U.S. DEPARTMENT OF THE INTERIOR

U.S. GEOLOGICAL SURVEY

Geology of Upper Cretaceous and Paleocene Gas-Bearing Rocks, Wind River Basin, Wyoming

by

Ronald C. Johnson, Thomas M. Finn, William R. Keefer, and Richard J. Szmajter[1]

Open-File Report 96-090

[1] USGS, Denver CO

GEOLOGY OF UPPER CRETACEOUS AND PALEOCENE GAS-BEARING ROCKS, WIND RIVER BASIN, WYOMING

By
Ronald C. Johnson, Thomas M. Finn, William R. Keefer, and Richard J. Szmajter

INTRODUCTION

The Wind River Basin in central Wyoming (Figures 1 and 2) is one of several large sedimentary and structural basins in the Rocky Mountain region 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 millidarcy (md) or less. Rocks with permeabilites of 0.1 to 1.0 md are categorized as near tight. 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 simple basin-centered accumulations. These accumulations differ from conventional hydrocarbon accumulations 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 (Spencer, 1985). The abnormal pressures of these reservoirs indicate that water, in hydrodynamic equilibrium with outcrop, is not the pressuring agent.

The Wind River Basin produces mainly oil around the basin margins and mainly gas from the deeper areas of the basin (Figure 3). Most of this deeper gas is from reservoirs of Upper Cretaceous and Tertiary age with permeabilities that vary from conventional to tight. The basin -centered accumulation in the Wind River Basin appears to extend through an enormously thick stratigraphic interval near the basin trough. At Madden Anticline in the north-central part of basin (Figure 3) and just south of the basin trough, stratigraphic units as young as the lower unnamed member of the Paleocene Fort Union Formation (Figure 4) possess some of the characteristics of a basin-centered gas accumulation including nearly continuous gas shows, slight overpressuring, and a general inability to predict production characteristics from geophysical logs (Dunleavy and Gilbertson, 1986, p. 111-112). The basin centered accumulation extends down at least to the base of the highly overpressured Upper Cretaceous Frontier Formation for a total stratigraphic thickness of as much as 15,000 ft.

Masters (1979) was one of the first to study these unusual accumulations, which occur downdip from more permeable, water-wet rocks, and proposed that gas generated in the deep, thermally mature areas of sedimentary basins is inhibited from migrating upwards and out of the basin by a capillary seal. Masters pointed out that low-permeability rocks (1 md), with 40% water saturation, are only three-tenths as permeable to gas as they are water, and at 65% water saturation, the rock is almost completely impervious to the flow of gas. The concepts for the development of basin-centered gas accumulations in the Rocky Mountains have been further refined by a number of workers (Meissner, 1980; 1981; 1984; McPeek, 1981; Law and others, 1979; 1980, Law and Dickenson, 1985; Macgowan and others, 1993; Spencer and Law, 1981; Spencer, 1985; Spencer, 1987: Yin and Surdam, 1983). In general, these models suggest that overpressuring in these basin-centered accumulations is a result of volumetric increases during hydrocarbon generation by coals, carbonaceous shales and marine shales that are interbedded

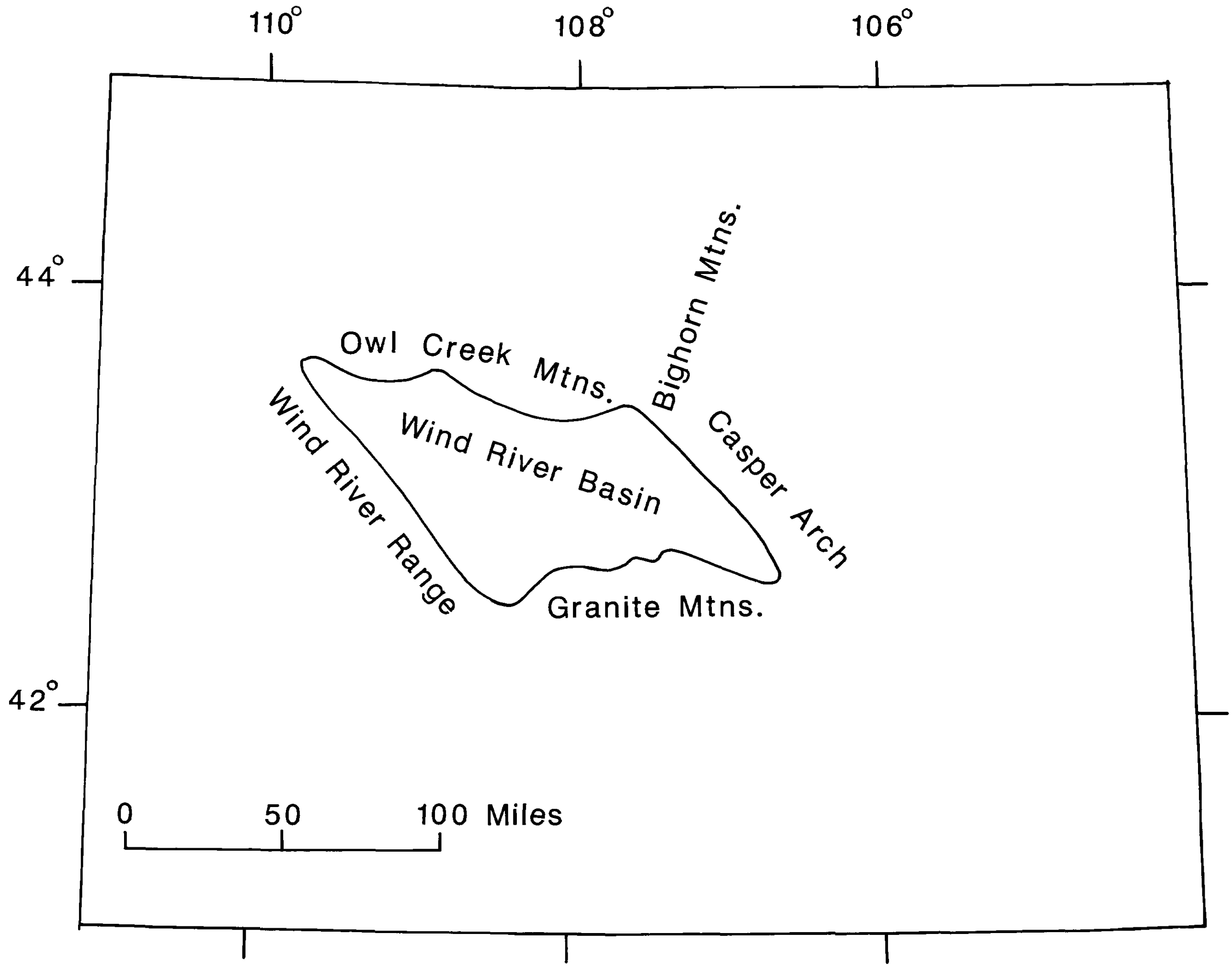


Figure 1 Index map showing location of Wind River Basin and surrounding uplifts.

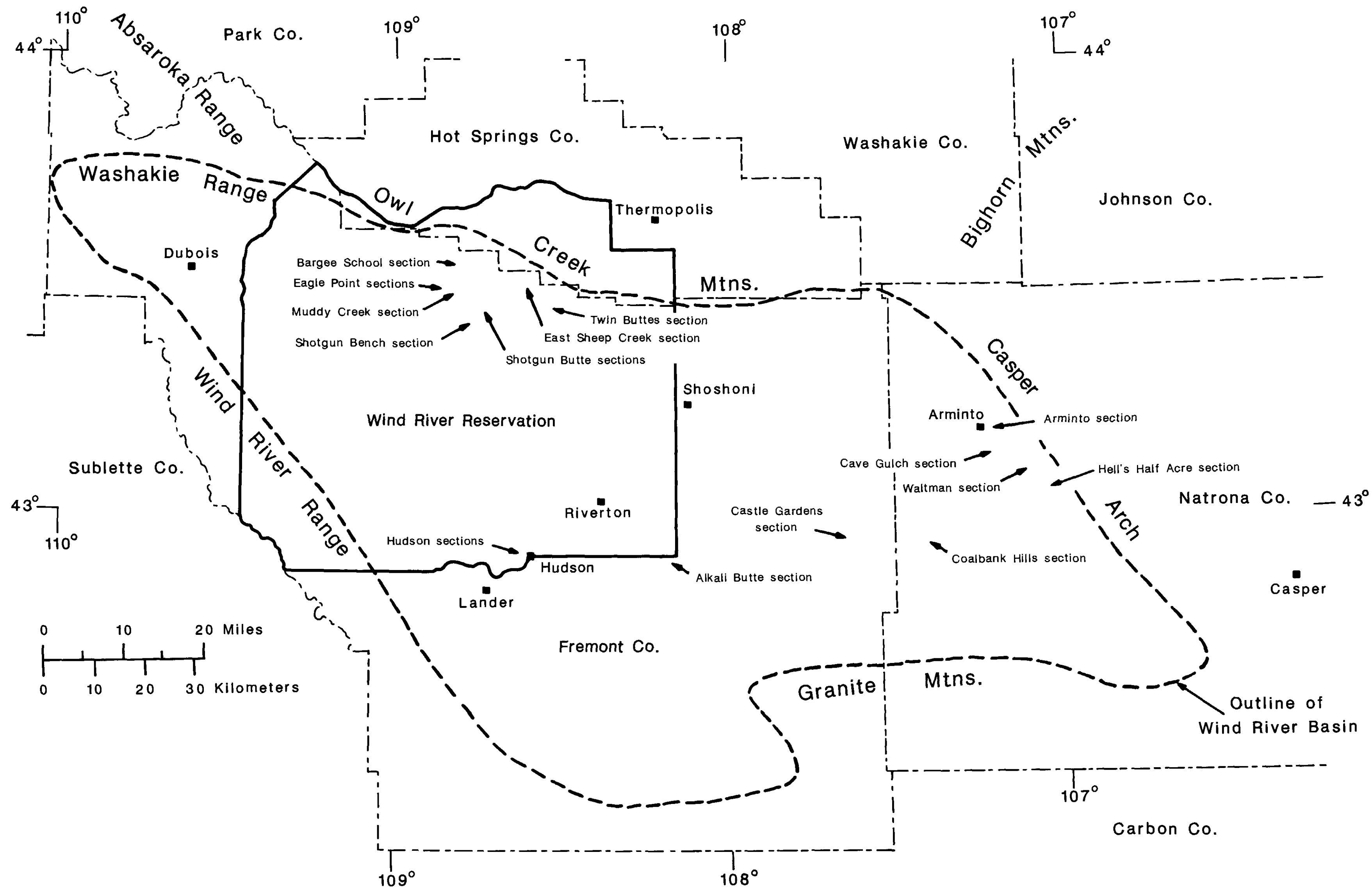


Figure 2: Index map of central Wyoming showing approximate outline of Wind River Basin and location of Wind River Reservation in the western part of the basin. Locations of measured sections and detailed outcrop studies also shown.

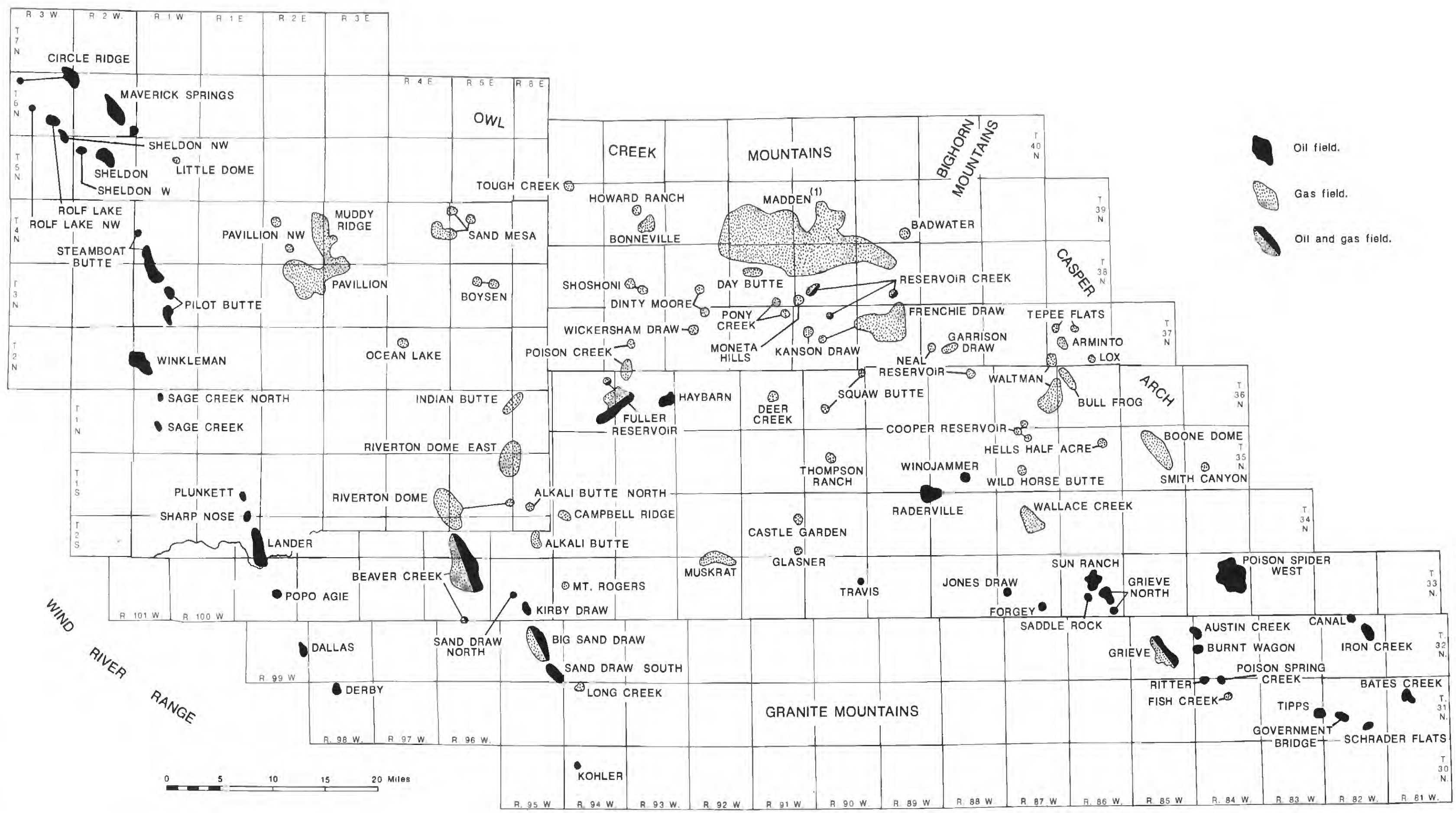


Figure 3: Map showing locations of oil and gas fields in Wind River Basin that produce from Upper Cretaceous and Lower Tertary rocks. Modified from De Bruin and Hostetler (1991).

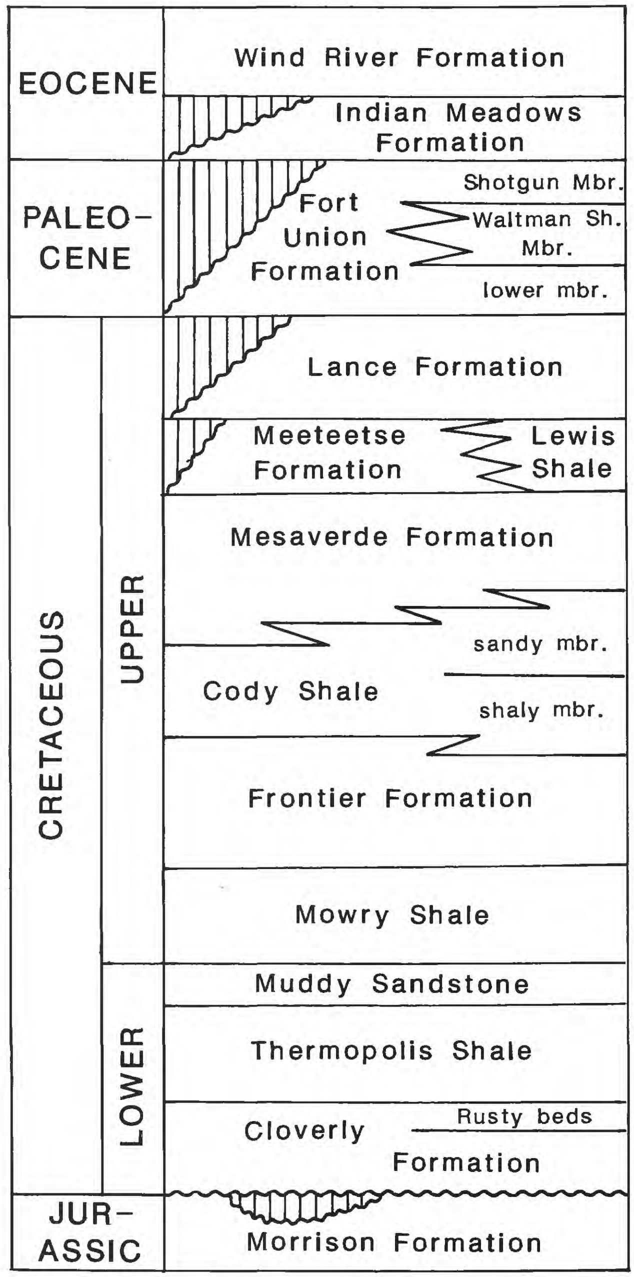


Figure 4: Generalized stratigraphic chart of Cretaceous and Lower Tertiary rocks, Wind River Basin, Wyoming.

with the sandstone reservoir rocks, and that migration distances from source rock to reservoir rock are not great. Much of the water that fills the pore spaces is displaced in these basin-centered hydrocarbon accumulations as the hydrocarbons are generated. Recent work by Jiao and Surdam (1993) in the Powder River Basin and by MacGowan and others (1993) in the Green River Basin further develops the concept of capillary seals introduced by Masters (1979). These seals develop in low permeability rocks as this system evolves from a single phase water system to multiple phase water and hydrocarbon systems. In addition, an overpressured accumulation can evolve into one that is underpressured if a basin undergoes significant cooling.

These basin-centered accumulations appear to contain very large in-place resources. Johnson and others (1987) estimated an in-place resource of 420 trillion cubic feet (tcf) of gas in the Piceance Basin of western Colorado, while Law and others (1989) estimated an in-place resource of 5,063 tcf for the Greater Green River Basin in Wyoming, Colorado, and Utah. These huge in-place numbers have helped spark considerable interest in developing these accumulations, although only a small fraction of the gas in place is ever likely to be produced. Finding gas in basin-centered accumulations is not difficult since almost all sandstones within the accumulation are capable of producing some gas. However, production histories for individual gas wells within an accumulation can vary widely. Much of this variation appears to be due to geologic factors, and a better understanding of these factors can lead to more economic development of tight gas accumulations.

Structure plays a different role in basin-centered gas accumulations than for conventional gas reservoirs. Unlike conventional reservoirs, gas is pervasive in basin-centered accumulations and occurs both on structure and off structure. The main role of structure in basin-centered gas accumulations is to create open fractures which allow the gas to travel to the well bore. At Madden anticline in the north-central part of the Wind River Basin (Figure 3), fracture enhancement along the crest of the anticline is the most important factor in determining reservoir productivity in the Upper Cretaceous "Sussex sandstone" and "Shannon sandstone" of the Cody Shale (Dunleavy and Gilbertson, 1986, p. 115, 120). In the Piceance Basin of western Colorado, wells along the highly fractured crest of the Rulison anticline have produced as much as 300% more gas than wells outside the fractured zone (Reinecke and others, 1991; Peterson, 1984; Mercer and Frohne, 1986).

Many recent studies of basin-centered gas accumulations in Rocky Mountain basins emphasize the importance of a systematic geologic evaluation in developing these resources. A recent study of tight gas production from sandstones in the Upper Cretaceous Lewis Shale in the Hay Reservoir area of the Red Desert Basin of Wyoming by Anderson (1994) found that the highest permeabilities were encountered near the updip pinchouts of the sandstones. He attributed these higher than average permeabilities to early hydrocarbon migration into these stratigraphic traps which prohibited later clay diagenesis. Forster and Horne (1994) in a recent study of tight gas production from the Upper Cretaceous Frontier Formation in the Green River Basin of Wyoming and Colorado, found that both the distribution of natural fractures and variations in sedimentary facies have enormous impacts on productivity. Fouch and others (1992) stress the importance of natural fractures to production from tight reservoirs in the Uinta Basin of Utah and Colorado.

Contrary to what the basin-centered gas models have predicted, water production can be significant from tight gas wells, and disposal of this water is usually expensive. In the southern part of the Piceance Basin of western Colorado the Upper Cretaceous Rollins or Trout Creek Sandstone of the Measverde Formation is water wet in an otherwise highly overpressured gas-charged interval. Water from the Rollins or Trout Creek, has leaked from behind pipe into perforations in other gas bearing intervals causing production problems (Mann and Malinowski, 1993). The Rollins or Trout Creek is a marginal marine blanket-like sandstone that crops out around much of the margin of the Piceance Basin. Normally pressured and commonly water-bearing sandstones appear to be in hydrodynamic equilibrium with basin ground water suggesting communication with surface recharge areas.

Variations in thermal maturity levels of source rocks are important in helping define the limits of basin-centered hydrocarbon accumulations because of the close proximity between source rocks and reservoirs. In the Piceance Basin of western Colorado and eastern Utah, Johnson and others (1987) used a vitrinite reflectance (Rm) level of 1.1% to roughly define the limits of the basin-centered accumulation while an Rm of from 0.73 to 1.1% was used to define a transition zone containing both tight reservoirs and reservoirs with near-tight and conventional permeabilities. Masters (1984, p. 27, Figure 25) in his study of the basin-centered gas accumulation in the Deep Basin of Alberta, shows that an Rm of 1.0% corresponds approximately to the limits of the accumulation. In the Greater Green River Basin of Wyoming and Colorado, Law and others (1989) found that an Rm of 0.80% generally corresponds to the top of overpressuring. Vitrinite reflectance (Rm) data were collected in the Wind River Basin to determine maturity levels in potential source rocks and their ability to generate hydrocarbons (Pawlewicz, 1993; Nuccio and others, 1993). This information was used by Johnson and others (in press) and Nuccio and others (in press) to construct maps showing the approximate elevations of the Rm. 0.73% and Rm. 1.1% thermal maturity levels throughout the basin.

