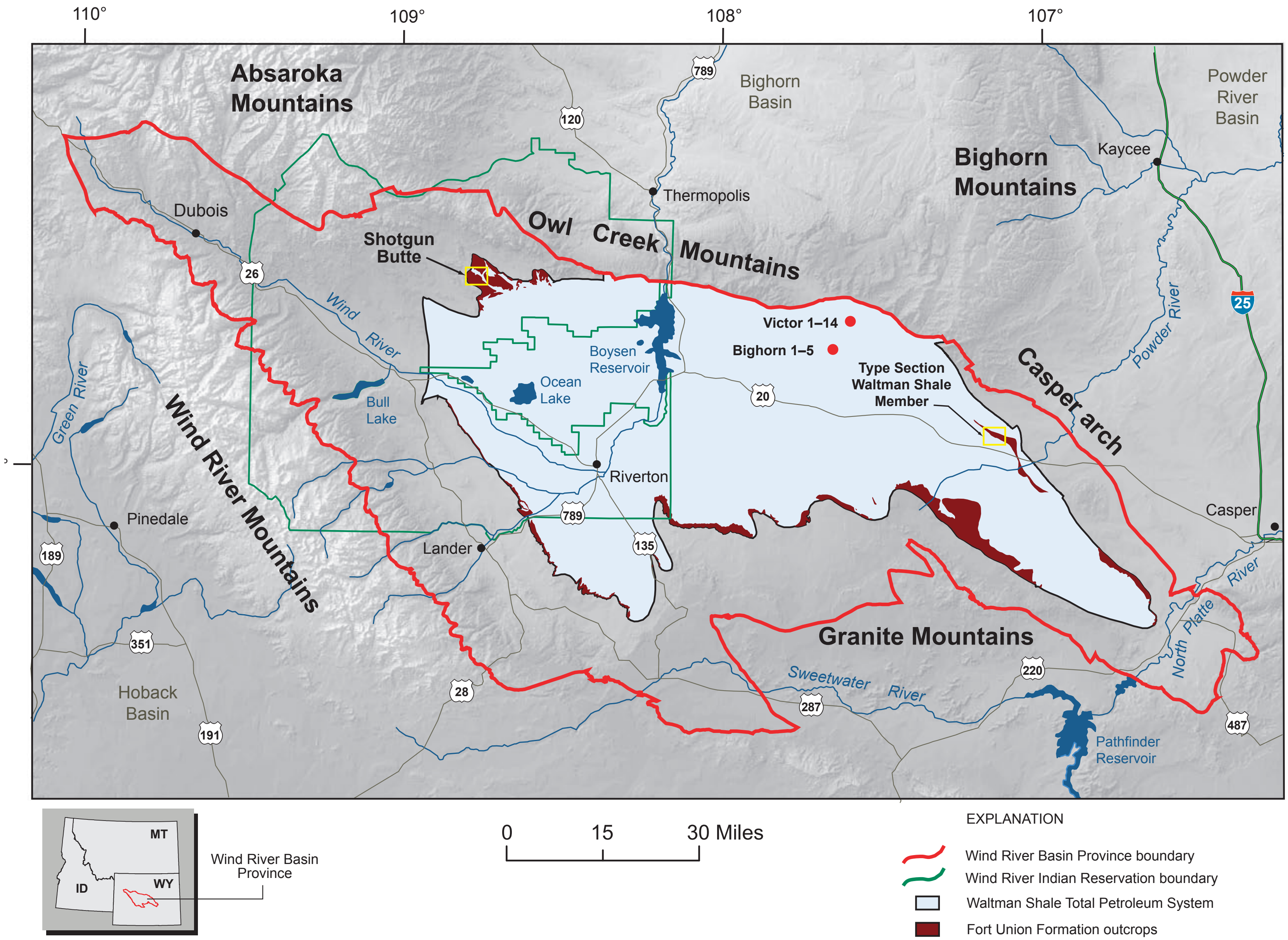

Figure 1. Location of the Waltman Shale Total Petroleum System (blue shade) in the Wind River Basin Province, Wyoming; red dots represent the locations of the Bighorn 1–5 and Victor 1–14 oil and gas exploration wells. Fort Union Formation outcrops from Green and Drouillard (1994) after Love and Christiansen (1985).

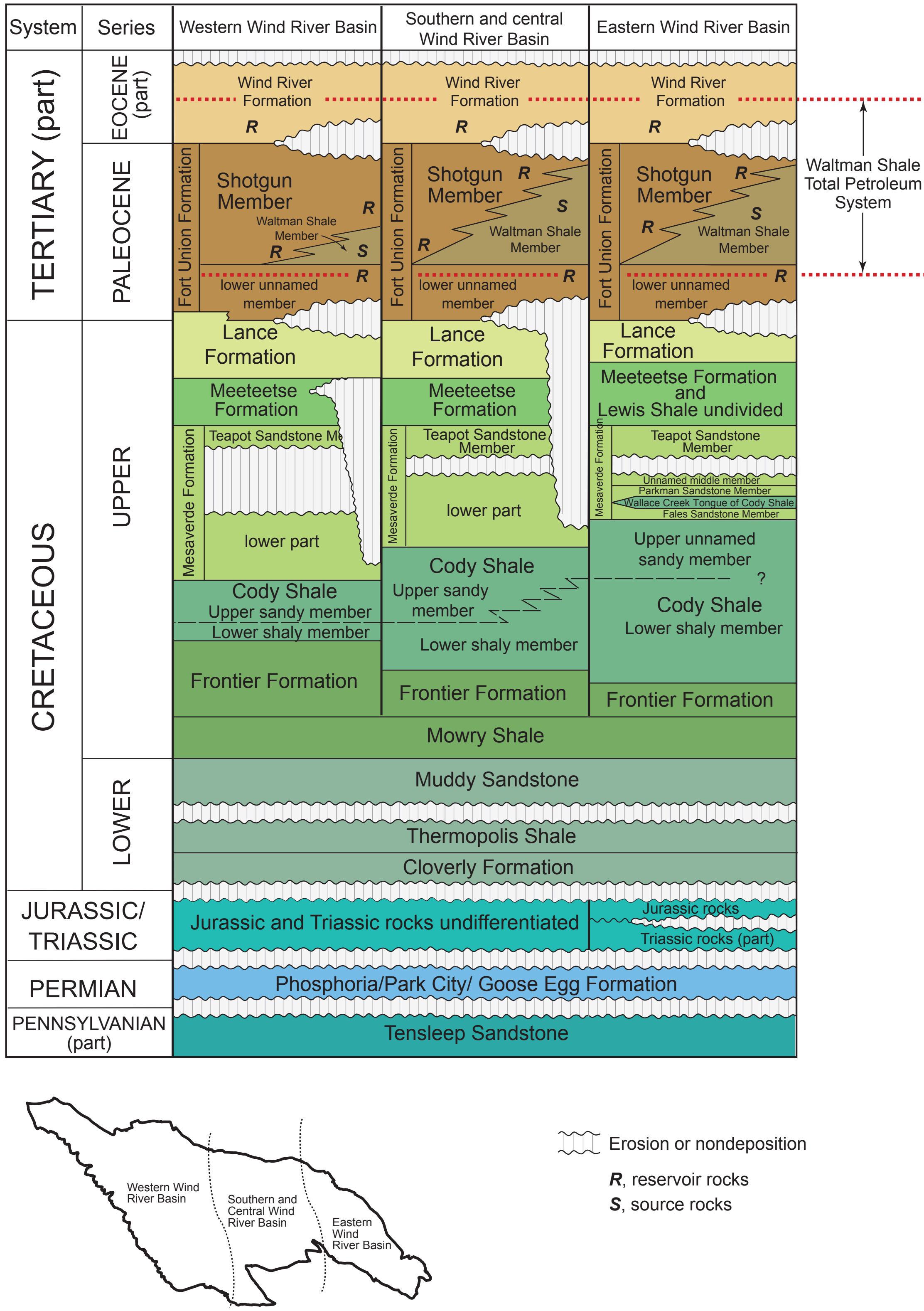

Figure 2. Generalized stratigraphic chart for the Wind River Basin Province, Wyoming, showing units in the Waltman Shale Total Petroleum System, and intervals of petroleum reservoir and source rocks. Ages of stratigraphic units older than Cretaceous Cloverly Formation were estimated using Love and others (1993). The ages at system and series boundaries were adjusted to the 1999 Geologic Time Scale (Palmer and Geissman, 1999) and ages of Cretaceous and younger stratigraphic units are from Finn (Chap. 9, pl. 1, this CD-ROM).

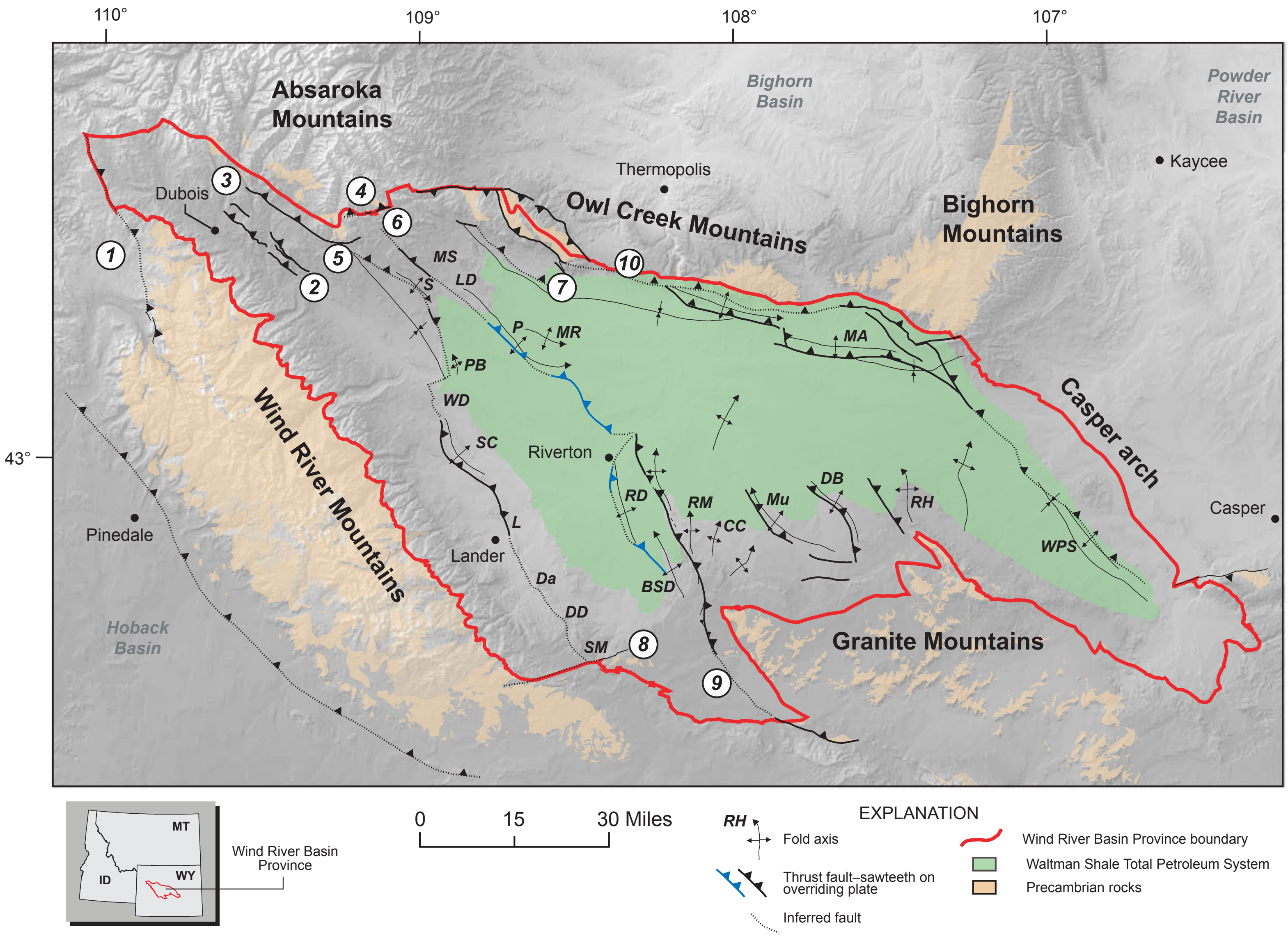

Figure 3. Generalized tectonic map of the Wind River Basin Province and adjoining areas, showing major structural features. All structures from Love and Christiansen (1985) are shown in black; dashed where inferred in subsurface; faults shown in blue are interpreted from unpublished seismic studies of M. A. Kirschbaum (USGS, written commun.). Numbered faults: 1, White Rock thrust; 2, Wind Ridge and Coulee Mesa thrust system; 3, Black Mountain thrust; 4, Red Creek thrust (Blackstone, 1990); 5, Rolff Lake fault; 6, Circle Ridge/Maverick Springs thrust; 7, Shotgun Butte thrust; 8, Clear Creek fault; 9, Emigrant Trail fault; and 10, South Owl Creek Mountains fault. Anticlines: BSD, Big Sand Draw; CC, Conant Creek; Da, Dallas; DB, Dutton Basin; DD, Derby Dome L, Lander; LD, Little Dome; MS, Maverick Springs; Mu, Muskrat; MR, Muddy Ridge; P, Pavillion; PB, Pilot Butte; RD, Riverton Dome/Beaver Creek; RH, Rattlesnake Hills; RM, Rogers Mountain; S, Sheldon; SC, Sage Creek; SM, Sheep Mountain; WD, Winkleman Dome; WPS, West Poison Spider; and MA, Madden anticline.

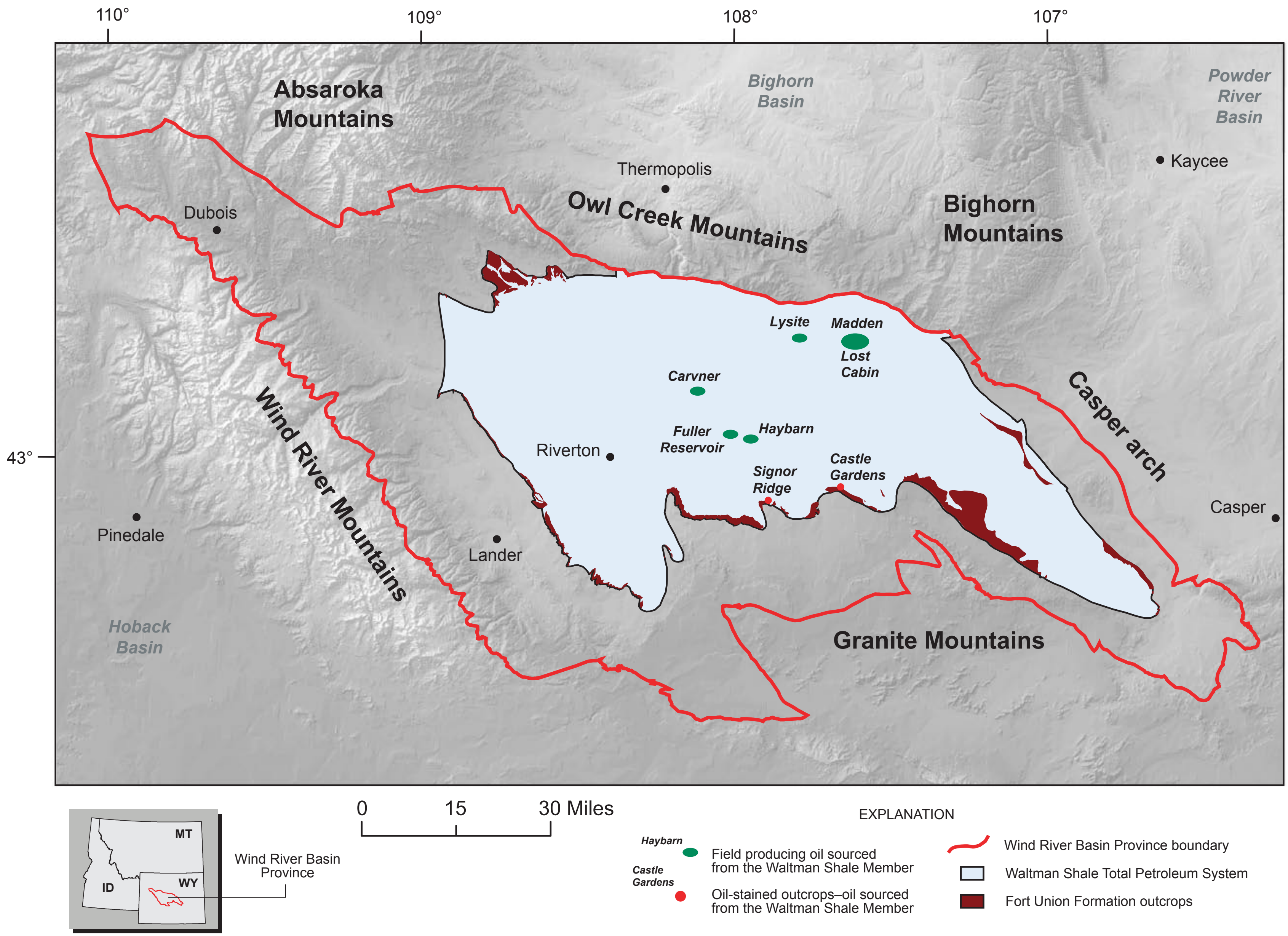

Figure 4. Locations of oil and gas fields producing oil derived from source rocks in the Waltman Shale Member of the Fort Union Formation, Wind River Basin Province, Wyoming. Identification of Waltman-sourced accumulations in fields shown is based on Ray (1982), Robertson (1984), Katz and Liro (1993), Palacas and others (1994), and Lillis and Palacas (U.S. Geological Survey, unpub. data, 2006). Fort Union Formation outcrops from Green and Drouillard (1994) after Love and Christiansen (1985).

