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Preliminary Geologic Characterization of Upper Cretaceous and Lower Tertiary Low-Permeability (Tight) Gas Bearing Rocks in the Wind River Basin, Wyoming

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OBJECTIVES

The Wind River Basin is one of several Rocky Mountain basins that contain significant resources of gas in low-permeability or tight reservoirs. Low-permeability gas reservoirs have an in situ permeability to gas of 0.1 millidarcies or less. These reservoirs cover vast areas of the structurally deeper parts of Rocky Mountain basins. They have also been referred to as "continuous-type (unconventional) hydrocarbon accumulations" (Schmoker, 1995) or simply basin-centered accumulations. They differ from conventional oil and gas deposits in that they (1) cut across stratigraphic units, (2) commonly are structurally down dip from more permeable water-filled reservoirs, (3) have no obvious structural or stratigraphic trapping mechanism, and (4) commonly are either abnormally overpressured or underpressured. The abnormal pressures of these reservoirs indicate that water, in hydrodynamic equilibrium with outcrop, is not the pressuring agent. Instead,

hydrocarbons within the tight reservoirs are thought to pressure these rocks. The objectives of the Wind River Basin tight gas sandstone project are to define the limits of the tight gas accumulation, characterize the geology of the sandstone reservoirs, estimate the in-place tight gas resources, and to estimate recoverable gas resources.

BACKGROUND INFORMATION

The Wind River Basin is a complex structural and sedimentary basin formed during the Laramide orogeny in latest Cretaceous, Paleocene, and early Eocene time (Figure 1). It is bounded on the north by the Absaroka Range, Owl Creek Mountains, and Bighorn Mountains; on the east by the Casper Arch; on the south by the the Granite Mountains; and on the west by the Wind River Range. The Wind River Basin is asymmetrical, with the deep trough adjacent to the east-west trending Owl Creek Mountains, which were

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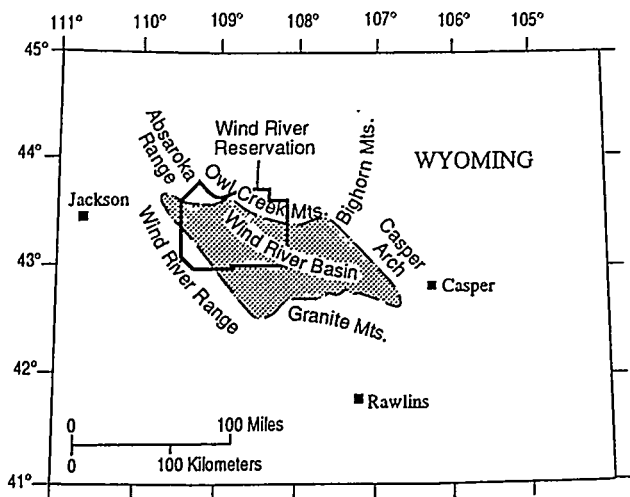


Figure 1. Index map showing location of Wind River Basin and surrounding uplifts. Location of Wind River Reservation is shown by heavy black line.

uplifted and faulted southward over the sedimentary basin. The west and southwest margins dip fairly gently away from the Wind River Range and the south margin dips away from the Granite Mountains. Numerous northwest-trending anticlines, many of which are bounded by reverse faults, occur along the basin margins.

Defining the limits of the basin-centered tight gas accumulation in the Wind River Basin is difficult because of the general sparseness of drilling data. Only a few permeability measurements from core in in the basin have been published, and most of these measurements were not taken under in-situ pressure conditions. The Wind River Basin differs significantly from other Rocky Mountain basins that contain basin-centered hydrocarbon accumulations. It is more faulted and generally more complex structurally than the Piceance Basin, the Greater Green River Basin, and the Uinta Basin. The Wind River Basin has far less topographic relief than the Piceance and Uinta Basins, and it is the only Rocky Mountain basin that contains a thick Paleocene-age lacustrine shale, the Waltman Shale Member of the Fort Union Formation. Understanding these differences is important in defining the limits of the basin-centered gas accumulation as well as in

predicting the economics of producing tight gas in the Wind River Basin. Several techniques used to define basin centered accumulations in other Rocky Mountain basins were tested in the Wind River Basin.

The Upper Cretaceous and lower Tertiary interval (Figure 2) in the Wind River Basin is capable of producing gas throughout a large area in the central part of the basin. Many of these formations, including the Upper Cretaceous Mesaverde, Meeteetse, and Lance Formations, and the Paleocene Fort Union Formation have been given tight sandstone designation. These gas-charged reservoirs vary from normally pressured, having conventional permeabilities in the shallower areas of the basin, to highly

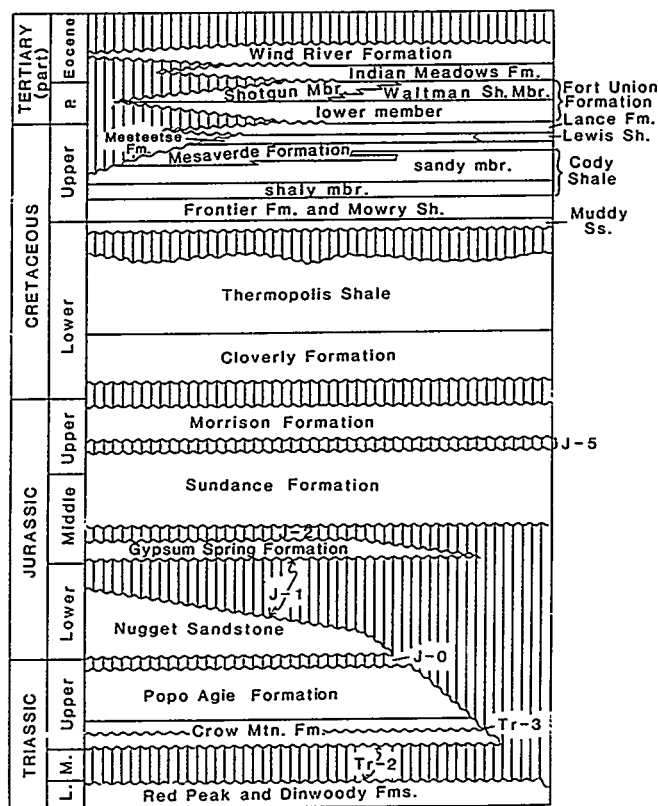


Figure 2. Generalized stratigraphic chart of Mesozoic and lower Cenozoic rocks, Wind River Basin, Wyoming. Patterns of vertical lines indicate hiatuses. Locations of Triassic unconformities (Tr-2, Tr-3) and Jurassic unconformities (J-0, J-1, J-2, J-5) from Pippingos and O'Sullivan (1978).

