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

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CONTRACT INFORMATION

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Contractor	United States Geological Survey Branch of Petroleum Geology MS 934, Denver Federal Center Denver, Colorado 80225-0046
Contractor Project Manager	Thomas D. Fouch
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This report is preliminary and has not been reviewed for conformity with the U.S. Geological Survey editorial standards or with the North American Stratigraphic Code.

OBJECTIVES

The Wind River Basin is a structural and sedimentary basin in central Wyoming (Figure 1) that was created during the Laramide orogeny from Late Cretaceous through Eocene time. The objectives of the Wind River Basin tight gas sandstone project are to define the limits of the tight gas accumulation in the basin and to estimate in-place and recoverable gas resources. The approximate limits of the tight gas accumulation will be defined from available drillhole information. Geologic parameters, which controlled the development of the accumulation, will be studied in order to better understand the origins of tight gas accumulations, and to predict the limits of the accumulation in areas where little drillhole information is available. The architecture of sandstone reservoirs will be studied in outcrop to predict

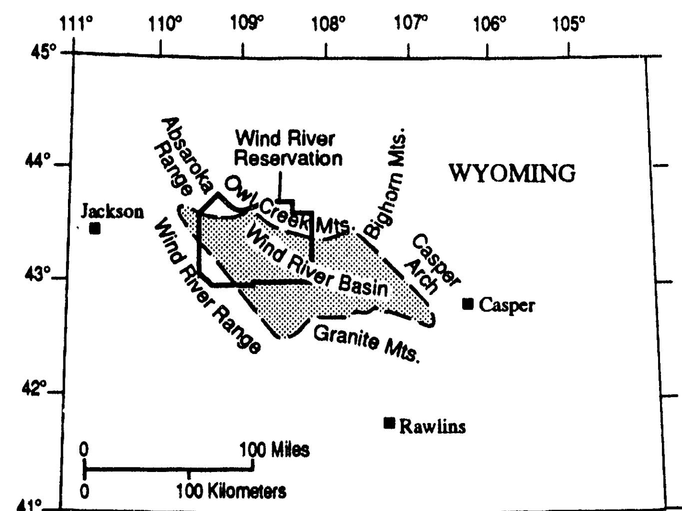

Figure 1. Index map showing location of Wind River Basin and surrounding uplifts. Location of Wind River Reservation is shown by heavy black line.

production characteristics of similar reservoirs within the tight gas accumulation. Core and cuttings will be used to determine thermal maturities, quality of source rocks, and diagenetic histories.

Our work thus far has concentrated in the Wind River Indian Reservation in the western part of the basin. The U.S. Geological Survey has has just completed a Bureau of Indian Affairs-funded three-year project with the Shoshone and Arapaho Tribes of the Wind River Indian Reservation to study the oil and gas and coalbed methane resources of the Reservation. The Reservation project culminated in August and provided three important products: 1) a field trip to the Reservation; 2) a special session highlighting our results at the Wyoming Geological Association Meeting in Casper Wyoming; 3) and the publication of a Wyoming Geological Association guidebook on the Wind River Basin. Many of the studies published in the guidebook were jointly funded by the Bureau of Indian Affairs and the U.S. Department of Energy funded tight gas sandstone project.