Recent work on the variations in the chemical and isotopic compositions of gases in the Wind River Basin, the Piceance Basin of western Colorado, and the Uinta Basin of eastern Utah (Johnson and Rice, 1993; Johnson and others, 1994a; 1994b) suggests that, in all three basins, there has been considerable vertical migration of gases from mature Cretaceous-age source rocks in the basin-centered hydrocarbon accumulations into overlying marginally mature to immature lower Tertiary sandstone reservoirs with conventional permeabilities. In the Wind River Basin, this vertical migration appears to be significantly impeded by the Waltman Shale Member of the Paleocene Fort Union Formation which acts as a seal, prohibiting gas from migrating vertically into reservoir rocks within and 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 these heavy gases are probably sourced by thermally mature Upper Cretaceous source rocks (Johnson and Rice, 1993; Johnson and others, 1994a). The isotopically light gases produced from the Waltman Shale and overlying unit, in contrast, are probably sourced by the Waltman. At Pavillion and Muddy Ridge fields in the western part of the basin and west of the pinchout of the Waltman Shale, isotopically heavy gases have migrated vertically from Upper Cretaceous source rocks into units as young as the lower Eocene Wind River Formation.

The purpose of this report is to characterize the geologic factors needed to assess the in-place tight gas resource in the Wind River Basin and to estimate recoverable gas resources under various economic models. Geologic factors examined include basin deformational and thermal history, distribution of potential source rocks, sandstone thicknesses and sandstone percentages in the total rock column, and sandstone architecture. Detailed surface sections were measured and described at several localities along the basin margins, and geophysical logs from almost all wells that penetrate thick sandstone-bearing formations of Late Cretaceous and early Tertiary ages in the basin interior have been examined. The resulting data were used to prepare isopach maps of individual formations, structure contour maps on selected horizons, and sandstone and coal thickness maps of various units. Information on the distribution, thickness, and lithologic character of the sandstone beds, combined with porosity and water saturation estimates, form the basis for calculating the volume of in-place and recoverable gas resources. This assessment will be presented in a future report.

The investigations on which this report is based were funded by the U. S. Department of Energy as part of its Western Tight Gas Sands Program.

SUMMARY OF GEOLOGIC HISTORY

The Wind River Basin is an extensive structural depression surrounded by broad belts of faulted and folded Paleozoic and Mesozoic rocks that occupy the flanks of the adjacent mountain ranges and anticlinal uplifts, including the Wind River Range on the west, the Washakie Range and Owl Creek and southern Bighorn Mountains on the north, the Casper arch on the east, and the Granite Mountains on the south (Figures 1 and 2). Along the south and west margins of the basin the sedimentary strata dip 10°-20° basinward, whereas along the north and east margins the dips are commonly vertical to overturned. The basin floor is thus markedly asymmetric; the structurally deepest parts are close to the Owl Creek and Bighorn Mountains on the north and the Casper arch on the east. The basin interior is covered by nearly flat-lying lower Eocene rocks, which mask the structural features of the older rocks except along the mountain flanks and adjacent basin margins.

The basin formed during the Laramide orogeny in latest Cretaceous, Paleocene, and early Eocene time as the Rocky Mountain foreland basin, an extensive area of downwarping extending from the arctic to the Gulf of Mexico, was gradually partitioned into much smaller Laramide basins by rising Laramide uplifts. Epicontinental seas transgressed and regressed central Wyoming many times. The final major episode of marine deposition in central Wyoming is represented by the Cody Shale and the basal sandstone member of the overlying Mesaverde Formation that accumulated during the eastward regression of the Late Cretaceous shoreline. Nonmarine conditions prevailed during the deposition of the remainder of the Mesaverde as well as the overlying Meeteetse Formation, except for limited transgressions westward into the eastern part of the basin area as evidenced by the presence of tongues of the marine Lewis Shale within the Meeteetse stratigraphic interval (Figure 5). The sedimentary environment during the nonmarine period was largely characterized by floodplains, lagoons, and coastal swamps.

Major Laramide deformation began in latest Cretaceous time (beginning of Lance deposition) with pronounced downwarping of the basin trough and broad doming of parts of the marginal areas. The intensity of movement increased through the Paleocene, and culminated in earliest Eocene time as high mountains were uplifted. Clastic debris, stripped from the flanks of the rising mountain arches, was shed basinward from all sides, and a complete record of orogenic events is now preserved in the many thousands of feet of nonmarine sedimentary rocks

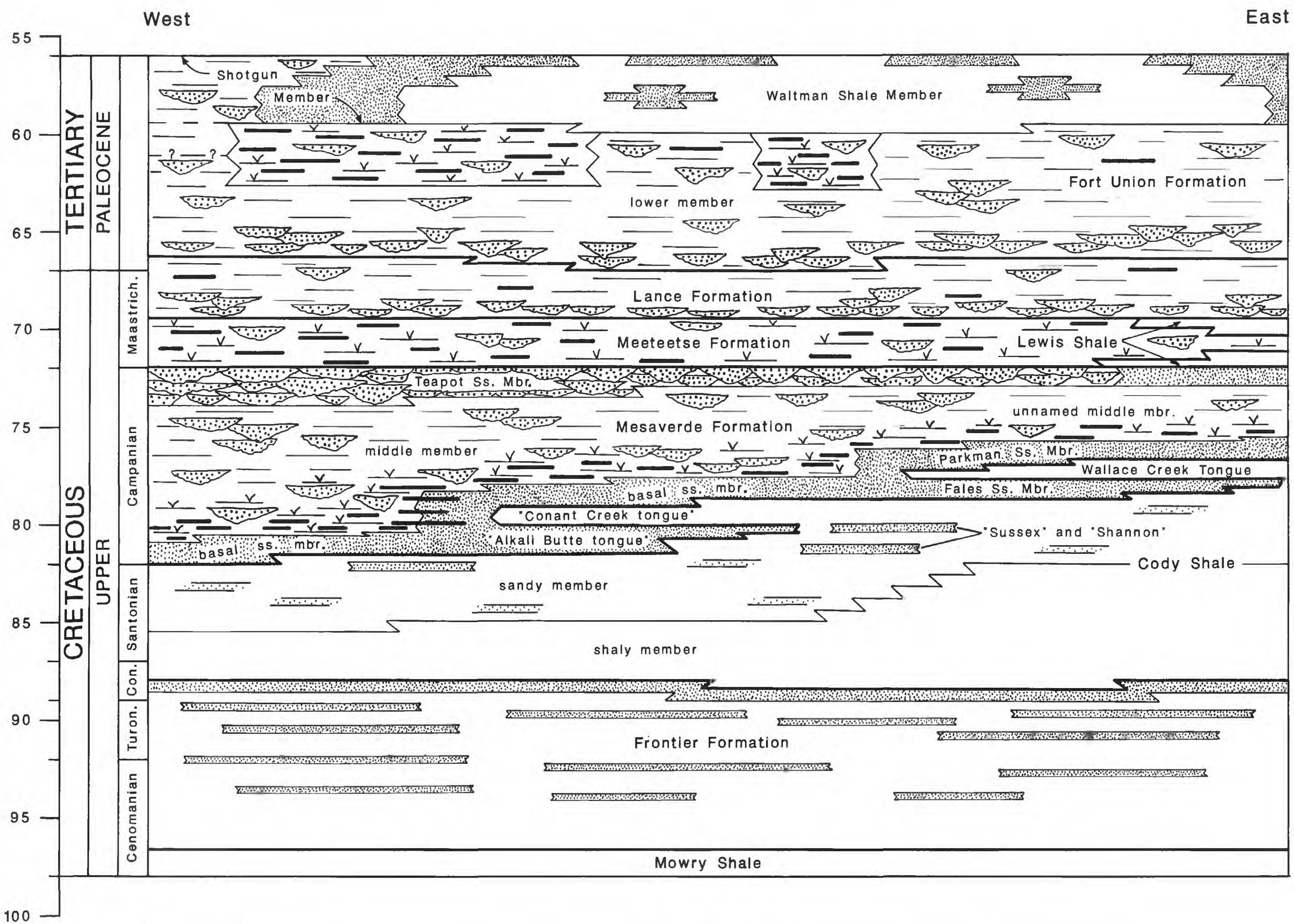
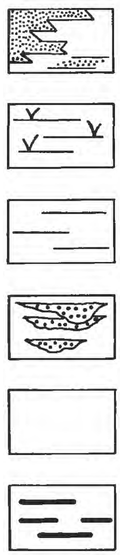


Figure 5: Detailed east-west correlation diagram for the Wind River Basin showing stratigraphic units and generalized sedimentary facies. Approximate age in millions of years before present shown on left.

EXPLANATION



Marine, marginal marine, or lacustrine sandstones.

Paludal and floodplain — carbonaceous shales, and mudstones.

Floodplain siltstones, and mudstones.

Fluvial sandstones.

Marine or lacustrine shale.

Coal.

in the Lance, Fort Union, Indian Meadows, and Wind River Formations (Figure 4) that accumulated in the areas of greatest subsidence.

Basin subsidence and mountain uplift had virtually ended by the close of early Eocene time. Renewed folding and faulting of existing structural features took place after deposition of the Eocene Wind River Formation, but with few exceptions these movements were of minor consequence and did not significantly modify the structural patterns that had already been established.

Extensive sedimentation resulted in deposition of thick basin-fill sediments in middle and late Tertiary times. These younger rocks, which were subsequently eroded from the area of the Wind River Basin, were estimated by Keefer (1970, p. D29) to be as much as 3,000 feet thick. Keefer's estimate was made by projecting across the Wind River Basin erosional remnants of pediment surfaces preserved along the flanks of Beaver Rim Divide to the south and the Absaroka Range to the northwest. Based on lithologies preserved in these remnants, this missing section was predominantly volcanoclastic, in sharp contrast to the predominantly non-volcanic, locally derived clastic material of the lower Eocene and older parts of the basin fill. By Pliocene time apparently only the highest mountain ridges projected above the sedimentary plain. Then, perhaps in middle or late Pliocene time, the entire region was uplifted several thousand feet, and a long period of degradation began which still continues. Re-excavation has now progressed to the point where only the lower Eocene and older rocks still remain in the central part of the basin. It should be emphasized, however, that the total thickness of basin-fill sediments that had accumulated by late Tertiary time (those remaining and those subsequently eroded away) should be taken into account in studies of the thermal maturity and burial histories of potential petroleum source rocks within the basin.

After the onset of the Laramide orogeny, the sedimentary history of the Wind River Basin is directly linked to the history of uplift on each of the surrounding uplifts. Flores and other (1994), in their paleogeographic reconstruction's of Wyoming, show that the present-day Wind River Basin developed gradually during Paleocene time as each of the uplifts that define the basin became successively active. According to Flores and others (1994) the Wind River Range and Sweetwater Arch south of the Wind River Basin were actively rising by early Paleocene time. The Washakie Mountains northwest of the basin and the Granite Mountains south of the basin became active in middle Paleocene time, while the Owl Creek Mountains north of the basin and Casper Arch northeast of the basin did not become active until late Paleocene time.

Multiple unconformities in the Upper Cretaceous and lower Tertiary section adjacent to the Wind River Range record several periods of uplift and/or base level lowering in the adjacent basin (Figure 4). The oldest unconformity along the flank of the Wind River Range occurs between the Meeteetse Formation and Lance Formation. In the western part of the basin, this unconformity progressively truncates through the Meeteetse Formation through a lateral distance of from about 1 1/2 to 6 miles (Figure 6). A second unconformity occurs between the Lance and the overlying Fort Union Formation (Figure 4)). The Lance appears to be completely truncated in outcrop along the flanks of the Wind River Range but is present in the subsurface a short distance basinward (Keefer and Johnson, 1993, Figure 3, Plates 2, 4 and 5).

Flores and others (1994) suggest that two major river systems developed in the area of the Wind River Basin during the early Paleocene, one flowing eastward near the trough of the

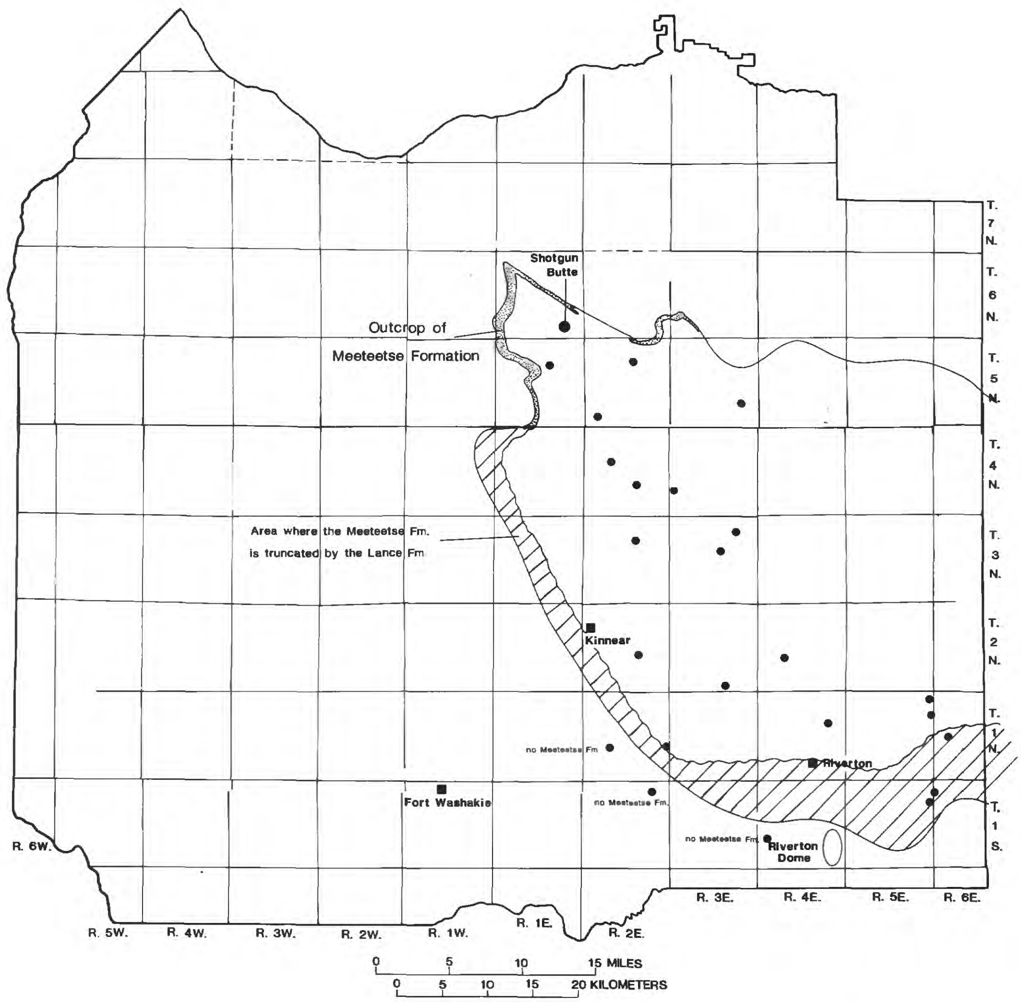


Figure 6: Map showing distribution of the Upper Cretaceous Meeteetse Formation in the Wind River Reservation, western part of the Wind River Basin. (Stipple - Meeteetse outcrop; hachure - area where Meeteetse is truncated by the Lance Formation). The Meeteetse is overalain conformably by the Lance in outcrops near Shotgun Butte. From Keefer and Johnson (1993).

basin, and a second flowing northeastward to eastward along the south flank of the basin. The first is represented in outcrop by conglomeratic, braided and meandering stream deposits in the Shotgun Butte area in the northwest part of the basin (Flores and Keighin, 1993). The second is represented by a 15 mile wide paleovalley incised into Upper Cretaceous rocks along the flank of the Wind River Range near the town of Hudson (Flores and others, 1993). This paleovalley appears to have trended generally northeastward to eastward into the Castle Garden area adjacent to the Granite Mountains. In late Paleocene time much of the basin was flooded by an extensive permanent lake, Lake Waltman, in which was deposited 3,000 feet or more of dark-colored, very fine-grained lacustrine sediments which now comprise the Waltman Shale Member of the Fort Union Formation (Figures 4 and 5). The basin may have evolved into a closed basin at this time as a result of uplift on the Owl Creek Mountains and Casper Arch (Flores and others, 1994). The lake was largely filled in prior to the end of the Paleocene.

GEOLOGIC STRUCTURE

Four structure contour maps were prepared for this study: 1) top of the Upper Cretaceous Frontier Formation; 2) top of the Upper Cretaceous Cody Shale; 3) top of the Upper Cretaceous Mesaverde Formation; and 4) base of the Paleocene Waltman Shale Member of the Fort Union Formation and laterally equivalent marginal lacustrine rocks (Plate 1). The structure contour map on the top of the Frontier Formation extends considerably farther toward the margins of the basin than the other three structure contour maps and hence best illustrates the overall structure in these marginal areas. A nearly continuous reverse fault system, with displacements of about 30,000 feet along the Owl Creek-Bighorn Mountain complex and 20,000 feet along the Casper arch, bounds the north and east margins of the basin, respectively. The structure contour maps extend as far north as a series of normal faults that cut the Owl Creek thrust (see Keefer, 1970, Plate 1). However, much of the Upper Cretaceous through lower Tertiary interval clearly extends farther to the north on the subthrust plate (Ray and Keefer, 1985) but, in the absence of drillhole data, no attempt was made to extend the structure contour map into this area. Structure along the Casper Arch is from Skeen and Ray (1983).

Elevations on top of the Frontier Formation range from about 7,000 ft above sea level along the northeast dipping south and southwest margins of the basin to more than 18,000 ft below sea level along the trough of the basin adjacent to the Owl Creek Mountains. The trough of the basin during the time of Frontier, Cody, and Mesaverde deposition is difficult to define, and may actually have been overidden by the Owl Creek Mountains and Casper arch during later deposition as shown by Blackstone (1990) in a series of generalized cross sections across the north margin of the basin. Skeen and Ray (1983), in their detailed study of the Casper arch structure from both seismic and drillhole information, do not show a basin trough at the Frontier level. Instead, the Frontier, which predates the onset of movement on the Casper arch, is shown to continue dipping northward under the Casper arch thrust until it is truncated by the thrust. As indicated by the structure contours on the base of the Waltman Shale Member and its marginal lacustrine equivalent, however, the present basin trough is located a few miles south of the Owl Creek thrust fault.

A series of southwest thrusting thrust or reverse faults appears to underly a nearly continuous line of sharply folded and faulted asymmetric anticlines which occurs a few miles northeast of the southwest margin of the basin interrupting the uniform basinward dip of strata off the east flank of the Wind River Range. West of this anticlinal trend a series of prominent synclines, overidden in part by the thrust or reverse faults that bound the west limbs of the anticlines, form the main basin structure in its western extremity. In contrast to the pronounced structural downwarping that took place in the major basin trough area to the north and east (see below), the floors of these synclines were not depressed enough for the deposition of thick basin-fill sedimentary sequences during latest Cretaceous and early Tertiary times.

Another major thrust, the Emigrant Trail fault (Figure 7), occurs about 18 miles northeast of the line of anticlines previously discussed creating a subsidary basin trough between the Wind River Range and the Granite Mountains. The thrust appears to have formed in the early stages of the Laramide deformation. Figure 7 is an isopach map of the interval from the top of the the Teapot Sandstone Member of the Upper Cretaceous Mesaverde Formation to the base of the Waltman Shale Member of the Paleocene Fort Union Formation. These two units are the most widespread regional markers in the Upper Cretaceous through lower Tertiary interval of the basin. The Emigrant Trail fault is represented by a broad area of thinning that extends northward considerably beyond the north terminus of the fault as it is now mapped.

Northwest-plunging en echelon folds occur along the south margin of the basin north of the Granite Mountains and southeast plunging en-echelon folds occur in the northwest corner of the basin south of the Absaroka Range. Both sets of folds are generally asymmetric and faulted toward the west and southwest.

GEOLOGIC FORMATIONS

MOWRY SHALE

Although the Upper Cretaceous Mowry Shale (Figure 4) is not one of the formations being considered for its gas resources in tight sand reservoirs, it is discussed briefly because of its importance as a potential source rock for petroleum throughout central Wyoming. Approximately the upper, two-thirds of the formation is characterized by black, hard, siliceous shales that contain numerous thin beds of bentonite and a few thin hard quartzitic fine- to medium-grained sandstones. Approximately the lower one-third of the Mowry is nonsiliceous, soft fissile black shale. The formation is easily recognized on geophysical logs, exhibiting a distinctive series of resistivity curves (Figure 8), and some individual beds can be traced in the subsurface for considerable distances. Formation thicknesses are generally in the range of 450-550 feet; a maximum thickness of about 700 feet occurs in the extreme northwest corner of the basin. The Mowry is of marine origin and is Upper Cretaceous early Cenomanian in age (Cobban and Kennedy, 1989)

The average organic content of the Mowry Shale ranges from 1.5 to 2.5 percent across central Wyoming, and Schrayer and Zarrella (1963) considered it a likely source rock for hydrocarbons. As supporting evidence, (Schrayer and Zarrella, 1963) showed that the highest incidence of petroleum production in adjacent stratigraphic units coincides with the area of highest organic content in the Mowry Shale.