Oil and Gas AU (fig. 5) and the Waltman Fractured Shale Continuous Oil AU (fig. 6). Although some potential for microbial (biogenic) gas generation from the Waltman is evidenced by gas production in one well within the basin (Johnson and Rice, 1993), no assessment of these resources was completed for this study.

The conventional assessment unit primarily addresses the potential for undiscovered petroleum accumulations that are derived from source rocks in the Waltman Shale Member, and trapped primarily within sandstone or conglomeratic reservoirs in the Shotgun Member, and the lower part of the overlying Wind River Formation. Potential Waltman-sourced accumulations also may exist in areally restricted reservoirs within basin margin fan-delta systems within the Waltman Shale Member, and in sandstone reservoirs in the uppermost part of the lower unnamed member of the Fort Union Formation.

The Waltman Fractured Shale Continuous Oil AU is based on concepts in Jorjorian and others (1989) and Katz and Liro (1993) describing the potential for hydrocarbon (oil) saturation and entrapment within the Waltman Shale Member in areas near Madden anticline. This AU is hypothetical and was not quantitatively assessed.

Geologic Setting

The Wind River Basin developed as Laramide deformation reshaped the Rocky Mountain foreland. Uplift of the Wind River, Granite, and Owl Creek Mountains (fig. 3) surrounding the basin began in the Late Cretaceous, and rapid basin subsidence in the latest Cretaceous (Maastrichtian) is evidenced by thickening of the Lance Formation in areas adjacent to the Owl Creek Mountains (Keefer, 1970; Johnson and others, 1996a). Structural development of the basin and uplifts continued during deposition of the Fort Union Formation in the Paleocene, with interpreted rise of the Casper arch along the eastern basin margin in late early (?) through late Paleocene time (for example, Gries, 1983; Flemings and Nelson, 1991; Flores and others, 1994). Subtle folds in the Waltman Shale Member of the Fort Union (fig. 7) and significant folding and uplift of the member on the Madden anticline resulted from post-Waltman deformation in the latest Paleocene (?) through early Eocene (for example, Dunleavy and Gilbertson, 1986). Subsidence and uplift ended by the close of early Eocene time (Keefer, 1970), during the latter stages of Wind River deposition.

Formations in the Waltman Shale TPS (Fort Union and Wind River Formations; fig. 2) reflect synorogenic deposition closely related to Laramide structural development of the Wind River Basin. The Fort Union Formation in much of the basin is divided into three members (ascending order): the lower unnamed member, the Waltman Shale Member, and the Shotgun Member (fig. 2) (Keefer, 1961). These members record the transition from deposition in dominantly fluvial, floodplain, and mire environments in the early Paleocene (lower unnamed member) to a depositional setting characterized by significant lacustrine development (Waltman Shale Member) and contemporaneous fluvial, and marginal lacustrine (deltaic) deposition (Shotgun Member) during the middle and late Paleocene (for example, Phillips, 1983; Liro and Pardus, 1990; Flores and others, 1994; Nichols, 1994; Osborn, 2001). Keefer (1961; 1965) previously recognized the Waltman member as deposits of an extensive body of water that developed in the basin during late Paleocene time, and suggested that this water body might represent an arm or embayment of the marine Cannonball Sea. However, based on the studies and interpretations in Liro and Pardus (1990), Katz and Liro (1993), Flores and others (1994), and Liro (1993), the Waltman Shale Member represents lacustrine deposits in this study.

The three members of the Fort Union Formation are not present or recognized everywhere in the basin. In areas where the Waltman Shale Member is absent (for example, Shotgun Butte; fig. 1), the Shotgun Member directly overlies the lower unnamed member (fig. 2). The Shotgun Member in outcrops along the south and southeast basin margins cannot be distinguished from the lower unnamed member and the entire Paleocene section is included in the undifferentiated Fort Union Formation (Keefer, 1965). At most outcrop locations the contact between the Fort Union and underlying Lance Formation is unconformable; however, this contact is likely conformable in the major basin trough areas (Keefer, 1965). Prior to deposition of the Wind River Formation, erosion removed significant portions of the underlying Fort Union Formation. At Shotgun Butte in the northern part of the basin (fig. 1), about 1,100 ft of the lower unnamed member of the Fort Union is exposed. There, the lower unnamed member consists mainly of conglomerate and sandstone with subordinate gray shale and brown carbonaceous shale (Keefer, 1997). The member thickens eastward to more than 4,500 ft in the deep basin trough in the west-central part of the basin (Johnson and others, 1996a), and through most of the central basin area, the member is characterized by sandstone (locally arkosic or containing chert clasts), siltstone, shale, carbonaceous shale, and coal (Keefer and Johnson, 1997). Coal is widespread in the upper part of the lower unnamed member and cumulative coal thickness exceeds 100 ft in some areas. Adjacent to the Owl Creek Mountains and Casper arch in the north and northeast basin-margin areas, subsurface studies show that the lower unnamed member is predominantly fine grained and consists mainly of sandy mudstone and thin (< 10 ft thick) 'muddy' sandstone (Johnson and others, 1996a).

The Waltman Shale Member, which overlies the lower unnamed member, is named for exposures of shale near the east basin margin (fig. 1). At the type locality, the Waltman is about 645 ft thick and characterized by chocolate-brown and gray silty and shaly claystone interbedded with a few thin resistant sandstone beds; disseminated mica is abundant within the claystone. Cuttings and core samples of the Waltman recovered in oil and gas exploration wells are characteristically

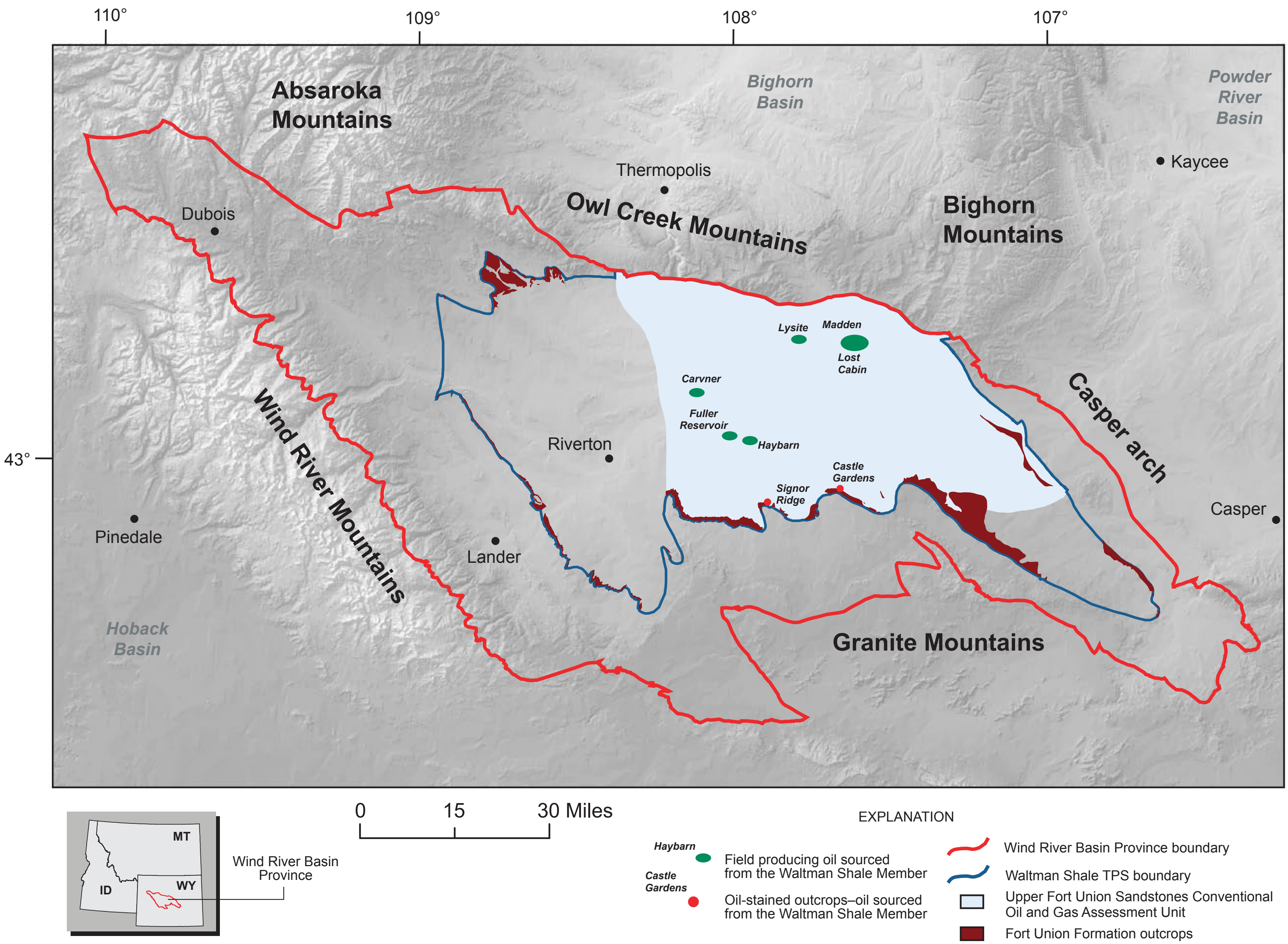

Figure 5. The extent of the Upper Fort Union Sandstones Conventional Oil and Gas Assessment Unit in the Waltman Shale Total Petroleum System, Wind River Basin Province, Wyoming. Identification of Waltman-sourced accumulations in fields shown is based on Ray (1982), Robertson (1984), Katz and Liro (1993), Palacas and others (1994), and Lillis and Palacas (U.S. Geological Survey, unpub. data, 2006). Fort Union Formation outcrops from Green and Drouillard (1994) after Love and Christiansen (1985).

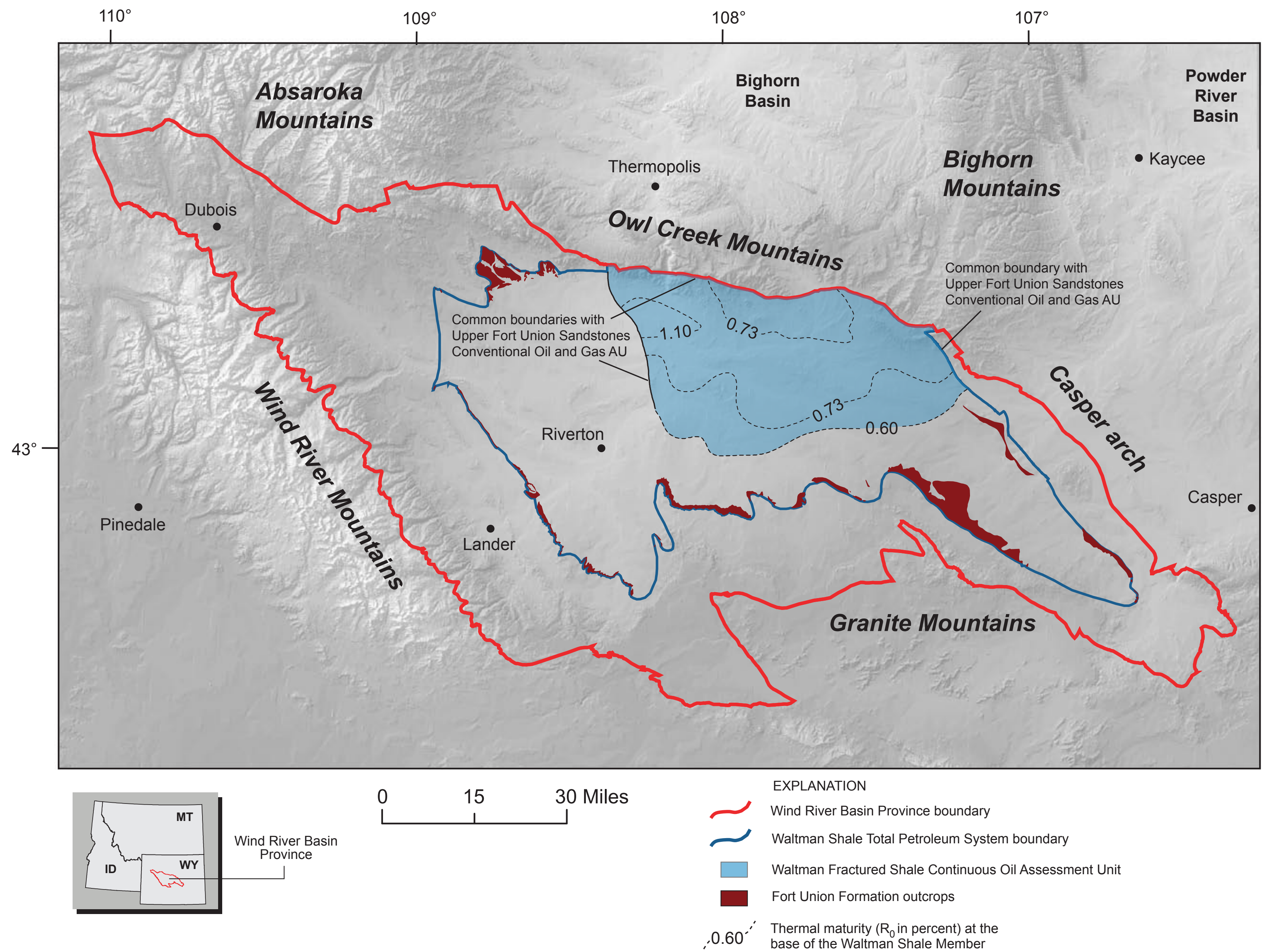

Figure 6. The extent of the Waltman Fractured Shale Continuous Oil Assessment Unit (hypothetical) in the Waltman Shale Total Petroleum System, Wind River Basin Province, Wyoming. Thermal maturity (isoreflectance) lines (R_0 in percent) modified from Johnson and others (1996b). Fort Union Formation outcrops from Green and Drouillard (1994) after Love and Christiansen (1985). R_0, vitrinite reflectance.