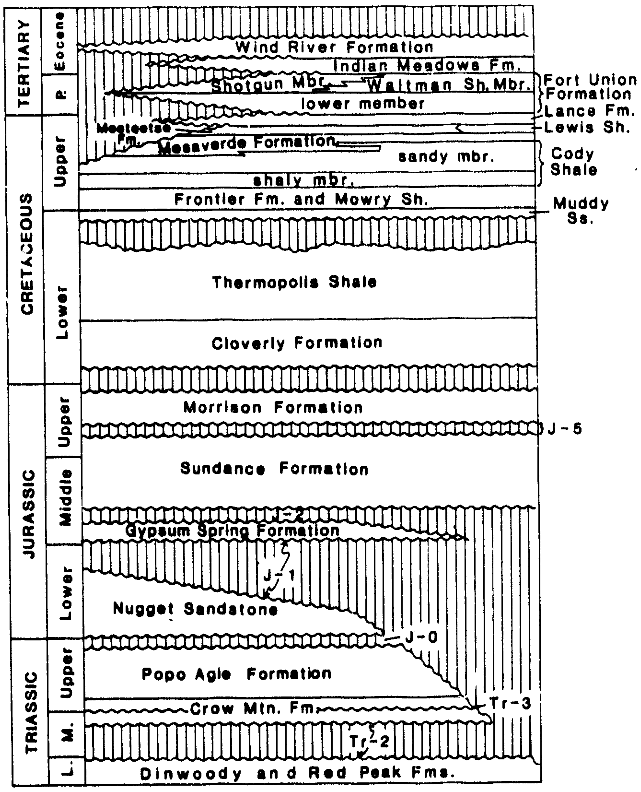

Figure 2. Generalized stratigraphic chart of Mesozoic age and Cenozoic age rocks, Wind River Basin, Wyoming. Patterns of vertical lines indicate hiatuses. Locations of Triassic unconformities (Tr-3, Tr-3) and Jurassic unconformities (J-0, J-1, J-2, J-5) from, Pipiringos and O'Sullivan (1978).

BACKGROUND INFORMATION

Geologic Setting

The principle tight gas sandstone interval in the Wind River Basin extends from the the Lower Cretaceous Muddy Sandstone through the lower member of the Paleocene Fort Union Formation (Figure 2). All of the formations in this interval have received tight formation designation in the basin, and abnormally high formation pressures, a common characteristic of tight sandstone intervals, were encountered throughout this interval at Madden anticline near the deep trough of the basin (Bilyeu, 1978).

The Wind River Basin is one of several large structural and sedimentary basins that formed in the Rocky Mountain region during Laramide deformation. The basin is surrounded by folded and faulted strata of Paleozoic and Mesozoic ages which form the flanks of the adjacent mountain ranges and anticlinal uplifts (Figure 1). Most of the basin interior is covered by rocks of early Eocene age, which mask the stratigraphic and structural relations of older underlying rocks throughout most of the basin interior (Keefer, 1970).

Until Late Cretaceous time, the present site of the Wind River Basin was part of the foreland or stable shelf region which lay to the east of the main miogeosynclinal trough area. Rocks representing all systems, except possibly the Silurian, were deposited during repeated transgressions and regressions of the epicontinental seas across central Wyoming.

Beginning in Late Cretaceous time, the main sites of sedimentary accumulation shifted eastward into the Wind River Basin area because of uplift west of the present Wyoming-Idaho boundary. The last major episode of marine deposition in central Wyoming is represented by the Cody Shale and the basal marginal marine part of the overlying Mesaverde Formation. The remainder of the Mesaverde reflects deposition of chiefly clastic sediments in broad floodplains, coastal swamps, deltas and lagoons. Similar conditions prevailed during deposition of the overlying Meeteetse Formation except in the easternmost part of the Wind River Basin where it intertongues with the marine Lewis Shale. In contrast, during deposition of the Lance Formation in latest Cretaceous time, local tectonic activity was recorded by accumulations of coarse clastic debris near highlands being actively uplifted and eroded, by incipient basin downwarping, and by the development of unconformities along the basin margins. These initial phases of the Laramide deformation were followed in Paleocene time by a period of mountain-building and basin subsidence of increasing intensity. This deformation culminated in early Eocene time in the uplift of high mountains along reverse faults of large magnitude that overrode the basin margins.

Coarse-grained detritus continued to accumulate along the flanks of the rising highlands during deposition of both the Lance and Fort Union Formations, but in the central part of the basin, thick sequences of fine-grained sands, silts, clays, and carbonaceous sediments were deposited in the subsiding syncline. A large lake, "Waltman Lake", covered much of the Wind River Basin in late Paleocene time.

RESULTS

Six detailed cross sections showing lithologies, correlations of lithologic units, and results from drillstem tests and perforations, were constructed and published. Four of these were on the Wind River Reservation (Keefer and Johnson, 1993), and two were east of the Reservation in the eastern part of the basin (Finn, 1993, Szmajter, 1993). Several more cross sections are being constructed and will be submitted for review in the next few months. These cross sections establish basin-wide correlation (Figure 3) and help define the limits of the limits of the tight gas accumulation.

Hydrocarbon generation from source rocks is directly related to thermal maturity, hence, thermal maturity studies can be used to define areas where hydrocarbons have been generated in the past. Subsurface and surface studies using vitrinite reflectance show variations in thermal maturity in the Wind River Basin (Figure 4) (Pawlewicz, 1993; Nuccio and others, 1993).. Comparison of calculated paleotemperatures with present temperatures demonstrates that significant cooling has occurred. Optimum areas for tight-gas generation and accumulation have been defined utilizing these data.