overpressured and having generally low permeabilities in the deeper areas of the basin. Although this interval appears to be able to produce gas throughout a large area of the basin, significant production is now established in only a handful of fields. Most of these fields occur on structural closures and structural noses. Many are single well gas fields that are shut in because there are no pipelines nearby. The fact that no further development occurred in these fields after gas rather than oil was discovered underlines the importance of pipeline availability in the development of the gas resources of the Wind River Basin. Frenchie Draw field, in contrast (Figure 3), occurs along a major pipeline and was developed largely because of the existence of this pipeline.

RESULTS

Source Rocks

Rich source rocks for oil and gas in the Upper Cretaceous and Lower Tertiary interval in the basin include the Upper Cretaceous Mowry Shale, the shaley member of the Upper Cretaceous Cody Shale, the lower part of the Upper Cretaceous Mesaverde Formation, the Upper Cretaceous Meeteetse Formation, and the lower unnamed member and Waltman Shale Member of the Paleocene Fort Union Formation (Figure 2). The Mesaverde and Meeteetse Formations, and the lower unnamed member of the Fort Union Formation contain mainly gas-prone Type III organic matter, while the Mowry Shale, the lower shaley member of the Cody Shale, and the Waltman Shale Member contain mixes of Type II (oil and gas prone) and Type III organic matter. Thermal maturity studies, using vitrinite reflectance, indicate that the Mowry Shale, the shaley member of the Cody Shale, the lower part of the Mesaverde Formation, and the Meeteetse Formation have reached a thermal maturity level of Rm 0.73 percent, sufficient for significant gas

generation throughout the area of the tight-gas accumulation in the basin. In contrast, the lower unnamed member and the Waltman Shale Member of the Fort Union Formation are thermally mature in only the deep trough area of the basin (Nuccio and Finn, 1993).

Evidence for Gas Migration in the Basin

Recent work on the chemical and isotopic composition of gases in the Wind River, Piceance, and Uinta Basins, (Johnson and Rice, 1993; Johnson and others, 1994a; 1994b) suggests that there has been considerable vertical migration of gases from mature Cretaceous-age source rocks into overlying marginally mature to immature lower Tertiary reservoirs in all three basins. In the Wind River Basin, the Waltman Shale Member acts as a seal, keeping gas from migrating vertically into younger formations above the Waltman or venting to the surface. Shale seals are seldom considered in conjunction with low-permeability gas accumulations, however, Masters (1984, p. 10) stressed the importance of the Lower Cretaceous Joli Fou Shale as a regional seal inhibiting the vertical migration of hydrocarbons out of the low-permeability hydrocarbon accumulation in the Alberta Deep Basin. Gases from below the Waltman are isotopically much heavier than gases produced from sandstones within or above the Waltman and are probably sourced by mature Upper Cretaceous source rocks. At Pavillion and Muddy Ridge fields, in the western part of the basin, where the Waltman is not present, gas has migrated vertically from Upper Cretaceous source rocks into units as young as the Eocene Wind River Formation (Figure 3) (Johnson and Rice, 1993).

Figure 3 is a structure contour map of the base of the Waltman Shale Member and its lateral equivalent. The contour map was extended beyond the limit of the Waltman by contouring the base of the sandy marginal lacustrine equivalent of the Waltman in the Shotgun Member of the