FRONTIER FORMATION

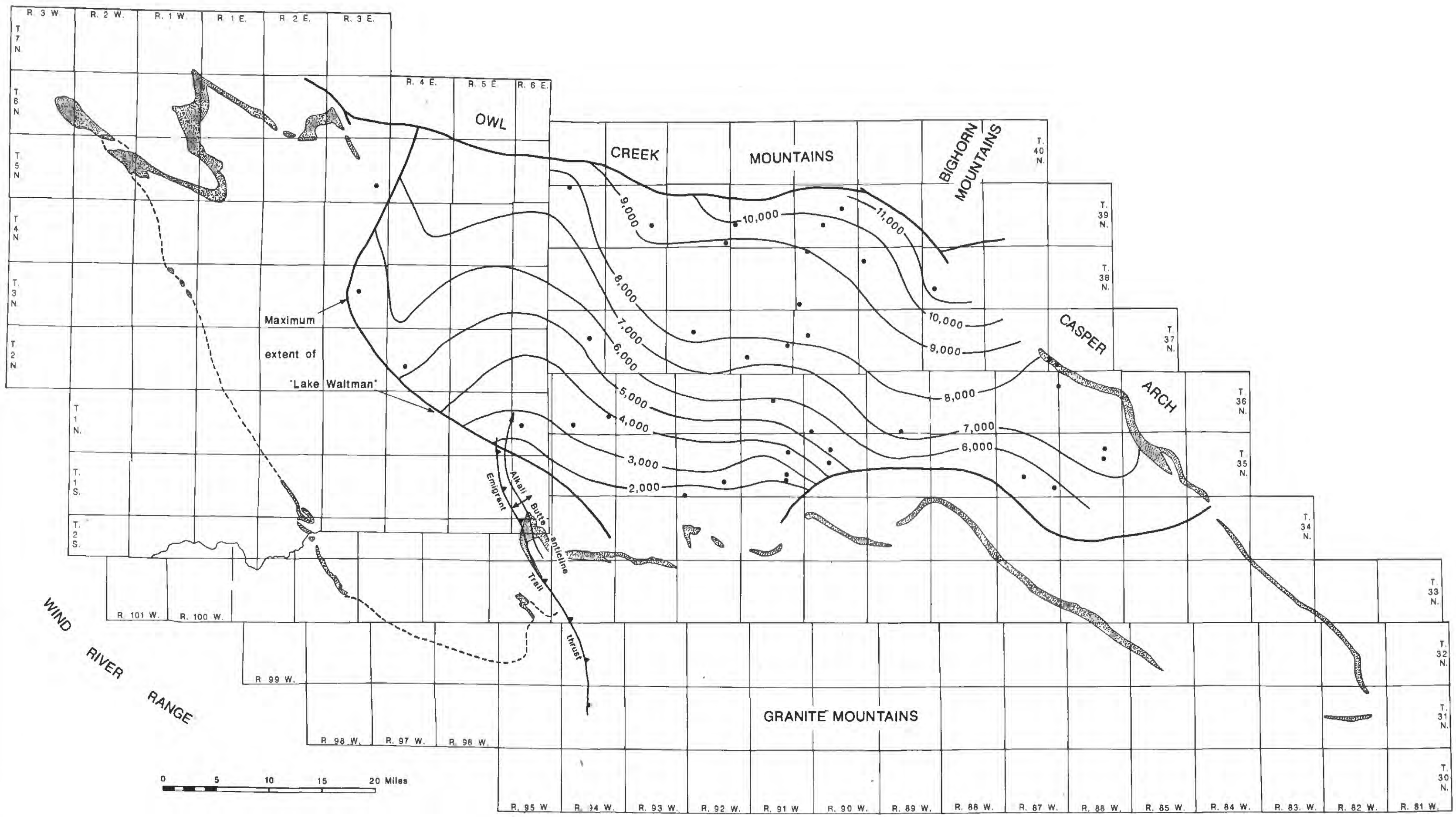


Figure 7: Isopach map of the interval from the top of the Teapot Sandstone Member of the Upper Cretaceous Mesaverde Formation to the base of theWaltman Shale Member of the Paleocene Fort Union Formation. Drillholes used for control are shown as black dots. Contour interval is 1,000 ft.

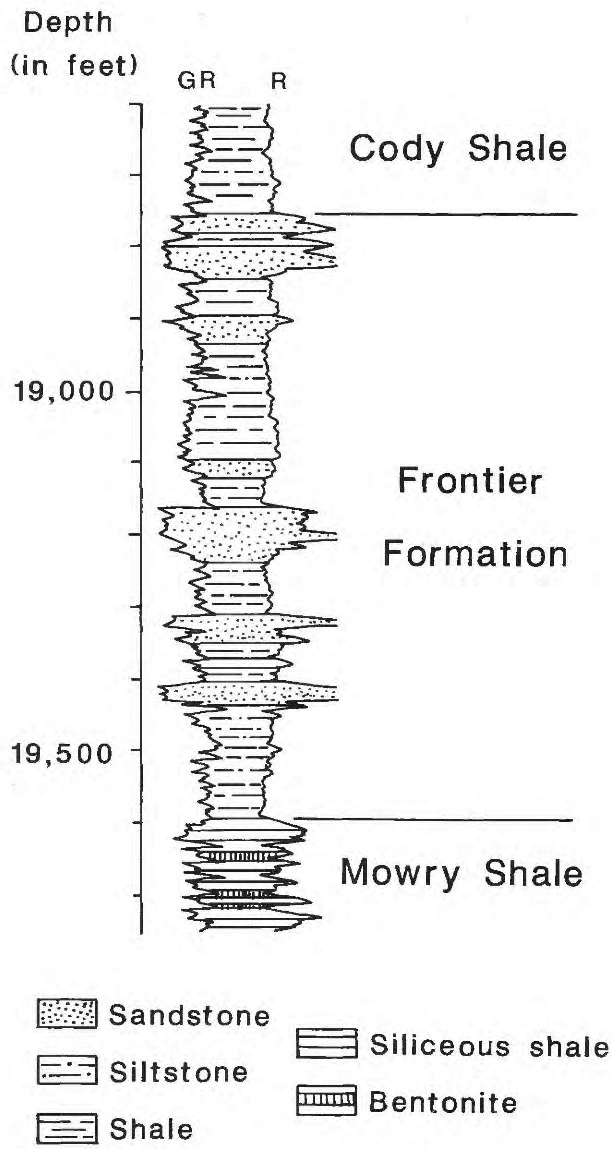


Figure 8 : Lithology, resisitivity (R), and gamma-ray (GR) logs of the Frontier Formation and Mowry Shale. Drill hole shown is Coastal Oil and Gas Bulfrog no. 2-7-36-86 (SE. 1/4 NW 1/4 sec. 7, T. 36N. R. 86W.).

The Upper Cretaceous Frontier Formation is a succession of regressive marine sandstones, nonmarine sandstones, and marine shale deposited above the black marine shales of the Mowry Shale in Late Cretaceous Cenomanian through early Coniacian time as the Cretaceous seaway withdrew into eastern Wyoming. Thicknesses vary from less than 700 feet along the west and north margins of the Wind River Basin to more than 1,200 feet at the east margin (Keefer, 1972). The more prominent sandstone beds are as much as 125 feet thick and form resistant ledges in outcrops and conspicuous intervals on geophysical logs (Figure 8). The number of these sandstone beds at any given locality varies considerably from a minimum of about three to a maximum of about eight; the average number is five to six. The total thickness of sandstone in beds 10 feet or more thick ranges from about 250 feet in the western part of the Wind River Basin to less than 100 feet in the southwestern and southeastern parts (Figure 9).

The Frontier sandstones are typically fine to medium grained, thin- to thick-bedded and in part cross bedded, and lenticular. Most beds contain a moderate proportion of dark-colored mineral grains which impart a distinctive "salt and pepper" appearance in freshly exposed surfaces and in well cuttings and cores. Locally, particularly along the Casper arch, some sandstones are coarse grained to conglomeratic, with rounded chert pebbles as much as two inches in diameter (Thompson and others, 1949).

Shales, which generally comprise more than 50 percent of the Frontier Formation, are fissile, silty or sandy, and locally carbonaceous. Individual units are as much as 350 feet thick, with the thickest sections located mainly in the southeastern part of the basin. Bentonite, tuff and (or) porcellanite, and coal are minor lithologies in the Frontier. Coal and carbonaceous shale beds are thin (a few inches to a few feet thick) and are largely confined to the western part of the basin.

Several discrete stratigraphic intervals can be identified and traced over wide areas in the basin (Keefer, 1972) despite facies changes, the lenticularity of many individual sandstone beds, and the presence of intraformational unconformities (Merewether, 1983). Resistivity and gamma-ray logs of these sequences indicate that they commonly coarsen upward and are capped by sandstone beds (Figure 8). The sandstone beds display characteristics of a wide variety of onshore, near-shore, and offshore environments (Merewether, 1983) resulting from constantly shifting shorelines, changing water depths, and varying sediment supply. At times, the area now covered by the western part of the Wind River Basin was emergent, and thin beds of carbonaceous sediments accumulated in fluvial and coastal swamp environments.

<u>Hydrocarbon production and reservoir characterization of sandstones in the Frontier Formation</u>

Many thick sandstone beds of the Frontier Formation are persistent over wide areas in the Wind River Basin offering considerable potential as petroleum-bearing reservoirs. Hydrocarbons have been produced from the Frontier Formation in about 22 fields in the Wind River Basin (Figure 3, Table 1). Frontier gas is typically low in CO_2 and contains little or no hydrogen sulfide, and oil from the Frontier is high gravity (38-56), paraffinic, and low in sulfur. Both oil and wet gas are produced at relatively shallow depths in the southern part of the basin while dry gas is produced in the Waltman and Tepee Flats fields in the northeast part of the basin near the deep basin trough at depths of 16,000 to 19,500 ft (Ptasynski, 1989; Gaskill, 1989). Hagen and Surdam (1984) in a study of Cretaceous source rocks in the Bighorn Basin, north of the Wind River Basin, found that shales in the Frontier Formation and underlying Mowry Shale and Thermopolis Shale were rich in Type II and Type III organic matter and may

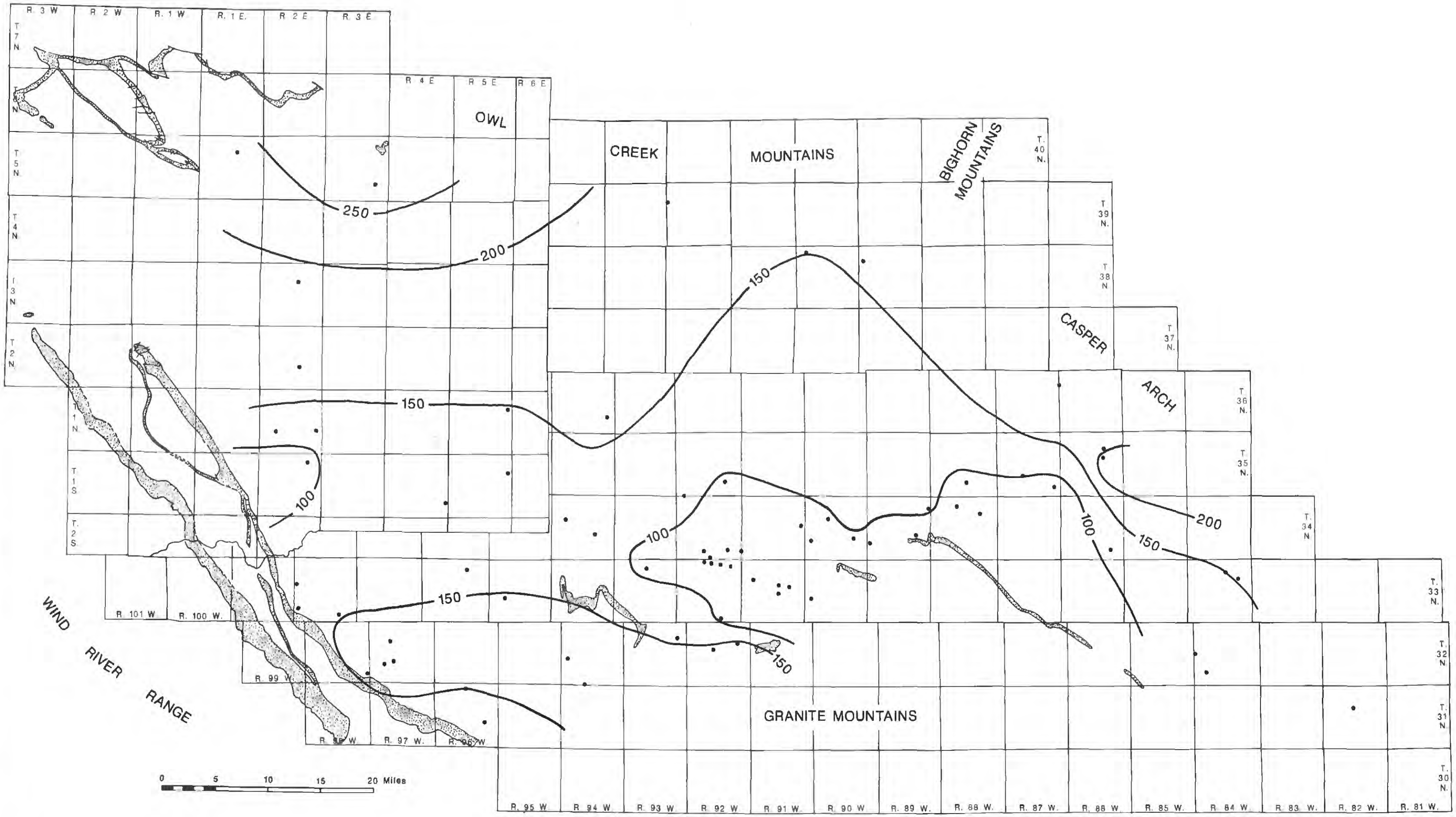


Figure 9: Isopach map showing total thickness of sandstone in the Upper Cretaceous Frontier Formation in beds 10 ft thick or greater. Outcrops of Frontier Formation shown as stipple pattern. Drillholes used for control are shown as black dots. Contour interval is 50 ft.

be potential source rocks for both oil and gas, and it is likely that much of the hydrocarbons found in the Frontier Formation was derived from these Cretaceous shales.

CODY SHALE AND TONGUES OF MESAVERDE FORMATION

The Cody Shale of Upper Cretaceous late Coniacian through early Campanian age (Keefer and Troyer, 1964; Keefer, 1972) consists of marine shale and marine sandstone. It thickens from less than 3,400 ft in the western part of the basin to over 5,300 ft in the eastern part, largely because the lower part of the overlying Mesaverde Formation grades eastward into Cody Shale (Figure 5). A complex zone of intertonguing lithologies of the Cody Shale and Mesaverde Formation was deposited as the Cretaceous seaway gradually retreated from west to east across the basin. A detailed understanding of this interval is hindered by a general lack of subsurface control. In the eastern part of the basin, the Fales Sandstone Member of the Mesaverde Formation is separated from the main body of the Mesaverde by the Wallace Creek Tongue of the Cody Shale, and in the western part of the basin, the informal "Conant Creek tongue of the Cody separates the informal "Alkali Butte member of the Mesaverde Formation" from the main body of the Mesaverde. A description of the two Mesaverde tongues are presented with the description of the Mesaverde Formation. Many lesser tongues of Cody Shale and Mesaverde Formation are as yet unnamed. The general lack of subsurface control makes it difficult to study individual tongues of Cody Shale and Mesaverde Formation throughout their extent. Shelf sandstones commonly occur eastward from the Mesaverde tongues, but control is generally too sparse to determine if individual sandstones are connected to Mesaverde shoreface sandstones or occur as isolated bodies. For simplicity, this entire zone of intertonguing is included in the isopach maps of the Cody Shale. The Cody Shale is informally subdivided into the lower shaly member and upper sandy member (Thompson and White, 1954; Yenne and Pipiringos, 1954; Keefer and Troyer, 1964) in all but the easternmost part of the basin where the sandy member becomes indistinguishable in lithology from the underlying shaly member (Finn, 1993).

Shaly member of the Cody Shale

The shaly member varies in thickness from about 1,150 to 2,250 ft across the basin (Figure 10) and is characterized by homogeneous dark gray shales, bentonitic shales, and bentonite. Coniacian age fossils were collected from the upper part of the shaly member along East Sheep Creek in the northwest part of the basin (Keefer and Troyer, 1964; Keefer, 1972). The shaly member contains no significant hydrocarbon reservoirs. The base of the shaly member is conformable and is placed at the top of the uppermost sandstone of the Frontier Formation. The stratigraphic position of this sandstone varies somewhat across the basin (Keefer, 1972). Recent subsurface stratigraphic studies (Keefer and Johnson, 1993; Finn, 1993; Szmajter, 1993) have demonstrated that the top of the shaly member climbs stratigraphically from west to east across the Wind River Basin (Figure 5). Keefer and Troyer (1964) measured about 1,620 ft of shaly member along East Sheep Creek in the northwest part of the basin (Figure 2) and placed the top of the member at approximately the top of a 50 to 180 ft thick interval of bentonitic shale (Keefer and Johnson, 1993, plate 2, section 1) This bentonitic sequence was traced southeastward in the subsurface by Keefer and Johnson (1993, pl. 2) to the

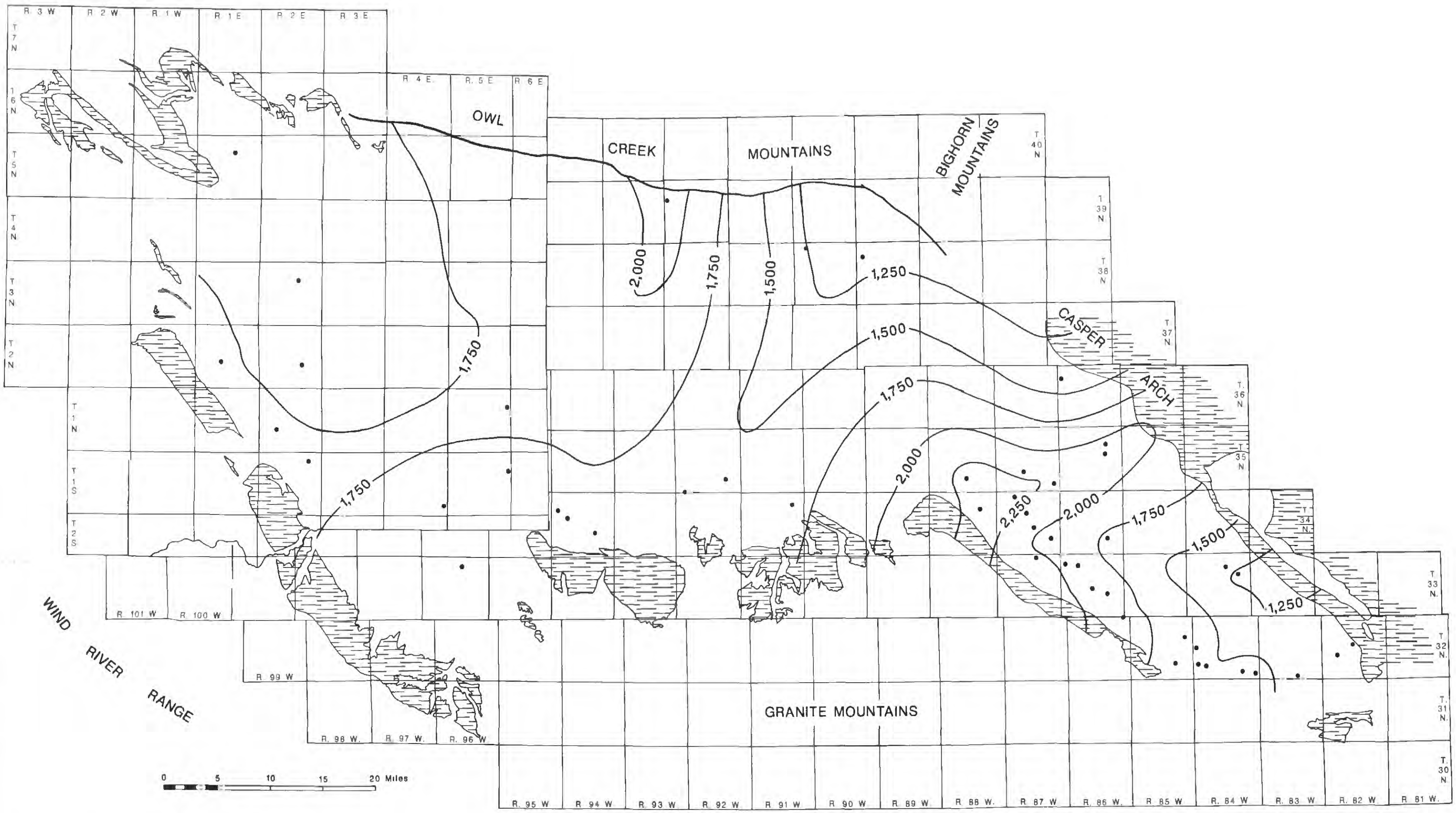


Figure 10: Isopach map of the shaly member of the Upper Cretaceous Cody Shale, Wind River Basin.

Outcrops of Cody shale shown as patterned areas. Drillholes used for control are shown as black dots.

Contour interva is 250 ft.

southwest corner of the Wind River Reservation. Here, Yenne and Pipiringos (1954) placed the top of the shaly member at the base of a sandy shale interval about 220 ft above the top of the interval of bentonitic shale. Szmajter (1993, Plate 1) traced both the bentonitic zone and the top of the shaly member across the central part of the basin. The top of the shaly member remains at about the same stratigraphic position 350 ft above the bentonitic zone throughout the central part of the basin, then abruptly climbs stratigraphically to about 1,200 ft above the bentonitic zone in the east-central part of the basin. Finn (1993) extended the sandy member into the easternmost part of the basin where it grades laterally into the underlying shaly member.

Sandy member of the Cody Shale and associated tongues of the Mesaverde Formation

The sandy member of the Cody Shale is present in all but the easternmost part of the basin. It varies in thickness from about 1,800 to 2,400 ft in the western part of the basin to more than 3,500 ft in the eastern part (Figure 11). Much of this thickening is due to intertonguing with the lower part of the overlying Mesaverde Formation as the Mesaverde-Cody rises stratigraphically from west to east across the basin. The contact is generally placed at the base of a interpreted marginal marine sandstone beneath the lowest occurrence of nonmarine rocks in the Mesaverde. Yenne and Pipiringos (1954) put the upper contact of the Cody "at the base of a massive, light-gray to white sandstone unit that is associated with thin coal beds". A similar criterion was used by Keefer (1972, p. E16-E17) who defined the contact between the Cody Shale and the overlying Mesaverde Formation as "the dividing line between strata that were deposited primarily in an offshore environment and those that were deposited in near-shore, brackish-water, swampy, or fluvial environments. The contact is generally marked by a lithologic change from thin-bedded sandstone interbedded with shale below to massive sandstone closely associated with carbonaceous shale and coal above". Late Niobrara-age fossils were collected from the lower part of the sandy member along East Sheep Creek in the northwest part of the basin (Keefer and Troyer, 1964; Keefer, 1972). Age of the uppermost part of the Cody Shale varies across the basin in response to the eastward stratigraphic rise in the position of the contact with the overlying Mesaverde Formation. Age of the uppermost Cody is Campanian and ranges from within the *Scaphites hippocrepis* I zone in the western part of the basin to the *Baculites perplexus* zone in the eastern part (Keefer, 1972).

The terms "Sussex" sandstone and "Shannon" sandstone have been applied to four or five sandstones in the upper 1,700 to 2,000 ft of the sandy member of the Cody Shale at Madden Anticline in the north-central part of the basin, but these sandstones are not equivalent to the Sussex and Shannon Sandstones Members of the Cody or Steele Shale in the Powder River Basin to the east. They were interpreted by Thomas (1979) in an unpublished oil company report (see Dunleavey and Gilbertson, 1986, p. 115) as nearshore bar complexes deposited along the edge of a delta. Sandstones in the "Sussex" and "Shannon" sandstones at Madden are described by Dunleavy and Gilbertson (1986, p. 115) as "gray, very fine to fine grained, subrounded to subangular, salt-and peppery, shaley and non-calcareous to slightly calcareous." Porosity and permeability at Madden field are considered to be controlled primarily by natural fractures and the dissolution of some feldspar and volcanic rock fragments (Dunleavy and Gilbertson, 1986).