The environments of deposition of the uppermost part of the Cody Shale and the Mesaverde and Meeteetse Formations of Late Cretaceous age were studied on outcrop in the Shotgun Butte area in the north-central part of the Wind River Reservation (Johnson and Clark, 1993). A marginal marine shoreface sandstone occurs in the lower part of the Mesaverde Formation at all localities studied, and is directly overlain by a coaly sequence. Repetitive coarsening-upward cycles of mudstone, siltstone, and sandstone occur in the 200 ft interval of the upper part of the Cody Shale below the shoreface sandstone. These Cody sandstones are typically hummocky cross stratified with symmetrical ripples near the top, indicating that they are largely storm surge deposits that were later reworked by less intense current and wave processes. Channel-form sandstones from 10 to 20 ft thick, with abundant locally derived clayey clasts, occur in a 75 ft thick interval below the shoreface at one locality. These unusual sandstones are

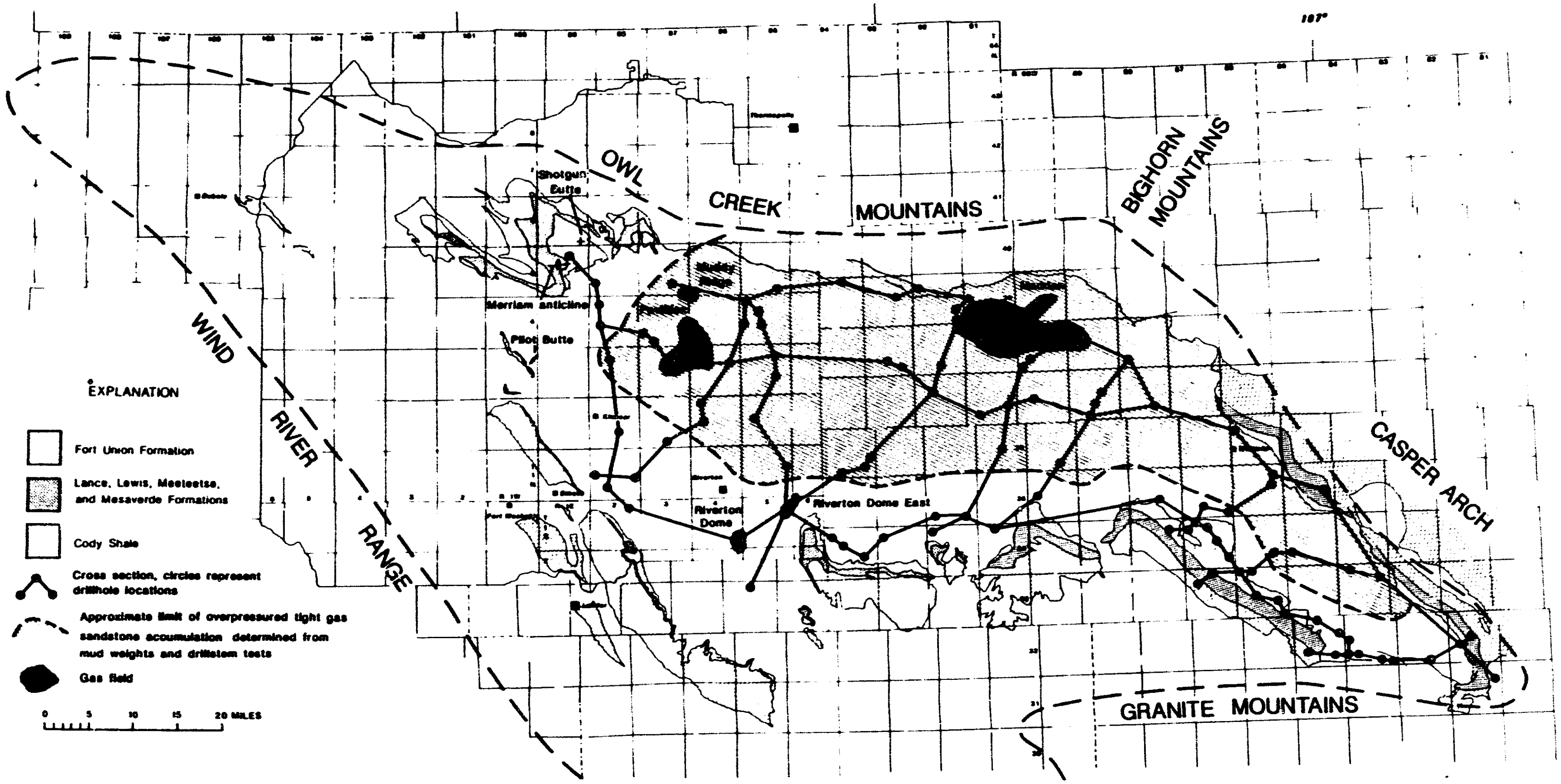

Figure 3. Map showing areas where tight gas formations crop out, approximate outline of overpressured tight gas accumulation, and locations of detailed cross sections.