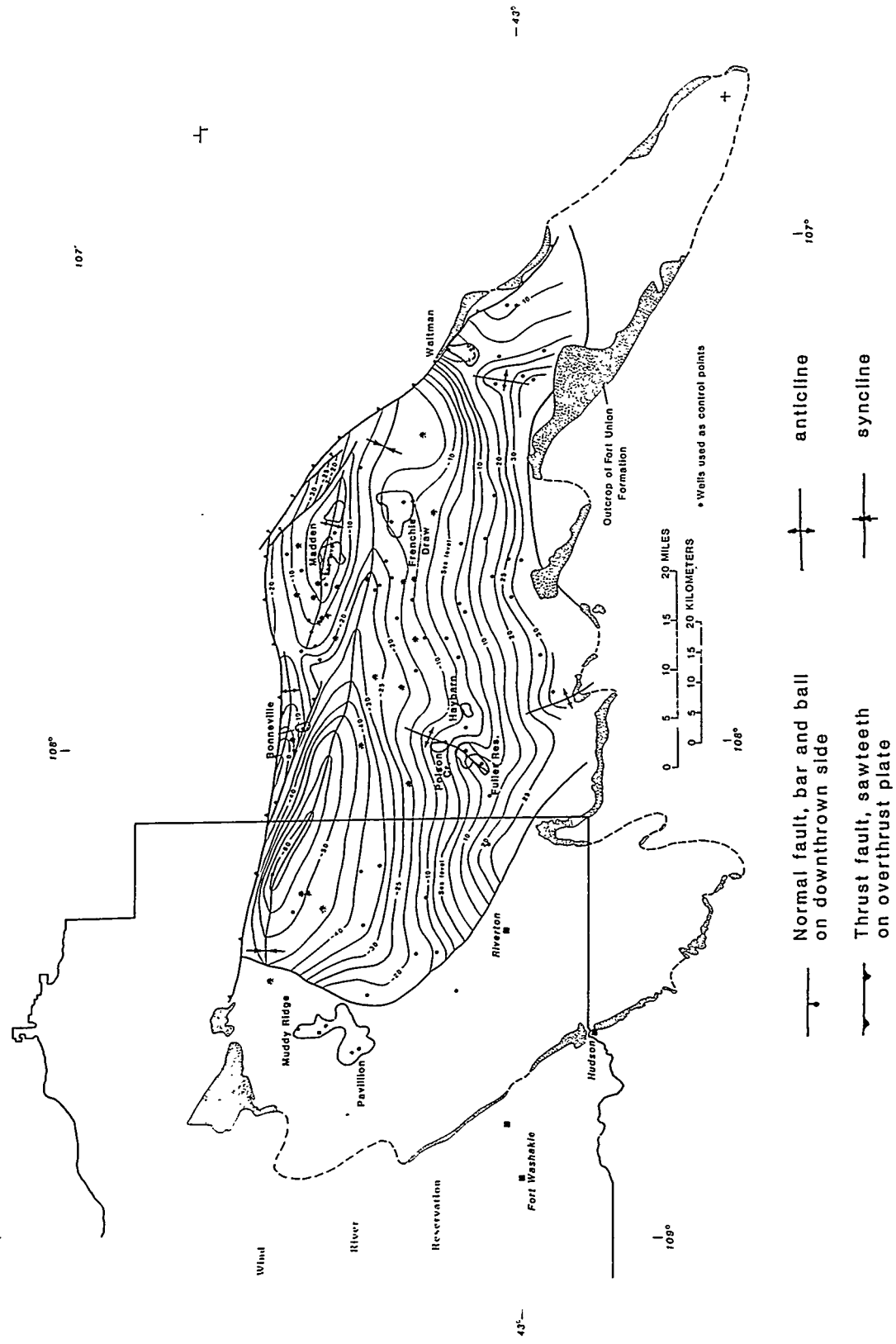


Figure 3. Structure contour map drawn on the base of the Waltman Shale Member of the Paleocene Fort Union Formation and its marginal-lacustrine equivalent in the Shotgun Member of the Fort Union. Contour interval: 500 ft. Heavy line shows limit of Waltman Shale Member and its equivalent. Gas shows and fields that produce from the lower unnamed member of the Fort Union Formation beneath the Waltman are shown.

Fort Union. Gas fields which produce from the underlying lower unnamed member of the Fort Union Formation are shown. Wells which had nearly continuous gas shows on mudlogs of the lower member are shown with an astrisk. Gas appears to be more-or-less ubiquitous in the lower unnamed member wherever the Waltman Shale is present. In many shallow fields such as Waltman (Ptasynski, 1989), Fuller Reservoir (Specht, 1989), Haybarn (Evans, 1989), and Poison Creek (Morton, 1989), the lower unnamed member appears to have conventional permeabilities. Deeper production from the lower unnamed member appears to be from either low-permeability sandstones or sandstones with unknown permeabilities.

Defining the overpressured pocket using mud weights

Mud weights used during drilling and pressures from drillstem tests were examined to help define the overpressured pocket in the basin. It should be remembered that tight accumulations can also be underpressured, and hence studying heavy mudweights will only define that part of the tight accumulation that is overpressured. The overpressured pocket in the Wind River Basin is unusual in that 1) normally pressured reservoirs or reservoirs occur interbedded with highly overpressured reservoirs, and 2) significant water is produced from many fields completed in overpressured rocks. On Madden Anticline, the Sussex Sandstone Member equivalent of the Cody Shale is normally pressured, with a pressure gradient of about 0.41 to 0.44 psi/ft, while pressure gradients in underlying and overlying sandstones are as much as 0.76 psi/ft (Dunleavy and Gilbertson, 1986). The normally pressured Sussex equivalent appears to be in communication with the regional hydrodynamic system while the overlying and underlying intervals are not. This problem is discussed further below. Water production on Madden Anticline from the overpressured interval

as of 1989, include 1,522,245 barrels from the Mesaverde Formation and 562,683 barrels from the Cody Shale (Brown and Shannon, 1989). At the Bonneville field west of Madden, significant water was produced with gas in the overpressured Upper Cretaceous Lance Formation (Gilbert, 1989).

The depths at which 10 lb mud and 12 lb mud were used during drilling were converted into elevations above and below sea level and plotted on Figure 4. Ten pound mud indicates a pressure gradient of 0.494 psi/ft or moderate overpressuring, while 12 lb mud indicates a pressure gradient of 0.625 psi/ft or significant overpressuring. The elevations of the 10 lb mud level shown on Figure 4 are probably somewhat below the true onset of overpressuring in the basin since normal hydrostatic pressure is significantly less than the 0.494 lbs/ft represented by the 10 lb mud weight. In addition, overpressuring is commonly not detected immediately while drilling through tight intervals.

Elevations where 10 lb mud was used generally fall between -5,500 and -8,500 ft throughout most of the basin, except on the Madden Anticline where 10 lb mud was used at elevations of +290 to -1,935 ft, and in some wells along the north margin of the basin where 10 lb mud was not used until elevations of from -11,000 to -12,395 ft were reached (Figure 4). Overpressuring on Madden Anticline begins at the base of the Waltman Shale Member, further evidence of the importance of the Waltman as a seal against vertical migration of gas in the basin. This overpressuring at relatively shallow depths has traditionally been attributed to a long gas column beneath the Waltman. A single long gas column supported by an underlying column of water seems unlikely. The lower unnamed member is productive through over a 3,500 ft stratigraphic interval, yet water has been recovered from as little as 200 ft below the crest of the anticline (Schmitt, 1975) indicating multiple gas-water contacts. There is no reliable permeability data available for the lower unnamed member of the

Fort Union Formation at Madden (Brown and Shannon, 1989) but the interval has some characteristics in common with low-permeability reservoirs. As in many tight intervals, defining potentially productive zones in the lower unnamed member at Madden using geophysical log interpretations has proven unreliable (Dunleavy and Gilbertson, 1986, p. 111-112).