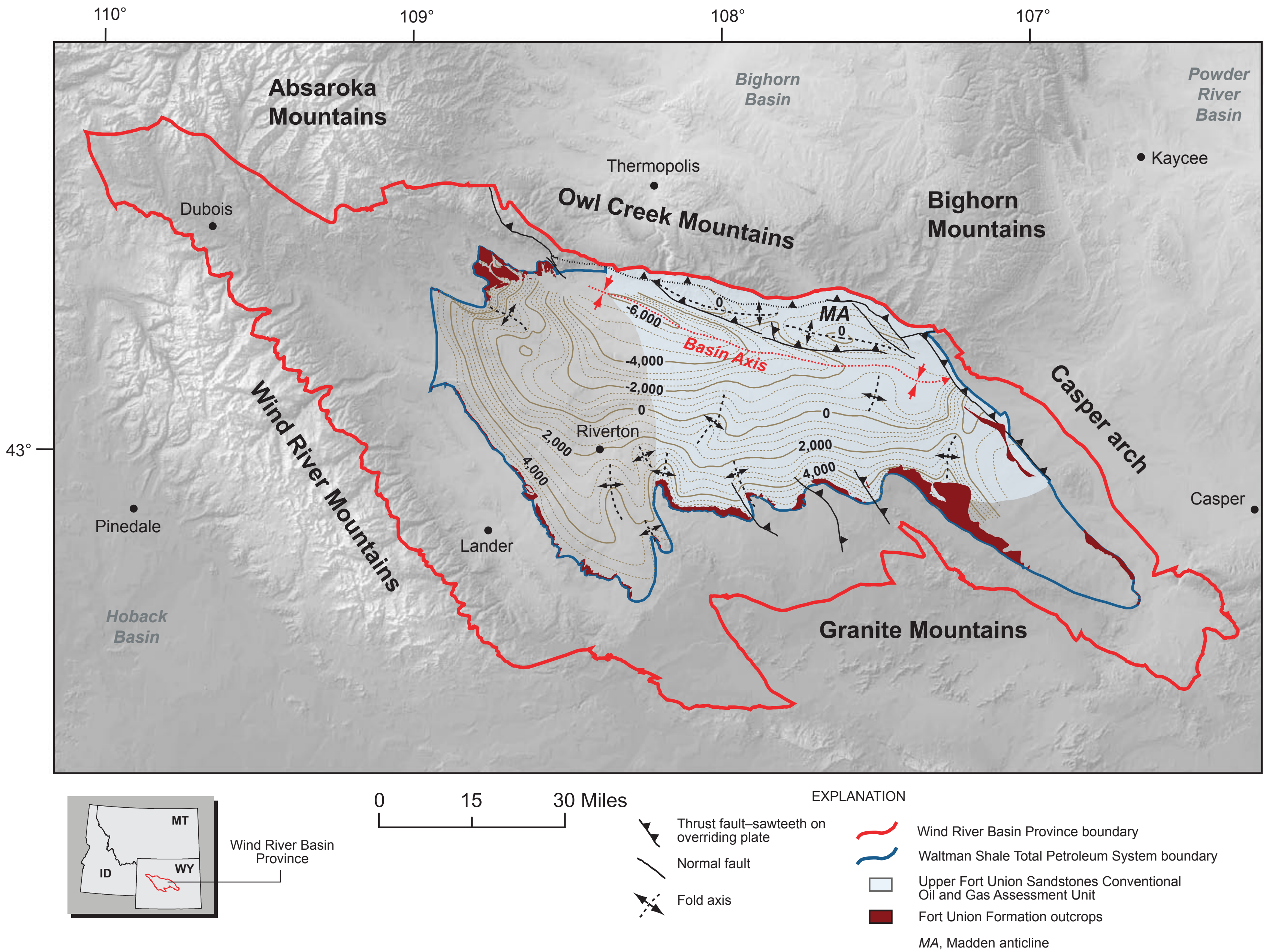

Figure 7. Structure contour map on the base of the Waltman Shale Member of the Fort Union Formation, Wind River Basin Province, Wyoming. Structure contours modified from Johnson and others (1996a) and based on new interpretations of Johnson and others (2005). Contour interval is 500 feet; contour values in elevation relative to mean sea level. Fort Union Formation outcrops from Green and Drouillard (1994) after Love and Christiansen (1985).

dark brown to black and uniformly silty and micaceous (Keefer, 1961; 1965). The thickness of the Waltman exceeds 3,800 ft in structurally deep areas near the basin axis (Keefer, 1997), and depth to the base of the member is more than 10,000 ft near the basin axis in areas west of Madden anticline (fig. 8). The contact between the Waltman Shale Member and underlying lower unnamed member in outcrops is transitional and is generally defined by a zone of interbedded sandstone, black micaceous shale, carbonaceous shale, and coal (Keefer, 1961). In electric logs, the Waltman is characterized by low self-potential and resistivity curves relative to underlying and overlying units (Keefer, 1965); in sonic logs, there is a distinct decrease in velocity within the shale (fig. 9). The contact between the Waltman Shale Member and the lower unnamed member is considered to be conformable (Keefer, 1965) although seismic studies in areas near the Carvner and Fuller Reservoir fields (fig. 4) indicate that an unconformity may separate the Waltman Shale Member from the underlying lower unnamed member (Ray, 1982). The Waltman covers an area exceeding 1,000 mi^2 and is interpreted to have also been deposited in areas overridden by the Casper arch thrust to the east (Keefer, 1965). Recent subsurface studies (Johnson and others, 2005; Johnson, Chapter 10, this CD-ROM) indicate that Waltman deposition also may have extended farther westward than previously interpreted (for comparison, see Johnson and others, 1996a); structure contours and depths at the base of the Waltman Shale Member shown in figures 7 and 8 are based on the newly interpreted extent.

The Shotgun Member, which overlies and intertongues with the Waltman Shale Member, was named for a succession of soft claystone, siltstone, shale, carbonaceous shale, and sandstone exposed at Shotgun Butte (fig. 1). At that locality, the Shotgun Member is about 2,830 ft thick; near the north margin of the basin, the member is more than 2,200 ft thick (Keefer, 1961; 1965). The Shotgun Member was deposited in fluvial and shoreline areas landward of open-water lacustrine environments that expanded during the late Paleocene; Waltman deposits reflect offshore deposition contemporaneous with onshore Shotgun Member deposition (Keefer, 1961). The contact between the Shotgun and Waltman Shale Members is transitional and typically characterized by alternating thin beds of black shale and fine-grained sandstone, carbonaceous shale, and coal (Keefer, 1965). The contact in the subsurface is typically placed at the base of the lowermost, coarsening-upward succession above the main shale mass, as expressed in gamma-ray (GR) and spontaneous potential (SP) logs (for comparison, see Keefer, 1965; Keefer and Johnson, 1997). These successions are indicative of shale or siltstone changing upward to sandstone, reflecting a facies shift from offshore lacustrine environments to nearshore, shoreface, or deltaic environments. However, in certain areas of the basin, units overlying the lowermost coarsening upward succession consist of alternating lacustrine and shoreface deposits resulting from oscillations in lake level and relative shoreline position. In these areas, placement of the contact separating the two members is problematic and can result in the inclusion of lacustrine shale tongues within the Shotgun Member, or alternatively, marginal lacustrine or deltaic sandstone in the Waltman Shale Member. Additionally, rapid lateral facies variations also can complicate the differentiation of the individual members. For example, in the Bighorn 1–5 well near the northern basin margin (fig. 1), geophysical logs indicate that about 2,000 ft of shale immediately overlies the lower unnamed member of the Fort Union; the contact separating the Shotgun and Waltman Shale Members is logically placed at the top of the thick shale interval (fig. 9). However, in the Victor 1–14 well, which is only a few miles north of the Bighorn 1–5 well (fig. 1), strata equivalent to the Waltman Shale Member include only about 1,000 ft of shale overlain by more that 1,500 ft of coarser lithologies (sandstone or conglomerate?) interpreted, in part, to represent deposits of a fan-delta system (for comparison, see Hollis, 2001) that developed contemporaneously with offshore lacustrine environments nearby. A strictly lithologic definition might place the contact at the top of the shale interval in the Victor 1–14 well; whereas, an alternative approach might include fan-delta deposits (in part) as a facies variant within the Waltman Shale Member. In this study, the latter approach is preferred and the fan-delta system (at least in part) is included within the Waltman Shale Member (fig. 9). However, circumstances such as this might be limited to only a few areas near the basin margins; throughout most of the basin, identification of the contact between the Shotgun Member and the Waltman Shale Member follows criteria set forth by Keefer (1961; 1965).

Lower Eocene alluvial strata overlie the Fort Union Formation and are present in outcrops throughout much of the Wind River Basin. In this study, the name Wind River Formation is applied to all lower Eocene rocks, including the Indian Meadows Formation and the Lost Cabin and Lysite Members of the Wind River Formation (Keefer, 1965). The Wind River nomenclature is applied because in subsurface (well-log) data, there are no viable criteria for distinguishing the individual members within the Wind River Formation or for differentiating the Indian Meadows Formation from the Wind River (Keefer, 1965).

The Wind River Formation unconformably overlies the Fort Union Formation at most outcrop localities, although the contact may be conformable in central basin areas. The maximum thickness of the Wind River may exceed 9,000 ft in the north-central and southeastern parts of the basin. The formation in the basin center is characterized by varicolored red, gray, and gray-green claystone interbedded with white or gray fine- to medium-grained sandstone (Keefer, 1965). The varicolored aspect of the Wind River Formation can, in some places, provide a basis for distinguishing Wind River strata from underlying Fort Union rocks, which tend to be drab and darker in color. However, in many cases, differentiation of these formations based on well-log data is difficult. The Wind River Formation includes a wide range of lithologies

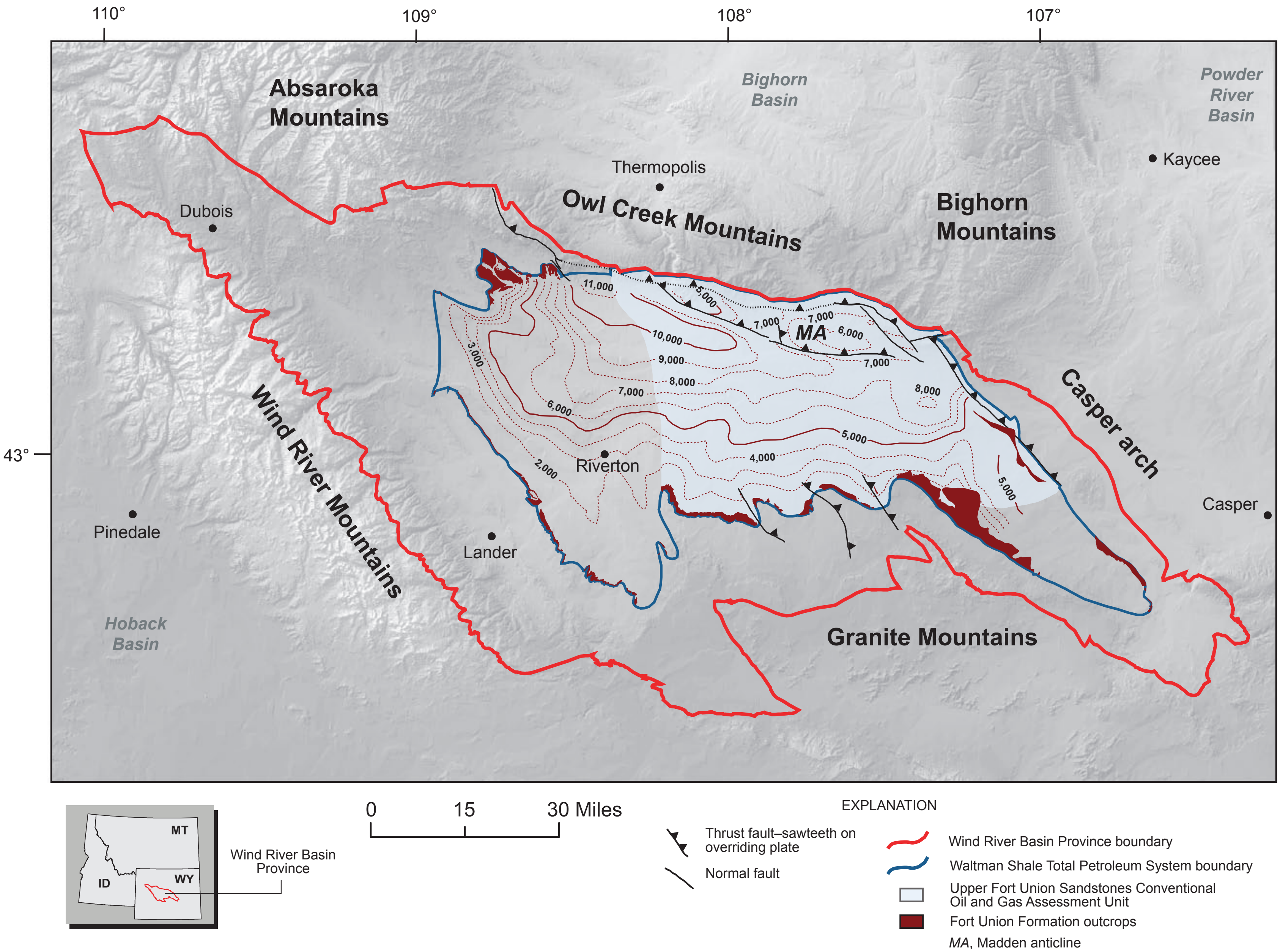

Figure 8. Estimated depth to the base of the Waltman Shale Member of the Fort Union Formation, Wind River Basin Province, Wyoming. Depth contours (in feet) based on revised structural interpretations for the base of the Waltman Shale Member (Johnson and others, 2005). Contour interval is 1,000 feet. Fort Union Formation outcrops from Green and Drouillard (1994) after Love and Christiansen (1985).

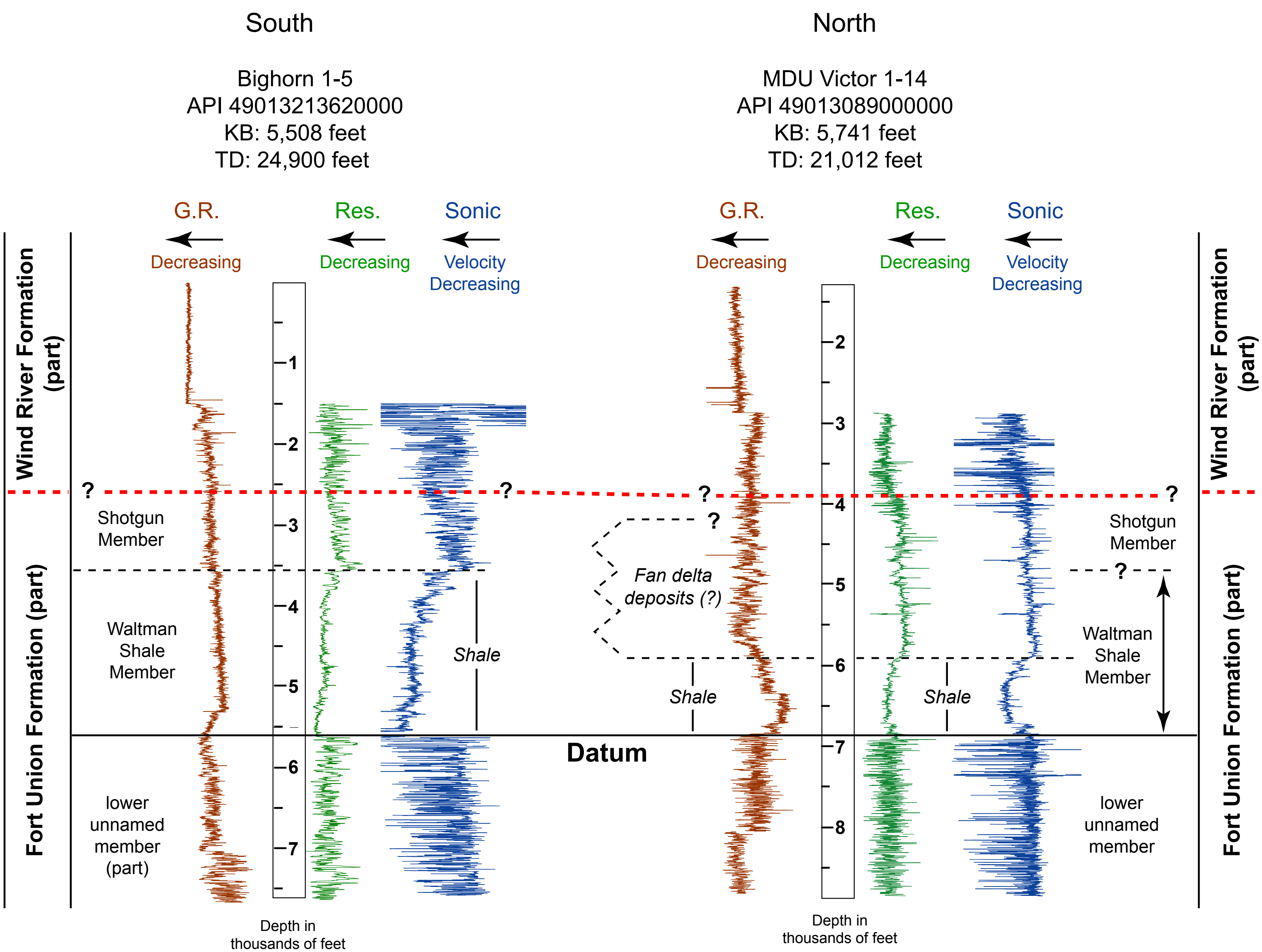

Figure 9. Subsurface interpretations of Fort Union Formation and Wind River Formation stratigraphy based on geophysical log traces from two drill holes in the northern part of the Wind River Basin Province, Wyoming; drill-hole locations are shown in figure 2. Datum is the top of the lower unnamed member of the Fort Union Formation. Contact (position queried) between the Wind River and Fort Union Formations (red-dashed line) is unconformable. G.R., gamma ray; Res., Resistivity; MDU, Madden Deep Unit.

representing a variety of depositional settings, including alluvial fans, fluvial and floodplain environments, and lake systems that developed during a time of intense folding and uplift during the latter stages of the Laramide orogeny (Keefer, 1965).