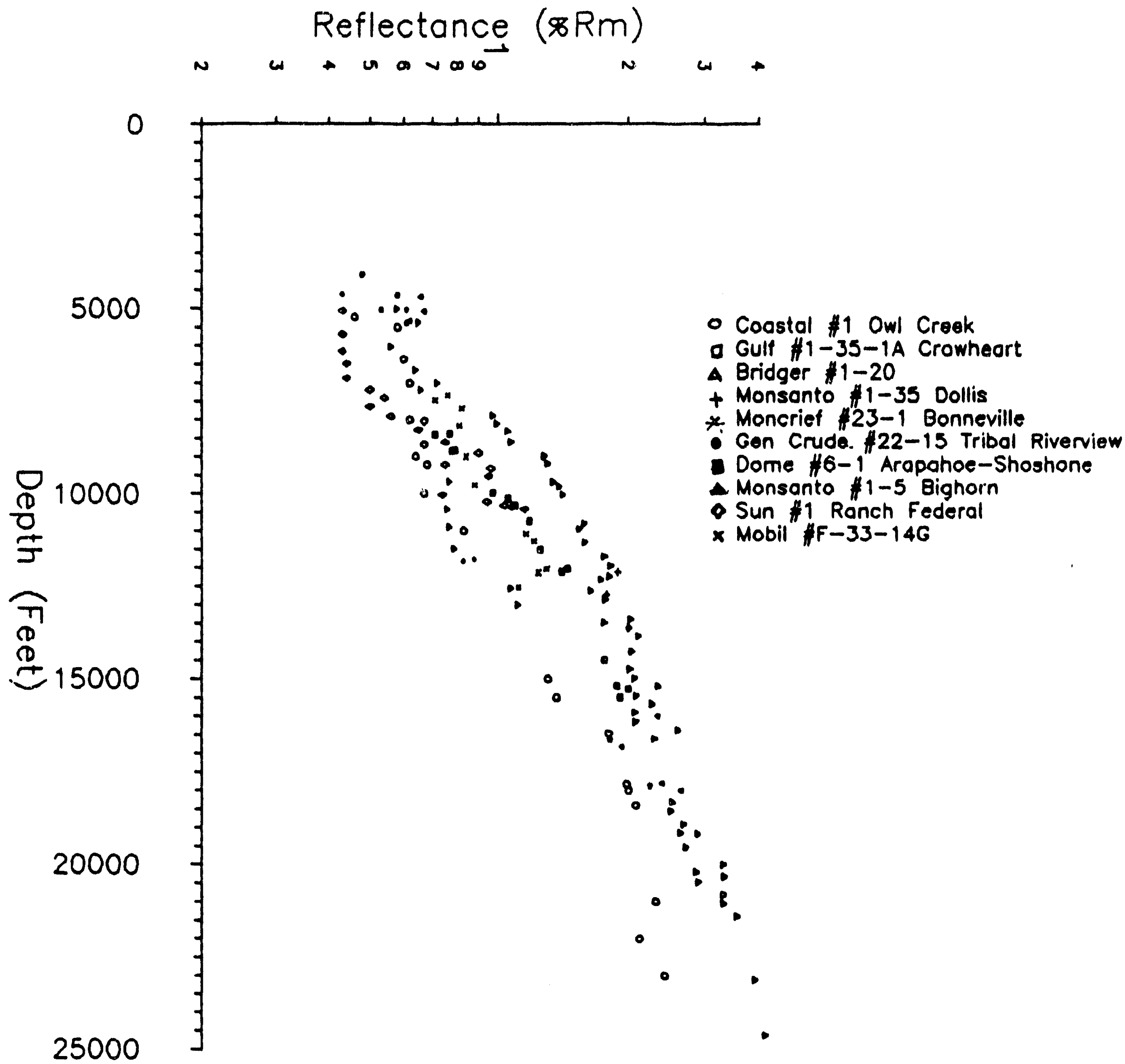

Figure 4. Composite depth versus Rm plot for ten boreholes from the Wind River Basin. From Pawlewicz (1993).

largely confined to a narrow area of the outcrop and grade laterally into more typical tabular shaped storm surge deposits. They may represent unusually large storm surge channels created when high-energy flow conditions were localized to a limited area of the shelf.