Twelve pound mud was used generally between elevations of -10,000 to -12,700 ft except on the Madden Anticline where 12 lb mud was used at somewhat higher elevations and along the northern margin of the basin where 12 lb mud use occurs at somewhat lower elevations (Figure 4). The limited drillstem test information available generally supports the outline of the overpressured pocket defined from mudweights. Figures 5 and 6 are schematic north-south and east-west cross sections through the basin showing the approximate positions where 10 lb and 12 lb mud weights were used. The shallow depth for the onset of overpressuring on Madden Anticline is clearly anomalous when compared to onset of overpressuring in the rest of the basin.

Using Variations in Thermal Maturity to Help Define the Low-Permeability Gas Accumulation

Variations in thermal maturity were examined to help define the limits of the basin-centered gas accumulation, particularly in areas where little pressure data is available. Thermal maturity defines areas where potential source rocks have generated gas at some time in the past. In the Piceance Basin (Johnson and others, 1987) used a vitrinite reflectance (Rm) of 1.1% to define the limits of the basin-centered accumulation while an Rm of 0.73 to 1.1% was used to define a transition zone containing both tight and more conventional reservoirs. Masters (1984, p. 27, Fig. 25), in a study of the basin-centered gas accumulation in the Deep Basin of Alberta, shows that an Rm of 1.0 corresponds approximately to

the limit of the accumulation. In the Greater Green River Basin (Law and others, 1989), found that an Rm of 0.80 generally corresponds to the top of overpressuring.

The approximate elevations of the Rm 0.73% and Rm 1.1% are shown on Figures 7 and 8. Vitrinite reflectance data is from Pawlewicz (1993) and from Nuccio and Finn (unpublished data). The elevations of the Rm 0.73 and 1.1% level are highest in the central part of the basin and lowest in the western and eastern parts. The Rm 0.73% and Rm 1.1% levels are also plotted on schematic north-south and east-west cross sections (Figures 5 and 6). The position of the Rm 1.1% thermal maturity level is approximately 1,000 to 2,000 ft above the 10 lb mud level throughout much of the basin except on Madden Anticline, where it dips below the 10 lb mud level and in the western part of the basin where the 10 lb mud level and the position of the Rm 1.1% thermal maturity level are nearly the same. The elevation of the Rm 0.73 thermal maturity level varies from about 3,000 ft above the 10 lb mud level in the eastern and western parts of the basin to about the same level as the 10 lb mud level at Madden Anticline in the central part of the basin.

Using Present-Day Formation Temperatures to Help Define the Low-Permeability Gas Accumulation

Present-day formation temperatures have also been used to help determine the boundaries of overpressured basin-centered accumulations in Rocky Mountain basins. Rates of gas generation are directly related to temperature. Spencer (1989) suggested that rates of gas generation need to exceed rates of gas loss in order to maintain abnormally high pressures in Rocky Mountain basin-centered gas accumulations and that this generally occurs at present-day temperatures of about 200° F or greater. A corrected geothermal gradient map for the basin, recently constructed by Pawlewicz (1993), showed that gradients vary

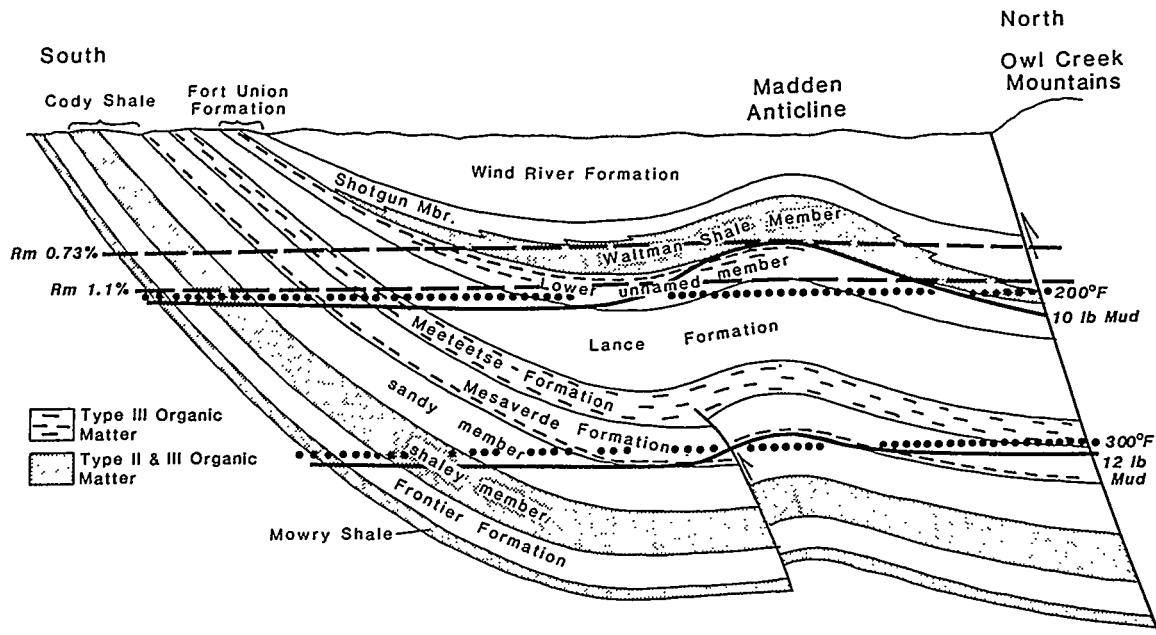


Figure 5. Schematic north-south cross section through the Wind River Basin, Wyoming showing Upper Cretaceous and lower Tertiary stratigraphic units, potential source rocks, approximate positions where 10 lb and 12 lb mud was used during drilling, approximate positions of Rm 0.73% and Rm 1.1% vitrinite reflectance levels, and approximate positions of 200° and 300° present-day isotherms.