Outcrop studies of the sandy member of the Cody Shale

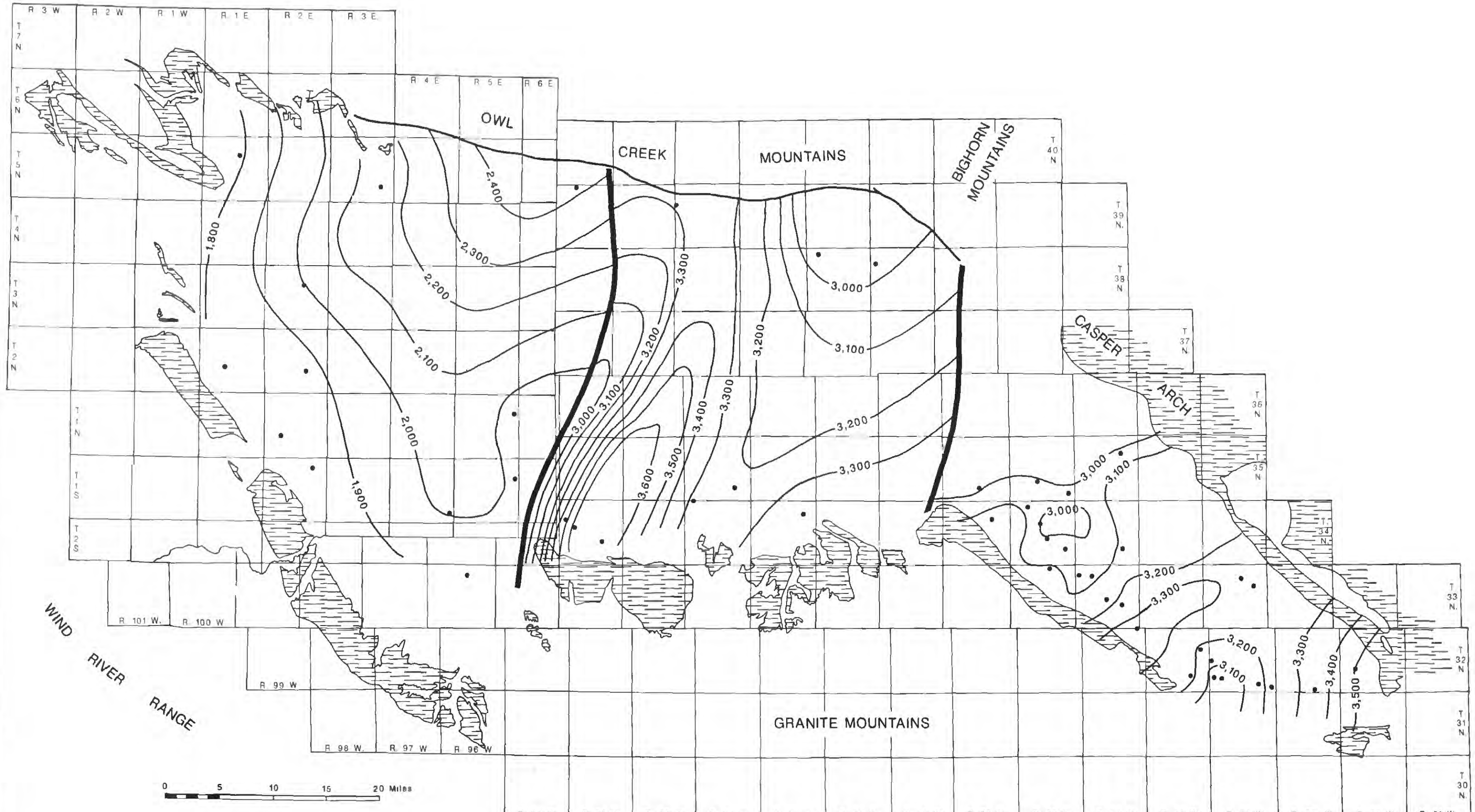


Figure 11: Isopach map of sandy member of the Upper Cretaceous Cody Shale. The isopach map includes the "Alkali Butte member" of the Mesaverde Formation in the western part and the Fales Sandstone Member of the Mesaverde Formation in the eastern part of the basin. Western limits of the "Alkali Butte member" and the Fales Sandstone Member are shown as heavy lines. Outcrops of Cody Shale shown as patterned areas. Drillholes used for control are shown as black dots. Contour interval is 100 ft.

The sandy member is generally deeply weathered, hence poorly exposed. Typically only the upper few hundred feet are exposed beneath the overlying more resistant Mesaverde Formation. Yenne and Pipiringos (1954) studied the sandy member in outcrop in the western part of the basin and described it as "light-gray to buff fine-grained sandstone, siltstone, and shale, each of which is thinly bedded and in places laminated." The beds are typically calcareous and frequently contain gypsum in crystals and veinlets. Near the top of the sandy member the beds of sandstone are thicker, more indurated, and better exposed than the lower beds of the member. Most of the sandstones are lenticular, ferruginous, concretionary, and glauconitic.

The uppermost part of the sandy member was examined at Bargee School, Muddy Creek, and Eagle Point (Figure 2) in the western part of the Wind River Reservation by Johnson and Clark (1993). These sections are described here and shown grahpically on Plate 2. In addition, a previously unpublished section of the upper 840 ft of the Cody Shale at Alkali Butte near the southeast corner of the Wind River Reservation is described here and presented graphically on Plate 3. The Alkali Butte section includes shelf sandstones which may be similar, and in part equivalent, to the highly productive "Sussex" and "Shannon" sandstones at Madden Anticline.

<u>Muddy Creek section</u>: The measured section along Muddy Creek is in secs. 12 and 13, T. 6N., R. 1W (Figure 2, Plate 2). The section begins 174 ft below the base of the basal marginal marine sandstone member of the Mesaverde Formation which is 91 ft thick here. The lowest 100 ft consists of interbedded very fine-grained sandstone, siltstone, and mudstone. Sandstones are as much as three feet thick but generally much thinner, are horizontal or parallel laminated near the base, and hummocky cross stratified at the top. These sandstones are interpreted to represent storm deposits in a shallow shelf or lower shoreface environment. The overlying 74 ft-thick interval (from 100 to 174 ft on plotted section) contains several sand-filled channel-form features (Figures 12 and 13). Individual channel-form sandstones vary from about 10 to 20 ft thick and can be traced along outcrop for distances of about 100 to 300 ft. The channel-form sandstones are fine to very-fine and appear to be mainly horizontal or parallel laminated but laminae are difficult to see. Chaotic lag blocks occur in zones as much as 10 ft thick at the base of many but not all of the channel-form sandstones (Figure 14). These basal lag deposits consist of angular siltstone and mudstone blocks as much as six feet across that are very similar in lithology to the finer-grained sediments interbedded with the channel-form sandstones.

These channel-form sandstones appear to be best developed in the vicinity of this measured section. To the south, this interval is not exposed. To the north, the channel-form sandstones become interbedded with well-laminated fine to very-fine sandstone, siltstone and mudstone, and the channel-form sandstones are rarely seen more than about 1,500 ft north of the measured section (Figures 15 and 16). In one place, a channel-form sandstone appears to grade into well-laminated sandstone. The well-laminated sandstones are as much as five feet thick, have horizontal and hummocky cross stratification, and thin and thicken along outcrop (Figures 16 and 17). Plant fragments to several inches across are common along laminae. The erosional surfaces at the base of the channel-form sandstones do not appear to extend beyond the edges of the sandstones suggesting that they are not regionally extensive.

The origin of the channel-form sandstones is problematical. The processes involved appear to have been largely confined to a narrow area of the continental shelf for an extended period of time. The sandstones occur in the stratigraphic position of a lower shoreface deposit,

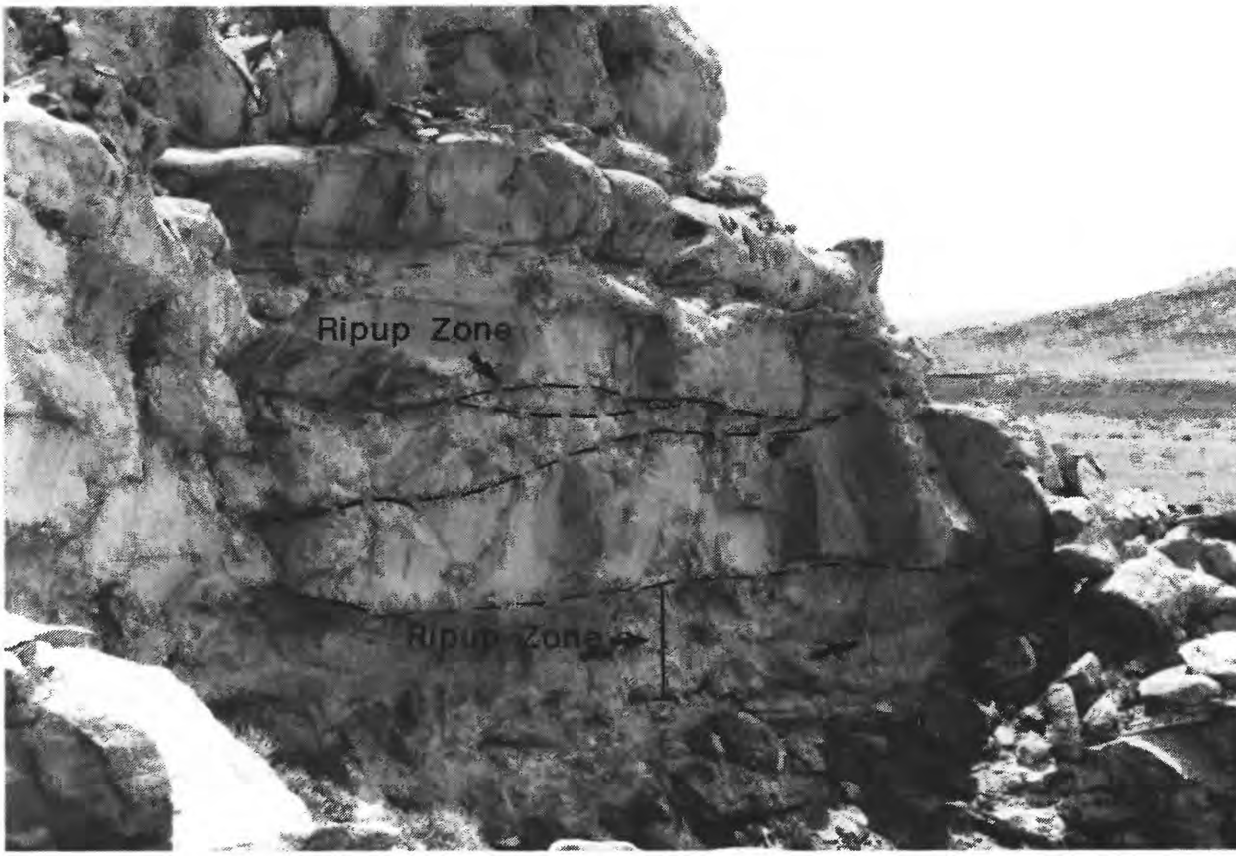


Figure 12: Photo showing stacked lenticular channel-form sandstones in the upper part of the Upper Cretaceous Cody Shale at Muddy Creek measured section in the northwest part of the basin (Plate 2; location on Plate 1c); Five foot Jacob Staff near base of photo for scale. Two ripup clast zones at the base of channels are outlined. From Johnson and Clark (1993).

Figure 13: Channel-form sandstone in the upper part of the Upper C
underlying horizontally bedded sandstone and mudstone a
northwest part of the basin (Plate 2; location on Plate 1c)
of the channel deposit. Man (6 feet tall) for scale. From Johnson and Cla

Figure 14: Basal lag deposit consisting of angular blocks of sandstone and mudstone at the base of a channel-form sandstone in the upper part of the Upper Cretaceous Cody Shale at Muddy Creek measured section in the northwest part of the basin (Plate 2, location on Plate 1c). Note seven inch hammer head. From Johnson and Clark (1993).

Figure 15: Photo showing channel-form sandstones in upper part of the Upper Cretaceous Cody Shale grading to the north (to the left) into a less sandy interval at Muddy Creek measured section in the northwest part of the basin (Plate 2; location on Plate 1c). Channel-form sandstone shown in Figure 13 is in center of photo (arrow). A shoreface sandstone about 90 ft thick caps the channeled interval. The combined channeled interval and overlying shoreface sandstone is about 180 ft thick and forms a nearly continuous sandstone outcrop in the center of the photo. From Johnson and Clark (1993).

Figure 16: Highly contorted or convoluted channel-form sandstone in the upper part of the Upper Cretaceous Cody Shale which is underlain and overlain by noncontorted horizontal bedded and hummocky cross stratified sandstone, and siltstone and mudstone at Muddy Creek measured section in the northwest part of the basin (Plate 2; location on Plate 1c). Note 10 ft scale. From Johnson and Clark (1993).

Figure 17: Hummocky cross stratification in sandstone below channel-form sandstone in upper part of Upper Cretaceous Cody Shale shown in Figure 16 at Muddy Creek measured section in the northwest part of the basin (Plate 2; location on Plate 1c). Large plant fragments are common along bedding planes. Note 13 inch hammer for scale. From Johnson and Clark (1993).

directly beneath an upper shoreface to foreshore sandstone that is 91 ft thick. They grade laterally into probable storm surge deposits suggesting that they may have been formed by storm processes as well. Brenner and Davis (1973) described similar channel-form sandstones with storm lag deposits (chaotic lag blocks), which they interpret as surge channel deposits, in Upper Jurassic rocks of Wyoming and Montana. According to Brenner and Davis (1973), the surge channel deposits were produced by storm-induced high-energy pulses from the passage of storm swells over the shallow shelf to the shoreface platform.

Eagle Point sections: A total thickness of 591 ft of the upper part of the Cody Shale and the lower part of the Mesaverde Formation was measured at Eagle Point in SE 1/4 sec 15, T. 6N., R. 1W., about two miles west-southwest of the Muddy Creek section (Figure 2, Plate 2). The section begins 183 ft below the base of the shoreface sandstone at the base of the overlying Mesaverde Formation. An additional 200+ ft of the sandy member is exposed at Eagle Point but was not described in detail. Strata below the measured interval consists mainly of interbedded sandstone, siltstone, and shale. Figure 18 is a photo of a hand specimen showing the complex interbedding and mild soft sediment deformation characteristic this interval of the sandy member. Individual sandstone and shale laminae are well preserved and not extensively bioturbated with sandstone composing from 50 to 75 percent of the rock. The lowest 21 ft of the measured part of the section consists of gray mudstone which becomes silty toward the top. The next 43 ft consists of interbedded fine-to very fine-grained sandstone, siltstone, and mudstone which becomes coarser and sandier towards the top. The sandstones are nonlaminated or have horizontal, climbing ripple, and symmetrical ripple laminations. The sandstone at the top of the interval is 12 ft thick and consists of a highly contorted "ball-and-pillow" sandstone between two non-convoluted sandstone beds (Figure 19).

Another generally coarsening-upward cycle of interbedded sandstone, siltstone, and mudstone begins at 64 ft and ends at the base of the thick shoreface sandstone of the Mesaverde Formation at 183 ft (Plate 1). Sandstones in this interval have horizontal laminations to low-angle crossbeds and climbing ripple laminations; these ripple laminations occur mainly near the tops of the sandstones. Hummocky cross stratification and small clayey-ripup clasts occur in sandstones in the upper part of this interval. Current ripple laminations in two beds indicate a south to southwest flow direction. Sole marks on the base of one of the sandstones trend west to east. Thin zones of symmetrical ripple laminations occur at the top of two of the sandstones. This interval is interpreted to have been deposited in a shelf to lower shoreface environment. Sandstones were probably deposited by storm surge events and later modified by gentle currents during fair-weather conditions.

Alkali Butte section: The upper 840 ft of sandy member of the Cody Shale was measured in secs. 23, 26, T.34N., R. 95W., and sec. 9, T. 2S., R. 6E. near the southeast corner of the Wind River Reservation (Figure 2, Plate 3). The lower 168 ft of the Alkali Butte section is a sandy, highly complex interval of fine to very fine-grained sandstone, silty sandstone, and minor mudstone. The lower 66 ft of section is well-exposed horizontal bedded, low-angle cross bedded, and ripple drift laminated, fine to very fine-grained silty sandstone with two conspicuous near-horizontal surfaces at 8 ft and at 35 ft. These surfaces may represent periods of minor erosion or nondeposition. The uppermost 10 ft of this 66 ft thick section has low-angle trough cross-bedding to one foot high and clay ripups with clasts to two inches across. Burrows occur throughout the sandstone, and the uppermost one foot is highly bioturbated. A paleocurrent measurement on ripple-drift laminae near the top of the sandstone indicates a S. 10 E. flow direction. The next 35

Figure 18: Photo of polished hand specimen of finely interbedded and contorted very-fine grained sandstone and gray mudstone from the upper part of the sandy member of the Upper Cretaceous Cody Shale at Eagle Point in the northwest part of the basin (location on Plate 1c). Note that discrete sandstone laminae are preserved indicating little or no bioturbation occurred.

Figure 19: Highly contortted "ball and pillow" sandstone between undeformed sandstone beds in upper part of the Upper Cretaceous Cody Shale at Eagle Point measured section in the northwest part of the basin (Plate 2; location on Plate 1c). Five foot Jacob Staff for scale. From Johnson and Clark (1993).

ft (66 to 101 ft on measured section) is 30 ft of poorly exposed moderately burrowed sandstone with irregular clayey laminae overlain by five feet of well-exposed horizontal and low angle cross-bedded sandstone which is highly bioturbated at the top. This bioturbated sandstone is overlain by 10 ft (101 to 111 ft in measured section) of poorly exposed, very fine silty sandstone with irregular flaser-like clayey laminae. A well-exposed sandstone, which is moderately burrowed and has trough-cross beds to 1.5 ft high and ripple drift laminae, occurs from 111 to 126 ft on the measured section. Flow direction on one trough was S. 22 E. Another complex sequence of sandstones occupies the interval 144 to 168 ft. Included are three discrete units: a lower non-bedded to faintly laminated unit (four feet); a middle unit with clayey horizontal laminae, symmetrical ripples, and trough cross-bedding to 6 in high capped by a thin highly bioturbated zone (five feet); and an upper unit which is largely non-bedded but has some contorted bedding and low-angle cross-bedding (14 ft). Directional readings on three troughs in the middle unit indicate a general southerly flow direction (Plate 3). Charcoalized logs to eight inches long occur in the lower one foot of the latter unit.

The next well exposed interval of the sandy member of the Cody Shale at Alkali Butte occurs between 296 and 325 ft. This sandstone is in sharp contact with a poorly exposed sandstone below, and has abundant clayey ripups to two inches across in the lower 1.5 ft. Several other irregular but roughly horizontal clayey ripup zones occur throughout this 29 ft thick sandstone. This sandstone is largely nonbedded but faint contorted bedding was observed, and some horizontal and hummocky zones are present. The overlying 265 ft is predominantly fissile, medium-to dark-gray shale with several 0.5 to 1 ft thick horizontal bedded and hummocky bedded sandstones. A conspicuous, 35 ft-thick white-weathering band occurs in the upper part of this shale interval. A 57 ft-thick, poorly exposed, heavily burrowed and bioturbated sandstone occurs above the shale. The remaining 194 ft of Cody Shale consists mainly of horizontal and hummocky-bedded sandstone and intervals of interbedded sandstone, siltstone, and shale. These interbedded intervals are not heavily bioturbated, and the thin lithologic units are largely preserved. The contact with the overlying Mesaverde Formation is placed at the base of a 34 ft-thick horizontal bedded sandstone overlain by carbonaceous rocks.

<u>Hydrocarbon Production and reservoir characterization of sandstones in the sandy member of the Cody Shale</u>

Sandstones in the upper part of the Cody Shale have produced gas and (or) oil at several fields in the Wind River Basin (e.g. Madden, Beaver Creek, Riverton Dome, Pilot Butte, and Raderville, Figure 3). The Madden field is by far the largest producer, with the principal reservoirs being the relatively clean "Sussex" and "Shannon" sandstones (see Figure 22). In addition, significant gas shows are commonly encountered in the complexly interbedded sandstone and shale intervals between the well-defined sandstone units in the sandy member as well. Although drillstem tests and perforation results indicate significant gas in these interbedded intervals (see Keefer and Johnson, 1993, pl. 2, well no. 5, pl. 3, well no. 7) no known sustained production from these rocks has occurred in the basin.

Figure 20 is an isopach map of total sandstone in units 10 ft thick or greater in the sandy member of the Cody Shale. In areas where the Cody intertongues with the overlying Mesaverde Formation, the map includes all sandstone up to the top of the highest tongue of Cody Shale and hence includes sandstones in the "Alkali Butte member" and Fales Sandstone Member of the Mesaverde Formation (Figure 5), which will be discussed later. The map includes only the intervals consisting predominantly of sandstone and does not include the complexly interbedded sandstone and mudstone intervals. Maximum thickness of sandstone in the sandy member west of where the "Alkali Butte member" joins the main body of the Mesaverde Formation is about 130 ft. East of where the "Alkali Butte member" splits off from the main body, total thickness of sandstone in this interval varies from over 400 ft near the western limit of the "Alkali Butte member" to a zero line in the eastern part of the basin. A broad eastward projecting bulge occurs in the central part of the basin just south of Madden anticline. This bulge resembles a delta, but data are sparse. A separate isopach map is shown on Figure 20 for sandstones in the eastern part of the basin where the Fales Sandstone Member of the Mesaverde Formation has split off from the main body. Total sandstone in beds 10 ft thick or greater for the Fales Member of the Mesaverde Formation and its lateral equivalent in the Cody Shale ranges from 12 to 206 ft.

Maximum thickness for individual sandstones in the "Alkali Butte member" is about 167 ft between the depths of 17,250 ft and 17,417 ft in the Energetics 21-16 Bucy State well in sec. 16, T. 37N., R. 92W. Many of the thicker sandstones in the "Alkali Butte member" appear to be stacks of nearshore marine sandstones similar to those found in the laterally equivalent marginal marine interval of the Mesaverde Formation west of where the "Alkali Butte member" joins the main body; these relationships will be described more fully below. These sandstones appear to trend generally north- south, parallel to the paleoshoreline. Fluvial channel sandstones are also present in the "Alkali Butte member", and these are more likely to trend generally east-west or perpendicular to the paleoshoreline. Maximum thickness for individual shelf sandstones in the sandy member is about 75 ft. Control is too sparse to determine whether these are isolated bodies encased in marine shale, such as the Shannon Sandstone Member of the Gammon Shale in southeastern Montana and northwestern South Dakota (Rice and Shurr, 1983), or whether they are extensions of the marginal marine sandstones in the "Alkali Butte member" to the west. Rice and Shurr (1983) found that shelf sandstones are generally elongate parallel to paleoshoreline. If the shelf sandstones in the Wind River Basin also trend parallel to paleoshoreline, they may also be elongated in a general north-south direction.