The Mesaverde Formation above the shoreface sandstone is divided into a middle member and the Teapot Sandstone Member. The lower part of the middle member is everywhere coaly. Erosional-based sandstones in the middle member are highly variable in thickness and architecture. Thin, single channel sandstone bodies were deposited by moderate to high sinuosity stream channels that were abandoned after a comparatively brief period of time. Thick, multistorey channel sandstone bodies, in contrast, were deposited by fluvial channel systems that

Figure 5. Photograph of multistory fluvial channel sandstone with several highly irregular zones of ripup clasts (outlined with dashed lines), Eagle Point measured section, Wind River Reservation. From Johnson and Clark (1993).

remained relatively stationary for extended periods of time (Figure 5). The multistorey sandstones occur at different stratigraphic levels at different localities suggesting long term stability of fluvial channel systems followed by major avulsion events.

The Teapot Sandstone Member consists of fairly continuous to lenticular white multistory sandstone units as much as 85 ft thick which contain trough cross beds as much as 5 ft high. These sandstone units are interbedded with gray mudstones and carbonaceous shales. Paleosols are preserved at the tops of individual sandstones in the multistory units in some places. It is suggested that these sandstones were deposited largely by low-sinuosity to braided streams.

The Meeteetse Formation consists of alternating coal and sandstone-rich intervals. The coal-rich intervals have relatively thin fluvial channel sandstones probably deposited by medium to high sinuosity streams whereas the sand-rich intervals have thick (to 105 ft) multistorey fluvial channel sandstones possibly deposited by low-sinousity to braided streams.

The geometry of Paleocene-age Fort Union Formation sandstone reservoirs was studied in detail near the town of Hudson (Flores and others, 1993) and in the Shotgun Butte area (Flores and Keighin, 1993) in the western part of the Wind River Basin (Figures 3 and 6). Four types of reservoirs were recognized in the Shotgun Butte area. Type I reservoirs consist of a sandstone, as