Source Rocks: Maturation and Petroleum Generation

As described previously, source rocks in the Waltman Shale TPS are the thick lacustrine shales and siltstones within the Waltman Shale Member. Katz and Liro (1993) completed a detailed study of Waltman source-rock characteristics, based on 226 samples of drill cuttings from 13 wells in the basin. Their analyses show that the total organic carbon (TOC) ranges from 0.93–6.21 weight percent, averaging 2.71 weight percent. For comparison, Hunt (1996) suggested that productive oil source rocks require a minimum TOC of 1.5 weight percent. Hydrocarbon generative potentials in 204 samples exceeded 2.5 milligrams of hydrocarbon per gram of rock (mg HC/g rock) and 132 samples had generative potentials exceeding 6.0 mg HC/g rock. The Waltman is considered an oil-prone source rock, and includes a mix of Type-II and Type-III kerogen (fig. 10), indicating organic input from a mix of algal and terrestrial plant matter, or a mix of algal and reworked or recycled material (Katz and Liro, 1993).

Thermal maturity at the base of the Waltman Shale Member ranges from a vitrinite reflectance (R_o) value of less than 0.60 percent along the south basin margin to projected values exceeding 1.10 percent in the deep basin west of the Lysite field (Johnson and others, 1996b) (fig. 11). Maturity values of 1.10 percent or greater are extrapolated from R_o measurements at stratigraphic horizons near the base of the Shotgun Member in the Dome Shoshone-Arapahoe 6-1 and Boysen Tribal 1-24 drill holes just west of the Upper Fort Union Sandstones Conventional Oil and Gas AU boundary (Nuccio and others, 1996) (fig. 11). These horizons are stratigraphically equivalent to the base of the Waltman Shale Member, and the level of thermal maturity at these horizons is interpreted to continue eastward into the deep basin area of the AU where thick shale is present. Nuccio and Finn (1994) suggested that R_o values at the base of the Waltman might not exceed 0.80 percent, even in deeper basin areas, although Johnson and others (1996b) indicate that higher thermal maturity levels have been attained (fig. 12).

Burial history reconstructions (methodology discussed in Roberts and others, Chapter 6, this CD–ROM) for three wells in the northern part of the Wind River Basin (fig. 13) indicate that the Waltman Shale Member was well within the oil window by the time of maximum burial about 15 million years ago (Ma), assuming an onset of oil generation at an R_o of 0.65 percent; maximum burial depths exceeded 10,000 ft at each of the three locations prior to uplift and cooling. The timing of oil generation calculated for the base of the Waltman

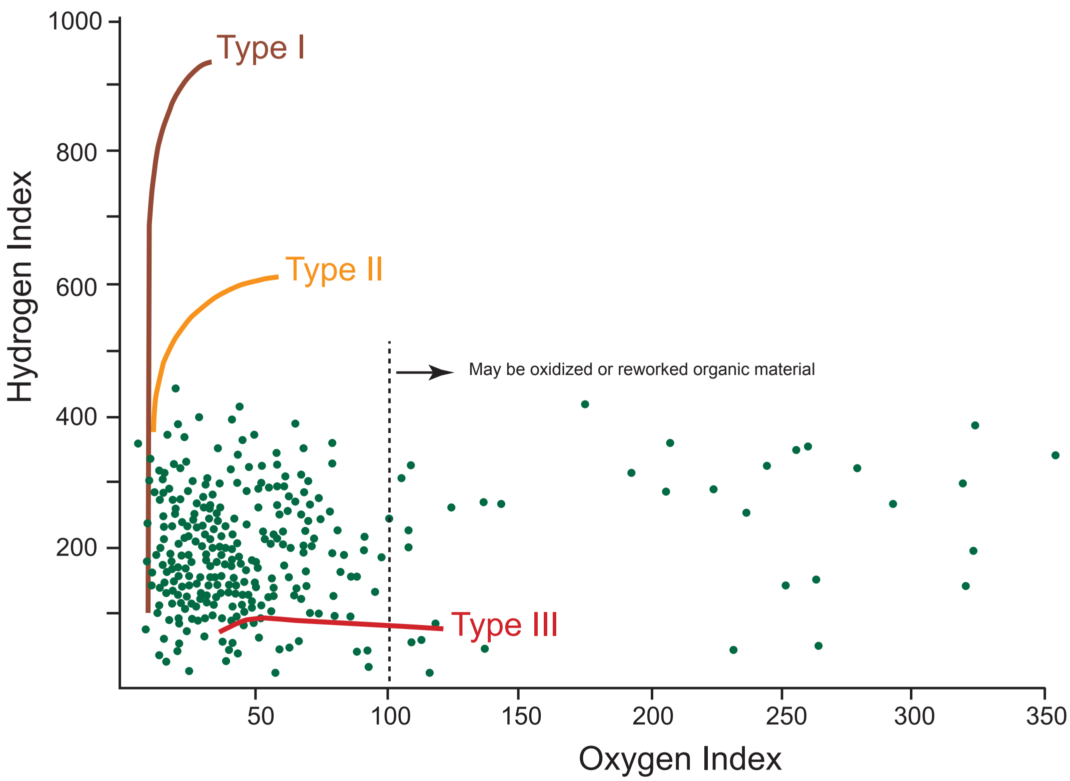

Figure 10. Modified van Krevelen diagrams based on whole rock Rock–Eval pyrolysis for drill cuttings samples from 13 oil and gas exploration wells (Katz and Liro, 1993) showing mixed kerogen types for the Waltman Shale Member of the Fort Union Formation, Wind River Basin Province, Wyoming.

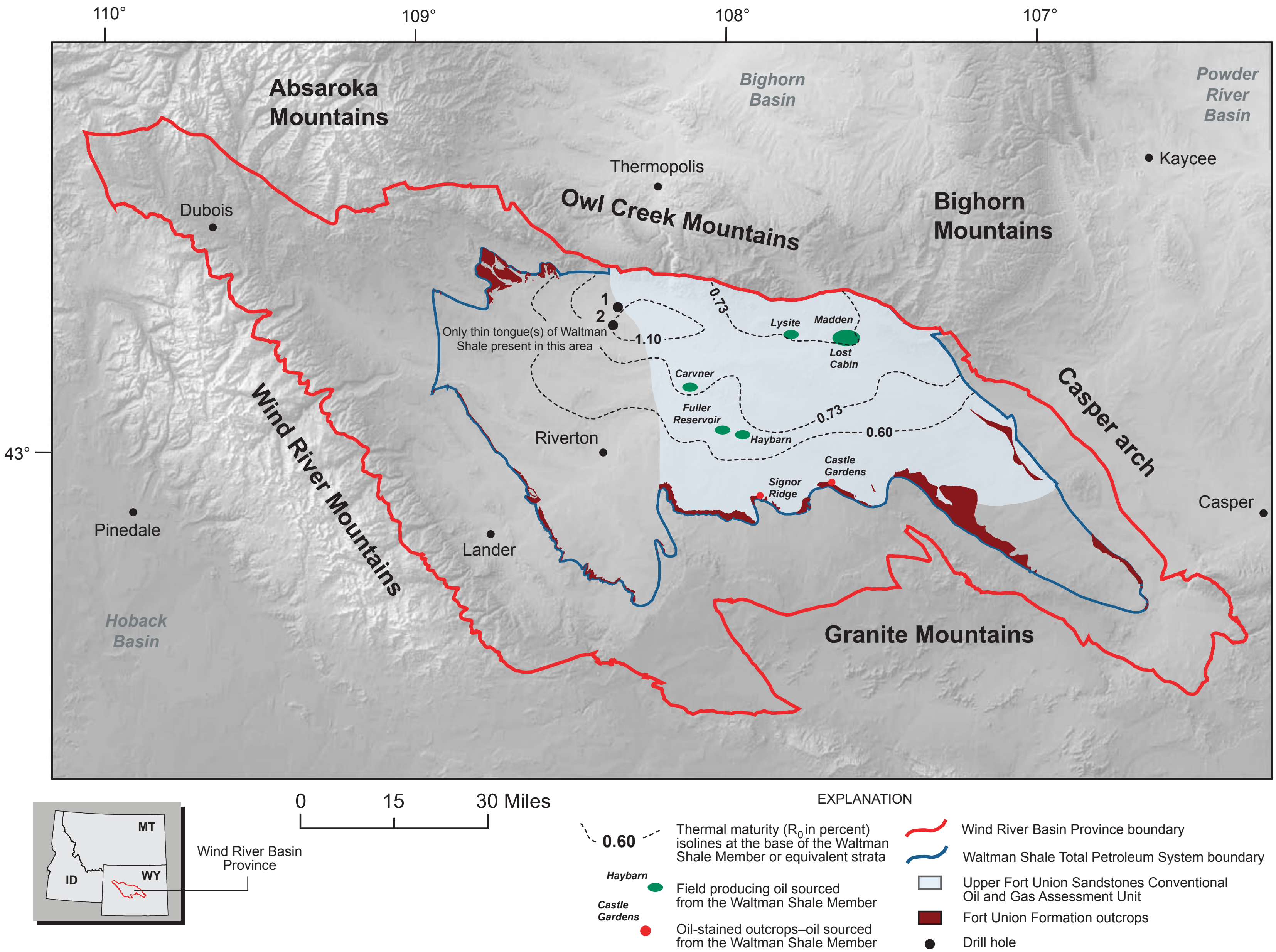

Figure 11. Estimated thermal maturity (R_0) values (in percent) at the base of the Waltman Shale Member of the Fort Union Formation, Wind River Basin Province, Wyoming. In drill holes (1) Dome Shoshone-Arapahoe 6-1 and (2) Boysen Tribal 1-24, R_0 values were estimated from strata in the Shotgun Member the Fort Union that are considered to be equivalent to the base of the Waltman Shale Member. Modified from Johnson and others (1996b). Fort Union Formation outcrops from Green and Drouillard (1994) after Love and Christiansen (1985).

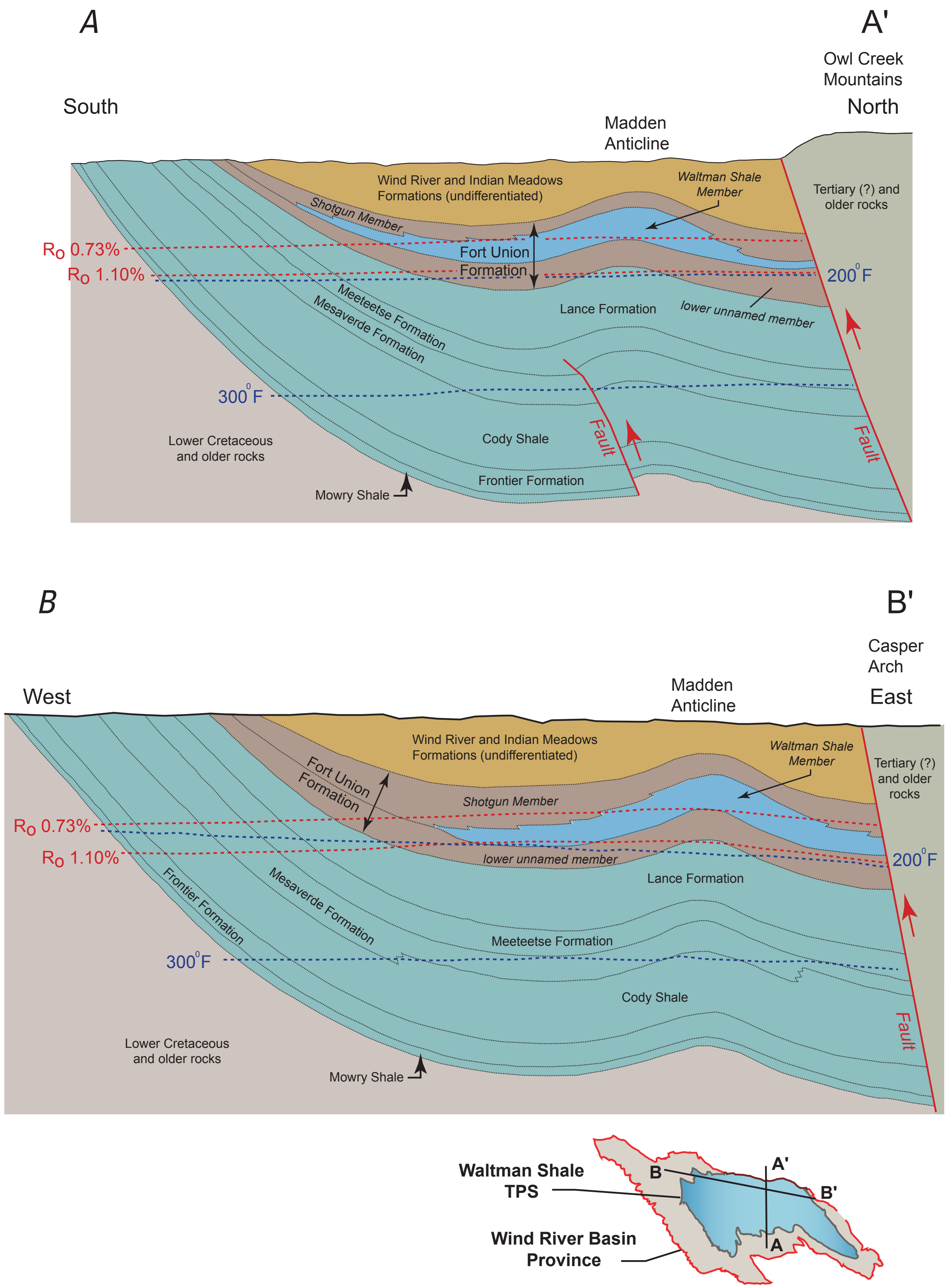

Figure 12. Schematic cross sections A–A′ and B–B′ showing Upper Cretaceous and Lower Tertiary stratigraphic units, the estimated position of the 0.73 percent and 1.10 percent vitrinite reflectance (R_O) levels, and the estimated positions of the 200° F and 300° F present-day isotherms in the Wind River Basin Province, Wyoming. Cross section locations are approximate. Modified from Johnson and others (1996b).

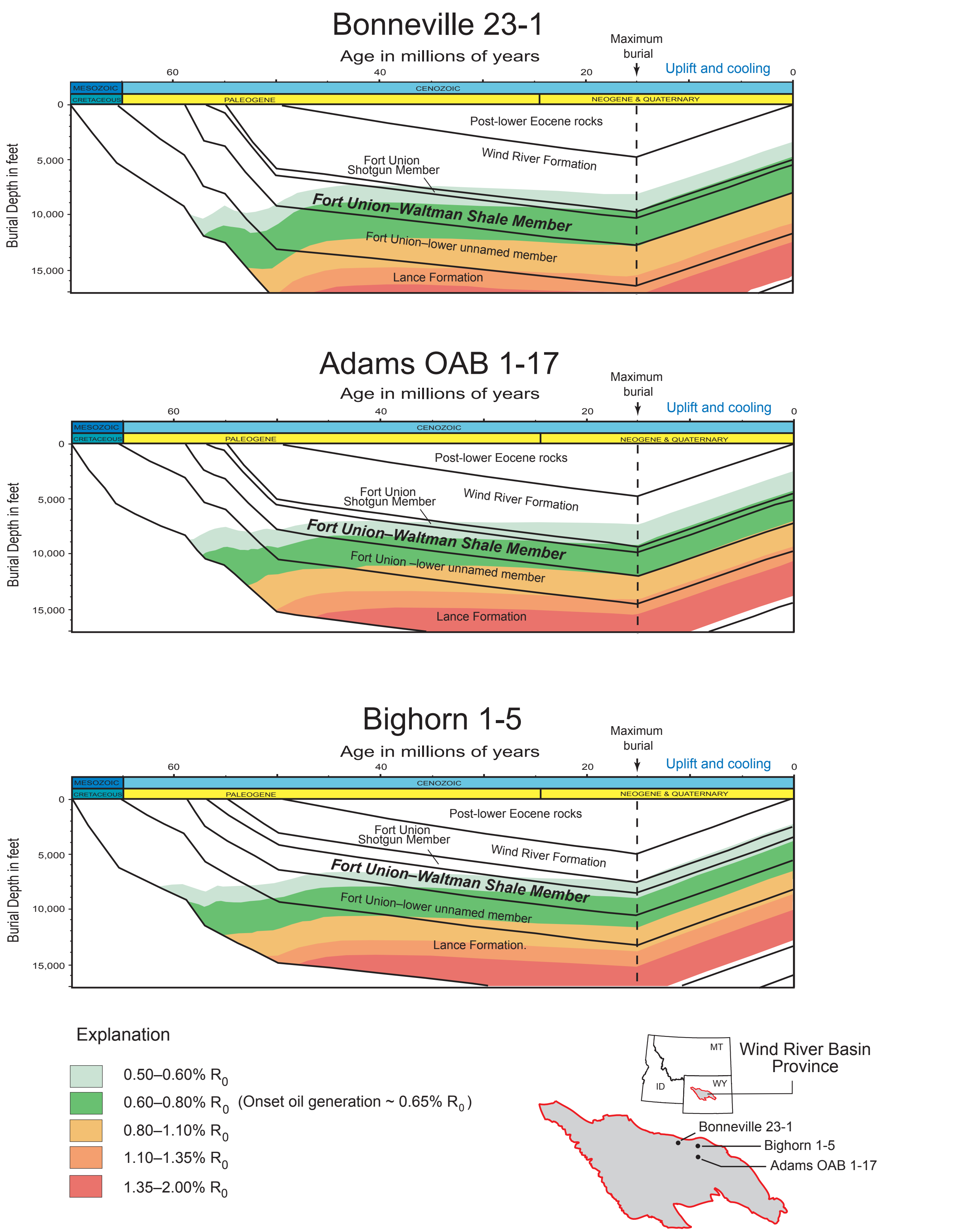

Figure 13. Burial history reconstructions and estimated vitrinite reflectance (R_0) levels for Upper Cretaceous (part) and lower Tertiary stratigraphic units estimated from three well locations in the north-central part of the Wind River Basin Province, Wyoming. Onset of oil generation from Type-II source rocks in the Waltman Shale Member of the Fort Union Formation is interpreted to be at an R_0 level of about 0.65 percent (Roberts and others, Chap. 6, this CD-ROM). Vertical dashed line at 15 million years ago represents beginning of major uplift, erosion, and subsequent cooling.