The complexly interbedded intervals of sandstone and shale appear to be very similar to the sandy shelf deposits of Upper Cretaceous age found in many parts of the Rocky Mountains (see Gautier, 1983, fig. 8-1). These intervals, which include the "Mancos B" Formation found on the Douglas Creek Arch in western Colorado and eastern Utah, and the Mosby Sandstone Member of the Belle Fourche Shale, Bowdoin dome area, Montana are commonly gas productive at depths less than 5,000 ft. The sandy member of the Cody crops out in a fairly narrow belt along the southern and western margins of the Wind River Basin.

MESAVERDE FORMATION

The Mesaverde Formation is a highly variable sequence of sandstone, siltstone, shale, carbonaceous shale, and coal which was deposited along the western margin of the Upper Cretaceous interior seaway as the seaway gradually receded eastward across Wyoming. The thickness ranges from over 2,300 feet in the western part of the Wind River Basin to less than 500 feet in the southeastern corner (Figure 21). Much of this variation results from the intertonguing at the base with the underlying Cody Shale (Figures 5 and 22). Several members and "tongues" have been designated by various investigators for the complexly intertongued

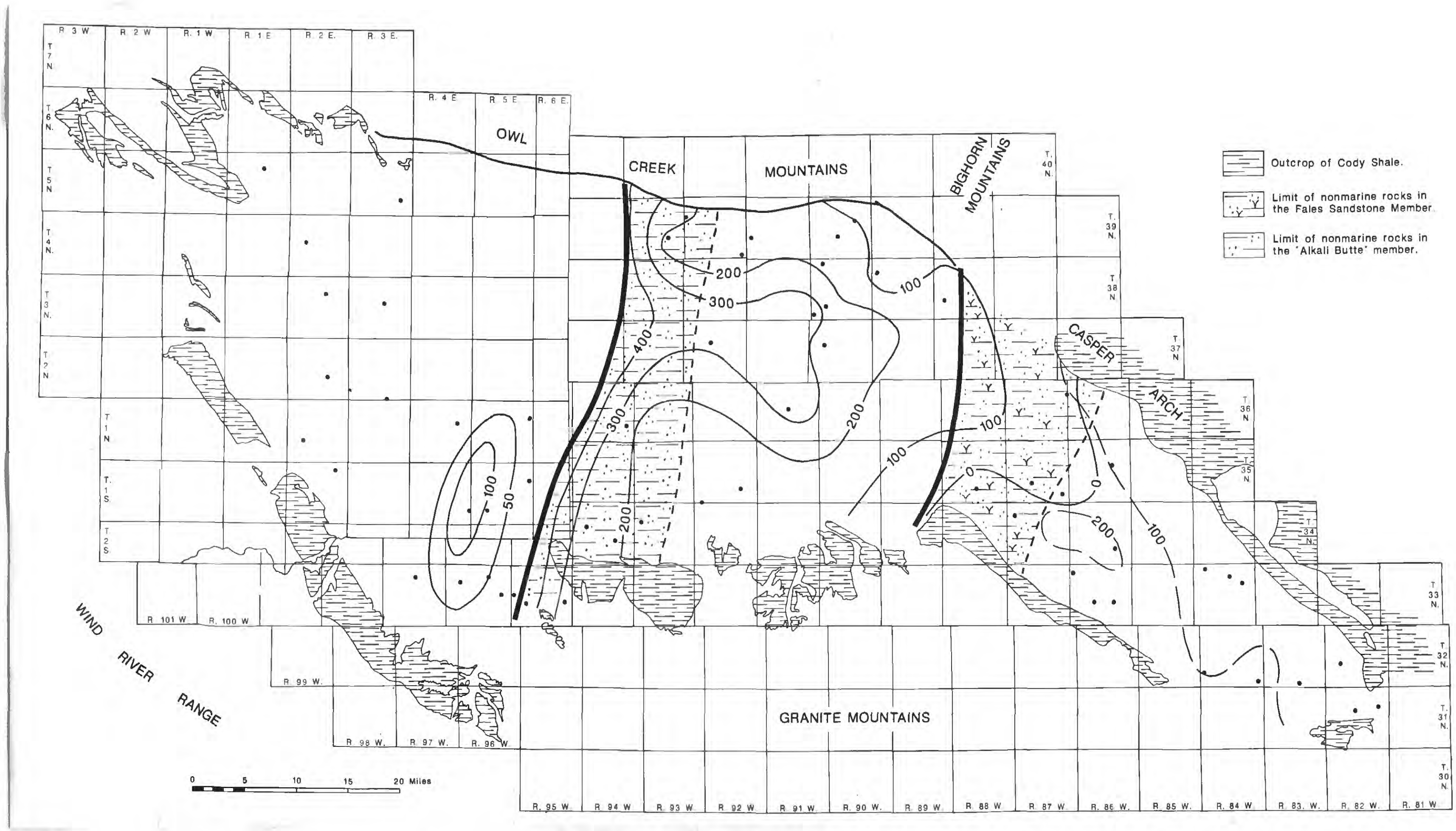


Figure 20: Isopach map of total sandstone in beds 10 ft thick or greater in the sandy member of the Upper Createceous Cody Shale including the "Alkali Butte member" of the Mesaverde Formation in the western part and the Fales Sandstone Member of the Mesaverde Formation in the eastern part of the basin. Western limits of the "Alkali Butte member" and the Fales Sandstone Member are shown as heavy lines. Drillholes used for control are shown as black dots. Contour interval is 100 feet.

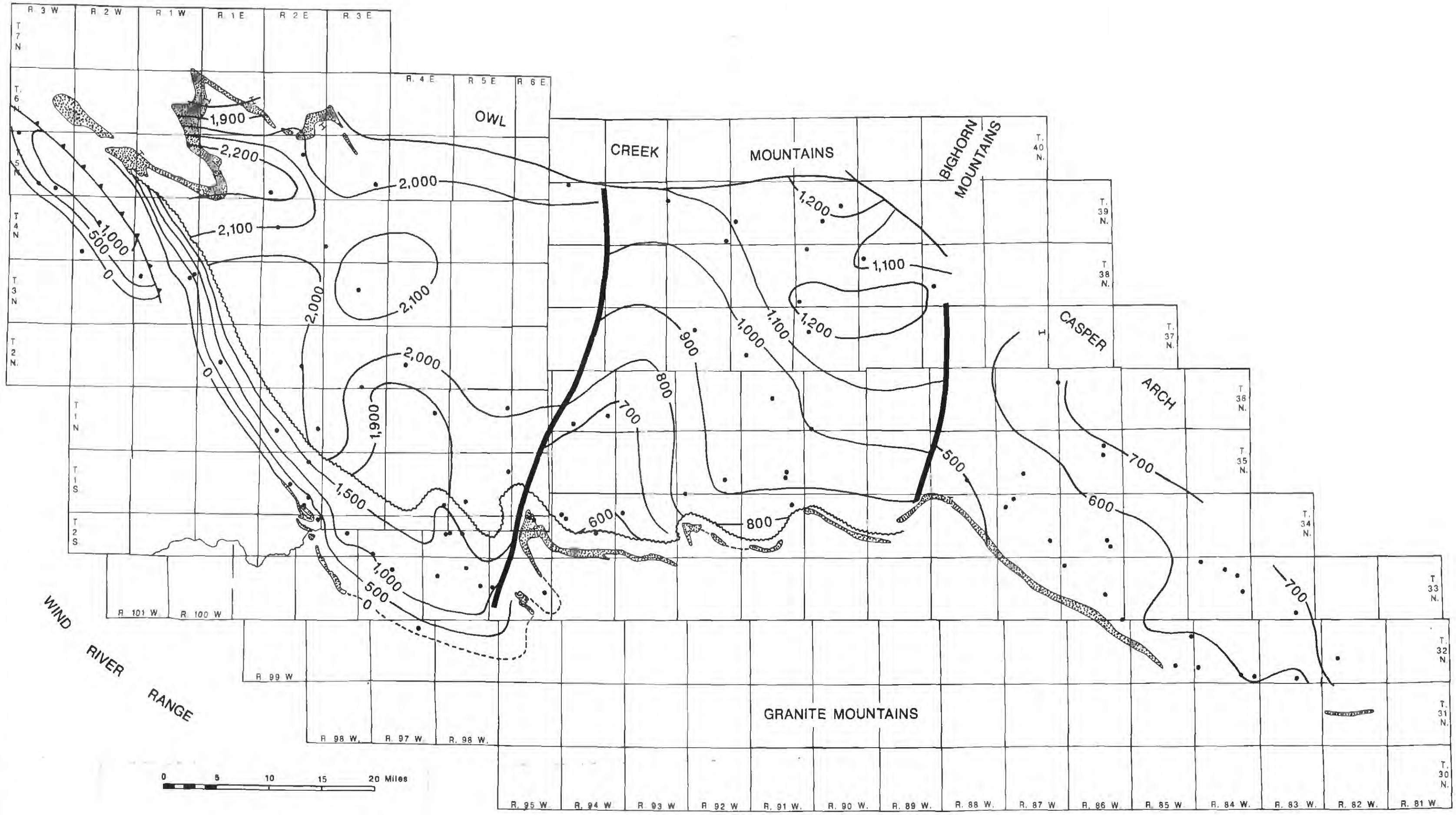


Figure 21: Isopach map of the Upper Createceous Mesaverde Formation in the Wind River Basin, Wyoming. The Mesaverde is partly to completely truncated beneath younger units southwest of the wavy line along the southwest margin of the basin. The map does not include the "Alkali Butte member" of the Mesaverde Formation in the west-central part of the basin or the Fales Sandstone Member of the Mesaverde Formation in the eastern part. These two members are included with the isopach map of the sandy member of the Upper Cretaceous Cody Shale (Figure 11). Modified from Johnson and others (1995). Drillholes used for control are shown as black dots. Contour interval is 100 ft.

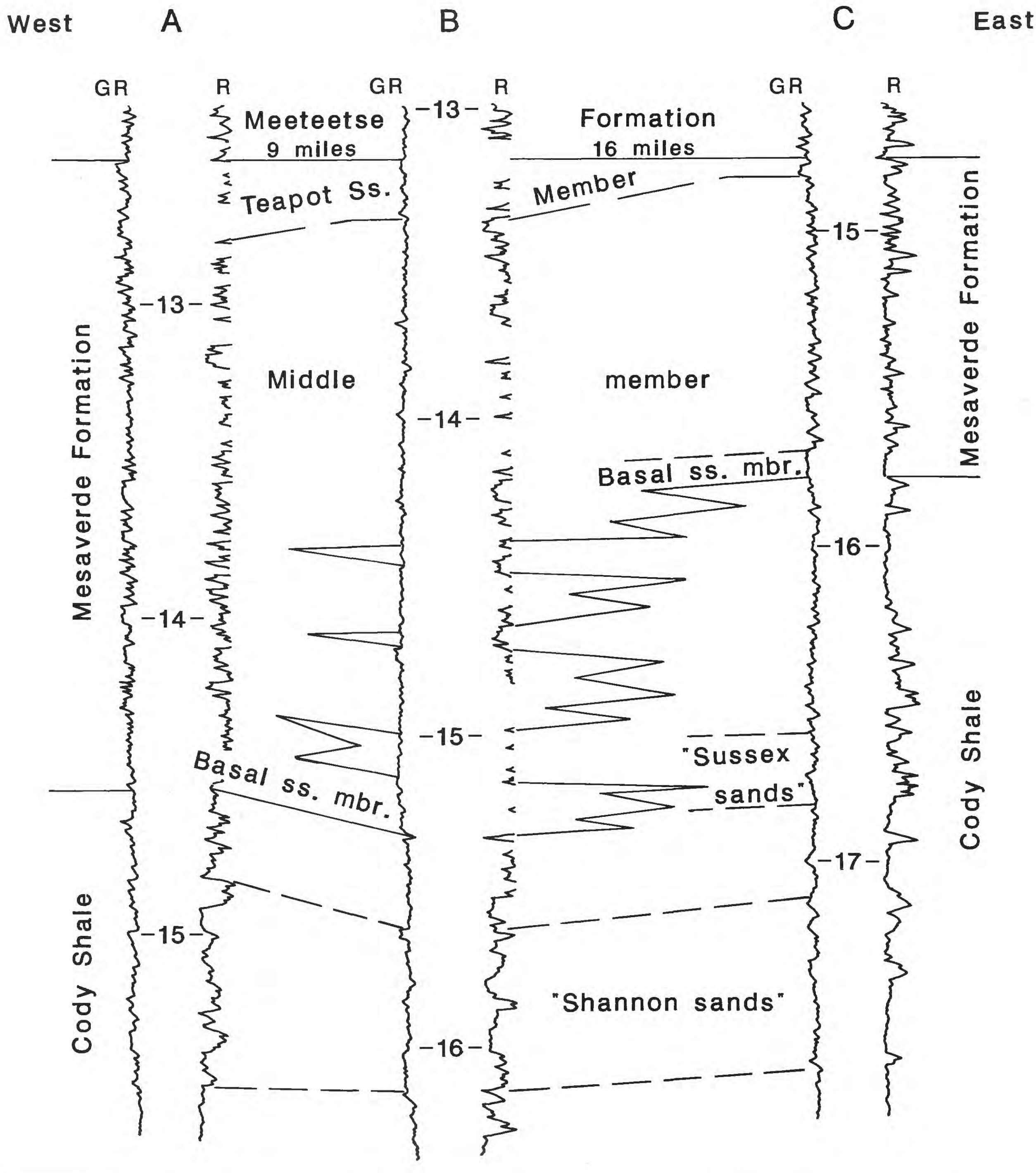


Figure 22: Resistivity (R) and gamma-ray (GR) logs of three drillholes in the north-central Wind River Basin, showing correlation of strata in the Upper Cretaceous Mesaverde Formation and upper part of the underlying Upper Cretaceous Cody Shale. Drillhole A - Coastal Interstate Gas Exploration Burdseye Creek no. 1-4-39-94 (NW1/4 NE1/4 sec. 4, T. 39N., R. 92W.); drillhole B - W. A. Moncrief Lysite no 7-1 (SW1/4 SW1/4 sec. 7, T. 39N., R. 92W); drillhole C - Monsanto Bighorn no. 1-5 (SW1/4 NW1/4 sec. 5, T. 38N., R. 90W.). Numbers inside columns are depths, in thousands of feet.

units in the upper part of the Cody-lower Mesaverde transition in various parts of the Wind River Basin (Figure 5). For the purposes of discussion, however, the Mesaverde is divided into four basic units: (1) the "Alkali Butte member", an informal name used by Hogle and Jones (1991) for the lower tongue of the formation in the west-central part of the basin; (2) the Fales Sandstone Member (originally called "Phales Reef Member" by Barwin, 1959); (3) a marginal marine sandstone interval, and (4) a nonmarine interval. The marginal marine sandstone interval extends from the base of the main body of the Mesaverde Formation to the top of the stratigraphically highest sandstone of marginal marine origin. It is equivalent to the basal sandstone member in the western part and the Parkman Sandstone Member in the eastern part of the basin. The nonmarine interval includes all nonmarine rocks above the marginal marine interval. It is equivalent to the unnamed middle member of Rich (1958) and the overlying Teapot Sandstone Member.

A petrographic study of a limited number of core samples from five shallow drill holes in the western part of the Wind River Basin (Keighin, 1993) indicates that Mesaverde sandstones are moderately well sorted, and composed of subangular to angular detrital grains. The dominant components are rock fragments, of which about 50% is chert, and quartz. The sandstones were found to generally possess good reservoir qualities, with porosities > 20% in most of the samples studied.

"Alkali Butte member" of the Mesaverde Formation

The Mesaverde Formation intertongues with the Cody Shale and has two prominent tongues (Figure 5). Hogle and Jones (1991) informally applied the names "Alkali Butte member" to a tongue of Mesaverde Formation in the west-central part of the basin. The "Alkali Butte member" is as much as 1,000 ft thick and is overlain by a westward projecting tongue (0 to 500 ft thick) of marine shale informally called the "Conant Creek tongue" (Szmajter, 1993; see Figure 5). To the west, the "Alkali Butte member" joins the main body of the Mesaverde Formation along a generally north-south trend near the eastern margin of the Wind River Reservation (Plate 1B). To the east, the "Alkali Butte member" pinches out into a sandy zone in the upper sandy member of the Cody Shale. This sandy zone includes several discrete sandstones of probably marine origin as well as intervals of interbedded marine sandstone and marine shale. Keefer (in press), using the sparse drillhole information available, constructed two east-west cross sections through the central and northern parts of the basin. Keefer's cross sections show that the highly gas-productive "Sussex" and "Shannon" sandstones of the sandy member of the Cody Shale at Madden Anticline, in the north-central part of the basin and about six to 16 miles east of the eastern pinchout of the "Alkali Butte Member", are in part correlative to the "Alkali Butte member".

Fales Sandstone Member of the Mesaverde Formation

A somewhat thinner tongue of the Mesaverde occurs in the eastern part of the basin (Figure 5) and was named the Phayles Reef Member of the Mesaverde Formation by Barwin (1959; 1961a; 1961b). This unit is as much as 350 ft thick and is separated from the main body of the Mesaverde by the Wallace Creek Tongue of the Cody Shale. The Phales Reef Member was named after Fales Rocks and hence the spelling was changed by Gill and Cobban (1966) to match that of the topographic feature. The Fales Sandstone Member falls within the *Baculites asperiformis* through *Baculites perplexus* zones of the Upper Cretaceous upper Campanian

(Keefer, 1972, Table 2). The Fales Sandstone Member was first studied in detail by Barwin (1965; 1961a; 1961b) who recognized three facies, which are, in ascending order, littoral and nearshore marine, coastal swamp, and lagoonal. The basal marine sandstone is described by Barwin (1961a) as weakly bedded but cross-bedded locally in the upper part. At the type section, in the Rattlesnake Hills (sec. 4, T. 33N., R. 87W.), the upper part of the basal sandstone is described as highly oil stained. The overlying coastal swamp facies was described as carbonaceous shale, some of which is lignitic, and very fine-grained carbonaceous sandstone and siltstone (Barwin, 1961a, p. 23). The upper lagoonal facies includes thin coquina beds with brackish-water pelcypods. According to Barwin (1961a, p. 25) only the basal marine sandstone is present east of the type locality. A titanium-rich black sandstone deposit, as much as five feet thick, was described by Barwin (1961a, p. 23) in the uppermost part of the basal marine sandstone in the Coalbank Hills (sec. 5, T. 34N., R. 88W.). This sandstone was also studied by Houston and Murphy (1977. The littoral and nearshore marine facies extends eastward beyond the eastern limit of the continental facies. In this area, the Fales, as defined by Barwin (1959; 1961a; 1961b), includes no nonmarine rocks.

Finn (1993; in press), using borehole data, traced the Fales Sandstone Member throughout much of the eastern part of the basin. He generally divided the Fales into a basal marine sandstone and an upper nonmarine part. The nonmarine facies pinches out in the southeast corner of the basin whereas the basal marine sandstone persists to near the eastern margin of the basin. The basal marine sandstone as defined by Finn (in press) is an interval of marginal marine sandstones as much 200 ft thick with individual sandstones as much as 107 ft thick.

The buildup of marginal marine sandstones west of where the Fales Member joins the main body of the Mesaverde Formation, but which occurs in the same approximate stratigraphic position of the Fales, can be seen on a series of cross sections in the central part of the basin constructed by Szmajter (1993; in press) from mainly borehole data. Here Szmajter (1993; in press-a; in press-b) defined three units in the Mesaverde Formation: 1) "basal marine strata"; 2) an unnamed middle member; and 3) an upper Teapot Sandstone Member. Szmajter showed that the basal marine strata, west of the pintchout of the Fales Member, thickens to over 400 ft in an eastward direction.

<u>Outcrop studies of the Fales Sandstone Member</u>

Detailed sections of the Fales Sandstone Member were measured at two localities during the present study: 1) Coalbank Hills near the titaniferous sandstone locality (sec. 5, T. 34N., R. 88W.; Figure 2, Plate 3); and 2) along a railroad cut east of Arminto (sec. 13, T. 37N., R. 87W.; Figure 2; Plate 3). The black titaniferous sandstone described by Barwin was not present along the line of section but occurs a short distance to the west. The black sandstone was traced into the measured section where it occurs in the upper part of the 15 ft thick sandstone near the base of the Fales (Plate 3).

<u>Coalbank Hills section</u>: In the Coalbank Hills section (Figure 2, Plate 3) the Fales is 362 ft thick. It includes four and possibly five distinct marginal marine sandstones. These sandstones vary from 15 to 36 ft in thickness, are scattered throughout the Fales, and are characterized by hummocky bedding and low-angle cross bedding, and Ophiomorpha burrows.

The lowest marine sandstone, which correlates with the titaniferous sandstone interval, is overlain by 68 ft of poorly exposed shale of possible marine origin. The other marine sandstones are overlain by carbonaceous shale.

Arminto section: In the railroad cut east of Arminto in sec. 13, T. 37N., R. 87W. (Figure 2, Plate 3), the Fales consists of a 34-ft-thick horizontally bedded, in part trough cross bedded, sandstone with carbonaceous and coaly laminae in the upper four feet. Above this unit is 35 ft of carbonaceous shale with coal beds as much as two feet thick overlain by an interbedded sequence of gray shale, siltstone, and sandstone with bioturbated zones and bivalves.

Hydrocarbon production and reservoir characterization of the Fales Sandstone Member

To date there has been little testing for hydrocarbons in the Fales Sandstone Member. Oil and gas production has been established in the Fales at only one field in the basin, at West Poison Spider field (Figure 3), a faulted anticline in the southeast corner of the basin, a few miles southwest of the Casper arch (Clark, 1978; Gouger, 1989). In this field, the Fales consists of two nearshore or marginal marine sandstones which are productive at depths of from about 10,000 to 11,000 ft. The Fales here was described by Clark (1978) as a very fine grained poorly sorted sandstone with 23 to 45 percent matrix and cement. Average porosity is 11.9 percent with a range from core of from 10.5 to 14.3 percent, and an average permeability of 1.4 md with a range from core of from 0.10 to 2.36 percent (Gouger, 1989).