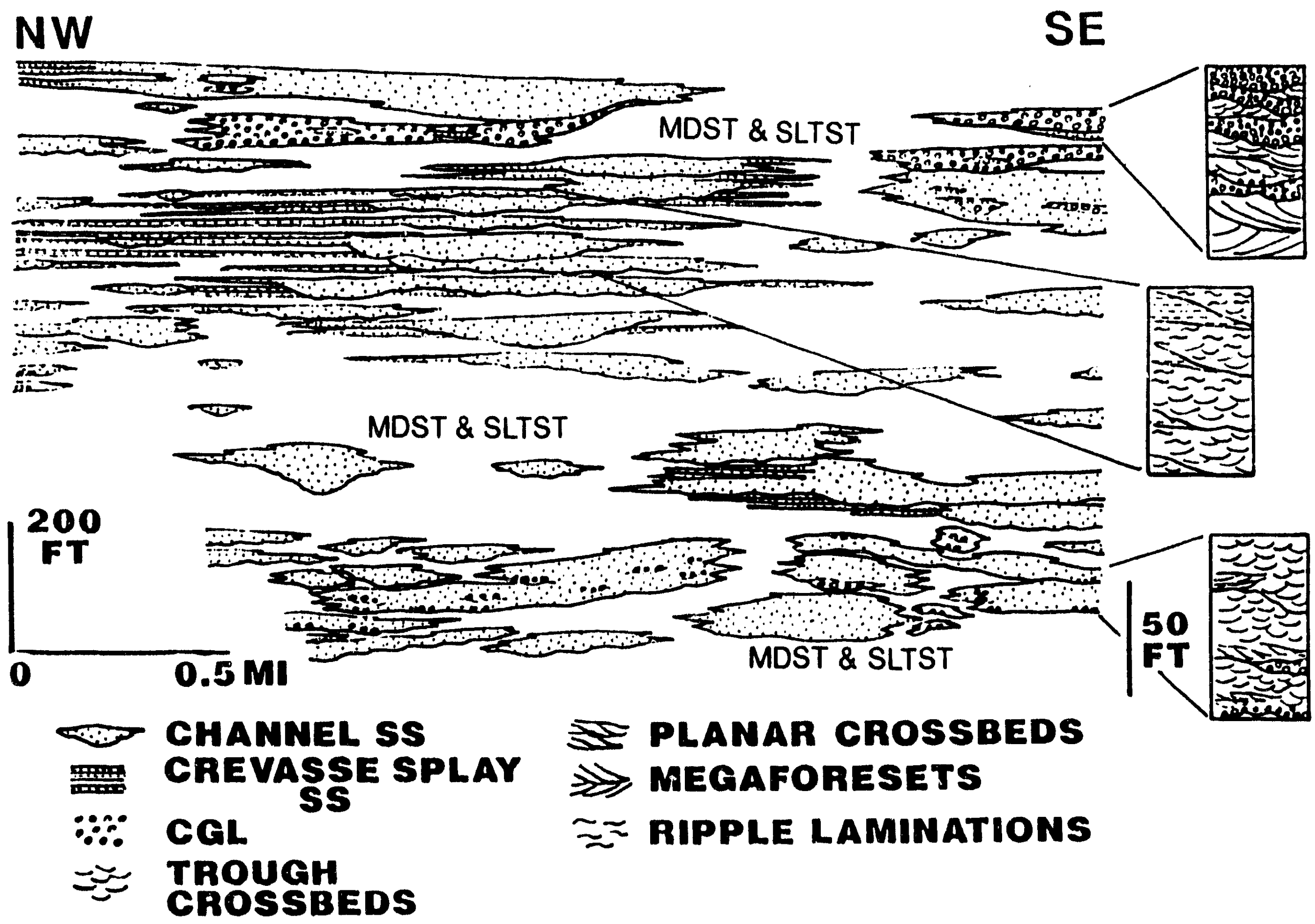

Figure 6. Cross section showing facies stratigraphic framework of sandstone and conglomerate reservoirs and associated seal rocks of mudstones, siltstones, silty sandstones, carbonaceous shales, and coals in outcrop at Merriam anticline, Wind River Reservation.

much as 58 ft thick and as much as 0.6 miles in lateral extent, that is probably basally erosional, and with internal scours marked by lag conglomerates. Large trough crossbeds (as much as 2 ft in height) and planar crossbeds (as much as 1.5 ft in height) internally compartmentalize the individual reservoir units bounded by scour surfaces. Type II reservoirs consist of sandstone, 12 to 30 ft thick, separated by siltstone and mudstone seal rocks, 3 to 20 ft thick. The sandstones form multistorey reservoir complexes to 80 ft thick and 0.25 miles in lateral extent. Type III reservoirs consist of sandstones, 8 to 45 ft thick, interbedded with siltstones and mudstones, 5-40 ft thick. Sandstones are stacked into multistorey sequences as much as 100 ft thick and 0.8 miles in lateral extent. Within the multistorey sequence, individual sandstones are laterally offset and separated by siltstone and mudstone interbeds. These interbeds thin and pinch out toward the direction of amalgamated sandstones and thicken toward their margins. Type IV reservoirs consist of tabular sandstones, as much as 20 ft thick and 1 mile in lateral extent, capping an interval of interbedded mudstone and siltstone. Stacked tabular sandstone reservoirs, as much as 100 ft thick are commonly laterally juxtaposed against type III sandstone reservoirs. This association makes type III and type IV reservoirs the most continuous reservoir system.

Variations in the chemical and isotopic compositions ($\delta^{13}C_1$) of gases from the Wind River Basin were studied in order to better understand the origins of the gases (Johnson and Rice, 1993). Gases from all producing intervals in conventional reservoirs at depths ranging from 2,321 to 18,050 ft are predominantly thermal in origin (C_1/C_{1-5} of 0.82 to 1.0, $\delta^{13}C_1$ of -31.12 to -47.40‰). Most gases sampled from conventional reservoirs appear to have migrated from deeper, more mature source rocks (Figure 7). Gases were collected from three fields where reservoirs from several stratigraphic levels are productive: the Madden field along the deep basin trough, and the Pavillion and East Riverton Dome fields in the western part of the basin. Considerable vertical migration has occurred at all of these fields (Figure 8). At Madden, for example, gases become only slightly heavier isotopically ($\delta^{13}C_1$ of -34.81 to -31.82‰) and chemically drier (C_1/C_{1-5} of 0.95 to 1.0) through more than 12,000 ft of section (5,556 to 18,050 ft). At Pavillion, gases from the shallow (3,437 to 3,564 ft), immature reservoirs (R_m 0.5 percent) in the lower Eocene Wind River Formation are isotopically heavy ($\delta^{13}C_1$ of -39.24 to -40.20‰) and were generated by mature to post-mature source rocks.