at seven well locations is shown in figure 14. Start (onset) and peak oil generation reflect transformation ratios of 0.01 and 0.50, respectively (Roberts and others, Chapter 6, this CD-ROM). This timing is based on hydrous-pyrolysis (HP) kinetic parameters derived from a Type-II, oil-prone source rock which, in the authors opinion, best represents the Waltman Shale Member. Source-rock oil-generation kinetic parameters from hydrous-pyrolysis experiments, combined with burial and thermal history, determine the timing of the generation of expelled oil where expulsion is considered a consequence of generation (Lewan, 1997). Timing of oil generation in the Dome Shoshone-Arapahoe 6-1 and Boysen Tribal 1-24 wells (fig. 11) is calculated for stratigraphic horizons in the basal part of the Shotgun Member that are equivalent to the Waltman base. Given that R_o values at these stratigraphic horizons approach 1.10 percent, HP kinetics applied with burial history in this area indicate that onset of oil generation probably occurred about 49–46 Ma, and peak oil generation might have been achieved about 31–26 Ma. At the remaining five locations, onset of oil generation from the Waltman ranged from about 39 to 20 Ma and peak generation was not achieved at any of these locations.

Hydrocarbon Migration and Accumulation

Oil generated by the Waltman Shale Member migrated laterally (up structural dip) and vertically, charging reservoirs in several fields within the Wind River Basin. Most of the fields are in or near areas where the Waltman is thermally mature for oil generation (R_o of 0.65 percent or greater; fig. 15), indicating that significant migration distances were not necessary for known accumulations. However, oil-stained outcrops sourced by the Waltman Shale Member in Fort Union Formation outcrops at Castle Gardens and Signor Ridge (Palacas and others, 1994; Keighin and Flores, 1994) (fig. 15) indicate migration distances at least on the order of 10–15 miles (mi), and may indicate distances exceeding 20 mi (Palacas and others, 1994). Fields producing Waltman-sourced oil on Madden anticline (Madden, Lost Cabin, and Lysite; fig. 11) might have been charged, at least in part, by vertical migration of oil from mature source rocks at depth, and it is likely that faults and fractures associated with the Madden structure are conduits for hydrocarbon migration in this area.

Traps in known oil accumulations in the Waltman Shale TPS are typically classified as stratigraphic or a combination of stratigraphic and structural. In Haybarn field (fig. 4), updip pinchout of deltaic sands (Shotgun Member) in lacustrine shale is considered the primary trapping mechanism (Robertson, 1984). The reservoirs are primarily fine- to medium-grained arkosic sandstone (noncalcareous) with porosities ranging from 18 to 26 percent (average 20 percent), and permeability of about 7 millidarcies (md), based on one core sample. Average pay thickness is about 13 ft and the oil column is from 0–25 ft in height (Evans, 1989). Oil produced in Haybarn Field has a high paraffin content, an API gravity of 43.7˚, a pour point near 80˚ F, and an average sulfur content of about 0.22 percent; associated gas is liquid-rich with a heating value of 1,365 BTUs and the gas to oil ratio is about 1,200 (Robertson, 1984).

In Fuller Reservoir field, traps are a combination of structural and stratigraphic; the field is located on a broad structural nose where lithofacies variations in lacustrine, marginal lacustrine (deltaic), and fluvial deposits enhance trapping potential (Ray, 1982; Specht, 1989). Sandstone and conglomerate reservoirs are present within the Fort Union (Shotgun Member) and Wind River Formations. Sandstone units are generally from 6 to 15 ft thick, with an average pay from 4 to 6 ft; porosities range from 18 to 30 percent (Ray, 1982; Specht, 1989). As in Haybarn field, the produced oil has a paraffin base, and the API gravity is about 45˚ with a pour point as high as 75˚ F (Specht, 1989).

In fields producing Waltman-sourced oil on Madden anticline (fig. 4), production also is from the Wind River and Fort Union Formations (Shotgun Member) (Wyoming Oil and Gas Conservation Commission, 2005). Traps are primarily stratigraphic, resulting from pinchout of discontinuous sandstones into surrounding shale; main producing intervals are interpreted to be deposits of an alluvial fan system that emanated from the Owl Creek Mountains (Osborn, 2001). Sandstone reservoirs in the Shotgun Member are typically fine grained, with average pay of 35 ft, log porosities ranging from 10 to 15 percent (average 13 percent), and permeability (in core) ranging from 6 to 44 md (average 19 md); produced oil has an API gravity of 36˚ (Brown and Shannon, 1989).

Assessment Units

Two assessment units were defined for the Waltman Shale TPS: (1) the Upper Fort Union Sandstones Conventional Oil and Gas AU (fig. 5), and (2) the Waltman Fractured Shale Continuous Oil AU (fig. 6), which was not quantitatively assessed.

Upper Fort Union Sandstones Conventional Oil and Gas AU (50350301)

This AU (fig. 5) includes about 1,176,000 acres, and represents the area where the Waltman Shale Member provides an effective seal preventing the migration of hydrocarbons from deeper sources below the shale into reservoirs interbedded with or overlying the shale; thus all petroleum production within the assessment unit is attributed to a Waltman source. To date, cumulative production from 53 wells within the AU exceeds 2.8 MMBO and 5.8 BCF of gas. Productive horizons in wells range from about 1,770

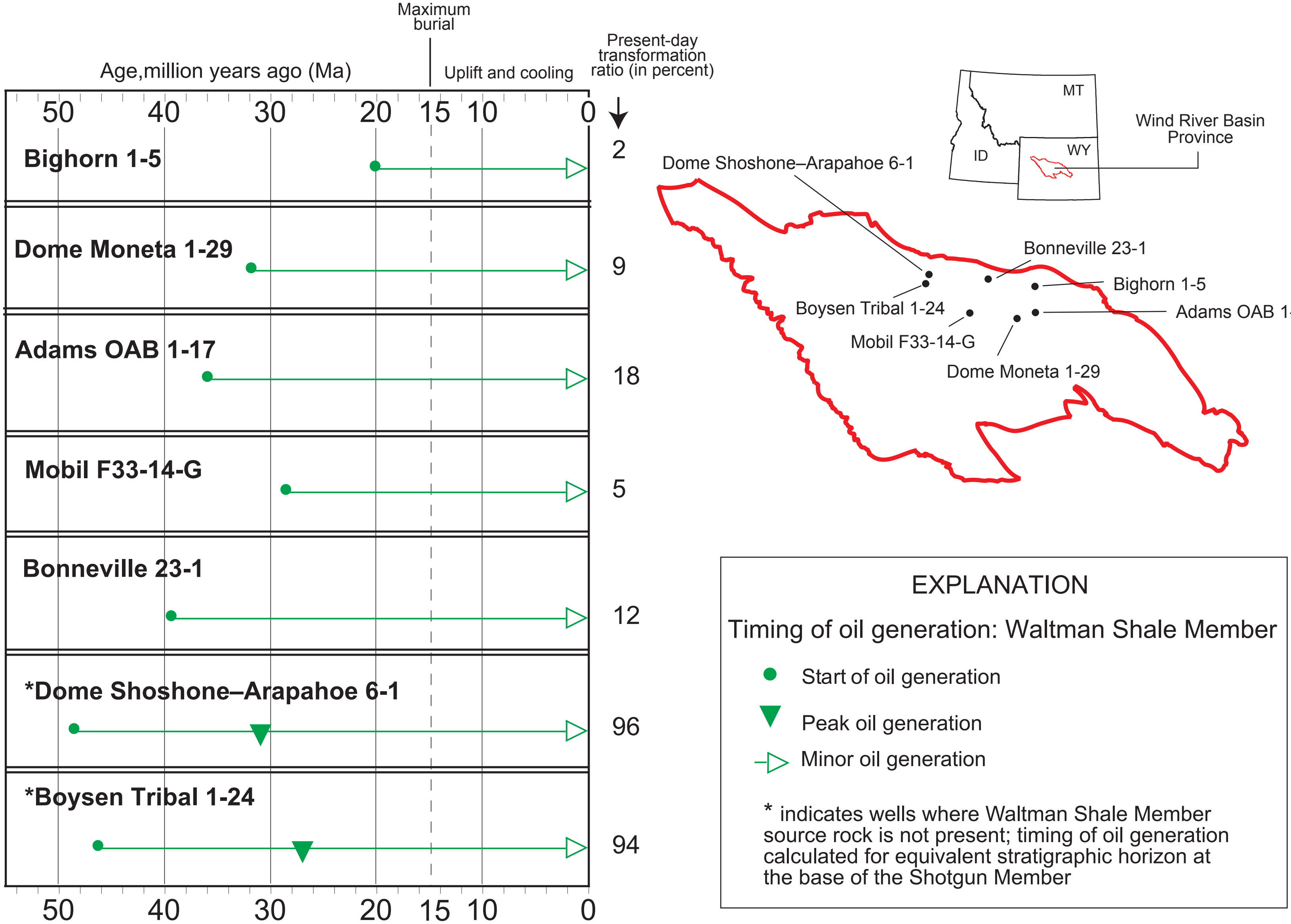

Figure 14. Timing of oil generation from source rocks at the base of the Waltman Shale Member of the Fort Union Formation in seven well locations in the Wind River Basin Province, Wyoming. Timing is based on hydrous-pyrolysis (HP) kinetic parameters derived from a Type-II, oil-prone source rock. Vertical dashed line at 15 million years ago represents beginning of major uplift, erosion, and subsequent cooling. The models indicate that oil generation is continuing; however, the rate of these reactions is significantly reduced with negligible generation during the last 15 million years. Start (onset) and peak oil generation reflect transformation ratios of 0.01 and 0.50, respectively (Roberts and others, Chap. 6, this CD-ROM).

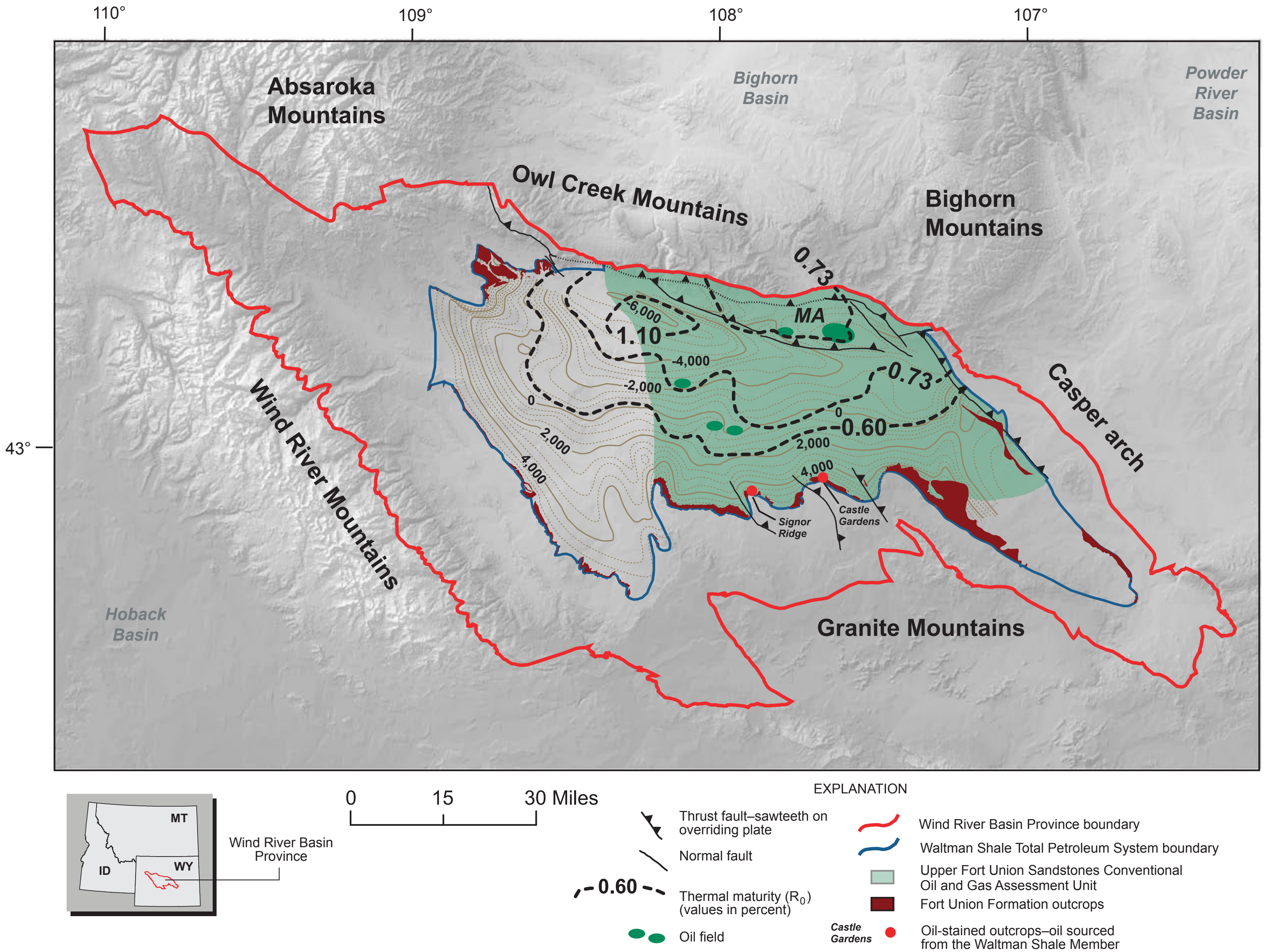

Figure 15. Structure contours and estimated thermal maturity (R_0) values (in percent) at the base of the Waltman Shale Member of the Fort Union Formation, Wind River Basin Province, Wyoming. Structure contours modified from Johnson and others (1996a) and based on new interpretations of Johnson and others (2005); structure contour interval is 500 ft and contour values in elevation relative to mean sea level. Thermal maturity contours modified from Johnson and others (1996b). MA, Madden anticline. Fort Union Formation outcrops from Green and Drouillard (1994) after Love and Christiansen (1985).

ft to 5,800 ft, and average about 3,400 to 3,500 ft in depth (Wyoming Oil and Gas Conservation Commission, 2005).

Input data used in the assessment of undiscovered resources within the AU are shown in appendix A. Geologic information that factored into estimates of the numbers and sizes of undiscovered accumulations included the location and distribution of mature source rocks, the potential for pathways of migration (updip and vertical migration) from mature source rocks into porous sandstone reservoirs, the location of structures (folds or faulted areas) that might entrap hydrocarbons, and trapping potential related to facies variations in vertically and laterally juxtaposed fluvial, marginal lacustrine, and lacustrine strata.

Based on structural trends at the base of the Waltman Shale Member (fig. 7) there seems to be a strong potential for numerous migration pathways throughout the AU that could facilitate the movement of petroleum from the deep basin into reservoirs adjacent to and updip from mature Waltman source rocks (fig. 16). This updip migration was probably the primary means for charging the more productive fields (Fuller Reservoir and Haybarn fields). In fields on Madden anticline (Lost Cabin, Lysite, and Madden fields) vertical fractures or faults may have provided conduits for petroleum migration from mature source rocks underlying productive reservoirs; high angle normal faults have been documented in seismic data near producing areas (for example, Osborn, 2001).