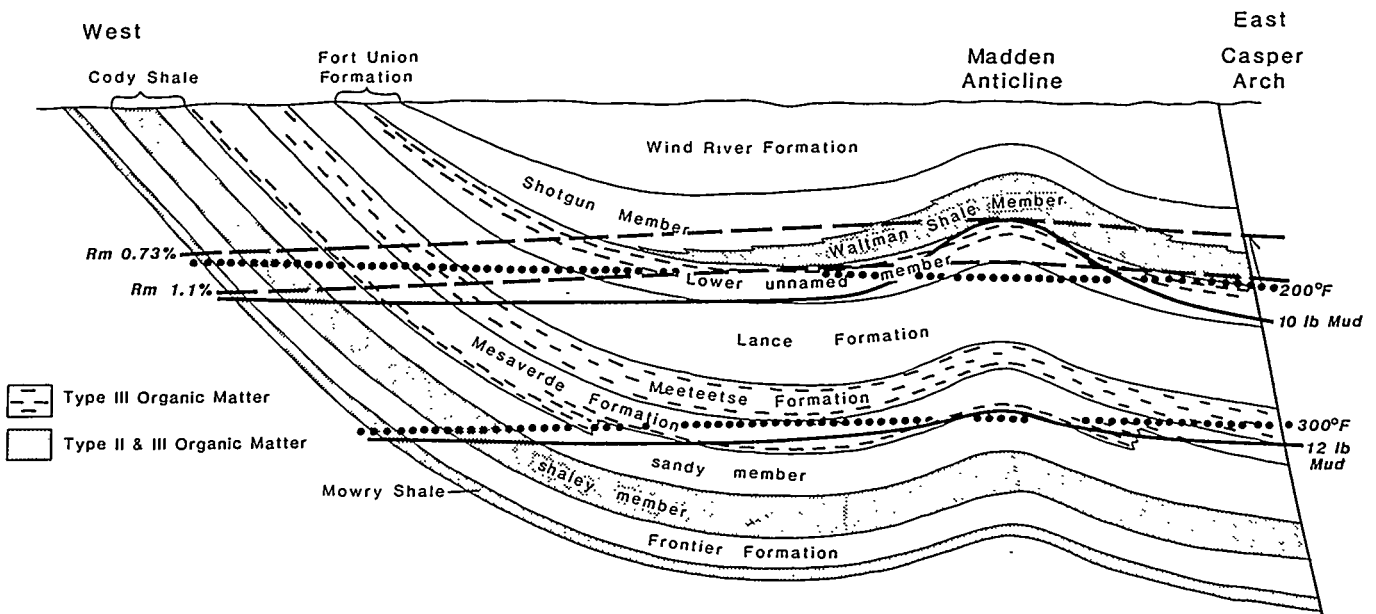


Figure 6. Schematic east-west cross section through the Wind River Basin, Wyoming showing Upper Cretaceous and lower Tertiary stratigraphic units, potential source rocks, approximate positions where 10 lb and 12 lb mud was used during drilling, approximate positions of Rm 0.73% and Rm 1.1% vitrinite reflectance levels, and approximate positions of 200° and 300° present-day isotherms.