The lacustrine Waltman Shale Member of the Paleocene Fort Union Formation, which is present throughout much of the eastern two-thirds of the basin, appears to inhibit the vertical migration of gas from deeper sources. Few gas fields produce from the marginally mature reservoirs above the Waltman Shale Member, and the gas that is produced from this interval appears to have originated in the Waltman. At Fuller Reservoir field, in the central part of the basin, gas from shallow (2,500-3,500 ft), marginally mature (R_m 0.60 to 0.65 percent) reservoirs in the Fort Union Formation above the Waltman Shale Member is associated with waxy oil, is wet chemically (C_1/C_{1-5} of 0.84) and is isotopically light ($\delta^{13}C_1$ of -46.99‰). This gas and oil appears to have been generated in the Waltman Shale Member deeper in the basin. Gases from below the Waltman

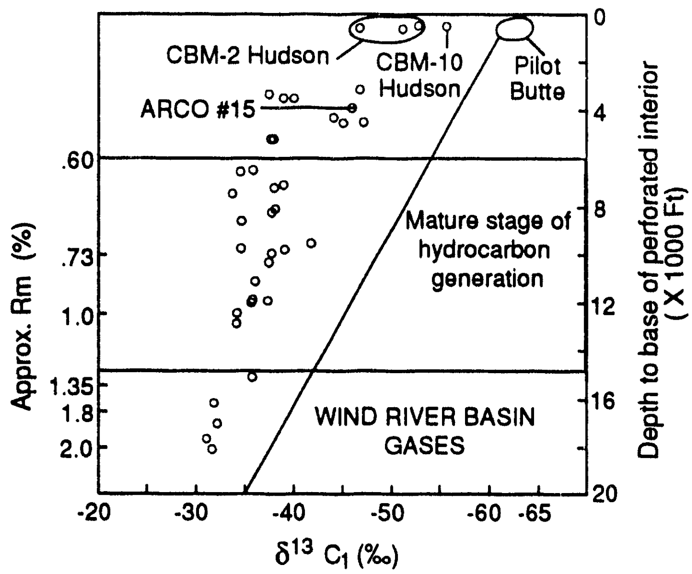

Figure 7. Depth to base of producing interval versus methane carbon isotopic composition (δ13C1) for gases, Wind River Basin, Wyoming. Approximate vitrinite reflectance (R_m) of reservoir rock is also shown. Gases from coalbed methane reservoirs are labeled. Locations of coalbed methane tests are shown on Figure 3. A line showing approximate changes in δ13C1 with increasing thermal maturity is shown. Gases which plot to the left of the line have probably migrated from deeper, more mature source rocks.

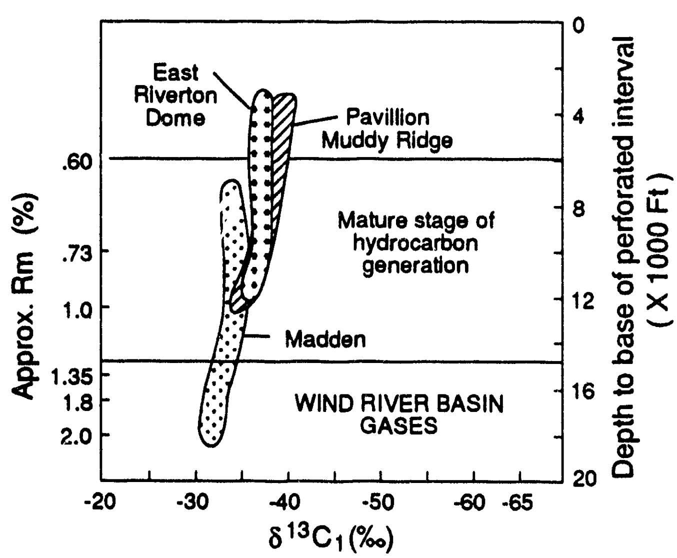

Figure 8. Depth to base of producing interval versus methane carbon isotopic composition (δ13C1) for gases from over wide depth ranges at Pavillion-Muddy Ridge, East Riverton Dome, and Madden fields.