A diagram depicting petroleum migration and accumulation scenarios in the area of Madden anticline is shown in figure 17. Potential reservoirs might be present in (1) marginal lacustrine (shoreface) sandstone units that prograded northward and eastward into lacustrine shale, (2) fluvial sandstones overlying the shoreface sandstones, (3) sandstones or conglomerates within a fan-delta system emanating from the Owl Creek uplift north of Madden, and (4) sandstones deposited within braided fluvial and braidplain environments in the Shotgun Member overlying the Waltman Shale Member along the axis of the Madden structure (Osborn, 2001). Traps might form due to updip pinchout of shoreface and fan-delta sandstone bodies into impermeable lacustrine shale, pinchout of discontinuous fluvial sandstone bodies in fine-grained floodplain deposits, and fault juxtaposition of porous sandstones with impermeable lacustrine or floodplain (braidplain) shale.

An additional potential for petroleum accumulation may exist within progradational successions that can be identified by the presence of clinoform morphologies (foresets or downlap surfaces; fig. 18) in seismic lines throughout much of the basin (fig. 19). In previous seismic studies of the Fort Union Formation, Ray (1982) and Liro and Pardus (1990) identified numerous clinoform packages within the Shotgun Member and concluded that well-developed or continuous reflectors within clinoforms represented the progradation of a delta. Ray (1982) also recognized low relief clinoforms in the transition zone from shoreface deposits to lacustrine shale and interpreted these as accretionary profiles on the shoreline of the lake; Ray indicated that potential traps for hydrocarbons might be present in zones of depositional onlap or erosional truncation within the progradational successions. A comparison of clinoform morphology in the Shotgun Member with chronostratigraphic models for hydrocarbon accumulation in the Sirikit oil field in Thailand (fig. 18) also might provide some insight into the potential for petroleum accumulation. In the Sirikit oil field, more than 100 MMBO have been produced from reservoirs within the fluvial and lacustrine Lan Krabu Formation (Ainsworth and others, 1999). The best reservoirs are within deposits of fluvio-lacustrine mouth-bar complexes that lie up-depositional dip from lacustrine shale. Down-depositional dip, reservoir quality decreases with the increase in thin-bedded heterolithic strata in transitional zones adjacent to lacustrine shale (Ainsworth and others, 1999). Although described fluvio-lacustrine sequences in the Sirikit oil field are much smaller in scale than clinoform morphologies in the Shotgun Member (fig. 18), the proven productivity of these depositional sequences in Sirikit might be an indication of the potential for petroleum accumulation in similar depositional sequences recognized in seismic in the Shotgun Member (figs. 18 and 19). In addition, future exploration might target higher (updip) positions on the foreset slopes in anticipation of better quality reservoirs.

Figure 20 summarizes the geologic units and timing of major geologic events related to petroleum generation, migration, and accumulation in the Upper Fort Union Sandstones Conventional Oil and Gas AU. The range in estimates for the number of undiscovered accumulations within the AU (appendix A) is based in large part on the considerations discussed previously (for example, potential for undiscovered accumulations in progradational successions and clinoform features) as well as the fact that the AU is largely untested. The minimum and mode estimates are somewhat conservative (1 and 3 undiscovered accumulations, respectively) and based primarily on the limited discoveries to date, but tempered somewhat at the mode with consideration for the largely untested nature of the AU. The maximum estimate of 15 undiscovered accumulations was influenced by the strong potential for migration pathways from mature source rocks in the central basin areas (fig. 16), and the presence of abundant progradational successions (clinoform morphologies) that have similar characteristics to the highly productive Sirikit oil field in Thailand (fig. 18) and are widely distributed throughout much of the basin (fig. 19).

The sizes (grown) of the undiscovered accumulations (appendix A) also reflects a high degree of uncertainty, in large part because there are not enough fields in the AU exceeding the USGS minimum (500,000 barrels of oil) to calculate a field size (grown) distribution based on past production. Only the Fuller Reservoir field has exceeded the USGS minimum size. Estimated ultimate recoveries (EURs) calculated for oil wells in the AU (fig. 21) indicate that the median oil production ranges from 20,000 barrels of oil per well (Madden and Haybarn fields) to a high of 70,000 barrels of oil per well (Fuller Reservoir field). Future discoveries might require a 10 to 20 well field in order to produce 500,000 barrels, based

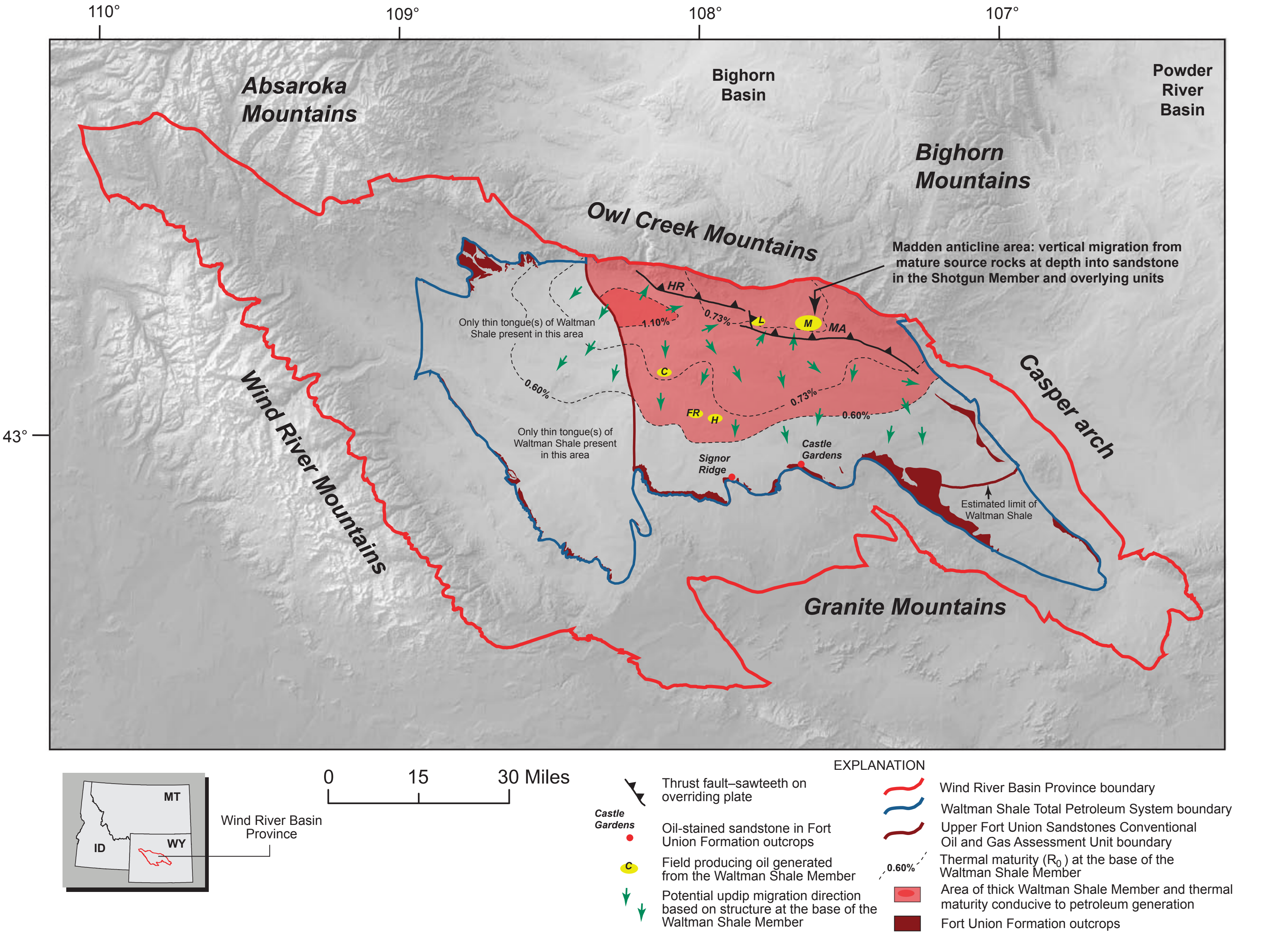

Figure 16. Interpreted orientations of petroleum migration pathways from mature source rocks in the Waltman Shale Member of the Fort Union Formation, Waltman Shale Total Petroleum System, Wind River Basin Province, Wyoming. MA, Madden anticline. Oil fields: C, Carvner field; L, Lysite field; M, Madden field (including Lost Cabin field); FR, Fuller Reservoir field; and H, Haybarn field. AU, assessment unit. Fort Union Formation outcrops from Green and Drouillard (1994) after Love and Christiansen (1985).

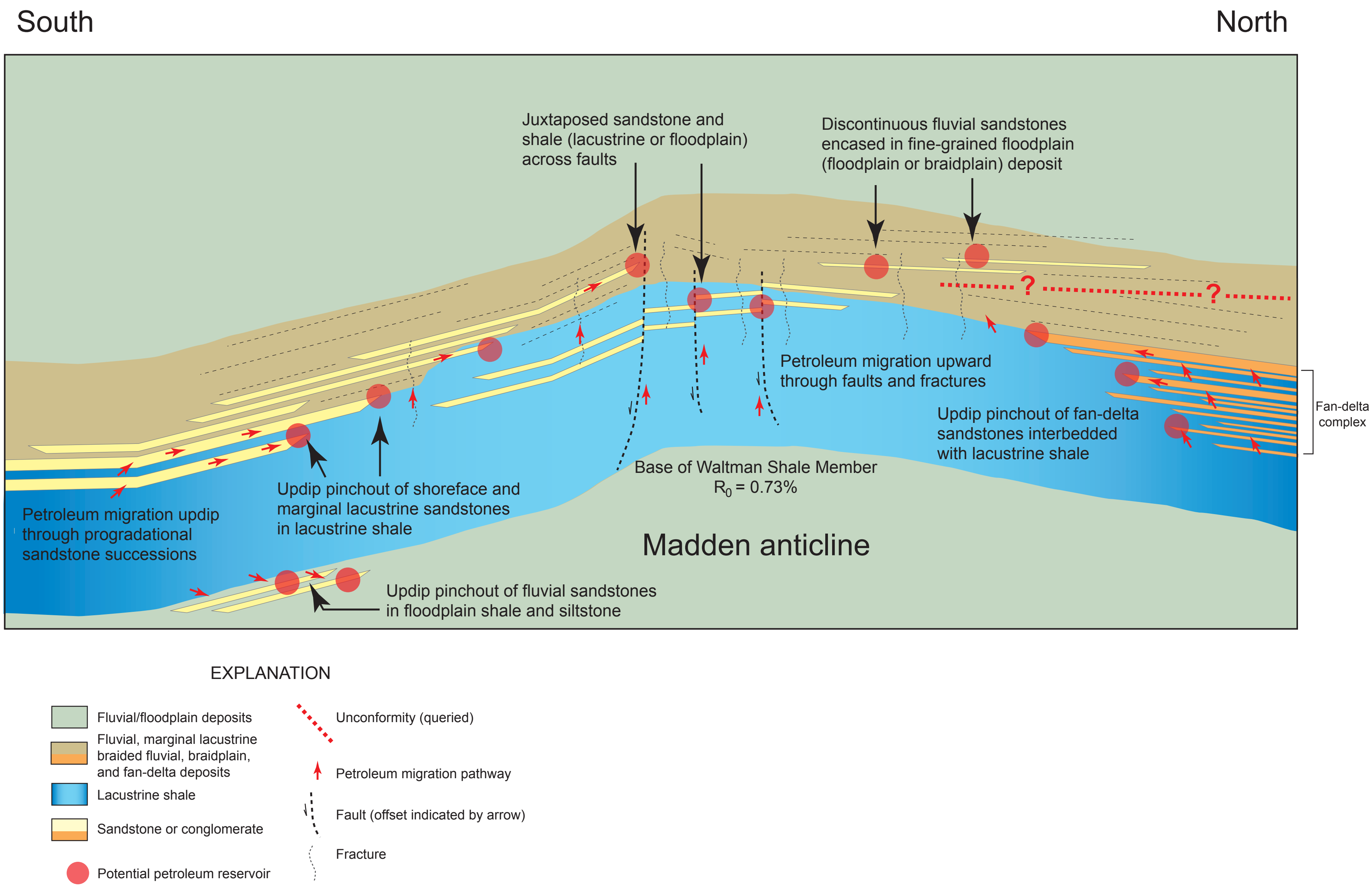

Figure 17. Schematic diagram showing proposed scenarios for petroleum migration and accumulation near Madden anticline in the Upper Fort Union Sandstones Conventional Oil and Gas Assessment Unit, Waltman Shale Total Petroleum System, Wind River Basin Province, Wyoming. Diagram is not to scale. R_0, thermal maturity based on vitrinite reflectance.

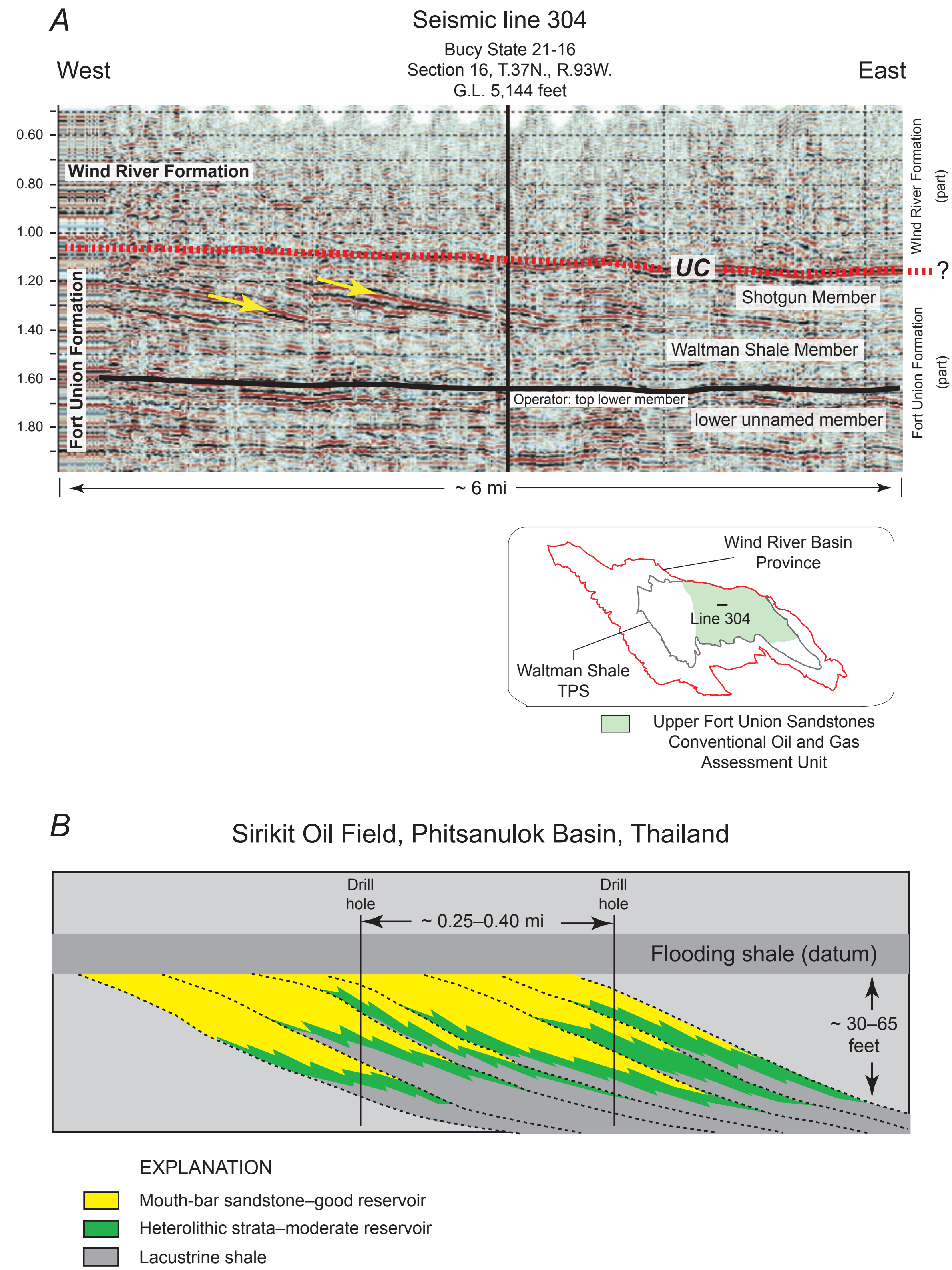

Figure 18. Examples of clinoform morphologies in lacustrine depositional sequences. A, seismic line 304 within the Fort Union Formation (Shotgun and Waltman Shale Members) in the Wind River Basin Province, Wyoming. B, Sirikit oil field, Phitsanulok Basin, Thailand. Interpretations (in part) shown in seismic line 304 are based on Ray (1982); stratigraphic position of the unconformity (UC) separating the Fort Union and Wind River Formations (red dashed line) is questionable; Sirikit oil field example is modified from Ainsworth and others (1999). G.L., ground level; TPS, total petroleum system.