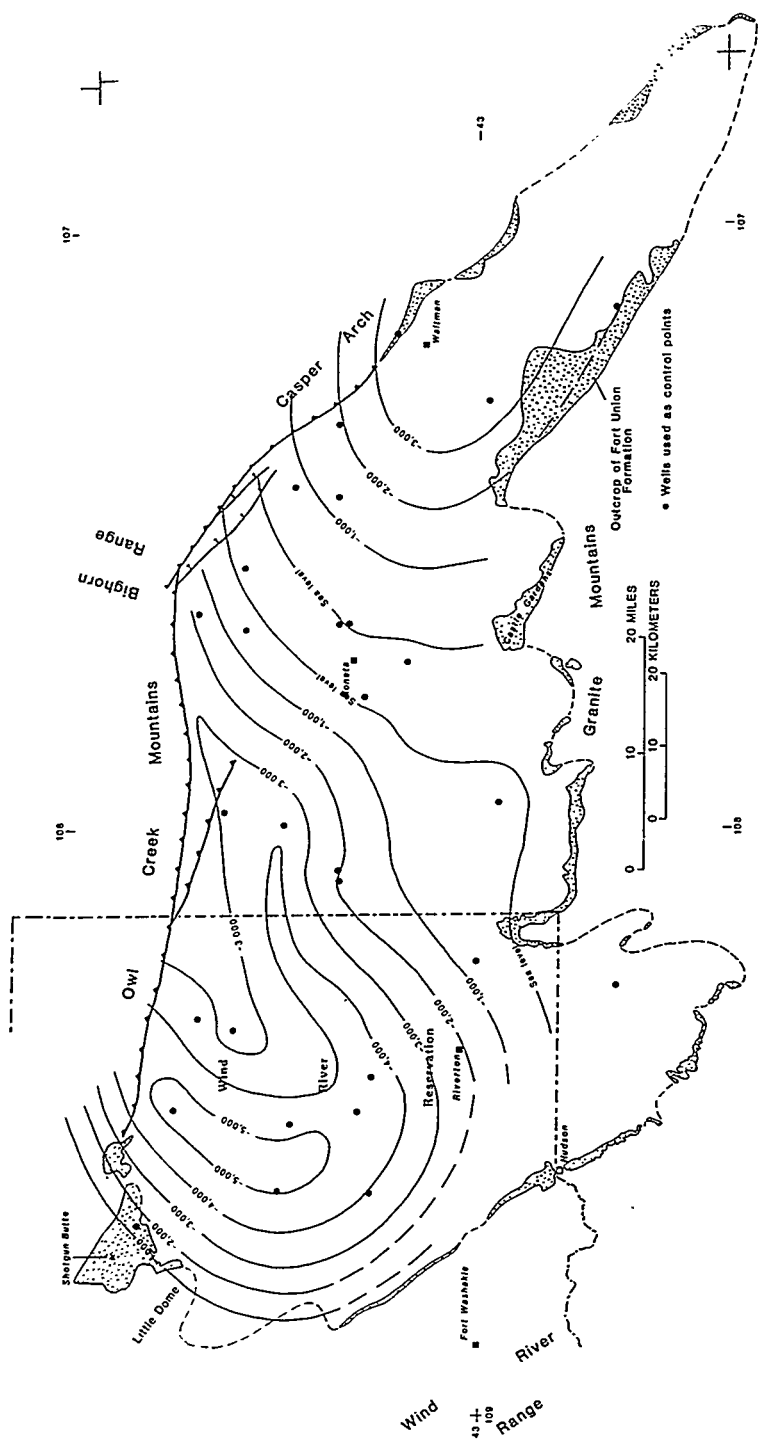


Figure 7. Map showing approximate elevation of the Rm 0.73 vitrinite reflectance level in the Wind River Basin. Contour interval: 1,000 ft. Data from Pawlewicz (1993), and Nuccio and Finn (unpublished data).

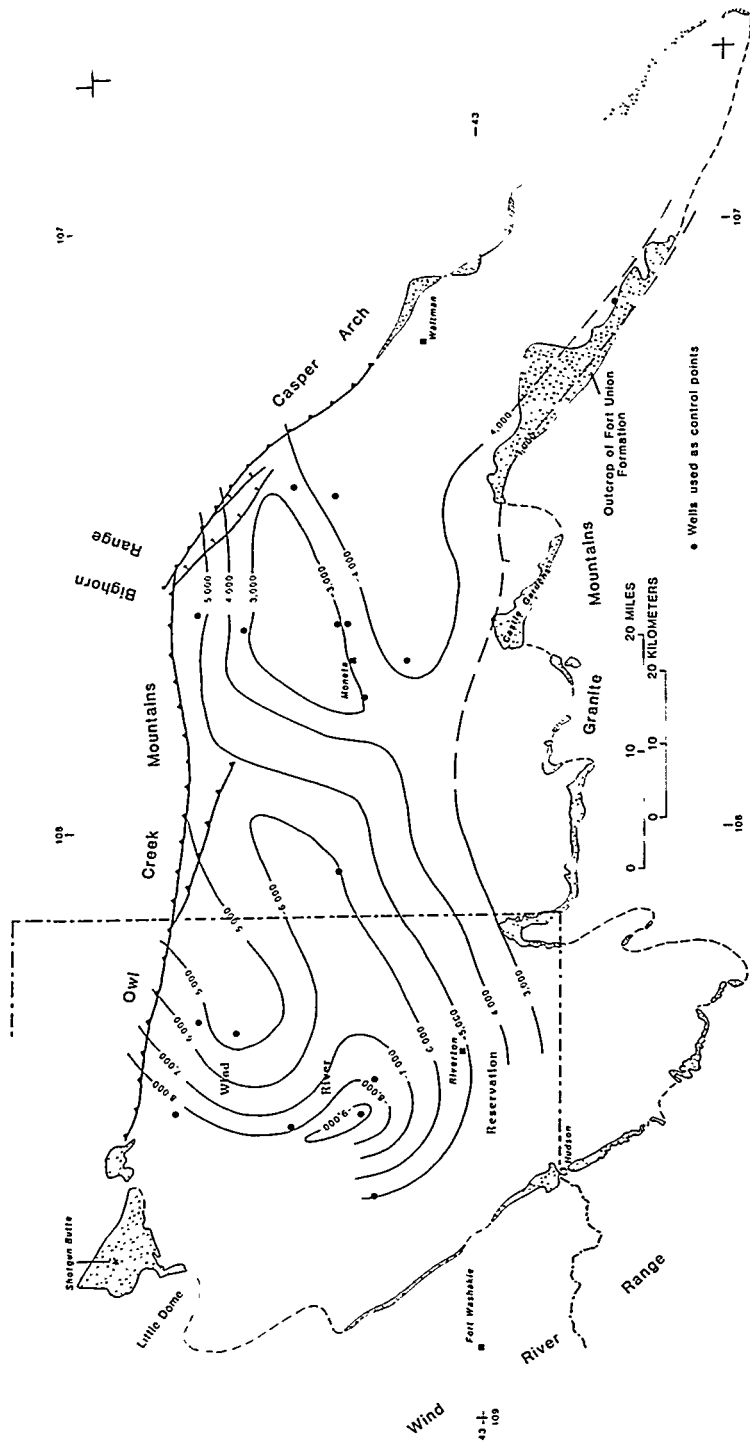


Figure 8. Map showing approximate elevation of the Rm 1.1 vitrinite reflectance level in the Wind River Basin. Contour interval: 1,000 ft. Data from Pawlewicz (1993), and Nuccio and Finn (unpublished data).

irregularly across the basin from less than 1.2°F/100 ft to over 2.0°F/100 ft. Geothermal gradients are on average somewhat higher in the central part of the basin where high thermal maturities were found but there is considerable scatter.

The geothermal gradient map of Pawlewicz (1993) was used to determine the approximate positions of two isotherms, the 200° F and the 300° F on the cross sections (Figures 5 and 6). On both cross sections, the 300°F isotherm fairly closely follows the 12 lb mud weight line. On the north-south cross section in the central part of the basin (Figure 5), the 200° isotherm closely follows the Rm 1.1% line; however, on the east-west cross section (Figure 6) the distance between the 200° isotherm and the Rm 1.1 line increases toward the east and west ends of the basin. This indicates that variations in present-day thermal gradients do not closely follow variations in thermal maturity throughout the basin, suggesting that thermal gradients in the basin have changed significantly since the presently observed thermal maturities were established.