Marginal marine sandstone interval

Sandstones deposited in a variety of marginal marine settings occur in the lower part of the Mesaverde Formation throughout the Wind River Basin. These units, which were deposited as the Cretaceous seaway retreated from west to east across the Wind River Basin area, commonly have bedding features characteristic of shoreface sequences or partial shoreface sequences including hummocky bedding, low-angle cross bedding and trough cross bedding, and Ophiomorpha burrows. On geophysical logs, these marginal marine sandstones are distinguished by: 1) a blocky character on resistivity and gamma-ray logs; 2) their stratigraphic position above coarsening upward cycles of interbedded sandstone, siltstone, and mudstone and below intervals of carbonaceous shale and coal; and 3) their lateral continuity between closely spaced wells, particularly if the wells are aligned in a general north-south direction, the approximate strike of the paleoshoreline.

The eastward retreat of the Upper Cretaceous seaway across the Wind River Basin area appears to have stalled for extended periods of time in three places; 1) near the western margin of the basin, 2) in the west-central part of the basin near the east boundary of the Wind River Reservation, and 3) in the east-central part of the basin. These relative stillstands created thick intervals in the Mesaverde Formation which contain relatively clean marginal marine sandstones. The sandstone buildups extend across the entire length of the Wind River Basin in a north-south direction or roughly parallel to the trend of the paleoshoreline and for 15 to 20 miles in an east-west direction. Figure 23 is an isopach map of the interval from the base of the Mesaverde Formation to the top of the highest marginal marine sandstone. The three areas of relative stillstands of the Cretaceous shoreline are shown as conspicuous "thicks" on the isopach map. Most of the sandstone in the isopached interval is of marginal marine origin, however, some sandstones of fluvial origin are also present. In the subsurface, individual marginal marine sandstone units can commonly be traced between wells many miles apart in a north-south direction whereas correlation of individual sandstones in an east-west direction between wells as little as a mile or two apart is generally uncertain.

The stillstand near the western margin of the basin is represented by an interval of predominantly marginal marine sandstones as much as 400 ft thick (Figure 23). This buildup thins to the east as the marginal marine sandstones intertongue and wedge out in the underlying Cody Shale (see Keefer and Johnson, 1993, pl. 2, wells 7 and 8).

The thickest and most significant buildup of marginal marine sandstones is associated with the stillstand near the east boundary of the Wind River Reservation where marginal marine sandstones occur throughout an at least 1,200 ft thick. This buildup is a few miles west of the western limit of the "Alkali Butte member" to which it appears to be largely equivalent. This shoreface buildup is only isopached west of the western limit of "Alkali Butte member" (Figure 23). The base of this thick shoreface sequence is probably in the *Scaphites hippocrepis* zone of the earliest Campanian based on fossils collected in the uppermost part of the Cody Shale at Alkali Butte by Yenne and Pipiringos (1954, section no. 8). The age of the top of this shoreface sequence is less well constrained. The top of this shoreface buildup is at about the same stratigraphic position as the western wedge-edge of the "Conant Creek tongue" of the Cody Shale which separates the "Alkali Butte member" of the Mesaverde Formation from the main body. Yenne and Pipiringos (1954, sections 9 and 10) collected fossils of Eagle age in the Conant Creek area but did not recognize the "Conant Creek tongue" of the Cody and, as a result, it is unclear how these fossil localities relate to the shoreface sequence described here.

The buildup of marginal marine sandstones in the east-central part of the basin appears to be largely laterally equivalent to the Fales Sandstone Member and attains a maximum thickness of over 500 ft (Figure 23). The area of maximum thickness of this interval occurs from about four to 12 miles west of the western limit of the Fales.

Coal in the Mesaverde Formation

Figure 24 is an isopach map of total thickness of coal in beds two feet thick or greater in the Mesaverde Formation. Most of this coal occurs in the marginal marine sandstone interval or directly above. The thickest coal is associated with the thick sandstone buildup in the Alkali Butte area near the east boundary of the Wind River Reservation, where as much as 124 ft of coal is present. Individual coal beds in this thick buildup appear to be generally elongate in a north-south direction or roughly parallel to the paleoshoreline and can commonly be traced between closely spaced wells aligned in a north-south direction. To the west, the total coal thickness decreases to between 20 and 60 ft. Keefer and Johnson (1993, p. 77) traced individual coal beds between two wells five miles apart in a north-south direction. The coals in this thick buildup have been mined in the past where they are exposed near Alkali Butte, but no mines are active today. Maximum reported thickness of an individual coal bed is 28 ft (Thompson and White, 1954). The thick coal accumulation near the eastern margin of the Wind River Reservation appears to be roughly aligned and temporally correlative with a northeast trending zone of thick coals in the Rock Springs Formation of the Green River Basin to the south (Tyler and others, 1995, p. 42, fig. 29).

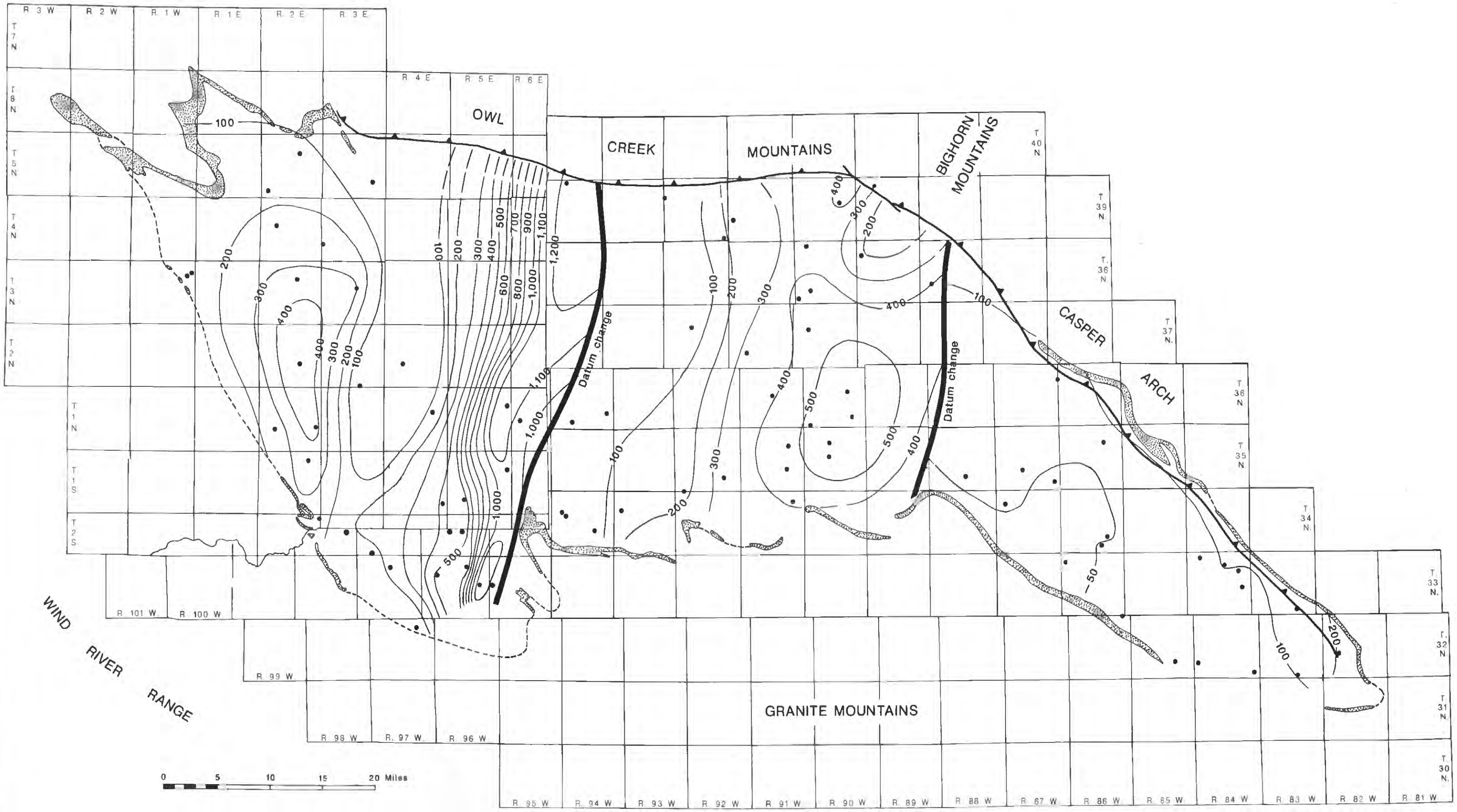


Figure 23: Isopach map of the marginal marine interval in the lower part of the Upper Cretaceous Mesaverde Formation. The map does not include marginal marine rocks in the "Alkali Butte member"or Fales Sandstone member of the Mesaverde Formation. Marginal marine rocks in these members are included in the isopach map of the sandy member of the Cody Shale (Figure 11). Modified from Johnson and others (1995). Western limits of the "Alkali Butte member" and the Fales Sandstone Member are shown as heavy lines. Drillholes used for control are shown as black dots. Contour interval is 100 ft except in the eastern part of the basin where a 50 ft contour is included.

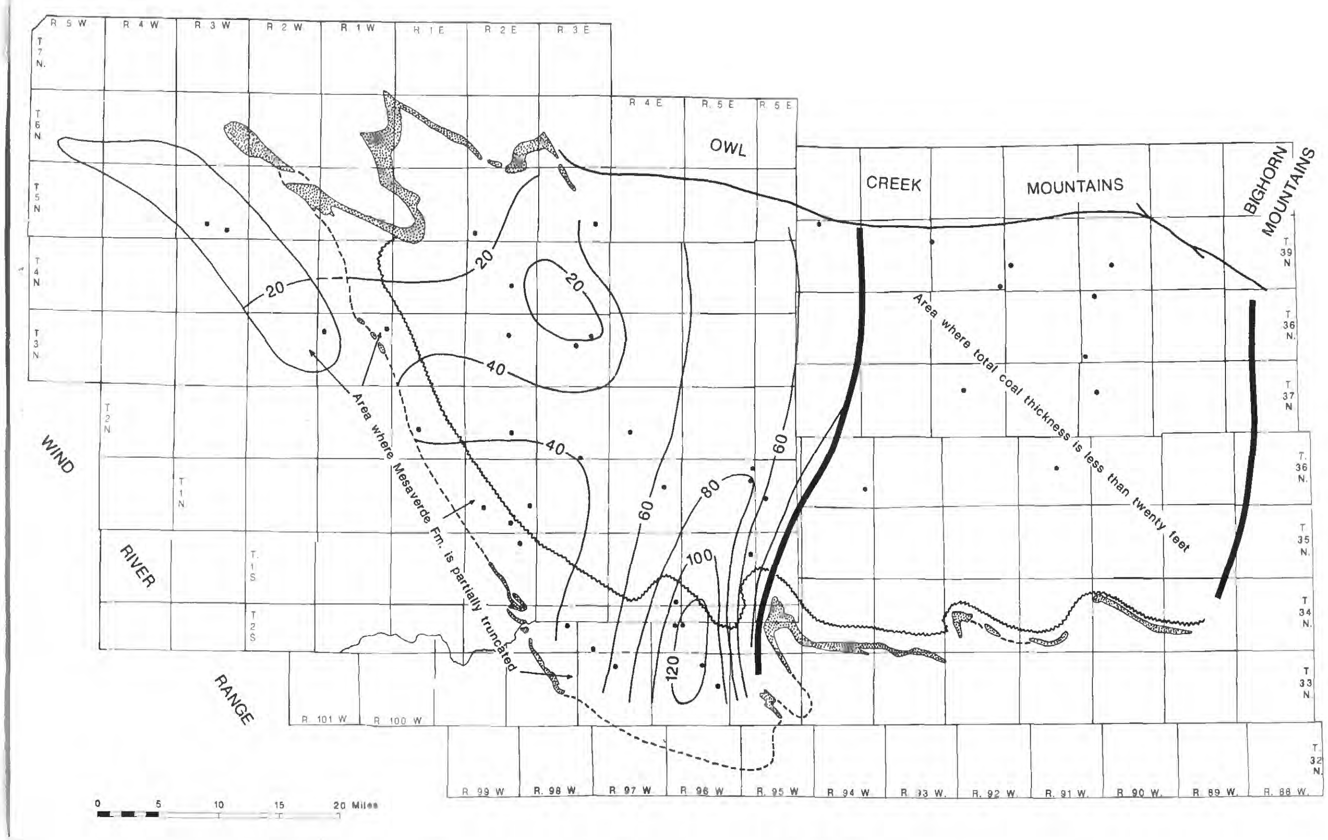


Figure 24: Isopach map of total coal in beds 2 ft thick or greater in the Upper Cretaceous Mesaverde Formation. Modified from Johnson and others (1993). Western limits of the "Alkali Butte member" and the Fales Sandstone Member are shown as heavy lines. Drillholes used for control are shown as black dots. Contour interval is 20 feet.

Detailed measured sections of the marginal marine sandstone part of the Mesaverde Formation

Shotgun Butte area: The marginal marine part of the Mesaverde Formation was described at four localities near Shotgun Butte in the northwest part of the basin by Johnson and Clark (1993). In this area, the marginal marine part of the Mesaverde consists of a single sandstone that varies in thickness from 63 ft at Eagle Point to 106 ft at Shotgun Bench (Figure 2, Plate 2). This sandstone is everywhere overlain by carbonaceous shale, coal beds, and channel sandstones of probable fluvial origin. These sandstones were interpreted by Johnson and Clark (1993) as shoreface sandstones.

Alkali Butte: The lower 646 ft of the thick buildup of marginal marine sandstones near the east boundary of the Wind River Reservation is exposed at Alkali Butte (Figure 2, Plate 3). The upper part of the interval there is truncated beneath the overlying Paleocene Fort Union Formation. The section is dominated by thick (24 to 115 ft), relatively clean, fine-to very fine-grained sandstones. The sandstones are relatively persistent and several were traced along outcrop for about 1 1/5 miles to the southeast. They exhibit horizontal bedding and low-angle cross bedding for the most part but some hummocky bedding is also present. The sandstones are interbedded mainly with carbonaceous shale and coal beds with beds to 8.5 ft thick (1,279 to 1,287.5 ft on measured section, Plate 2). An elongate slab of carbonaceous shale 15 ft long by 1.5 ft high occurs near the base of one of the marginal marine sandstones (Figure 25, 994 ft on measured section). This is interpreted to have been a large slab of peat that was torn from a bog and incorporated into the sand during a minor transgression. Small scour-based channel sandstones as much as 5 ft thick occur in some of the carbonaceous shale and coal intervals. These were the only channel-form sandstones observed in the section. Oyster beds occur in one of these channel intervals near the base of the marginal marine interval (895 to 906 on the measured section). The channel sandstones and associated oyster beds occur immediately above a carbonaceous interval and below a thick sandstone of probable shoreface origin. Patchy dead oil occurs in one of the sandstones near the base of the interval (Figure 26), and dead oil was observed at several other outcrops in the vicinity.

Coalbank Hills: At Coalbank Hills in the southeastern part of the basin (Figure 2, Plate 3) the marginal marine interval is equivalent to the Parkman Sandstone Member of the Mesaverde Formation and consists of a single 43 ft thick shoreface sandstone with large-scale trough cross bedding and hummocky bedding. The Parkman is overlain by carbonaceous shale and is separated from the Fales Sandstone Member of the Mesaverde Formation below by 45 ft of interval poorly exposed Wallace Creek Tongue of the Cody Shale.

Arminto: At Arminto in the northeast part of the basin (Figure 2, Plate 3) the marginal marine interval is also equivalent to the Parkman Sandstone and consists of a single 76 ft thick sandstone which sharply overlies interbedded sandstone and shale in the Cody Shale. The Parkman contains pelcypods near the base and is horizontal bedded and low-angle cross bedded throughout all but the upper 7 ft where trough-cross beds to 3 ft high are the dominant sedimentary structure. The Parkman is overlain by carbonaceous shale and interbedded sandstone and gray shale.

Figure 25: Slab of carbonaceous shale about 15 ft x 1.5 ft in the lower part of marginal marine sandstone interval of the Upper Cretaceous Mesaverde Formation at 993 ft in the Alkali Butte measured section in the southeast corner of the Wind River Reservation (Plate 3; location on Plate 1c). Note 26 in long pick for scale.

Figure 26: Marginal marine sandstone of the Upper Cretaceous Mesaverde Formation saturated with bitumen or dead oil at Alkali Butte measured section in the southeast corner of the Wind River Reservation (Plate 3; location on Plate 1c). Dead oil is common in marginal marine sandstones here. Note two-six foot men for scale.

Hydrocarbon Production and Reservoir characterization of sandstones in the marginal marine interval

The marginal marine interval appears to be productive at only one field in the basin, the West Poison Spider field, a faulted anticline with structural closure in the eastern part of the basin, where some oil and gas is produced from the Parkman Sandstone Member of the Mesaverde Formation (Gouger, 1989). At West Poison Spider, the Parkman has an average core measured porosity of 13.7% with a range of 5.1 to 17.5% and an average core measured permeability of 0.46 md with a range of 0.01 to 1.19 md at depths of 9,750 to 9,814 ft (Gouger, 1989). Limited results from drillstem tests and perforations of marginal marine sandstones in the thick marginal marine interval near the east boundary of the Wind River Reservation in the western part of the basin (see Keefer and Johnson, 1993, Plate 5, wells no. 1, 2, and 3) have been disappointing, indicating water-wet or tight (low-permeability) conditions at depths of as great as 8,540 ft. The marginal marine sandstones, which comprise most of the sandstone in this interval, are blanket-like from a hydrocarbon reservoir perspective, and relatively free of shale breaks. Many of the individual sandstones tested in these wells can be traced to outcrops near Alkali Butte along the southern margin of the basin. It is suggested that these relatively persistent sandstones may serve as conduits for the movement of fluids between these outcrops and the deeper parts of the basin, and that these sandstones may tend to be water-wet to deeper depths in the basin than more lenticular, fluvial sandstones found in the overlying nonmarine interval of the Mesaverde. Patchy dead oil is commonly observed in these sandstones in the vicinity of Alkali Butte (Figure 26), indicating that fluid has moved through these sandstones from deep thermally mature areas of the basin at some time in the past. In addition, large quantities of slightly artesian fresh water was encountered in these marginal marine sandstones at the USGS CBM-1 coalbed methane test in SE1/4 sec. 29, T. 1S., R. 6E., about 2 miles north of where the sandstones outcrop at Alkali Butte (Johnson and others, 1993) suggesting that the sandstones at the CBM-1 corehole were being recharged by fresh water from outcrops in the Alkali Butte area.

Figure 27 is an isopach map of total sandstone in units 10 ft thick or greater in the interval with predominantly shoreface sandstones. The isopach map includes some fluvial sandstones which occur in the marginal marine interval. Maximum total sandstone thicknesses for the three stillstands are 284 ft for the westernmost stillstand, 570 ft for the stillstand near the east margin of the Wind River Reservation, and 262 ft for the stillstand in the east-central part of the basin. The map does not include sandstones in the "Alkali Butte member" or the Fales Sandstone Member. As previously discussed, sandstone in these two members are included in the isopach map of sandstones 10 ft thick or greater in the sandy member of the Cody (Figure 20).

The nonmarine interval of the Mesaverde Formation

The nonmarine interval of the Mesaverde Formation includes the unnamed middle member and the Teapot Sandstone Member. The interval consists of interbedded sandstone, siltstone, shale, carbonaceous shale, and coal that accumulated in nonmarine, largely fluvial sedimentary environments. Thicknesses range from over 2,200 ft in the western part of the basin to less than 500 ft in the eastern part (Figure 28). The sandstones typically display

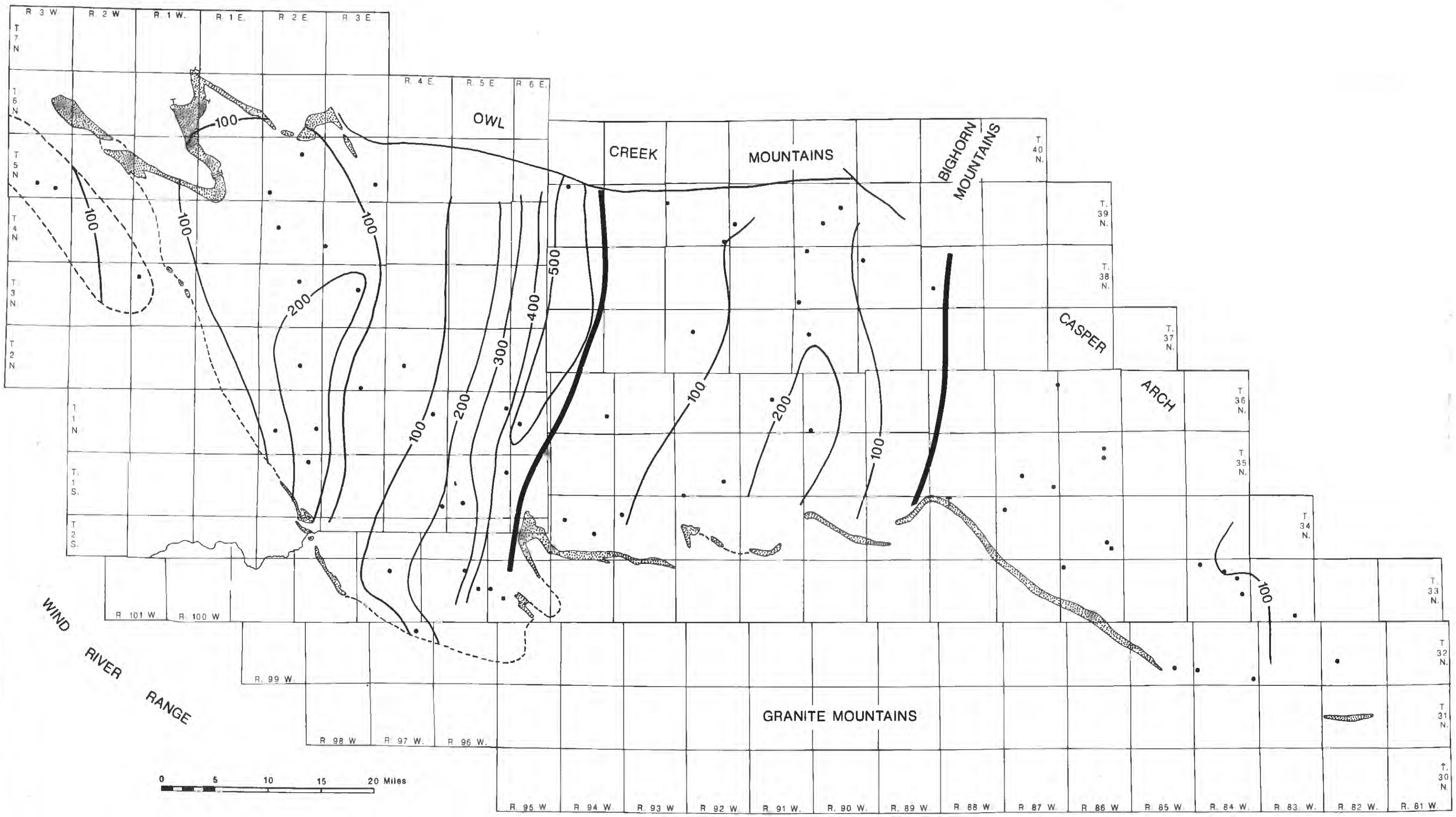


Figure 27: Isopach map of total sandstone in beds 10 ft thick or greater in the marginal marine interval of the Mesaverde Formation. The map does not include marginal marine sandstones in the "Alkali Butte member" or the Fales Sandstone Member. Sandstones in these two members are included in the isopach map of total sandstone in the sandy member of the Cody Shale (Figure 20). Western limits of the "Alkali Butte member" and the Fales Sandstone Member are shown as heavy lines. Drillholes used for control are shown as black dots. Contour interval is 100 ft.