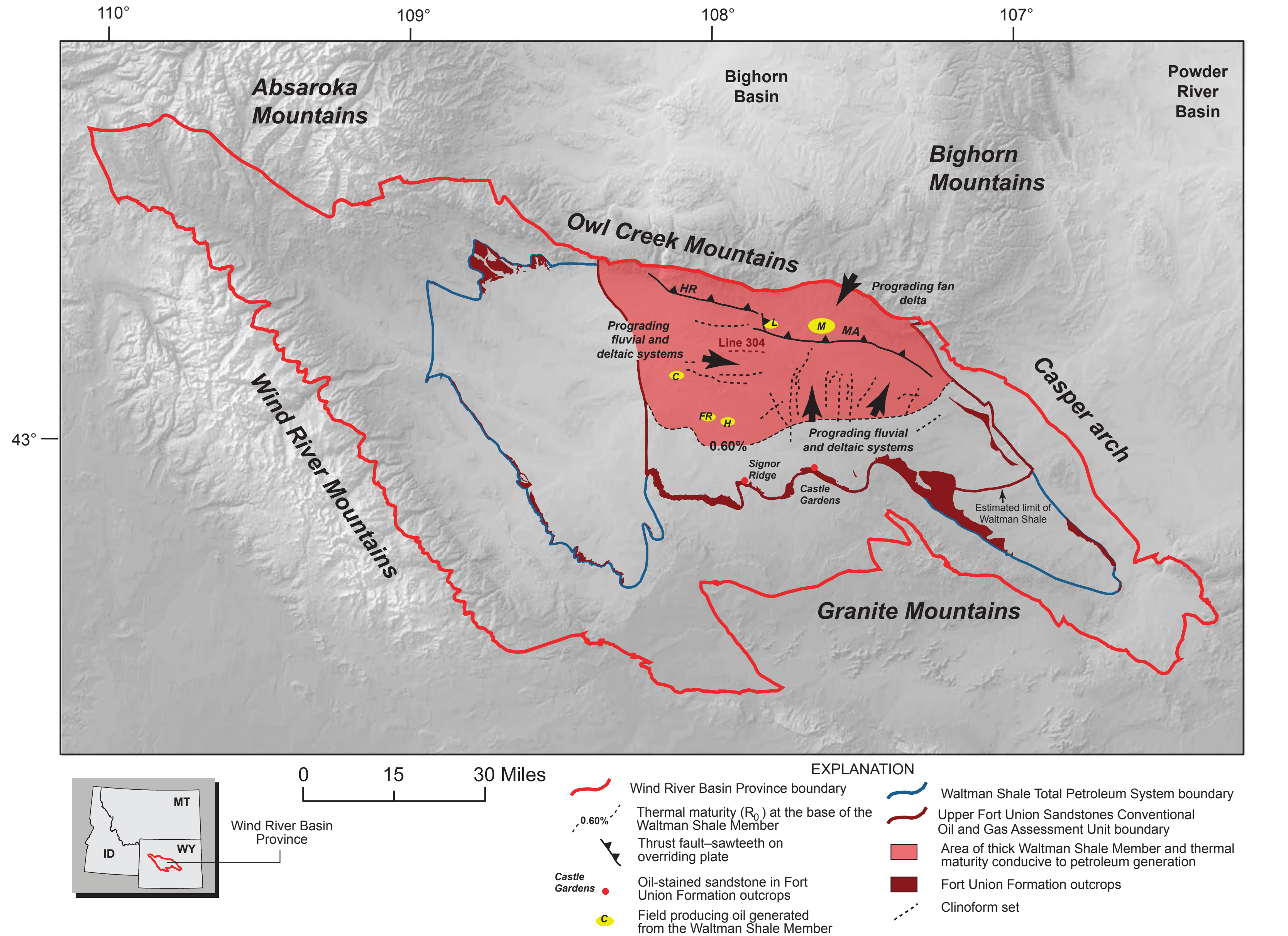

Figure 19. Locations of clinoform morphologies expressed in seismic lines in the Wind River Basin Province, Wyoming. Bold arrows indicate generalized directions of progradation based on apparent dip orientations of foresets in seismic lines or, in the case of the fan-delta system, the arrow orientation is based on correlations of geophysical logs from oil and gas wells. MA, Madden anticline. Oil fields: M, Madden field (including Lost Cabin field; L, Lysite field; C, Carvner field; FR, Fuller Reservoir field; and H, Haybarn field.

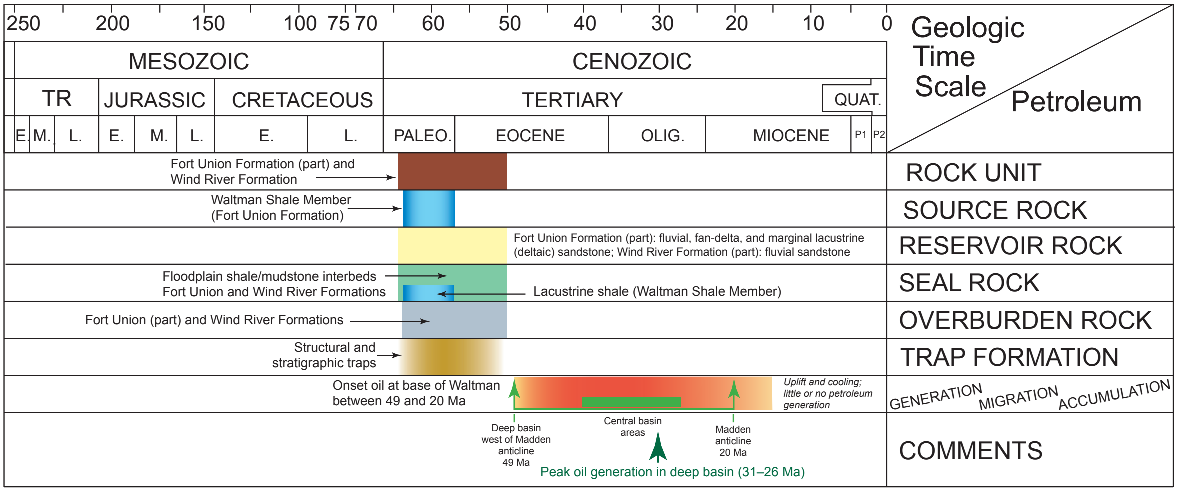

Figure 20. Events chart showing interpreted timing of elements and processes related to hydrocarbon (oil) generation and accumulation in the Upper Fort Union Sandstones Conventional Oil and Gas Assessment Unit (50350301), Waltman Shale Total Petroleum System, Wind River Basin Province, Wyoming. Onset of oil generation and timing of peak oil generation are from Roberts and others (Chap. 6, this CD–ROM). Peak generation refers to maximum rate of oil generation (transformation ratio 0.50). TR., Triassic; E., Early; M., Middle; L., Late; Paleo., Paleocene; Olig., Oligocene; P1, Pliocene; P2, Pleistocene; Quat., Quaternary. Events chart format modified from Magoon and Dow (1994).

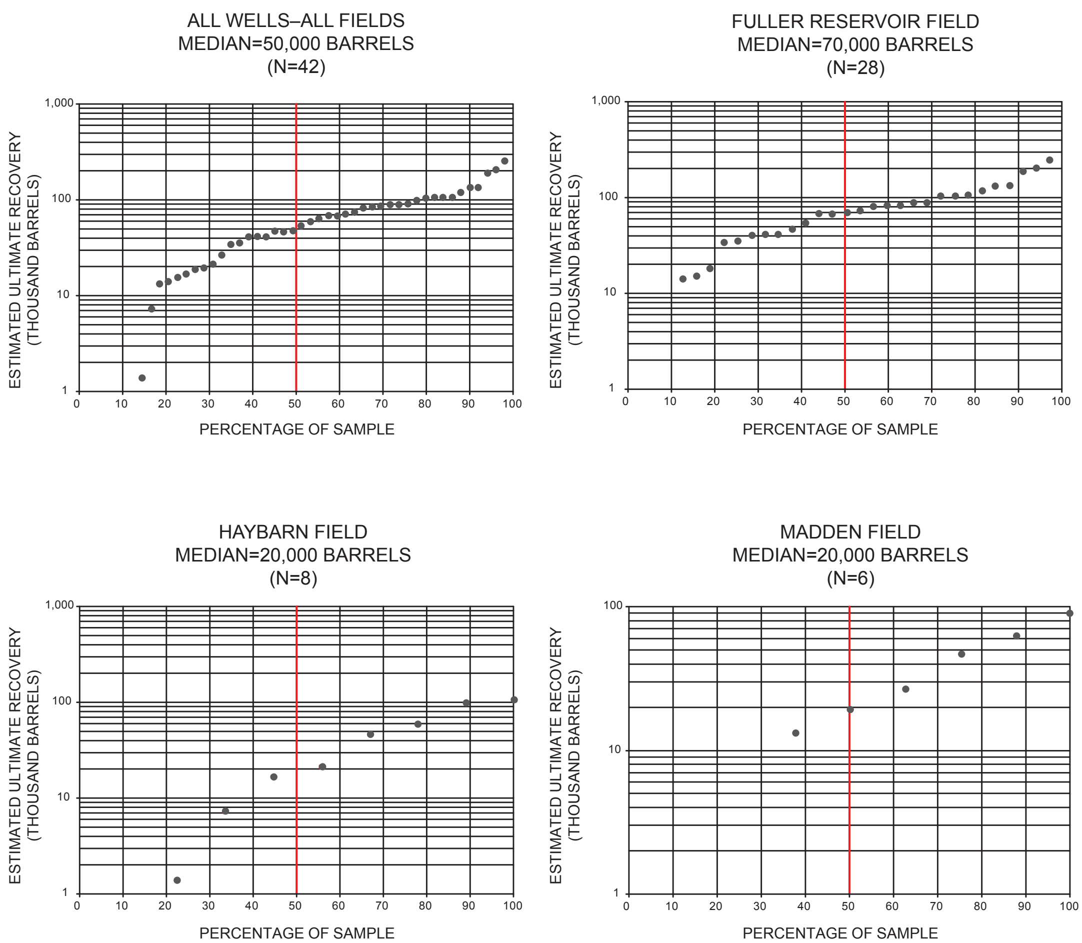

Figure 21. Estimated ultimate recoveries calculated for wells producing oil sourced by the Waltman Shale Member in the Upper Fort Union Sandstones Conventional Oil and Gas Assessment Unit, Waltman Shale Total Petroleum System, Wind River Basin Province, Wyoming. Madden field includes data from Madden, Lost Cabin, and Lysite fields. Graphs are based on production data from IHS Energy Group (2005).

on current EURs. The minimum and median estimates for sizes (grown) of undiscovered accumulations were strongly influenced by the limited cumulative production from known fields. The maximum estimate of 15 MMBO far exceeds the size of the largest field discovered to date (Fuller Reservoir field; ~ 2.3 MMBO). However, this maximum is significantly smaller than the analog Sirikit oil field (Thailand), which has produced more than 100 MMBO.

Waltman Fractured Shale Continuous Oil AU (50350361)

The Waltman Fractured Shale Continuous Oil AU (fig. 6) encompasses about 745,000 acres, and includes areas within the Upper Fort Union Sandstones Conventional Oil and Gas AU where thermal maturity at the base of the Waltman Shale Member is at an R_o level of 0.60 percent or greater. This assessment unit was defined based on interpretations in Jorjorian and others (1989) and Katz and Liro (1993) who described the potential for hydrocarbon (oil) saturation and entrapment within the Waltman member in areas near Madden anticline. Jorjorian and others (1989) recognized decreasing sonic velocities in the shale relative to overlying and underlying units (fig. 9) and suggested that this sonic anomaly resulted from overpressure due to generation of oil and an inability for the oil to be expelled from the shale because of the lack of porous conduits for hydrocarbon migration. In following this concept, the authors defined the assessment unit to include those areas within the Upper Fort Union Sandstones Conventional Oil and Gas AU in which thermal maturity at the base of the Waltman Shale is mostly within the oil generation window (R_o of 0.65 percent or greater). However, because of limited thermal maturity data, the south boundary of the AU was extended to the 0.60 percent isoreflectance (R_o) line as defined by Johnson and others (1996b) (fig. 6). This AU was not quantitatively assessed because current data are insufficient for proving or disproving the presence of petroleum trapped in the manner described above. However, similar sonic velocity decreases were observed in essentially all wells investigated in this study that penetrated the shale in the Waltman Fractured Shale Continuous Oil AU, indicating that overpressuring conditions may involve a significantly larger area than previously thought. On the other hand, the anomaly might be due to some other phenomenon, such as the velocity decrease being in response to the organic richness of the shale (Passey and others, 1990); however, this possibility was not investigated as part of this study.

Assessment of Undiscovered Resources–Summary of Results

Results of the assessment of undiscovered, technically recoverable resources in the Upper Fort Union Sandstones Conventional Oil and Gas AU (50350301) are shown in table 1. Mean estimates of the total undiscovered petroleum resources AU indicate the potential for 12 MMBO, 24 BCF of gas, and 1.4 million barrels of natural gas liquids.

Numerous positive aspects of the Waltman Shale TPS favor the presence of undiscovered resources in conventional accumulations. The Waltman Shale Member is a good source rock with TOCs as high as 6.2 percent and averaging about 2.7 percent (Katz and Liro, 1993). Thermal maturity values at the base of the shale are well within the oil window (equal to or greater than 0.65 percent) and may exceed 1.10 percent R_o in untested, deep basin areas (Johnson and others, 1996b). The petroleum system has a history of production from marginal lacustrine (deltaic) and fluvial sandstone reservoirs, and numerous progradational successions within the Shotgun Member place porous sandstone in contact with lacustrine shale source rocks; well-developed clinoforms within these successions might provide conduits for oil migration up depositional dip into sandstone reservoirs. In addition, there

Table 1. Waltman Shale Total Petroleum System assessment results.

[MMBO, million barrels of oil; BCFG, billion cubic feet of gas; MBNGL, thousand barrels of natural gas liquids. Results shown are fully risked estimates. For gas fields, all liquids are included under the NGL (natural gas liquids) category. F95 represents a 95-percent chance of at least the amount tabulated. Other fractiles are defined similarly. Fractiles are additive under the assumption of perfect positive correlation. Gray shade indicates not applicable]

Total Petroleum Systems (TPS) and Assessment Units (AU)	Field type	Total undiscovered resources: Oil (MMBO)				Gas (BCFG)				NGL (MBNGL)			
		F95	F50	F5	Mean	F95	F50	F5	Mean	F95	F50	F5	Mean
Waltman ShaleTPS													
Upper Fort Union Sandstones Conventional Oil and Gas AU 50350301	***Oil***	3	11	25	12	6	21	54	24	330	1,250	3,370	1,470
	Gas					0	0	0	0	0	0	0	0
Waltman Fractured Shale Continuous Oil AU 50350361	***Oil***	Not quantitatively assessed											
Total Undiscovered Oil and Gas Resources		**3**	**11**	**25**	**12**	**6**	**21**	**54**	**24**	**330**	**1,250**	**3,370**	**1,470**

also are large areas in the basin, particularly in the deep basin, where the Shotgun Member might not have been adequately tested.

However, not all characteristics of the TPS are necessarily positive for undiscovered petroleum accumulations. Transformation ratios based on hydrous pyrolysis kinetics of a Type-II kerogen calculated at several locations throughout the basin are generally less than 20 percent; peak generation (transformation ratio of 0.50) may only have occurred in the deep basin west of Madden anticline. These data indicate that the Waltman Shale Member as a source rock may not have reached its full potential for hydrocarbon generation and expulsion in much of the basin. Additionally, although progradational successions in areas south and west of mature Waltman source rocks might provide effective conduits for petroleum migration, oil-stained outcrops at Castle Gardens and Signor Ridge (Palacas and others (1994) also might signal the potential for leakage of hydrocarbons out of the system. This leakage could be due to factors such as the lack of adequate seal or trap development, or oil generation and expulsion that preceded trap formation. In addition, in the past 20–30 years, only one field (Fuller Reservoir) has produced enough oil to exceed the USGS minimum field size of 500,000 barrels.

In summary, data indicate that the Waltman Shale TPS does have the potential for undiscovered oil accumulations exceeding 500,000 barrels, although fields might tend to be small or moderate in size. Future exploration might target deeper horizons where thermal maturity of the Waltman Shale Member exceeds 0.70 percent, and progradational successions (clinoform packages) in close contact with lacustrine shale provide conduits for migration into marginal lacustrine, deltaic, and fluvial reservoir sandstones.