A comparison between variations in thermal maturity, present-day temperatures, and overpressuring indicated by mud weights, (Figures 5 and 6) indicates that both the 200° isotherm and the Rm 1.1% level fairly closely follow the top of the overpressured pocket in the central part of the basin. However, toward the western margin of the basin, only the Rm 1.1% line fairly closely tracks the 10 lb mud line. This suggests that the position of the Rm of 1.1% thermal maturity level in the basin may fairly closely correspond to the onset of overpressuring.

Geologic Characterization of Stratigraphic Units Within the Low-Permeability Accumulation

A comprehensive geologic characterization of each formation within a low-permeability gas accumulation can lead to a better understanding of some of the variations in production characteristic

found within the accumulation. Although water production is not typically a problem in low-permeability accumulations until gas production is well into decline, certain intervals produce significant water from the start. The Mesaverde Formation in the Wind River Basin is used here as an example of the importance of geologic characterization. The Mesaverde Formation was deposited along the western margin of the Upper Cretaceous interior seaway as the seaway gradually retreated eastward across Wyoming. The thickness of the Mesaverde varies from over 2,400 ft in the western part of the basin to less than 500 ft in the eastern part (Figure 9). The Mesaverde thins largely by grading laterally into the underlying marine Cody Shale in an easterly direction. This lateral facies change is not gradual across the basin, however, but occurs in two distinct jumps (indicated as datum changes), where significant thicknesses of Mesaverde Formation grade into Cody over relatively short distances. This indicates that the eastward retreat of the shoreline stalled near these two positions for considerable periods of time.

The Mesaverde Formation can be subdivided into a lower sequence containing mainly regressive shoreface sandstones and an upper sequence of mainly fluvial sandstones. The two positions where the eastward retreat of the shoreline stalled for considerable periods of time are readily apparent on an isopach map of the thickness of the lower shoreface sequence (Figure 10). An interval of stacked shoreface sandstones over 1,200 ft thick occur just westward of the western facies change. These shoreface sandstones trend generally north-south or parallel to the paleoshoreline. Sandstones were also deposited on the continental shelf east of the Cretaceous shoreline, and these sandstone also appear to trend generally north-south. More lenticular sandstones in the overlying fluvial part of the Mesaverde trend generally east-west or perpendicular to the paleoshoreline.

The shoreface sandstones and their shelf equivalents commonly extend to outcrop along the south margin of the basin. They appear to be

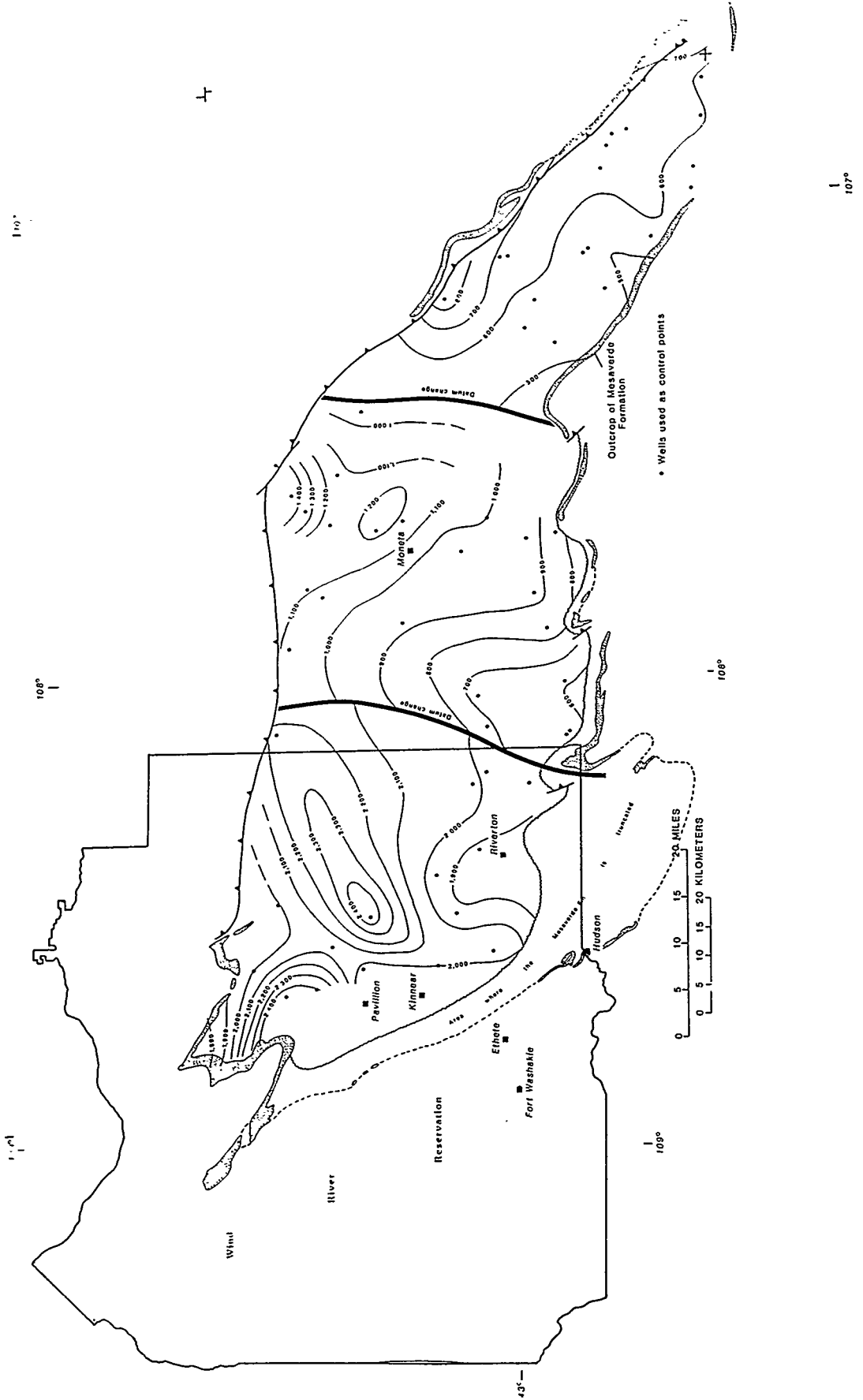


Figure 9. Isopach map of the Upper Cretaceous Mesaverde Formation, Wind River Basin, Wyoming. Contour interval: 100 ft.