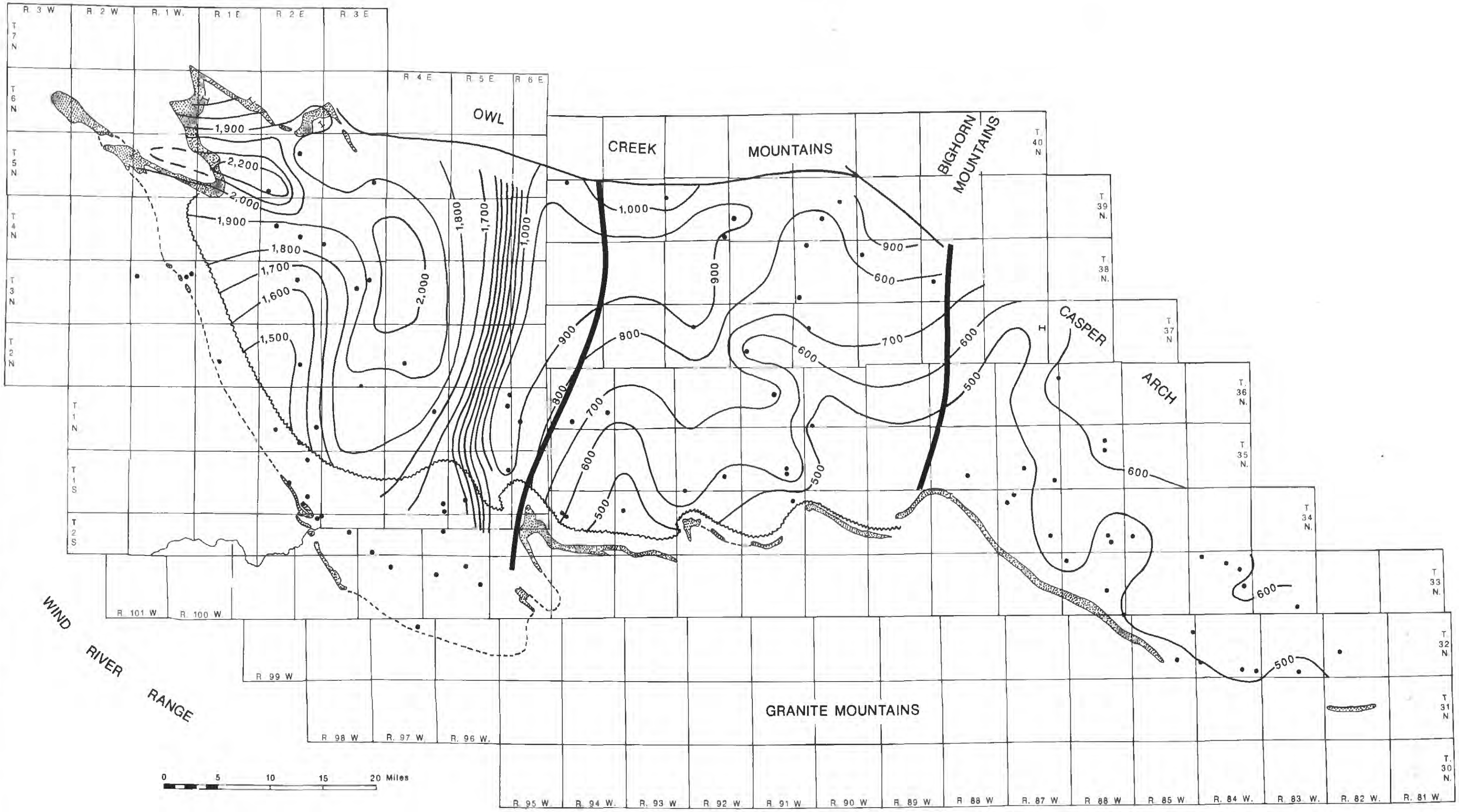


Figure 28: Isopach map of the middle member and Teapot Sandstone Member of the Upper Cretaceous Mesaverde Formation, Wind River Basin, Wyoming. Western limits of the "Alkali Butte member" and the Fales Sandstone Member are shown as heavy lines. Drillholes used for control are shown as black dots. Contour interval is 100 ft.

characteristics of having originated as flood plain, stream channel, and crevasse splay deposits. Individual units, locally as much as 100 ft thick, are highly lenticular and can be traced only short distances laterally. Shale units, many of which are partly carbonaceous, are generally less than 50 ft thick, and to a large extent probably represent overbank deposits. Coal beds are thin (generally a few inches to only a few feet thick; maximum thickness, about 10 ft) and discontinuous; they occur at various horizons, but most commonly near the base where they probably represent coastal swamp and delta plain deposits on top of the marginal marine interval of the Mesaverde. The sharply alternating sequence of varying lithologies in the unnamed middle member is reflected by a distinctive set of jagged curves on resistivity and gamma-ray logs of most wells that penetrate the member across the basin (Figure 22).

The Teapot Sandstone Member of the Mesaverde Formation, which forms the upper part of the nonmarine interval, is easily recognized in both outcrops and drillholes by its distinctive white color and coarse grain size. For these reasons, the top of the member was selected as a convenient datum for the correlation of Cretaceous strata during this study of tight gas sand resources across the Wind River Basin. The Teapot consists of very fine- to coarse-grained sandstone that varies in thickness from about 500 ft in the western part of the basin to only 50 ft in places near the east margin. In the thicker sections, the member commonly contains a few thin shale, siltstone, and carbonaceous shale beds, but in the thinner sections it may include only a single sandstone bed (see drillhole C, Figure 22). The sandstones are considered to be entirely of nonmarine origin in the western part of the (Johnson and Clark, 1993), while the Teapot includes marginal marine rocks in the easternmost part of the basin. The contact between the Teapot Sandstone Member and the unnamed middle member of the Mesaverde is sharp and distinct, and some investigators (Gill and Cobban, 1966; Reynolds, 1966) consider it to mark a regional disconformity across central Wyoming; however, no direct evidence of a disconformity was observed during the present study. Although the base of the white colored Teapot is easy to distinguish in outcrop it is commonly difficult to define in the subsurface without good sample descriptions.

Detailed measured sections of the unnamed middle Member of the Mesaverde Formation

The unnamed middle member of the Mesaverde Formation was described in detail by Johnson and Clark (1993) at several localities in the western part of the basin including partial sections at Bargee School, Muddy Creek , and Eagle Point and a complete section at Shotgun Bench (Figure 2, Plate 2). The section at Muddy Creek was later completed and is presented here for the first time along with complete sections of the unnamed middle member at Coalbank Hills in the southeastern part and Arminto in the northeastern part of the basin.

Bargee School section: At Bargee School locality (Figure 2, Plate 2), A 55-ft-thick, multistorey fine-to very fine-grained sandstone, containing several scoured surfaces overlain by clayey-ripup clast zones, occurs a short distance above the top of the marginal marine sandstone interval. This multistorey sandstone thins along outcrop and is not present at the Muddy Creek section, 2.5 mi to the south-southeast. The sandstone has horizontal laminae, climbing-ripple laminae, and trough crossbeds as much as 2 ft in height. Most trough crossbed axes appear to trend about N. 65^0E. This sandstone consists of two, or possibly more, erosional-based bodies indicating deposition in fluvial channels that reoccupied the same area of the coastal plain several times.

The remaining section consists of zones that contain relatively thick, erosionally-based sandstones, probably deposited by fluvial channels (311 to 435 ft, 538 to 560 ft on Plate 2) alternating with zones containing much thinner sandstones (220 to 311 ft, 435 to 538 ft on Plate 1) of probable crevasse splay origin. Fluvial channel sandstones are about 10 to 20 ft thick, very fine to medium grained, and have horizontal laminae, climbing ripples, and trough crossbeds to about 2 ft in height. Lateral accretion units, with mudstone and siltstone drapes, were observed in two of the sandstones suggesting that they were deposited by mixed load moderate to high sinuosity streams. Another multistoried sandstone body with a scoured surface in the middle part occurs at the top of the section between 538 and 560 ft (Plate 2). Crevasse splay sandstones are from about 1 to 8 ft thick, and consist of small-scale trough crossbeds and climbing ripple laminations.

Seven coal beds occur in the Bargee School section, and all but one of these occurs in the two intervals that do not contain fluvial channel sandstones. Coal beds are from 0.5 to 2 ft thick, generally dull banded and somewhat dirty, and contain carbonaceous shale partings. Three of the coal beds are overlain by crevasse splay sandstones, two by channel sandstones, and two are overlain by carbonaceous shale.

Muddy Creek section: The unnamed middle member is 1,321 ft thick at Muddy Creek (Figure 2, Plate 2) of which the lower 408 ft is coal-bearing with 16 coal beds from 0.4 to 3.2 ft thick. Three fluvial channel sandstones, each about 40 ft thick, occur in this coal-bearing interval; they appear to be single channels, and displays well-developed lateral accretion. Sandstones of probable crevasse splay origin also occur in the coal-bearing interval. These sandstones are as much as 4.5 ft thick, are fairly persistent laterally, and have small trough cross beds and climbing ripple laminations.

The upper part contains fluvial channel sandstones as much as 46 ft thick and only two thin coal beds. The sandstones have scour bases, and several contain one or more scour surfaces above the base indicating that they are multistorey sandstones. Lateral accretion was observed in two of the sandstones. Thinner sandstones of probable crevasse splay origin are scattered throughout the section. In total, the unnamed middle member at Muddy Creek contains 15 fluvial channel sandstones 10 ft thick or greater for a total sandstone thickness of 436 ft or 33 percent. Individual channel sandstones and coal beds are lenticular in the Muddy Creek section because they die out before reaching the Bargee School section about two miles to the north.

Eagle Point Sections: Several multistory sandstone bodies with scour surfaces and associated clayey-ripup clasts occur in the 345 ft of section measured above the marginal marine sandstone interval of the Mesavede Formation (Figure 2, Plate 2). These sandstones are as much as 76 ft thick. Only four coal beds, varying in thickness from 0.3 to 1.5 ft, were observed. One sandstone, interpreted as a crevasse splay deposit, is 11 ft thick (550 to 561 on measured section). Deformed laminations interpreted as escape structures are common in this unit.

A second section at Eagle Point was measured 400 ft to the southwest to study the variability in the fluvial sandstones at Eagle Point. Only 185 ft of the unnamed middle member is exposed at the second locality (Plate 2). Two 0.4-ft-thick coals occur in the interval just above the base that were not observed at the first Eagle Point section; however, these thin coals may have been missed because that interval is not well exposed there. The three fluvial channel sandstones between 290 and 365 ft at the first Eagle Point section were observed to coalesce into one 64-ft-thick multistoried sandstone complex with multiple scoured surfaces and associated ripup zones (Figure 29). The exact relationship between the three fluvial channel sandstones in the first Eagle Point section and the multistoried fluvial channel sandstone at the second section is difficult to determine because of the relatively poor exposures in a gully between these two measured sections. Basal lag deposits consisting of angular ripup clasts of coal, sandstone, siltstone, and mudstone as much as several feet across occur in zones as much as 10 ft thick at the second locality (Figure 30). The sandstone has horizontal beds and trough crossbeds to as much as 2 ft high and is not highly contorted. The same stratigraphic interval at the first Eagle Point section contains two coal beds (Plate 2), and the presence of large coal ripup clasts in lag deposits in this sandstone suggests that the peat accumulations, which formed the coal beds, were channeled out at the second locality.

Shotgun Bench section: The unnamed middle member of the Mesaverde at Shotgun Bench is 1,902 ft thick (Figure 2, Plate 2). It contains nineteen sandstones 10 ft thick or greater for a total thickness of 418 ft, which is 22 percent of the stratigraphic interval. Average thickness of these sandstones is 22 ft, and maximum sandstone thickness observed was 45 ft. The member here can be generally divided into three zones. In ascending order, they are: a coal-bearing interval 390 ft thick (215 to 605 ft on the plotted section, Plate 2), a sandy interval with abundant fluvial channel sandstones 475 ft thick (605 to 1,080 ft), and an upper zone with few fluvial channel sandstones 1,037 ft thick (1,080 to 2,117). No attempt was made to trace these zones laterally and, with the exception of the coaly zone above the basal marginal marine interval, they cannot be identified in the other measured sections in the area. The thick sandstones of probable multistory fluvial channel origin, for example, occur at varying stratigraphic levels of the unnamed middle member of the Mesaverde in the different sections studied. The distribution pattern suggests that major fluvial systems may have remained in one area of the coastal plain for extended periods of time. Stable periods were followed by abandonment and major avulsion that shifted the fluvial channels to another area of the coastal plain.

Nine coal beds varying from 0.5 to 2.0 ft thick occur in the 390-ft-thick coal-bearing interval. Sandstones in this interval are mainly thin tabular sandstones interpreted as crevasse splay deposits ranging from about 0.6 to 5.0 ft thick, which have climbing ripple laminations and trough crossbeds as much as 1 ft high. Only four or possibly five fluvial channel sandstones, ranging from 4 to 25 ft thick, are present in the coal-bearing interval. Well-developed lateral accretion, marked by mud drapes, can be observed in two of these sandstones, suggesting deposition in moderate to high sinuosity streams. Sandstones 10 ft thick or greater comprise only 15 percent of the rock in the coal-bearing interval. The unit here is much less sandy than the approximately equivalent coal-bearing unit, above the marginal marine interval, at all four of the other measured sections. As indicated previously, thick, multistory channel sandstones are interbedded with the coals and carbonaceous shales at the other localities.

The overlying sandy interval contains 183 ft or 39 percent sandstone in beds 10 ft thick or greater and only one-9-inch thick coal bed. The erosional-based sandstones are as much as 45 ft thick, and exhibit trough crossbeds as much as 3 ft high, horizontal bedding and ripple-drift laminae. Lateral accretion of mud drapes was observed in three of the sandstones, two of which were only 8 ft and 9 ft thick suggesting that some fluvial channels were relatively small and sinuous. A few probable crevasse splay sandstones are also present. The upper 1,037 ft of the unnamed middle member is an alternating sequence of thin, fine-to very fine-grained fluvial channel sandstones and crevasse splay sandstones. Many of the lenticular sandstone bodies are

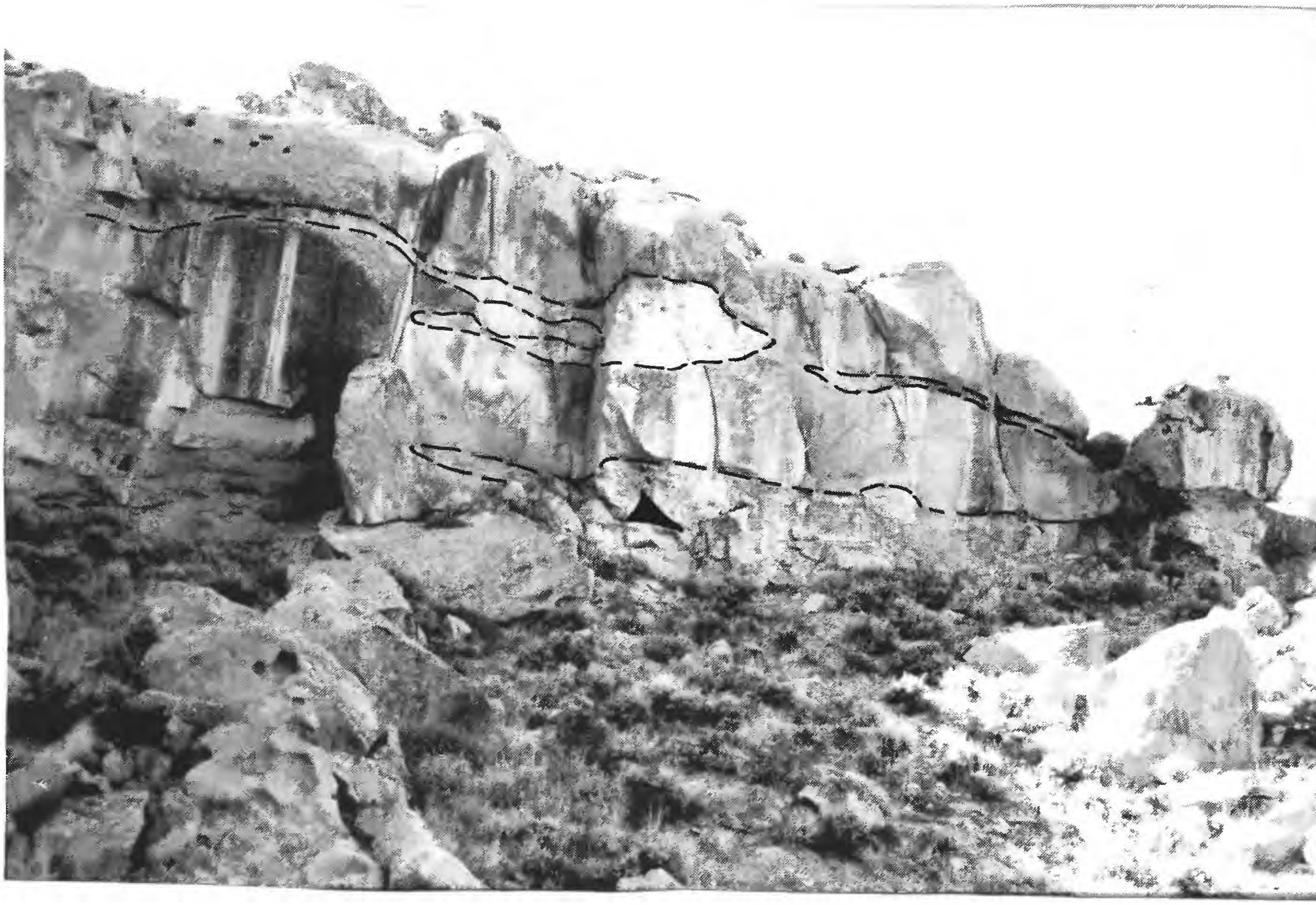


Figure 29: Multistorey fluvial channel sandstone with several highly irregular zones of ripup clasts (outlined with dotted lines) in the nonmarine interval of the Upper Cretaceous Mesaverde Formation at the second Eagle Point measured section in the northwest part of the basin (Plate 2; location in Plate 1c). Note six foot man for scale.

Figure 30: Ripup zone with large, angular coal, siltstone, and sandstone clasts at base of multistoried, multiscoured fluvial channel sandstone body in the nonmarine interval of the Upper Cretaceous Mesaverde Formation at second Eagle Point measured section in the northwest part of the basin (Plate 2; location on Plate 1c). Notebook (5x8 inches) for scale.

only 8 to 10 ft thick. Only nine sandstones are 10 ft thick or greater, and total 176 ft (17 percent) of the interval. Forty-one feet of this total is a single lenticular sandstone bed near the top of the interval. Four thin coal beds, from 3 inches to 1 ft thick are also present.

Coalbank Hills section: The unnamed middle member of the Mesaverde Formation is 407 ft thick at Coalbank Hills in the southeastern part of the Wind River Basin (Figure 2, Plate 3). The lower 60 ft is carbonaceous but contains no coal beds and no sandstone beds. The remaining 347 ft consists of fluvial channel sandstones from 10 to 23 ft thick, thin splay sandstones to as much as 2 ft thick, and gray mudstone. Channel sandstones are single rather than multistorey bodies and have display cross bedding and ripple drift laminae. Only four channel sandstones 10 ft thick or greater are present and have a combined thickness of 65 ft or 16 percent of the middle member.

Arminto section: At Arminto, in the northeast part of the basin, the unnamed middle member is 489 ft thick (Figure 2, Plate 3). The carbonaceous and coaly interval, typically found at the base of the unnamed middle member, is not present here. Individual channel sandstones vary from about 5 to 38 ft thick. Figure 31 is a photo which shows an 81-ft-thick complex sequence of sandstones that occurs between 698 and 779 ft on the measured section. Three discrete sandstones 25 ft, 8 ft, and 35 ft thick, in ascending order, occur in this interval. The upper and lower sandstones are mainly trough-cross bedded with multiple minor scour surfaces. The middle, much thinner sandstone displays well-developed lateral accretion with mud drapes along accretion units as well as trough cross bedding and ripple drift laminae. Figure 32 is a photo of the upper part of the unnamed middle member, from about 923 ft to 1,082 ft. Six fluvial channel sandstones from 5 to 38 ft thick occur in this interval and are highly variable laterally. The sandstones display well-developed lateral accretion with clay drapes along accretion units. Six sandstones 10 ft thick or greater for a total thickness of 160 ft or 33 percent occur in the unnamed middle member at Arminto.

Detailed measured sections of the Teapot Sandstone

The Teapot Sandstone was described in detail at Muddy Creek and Shotgun Bench in the western part of the basin and at Coalbank Hills, Arminto, Hells Half Acre, and Cave Gulch in the eastern part (Figure 2, Plates 2 and 3). The Shotgun Bench section is from Johnson and Clark (1993). The remaining sections of the Teapot are new data.