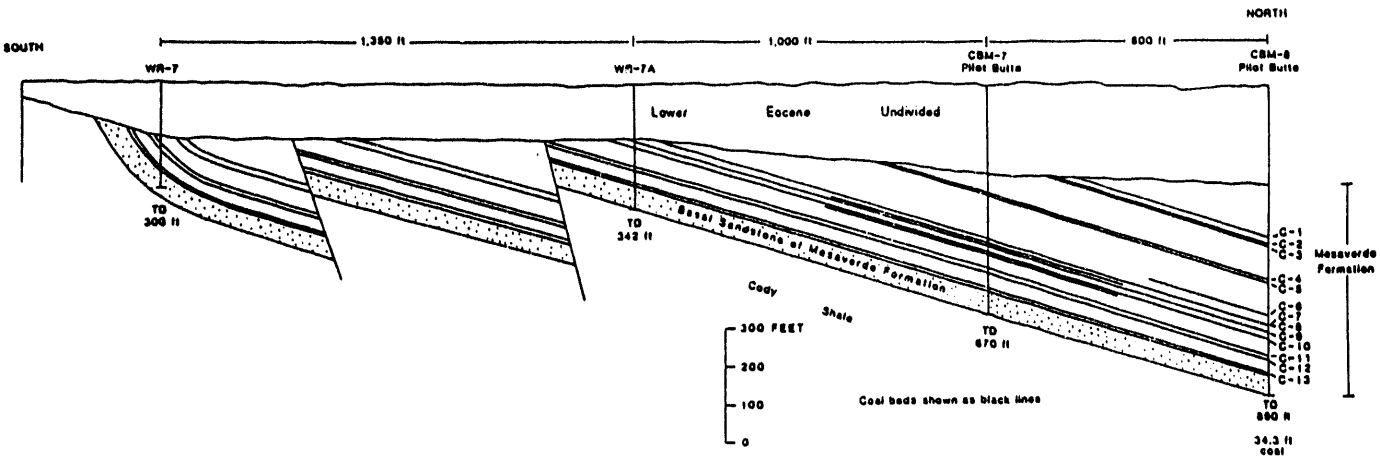

Figure 9. Generalized cross section through Pilot Butte coalbed methane test site, Wind River Reservation, showing coal beds in the Upper Cretaceous Mesaverde Formation truncated and sealed beneath younger strata. Coal beds sealed in this fashion typically contained significant methane in the shallow subsurface. Location of Pilot Butte site on Figure 3. From Johnson and others (1993). Drillholes CBM-7 and CBM-8 from U.S. Geological Survey coalbed methane drilling program. Drillholes WR-7 and WR-7A are from Windolph and others (1982).

Shale Member are chemically dry (C_1/C_{1-5} of 0.94 to 0.95) and isotopically heavy ($\delta^{13}C_1$ of -34.79 to -36.19‰) and probably migrated from underlying Upper Cretaceous source rocks. In contrast, at Pavillion field, west of the pinchout of the Waltman Shale Member, mature gases from probable Upper Cretaceous source rocks were able to migrate into the shallow marginally mature reservoirs of the lower Eocene Wind River Formation.

A single coalbed methane well is producing in the western part of the basin, at Riverton Dome in the southeast corner of the Wind River Reservation. Gas from this well, which is completed in Upper Cretaceous Mesaverde Formation coals at depths of 3,270 to 3,839 ft., appears to be of thermogenic origin ($\delta^{13}C_1$ -46.15‰, C_1/C_{1-5} 0.98). Shallow coalbed gases (307 to 818 ft) desorbed from cores of the thermally immature (R_m 0.40 to 0.54 percent) Mesaverde Formation in the Wind River Reservation have highly varied chemical and isotopic compositions and appear to have complex and varied origins. Coalbed gases from the Hudson area in the southeastern corner of the Reservation have the isotopic compositions of a thermally generated gas ($\delta^{13}C_1$ -47.0 to -55.91‰). Coalbed gases from the Pilot Butte area about 25 miles to the northwest (Figure 9) appear to be a mixture of biogenic and thermogenic gas. The methane fraction is isotopically light ($\delta^{13}C_1$ -61.85 to -66.21‰) and is probably largely biogenic, but the gases contain as much as 5.6 percent C_{2+} and this fraction is probably of thermogenic origin. These coals appear to be too thermally immature to have generated significant quantities of thermogenic gas, and it is suggested that the thermogenic component of these gases migrated into the coals from a deeper, more thermally mature source.

FUTURE WORK

Our studies, which have concentrated in the western part of the Wind River Basin, will be extended into the eastern part of the basin. We will continue to work with drillstem test, perforation recoveries, and mudweights to help better define the extent of the tight gas accumulation. This subsurface information will be used in conjunction with reservoirs architecture studies in order to define the production characteristics of various types of sandstone reservoirs within the tight gas interval.

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