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References Cited

Ainsworth, R. Bruce, Sanlung, Montree, and Duivenvoorden, S. Theo C., 1999, Correlation techniques, perforation strategies, and recovery factors—An integrated 3-D reservoir modeling study, Sirikit Field, Thailand: American Association of Petroleum Geologists Bulletin, v. 83, no. 10, p. 1535–1551.

Blackstone, Jr., D.L., 1990, Rocky Mountain foreland structure exemplified by the Owl Creek Mountains, Bridger Range, and Casper arch, central Wyoming, *in* Specht, R.W., ed., Wyoming Sedimentation and Tectonics: Wyoming Geological Association Guidebook, 41st Field Conference, p. 151–166, 2 pls.

Brown, R.G., and Shannon, L.T., 1989, Madden (Greater)–Long Butte, *in* Cardinal, D.F., Miller, Terry, Trotter, J.F., and Stewart, W.W., eds., Wyoming Oil and Gas Fields Symposium—Bighorn and Wind River Basins: Casper, Wyoming, Wyoming Geological Association, p. 293–295.

Dunleavy, J.M., and Gilbertson, R.L., 1986, Madden anticline—Growing giant, *in* Noll, J.H., and Doyle, K.M., eds., Rocky Mountain oil and gas fields: Wyoming Geological Asociation, 1986 Symposium, Casper, Wyoming, p. 107-157.

Evans, J.G., 1989, Haybarn, *in* Cardinal, D.F., Miller, Terry, Trotter, J.F., and Stewart, W.W., eds., Wyoming Oil and Gas Fields Symposium—Bighorn and Wind River Basins: Casper, Wyoming, Wyoming Geological Association, p. 228–229.

Flemings, P.B., and Nelson, S.N., 1991, Paleogeographic evolution of latest Cretaceous and Paleocene Wind River Basin: The Mountain Geologist, Volume 28, No. 2/3, p. 37–52.

Flores, R.M., Roberts, S.B., and Perry, W.J., Jr., 1994, Paleocene paleogeography of the Wind River, Bighorn, and Powder River Basins, Wyoming, *in* Flores, R.M., Mehring, K.T., Jones, R.W., and Beck, T.L., eds., Organics and the Rockies Field Guide: Wyoming State Geological Survey, Public Information Circular No. 53, p. 1–16.

Green, G.N., and Drouillard, P.H., 1994, The digital geologic map of Wyoming in ARC/INFO format: U.S. Geological Survey Open-File Report 94–0425, scale 1:500,000.

Gries, Robbie, 1983, North-south compression of Rocky Mountain foreland structures, *in* Lowell, J.D., and Gries, Robbie, eds., Rocky Mountain foreland basins and uplifts: Rocky Mountain Association of Geologists Guidebook, October 3, 1983, Symposium, Steamboat Springs, Colorado, p. 9–32.

Hollis, S.H., 2001, Upper Fort Union (Paleocene) deposition on the north flank of Madden anticline, Wind River Basin, Wyoming, *in* Stilwell, D.P., ed., Wyoming gas resources and technology: Wyoming Geological Association Guidebook, 52nd Field Conference, p. 194.

Hunt, J.M., 1996, Petroleum geochemistry and geology (2nd edition): W.H. Freeman and Company, New York, New York, United States, 743 p.

IHS Energy Group, 2005, [includes data current as of December, 2000] PI/Dwights Plus U.S. Production Data: Englewood, Colo., database available from IHS Energy Group, 15 Inverness Way East, D205, Englewood, Colorado 80112, U.S.A.

Johnson, R.C., and Rice, D.D., 1993, Variations in composition and origins of gases from coal bed and conventional reservoirs, Wind River Basin, Wyoming, *in* Keefer, W.R., Metzger, W.J., and Godwin, L.H., eds., Wyoming Geological Association Special Symposium on Oil and Gas and Other Resources of the Wind River Basin, Wyoming, 1993: Wyoming Geological Association, Casper, Wyoming, p. 319–335.

Johnson, R.C., Finn, T.M., Keefer, W.R., and Szmajter, R.J., 1996a, Geology of Upper Cretaceous and Paleocene gas-bearing rocks, Wind River Basin, Wyoming: U.S. Geological Survey Open-File Report 96-090, 120 p.

Johnson, R.C., Finn, T.M., Crovelli, R.A., and Balay, R.H., 1996b, An assessment of in-place gas resources in low-permeability Upper Cretaceous and Lower Tertiary sandstone reservoirs, Wind River Basin, Wyoming: U.S. Geological Survey Open-File Report 96-264, 204 p.

Johnson, R.C., Roberts, S.B., and Nichols, D.J., 2005, New stratigraphic and palynologic studies of the Paleocene Waltman Shale Member, Wind River Basin, Wyoming—Implications for basin depositional environments [abs.]: American Association of Petroleum Geologists, Rocky Mountain Section Jackson Hole Meeting, Jackson, Wyoming, Abstracts with Programs, p. 34.

Jorjorian, Thomas, Liro, L.M., and Katz, B.J., 1989, Geochemical and well-log investigation of an actively generating source rock sequence—Waltman Shale, Wind River Basin, Wyoming [abs.]: American Association of Petroleum Geologists Bulletin, v. 73, no. 9, p. 1162.

Katz, B.J., and Liro, L.M., 1993, The Waltman Shale Member, Fort Union Formation, Wind River Basin—A Paleocene clastic lacustrine source system, *in* Keefer, W.R., Metzger, W.J., and Godwin, L.H., eds., Wyoming Geological Association Special Symposium on Oil and Gas and Other Rresources of the Wind River Basin, Wyoming, 1993: Wyoming Geological Association, Casper, Wyoming, p. 163–174.

Keefer, W.R., 1961, Waltman Shale and Shotgun Members of Fort Union Formation (Paleocene) in Wind River Basin, Wyoming: American Association of Petroleum Geologists Bulletin, v. 45, no. 8, p. 1310–1323.

Keefer, W.R., 1965, Stratigraphy and geologic history of the uppermost Cretaceous, Paleocene, and lower Eocene rocks in the Wind River Basin, Wyoming: U.S. Geological Survey Professional Paper 495-A, 77 p.

Keefer, W.R., 1970, Structural geology of the Wind River Basin, Wyoming: U.S. Geological Survey Professional Paper 495-D, 35 p.

Keefer, W.R., 1997, Stratigraphy and correlation of Cretaceous and Paleocene rocks, northern Wind River Basin, Wyoming: U.S. Geological Survey Oil and Gas Investigations Chart OC–146–A, 2 sheets.

Keefer, W.R., and Johnson, R.C., 1997, Stratigraphy and correlation of Cretaceous and Paleocene rocks, west-central Wind River Basin, Wyoming: U.S. Geological Survey Oil and Gas Investigations Chart OC–146–B, 2 sheets.

Keighin, C.W., and Flores, R.M., 1994, Characteristics of oil-saturated fluvial channel sandstone reservoirs, Paleocene upper Fort Union Formation, south-central Wind River Basin, Wyoming, *in* Flores, R.M., Mehring, K.T., Jones, R.W., and Beck, T.L., eds., Organics and the Rockies Field Guide: Wyoming State Geological Survey, Public Information Circular No. 53, p. 99–108.

Lewan, M.D., 1997, Experiments on the role of water in petroleum formation: Geochimica et Cosmochimica Acta, v. 61, p. 3691–3723.

Liro, L.M., 1993, Sequence stratigraphy of a lacustrine system: Upper Fort Union Formation (Paleocene), Wind River Basin, Wyoming, USA, *in* Weimer, Paul, and Posamentier, Henry, eds., Siliciclastic Sequence Stratigraphy—Recent Developments and Applications: American Association of Petroleum Geologists Memoir 58, p. 317–333.

Liro, L.M., and Pardus, Y.C., 1990, Seismic facies analysis of fluvial-deltaic lacustrine systems—Upper Fort Union Formation (Paleocene), Wind River Basin, Wyoming, *in* Katz, B.J., ed., Lacustrine Basin Exploration—Case Studies and Modern Analogs: American Association of Petroleum Geologists Memoir 50, p. 225–242.

Love, J.D., Christiansen, A.C., and Ver Ploeg, A.J., compilers, 1993, Stratigraphic chart showing Phanerozoic nomenclature for the state of Wyoming: Wyoming State Geological Survey Map Series no. 41, 1 pl.

Love, J.D., and Christiansen, A.C., 1985, Geologic Map of Wyoming: U.S. Geological Survey and Wyoming State Geological Survey, scale 1:500,000.

Magoon, L.B., and Dow, W.G., 1994, The petroleum system, *in* Magoon, L.B., and Dow, W.G., eds., The petroleum system—From source to trap: American Association of Petroleum Geologists, AAPG Memoir 60, p. 3–24.

Nichols, D.J., 1994, Palynostratigraphic correlation of Paleocene rocks in the Wind River, Bighorn, and Powder River Basins, Wyoming, *in* Flores, R.M., Mehring, K.T., Jones, R.W., and Beck, T.L., eds., Organics and the Rockies Field Guide: Wyoming Geological Survey, Public Information Circular No. 33, p. 17–29.

Nuccio, V.F., and Finn, T.M., 1994, Structural and thermal history of the Paleocene Fort Union Formation, central and eastern Wind River Basin, with emphasis on petroleum potential of the Waltman Shale Member, *in* Flores, R.M., Mehring, K.T., Jones, R.W., and Beck, T.L., eds., Organics and the Rockies Field Guide: Wyoming State Geological Survey, Public Information Circular No. 33, p. 53–68.

Nuccio, V.F., Finn, T.M., and Johnson, R.C., 1996, Thermal maturity data used for the assessment of gas resources in the Wind River Basin, Wyoming: U.S. Geological Survey Open-File Report 96-064, 57 p.

Osborn, Amy, 2001, Surface and subsurface geology of the Shotgun Member of the Fort Union Formation (Paleocene), Madden field, Wyoming: Golden, Colorado, Colorado School of Mines, master's thesis, Golden, Colorado, 167 p.

Palacas, J.G., Flores, R.M., Keighin, C.W., and Anders, D.E., 1994, Origin of oil in oil-stained sandstones in the upper part of the Fort Union Formation (Paleocene), Castle Gardens and Signor Ridge areas, Wind River Basin, Wyoming, *in* Flores, R.M., Mehring, K.T., Jones, R.W., and Beck, T.L., eds., Organics and the Rockies Field Guide: Wyoming State Geological Survey, Public Information Circular No. 33, p. 83–97.

Palmer, A.R., and Geissman, John, comps., 1999, Geologic time scale, Product Code CTS004, Geological Society of America.

Passey, Q.R., Creaney, Stephen, Kulla, J.B., Moretti, F.J., and Stroud, J.D., 1990, A practical model for organic richness from porosity and resistivity logs: American Association of Petroleum Geologists Bulletin, v. 74, no. 12, p. 1777-1794.

Phillips, S.T., 1983, Tectonic influence on sedimentation, Waltman Member, Fort Union Formation, Wind River Basin, Wyoming, *in* Lowell, J.D., and Gries, Robbie, eds., Rocky Mountain Foreland Basins and Uplifts: Rocky Mountain Association of Geologists, Denver, Colorado, p. 149–160.

Ray, R.R., 1982, Seismic stratigraphic interpretation of the Fort Union Formation, western Wind River Basin—example of subtle trap exploration in a nonmarine sequence, *in* Halbouty, M.T., ed., The deliberate search for the subtle trap: American Association of Petroleum Geologists, Memoir 32, p.169–180.

Robertson, R.D., 1984, Haybarn Field, Fremont County, Wyoming—An upper Fort Union (Paleocene) stratigraphic trap: The Mountain Geologist, v. 21, no. 2, p. 47–56.

Specht, R.W., 1989, Fuller Reservoir, in Cardinal, D.F., Miller, Terry, Trotter, J.F., and Stewart, W.W., eds., Wyoming Oil and Gas Fields Symposium—Bighorn and Wind River Basins: Wyoming Geological Association, Casper, p. 179–181.

Wyoming Oil and Gas Conservation Commission accessed March 1, 2005, http://wogcc.state.wy.us

Appendix A. Basic input data (Seventh Approximation data form [part]) used in estimates of the numbers and sizes of undiscovered petroleum accumulations in the Upper Fort Union Sandstones Conventional Oil and Gas Assessment Unit (50350301) in the Waltman Shale Total Petroleum System, Wind River Basin Province, Wyoming. Complete data input form is in Klett and Lee, Chap. 12, this CD–ROM.

IDENTIFICATION INFORMATION

Assessment Geologist:	**S.B. Roberts**	**Date:**	**9/21/2005**
Region:	**North America**	**Number:**	**5**
Province:	**Wind River Basin**	**Number:**	**5035**
Total Petroleum System:	**Waltman Shale**	**Number:**	**503503**
Assessment Unit:	**Upper Fort Union Sandstones Conventional Oil and Gas**	**Number:**	**50350301**
Based on Data as of:	**IHS Energy Group (2005), Wyoming Oil and Gas Conservation Commission (2005)**		
Notes from Assessor:	**Uinta Green River Conventional Oil and Gas Assessment Unit (50200501) as partial analog.**		

CHARACTERISTICS OF ASSESSMENT UNIT

Oil (<20,000 cfg/bo overall) **or** Gas (≥20,000 cfg/bo overall): Oil

What is the minimum accumulation size? 0.5 mmboe grown
(the smallest accumulation that has potential to be added to reserves)

No. of discovered accumulations exceeding minimum size: Oil: 1 Gas: ____
Established (>13 accums.) ____ Frontier (1-13 accums.) X Hypothetical (no accums.) ____

Median size (grown) of discovered oil accumulations (mmbo):
1st 3rd ____ 2nd 3rd ____ 3rd 3rd ____
Median size (grown) of discovered gas accumulations (bcfg):
1st 3rd ____ 2nd 3rd ____ 3rd 3rd ____

Assessment-Unit Probabilities:

Attribute	Probability of occurrence (0-1.0)
1. **CHARGE:** Adequate petroleum charge for an undiscovered accum. ≥ minimum size:	1.0
2. **ROCKS:** Adequate reservoirs, traps, and seals for an undiscovered accum. ≥ minimum size:	1.0
3. **TIMING OF GEOLOGIC EVENTS:** Favorable timing for an undiscovered accum. ≥ minimum siz	1.0

Assessment-Unit GEOLOGIC Probability (Product of 1, 2, and 3): 1.0

UNDISCOVERED ACCUMULATIONS

No. of Undiscovered Accumulations: How many undiscovered accums. exist that are ≥ min. size?:
(uncertainty of fixed but unknown values)

Oil Accumulations:	minimum (>0) 1	mode 3	maximum 15
Gas Accumulations:	minimum (>0)	mode	maximum

Sizes of Undiscovered Accumulations: What are the sizes (**grown**) of the above accums?:
(variations in the sizes of undiscovered accumulations)

Oil in Oil Accumulations (mmbo):	minimum 0.5	median 1.5	maximum 15
Gas in Gas Accumulations (bcfg):	minimum	median	maximum

Appendix A. Basic input data (Seventh Approximation data form [part]) used in estimates of the numbers and sizes of undiscovered petroleum accumulations in the Upper Fort Union Sandstones Conventional Oil and Gas Assessment Unit (50350301) in the Waltman Shale Total Petroleum System, Wind River Basin Province, Wyoming. Complete data input form is in Klett and Lee, Chap. 12, this CD–ROM.—Continued

Assessment Unit (name, no.)
Upper Fort Union Sandstones Conventional Oil and Gas, 50350301

AVERAGE RATIOS FOR UNDISCOVERED ACCUMS., TO ASSESS COPRODUCTS
(uncertainty of fixed but unknown values)

Oil Accumulations:	minimum	mode	maximum
Gas/oil ratio (cfg/bo)	1000	2000	3000
NGL/gas ratio (bngl/mmcfg)	30	60	90

Gas Accumulations:	minimum	mode	maximum
Liquids/gas ratio (bliq/mmcfg)			
Oil/gas ratio (bo/mmcfg)			

SELECTED ANCILLARY DATA FOR UNDISCOVERED ACCUMULATIONS
(variations in the properties of undiscovered accumulations)

Oil Accumulations:	minimum	mode	maximum
API gravity (degrees)	30	45	55
Sulfur content of oil (%)	0.05	0.15	0.5
Depth (m) of water (if applicable)			

	minimum	F75	mode	F25	maximum
Drilling Depth (m)	600	1500	2000	2100	2800

Gas Accumulations:	minimum	mode	maximum
Inert gas content (%)			
CO_2 content (%)			
Hydrogen-sulfide content (%)			
Depth (m) of water (if applicable)			

	minimum	F75	mode	F25	maximum
Drilling Depth (m)					

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