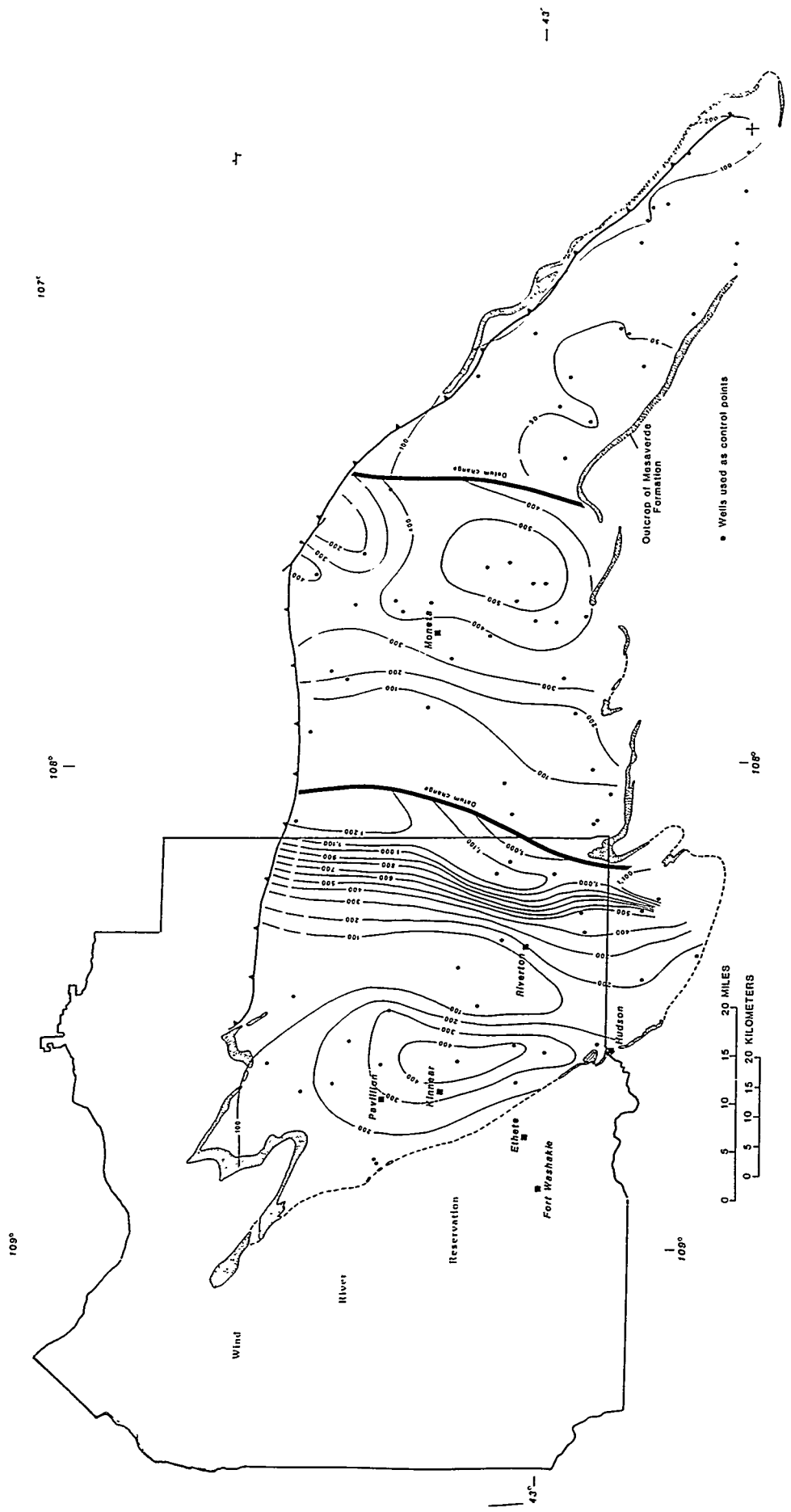


Figure 10. Isopach map of the lower shoreface sequence in the Mesaverde Formation, Wind River Basin, Wyoming. Contour interval: 100 ft.

recharged by fresh-water from these outcrops and are water-wet far down dip into the basin. Water production problems are far less common in the overlying fluvial sandstones which lense out before reaching recharge areas along the southern margin of the basin. This recharge can reach to the deepest parts of the basin. As previously mentioned, the Sussex Sandstone Member equivalent of the Cody Shale is in the highly overpressured interval on Madden Anticline near the deep trough of the basin but is normally pressured and in apparent hydrodynamic equilibrium with the outcrop.

FUTURE WORK

Our studies of the low-permeability gas accumulation in the Wind River Basin are nearing completion. A combination of mudweights, levels of thermal maturities, and present-day formation temperatures will be used to generally define the limits of the accumulation. Sandstone isopach maps will be used in conjunction with porosity and water saturation estimates, and pressure estimates to estimate in-place gas resources. Estimates of economically recoverable gas will be made using the in-place gas estimates, production characteristics from existing fields, and geologic characterization studies.

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