Shotgun Bench section: The Teapot Sandstone Member at the Shotgun Bench locality is 503 ft thick (Figure 2, Plate 3). Its basal contact is distinct and sharp, with a thick fine-to medium-grained white sandstone overlying a thin fine-to very-fine grained gray sandstone of the unnamed middle member. Six prominent sandstones from 21 to 85 ft thick are present one of which pinches out along the outcrop. Bedding features are generally difficult to distinguish in these sandstones but trough crossbeds as much as 5 ft high and horizontal to subhorizontal laminae can be seen. Climbing ripples were observed on some of the trough surfaces. Possible erosion surfaces were observed in some of the sandstones, suggesting that they might be multistory, although no clayey ripup clasts were found. One 0.5 to 1 ft thick nonlaminated calcareous zone which may be a paleosoil occurs within a thick sandstone at 2,444 ft on the plotted section (Plate 2). A distinctive crisscross pattern of tabular-shaped veinlets as much as 2 in thick and from about two to six inches apart occur in abundance in many of these sandstones. These veinlets are non-calcareous, more resistant to weathering than the host sandstone, and

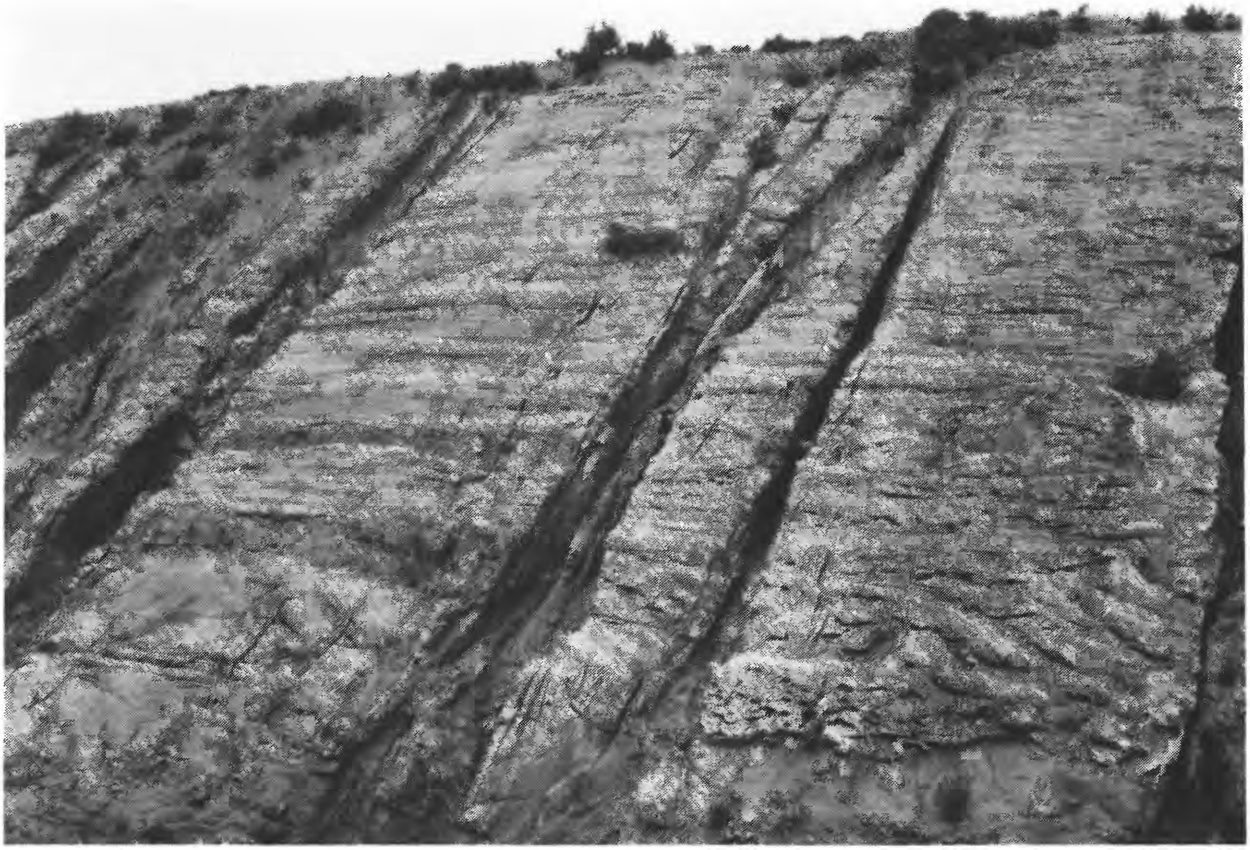


Figure 31: Photo of three fluvial channel sandstones in the in the nonmarine interval of the Upper Cretaceous Mesaverde Formation at Arminto measured section in the northeast part of the basin (Plate 3; location on Plate 1c). The sequence is 81 ft thick; the two thickest sandstones are about 30 to 35 ft thick; up section is to left.

Figure 32: Photo of six fluvial channel sandstones in the nonmarine interval of the Upper Cretaceous Mesaverde Formation at Arminto measured section in the northeast part of the basin (Plate 3; location on Plate 1c). The sandstones are from 5 to 38 ft thick and display well-developed lateral accretion.

occur at oblique angles to both bedding and the horizontal. A single thin section of a veinlet from a somewhat weathered outcrop sample (C. W. Keighin, oral comm., 1/96) failed to reveal any significant differences in grain size or cementation between the veinlet and the host sandstone. Clay cement is somewhat more abundant and porosity somewhat lower in the veinlet than in the host sandstone. These veinlets were also noted in the Teapot Sandstone Member by Keefer and Troyer (1964, p. 24). Interbedded with the thicker sandstones are gray mudstone, carbonaceous shale, and thin, largely lenticular sandstones. Many of the thin sandstones are bioturbated, but a few have small-scale trough crossbeds as much as 1 ft high and ripple drift laminae. The contact of the Teapot Sandstone Member with the overlying Meeteetse Formation is placed at the top of the highest white sandstone.

Muddy Creek section: The Teapot Sandstone Member is 330 ft thick at Muddy Creek (Figure 2, Plate 2). It is distinguished from the underlying unnamed middle member by its coarser grain size and white color. The basal contact, which is thought to be part of a regional unconformity by Gill and Cobban (1966) and Reynolds (1966), was walked out along outcrop in a north-south direction for about a half mile (Plate 2). Along this traverse, the white, medium- to coarse-grained sandstones of the Teapot are interbedded with the brown, fine-to very fine-grained sandstones of the unnamed middle member, and deposition of the lithologically different sandstones appears to overlap in time (Figures 33 and 34). The basal white sandstone of the Teapot is lenticular along outcrop whereas white sandstones above the basal sandstone appear to be quite extensive laterally (Figure 35). Sandstones in the Teapot are as much as 121 ft thick and commonly display an intense crisscrossing pattern of veinlets previously described by Keefer and Troyer (1964), and Keefer (1972) (Figure 36). These veinlets, where present, largely obscure bedding features. The sandstones appear to contain multiple scour surfaces with white clayey ripups and, in some places, large fossilized logs along scour surfaces (Figure 37). They are trough cross bedded with troughs as much as 4 ft high. The contact with the overlying Meeteetse Formation is placed at the top of the highest white sandstone of the Teapot. Only the lower 150 ft of Meeteetse is exposed at Muddy Creek. The Teapot Sandstone Member at the Muddy Creek section contains five sandstones 10 ft thick or greater with a combined thickness of 272 ft.

Coalbank Hills section: At Coalbank Hills (Figure 2, Plate 3), the Teapot Sandstone Member consists of a single, 20-ft-thick, fine- to very fine-grained white sandstone in sharp contact with the underlying gray mudstones and coarser grained sandstones of the middle member. Internally, the sandstone has small scour surfaces, low-angle cross bedding, trough cross bedding, and ripple drift laminae. It has some of the crisscross veinlets that characterizes the Teapot in many areas of the basin (Figure 38). Interestingly, this veining was never seen in any sandstones in the basin except those in the Teapot. Only the lower few feet of carbonaceous shales and sandstones of the overlying Meeteetse Formation are exposed at the Coalbank Hills locality.

Arminto section: At Arminto (Figure 2, Plate 3) the Teapot Sandstone Member is a single 27-ft-thick, white, medium grained sandstone. It contains multiple small scour surfaces with white clayey ripups above the surfaces, and numerous clayey drapes (Figure 39). About 48 ft of carbonaceous shale, thin coal beds, and thin sandstone of the overlying Meeteetse Formation are exposed in this section.

Hell's Half Acre: A detailed section of the Teapot Sandstone Member, and overlying Lewis Shale and Meeteetse Formation was measured and described in detail near Hell's Half

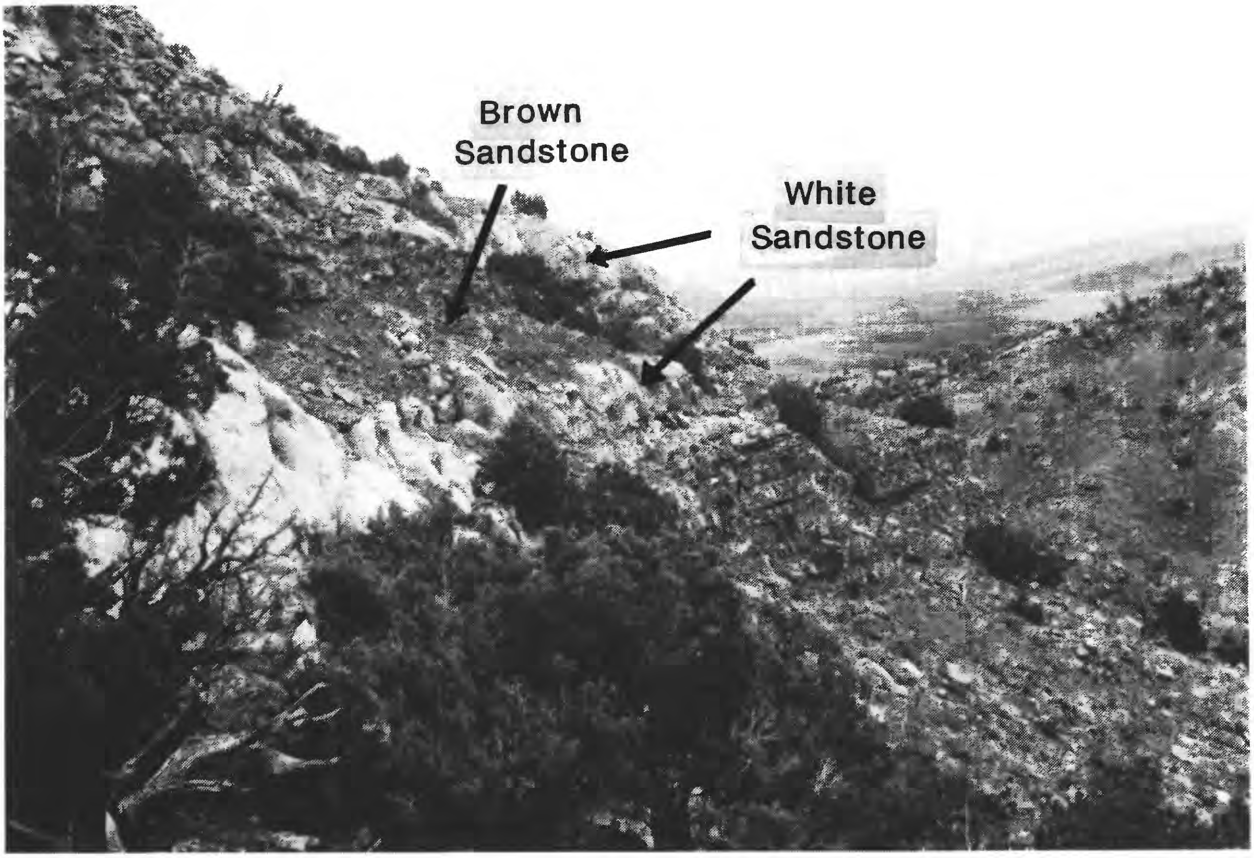


Figure 33: Photo of base of Teapot Sandstone Member of the Upper Cretaceous Mesaverde Formation at Muddy Creek measured section in the western part of the basin (Plate 2; location on Plate 1c) showing intertonguing of white medium-grained sandstones typical of the Teapot (just above six foot tall man's head and at far left of photo) and brown, very-fined grained sandstone that is ripple drift laminated and typical of the underlying middle member (arrow).

Figure 34: Closeup of very-fine grained, brown, ripple drift laminated sandstone above lowest medium-grained, white sandstone of the Teapot Sandstone Member of the Upper Cretaceous Mesaverde Formation at the Muddy Creek measured section in the western part of the basin (Plate 2; location on Plate 1c). Note 26 inch long pick for scale.

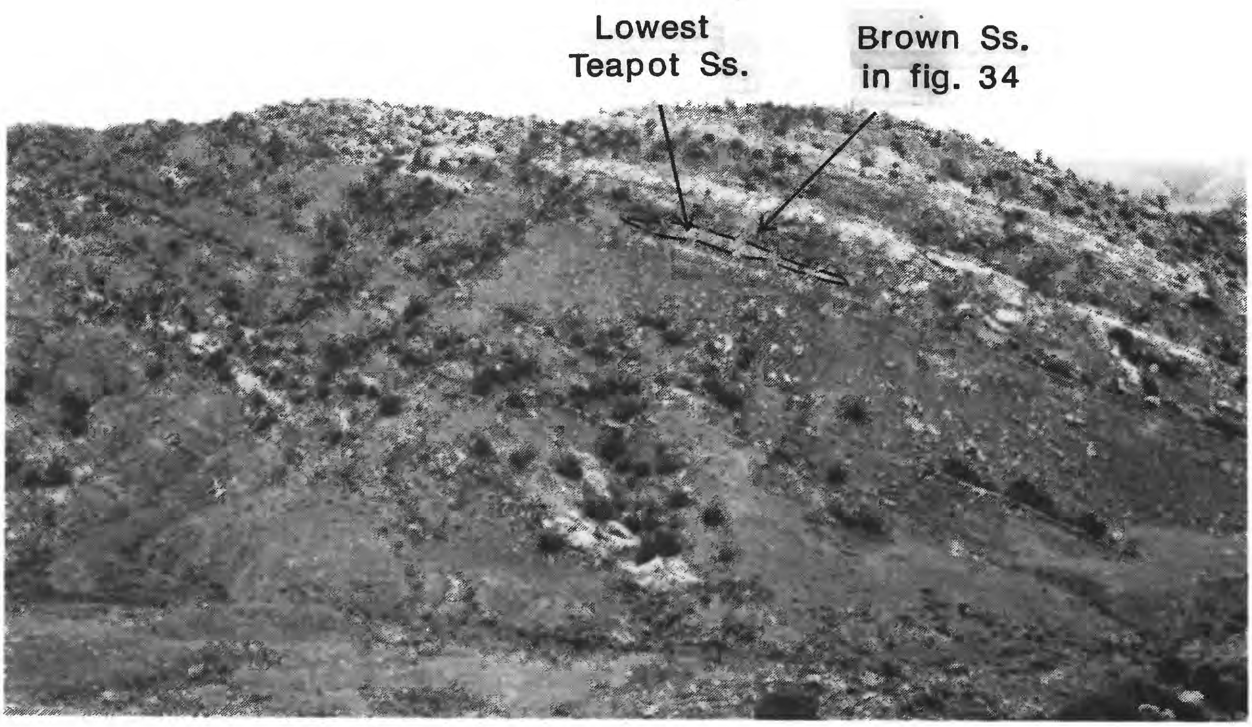


Figure 35: Distant shot of wihte sandstones of the Teapot Sandstone Member of the Upper Cretaceous Mesaverde Formation at Muddy Creek measured sectionin the northwest part of the basin (Plate 2; location on Plate 1c). Note lenticular nature of basal white sandstone of the Teapot and much more persistent nature of sandstone in the Teapot above the basal sandstone. The Teapot is about 300 ft thick here.

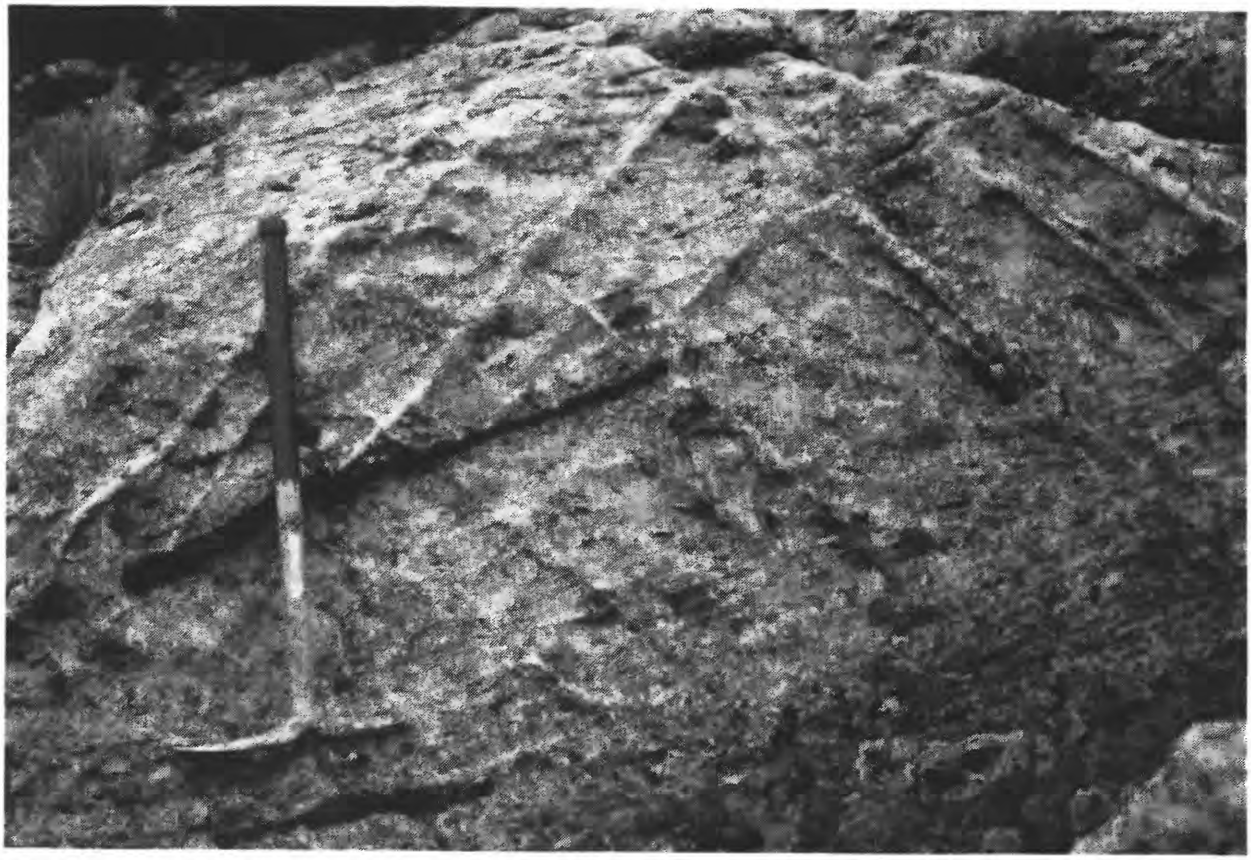


Figure 36: Unusual cross-cutting veinlets that characterize the Teapot Sandstone Member of the Upper Cretaceous Mesavede Formation at Muddy Creek measured section in the northwest part of the basin (Plate 2; location on Plate 1c). This feature was observed in the Teapot at many localities across the Wind River Basin.

Figure 37: Large log above scour surface in the Teapot Sandstone Member of the Mesaverde Formation at Muddy Creek measured section in the northwest part of the basin (Plate 2; location on Plate 1c).

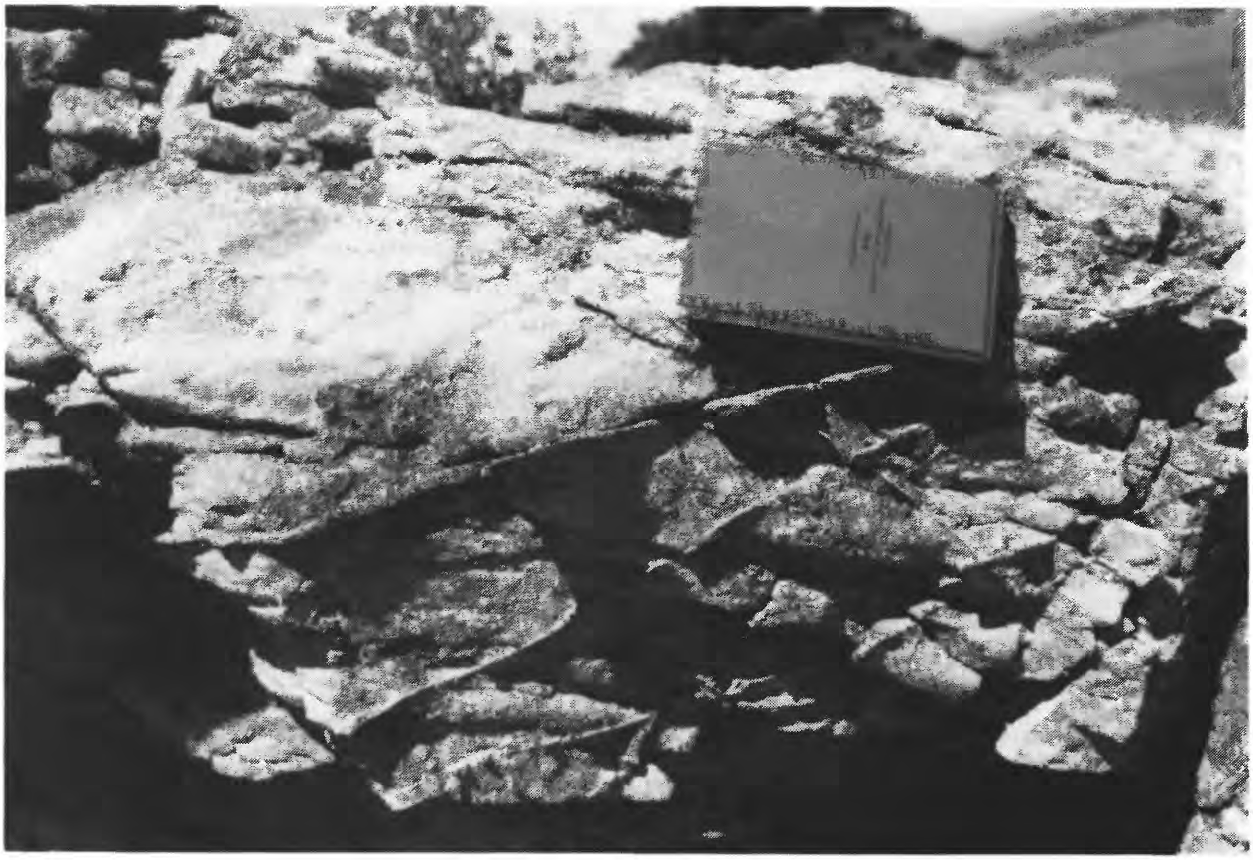


Figure 38: Unusual cross-cutting veinlets found in the Teapot Sandstone Member of the Upper Cretaceous Mesaverde Formation at Coalbank Hills measured section in the southeastern part of the basin (Plate 3; location on Plate 1c). Note 5 by 8 inch notebook for scale.

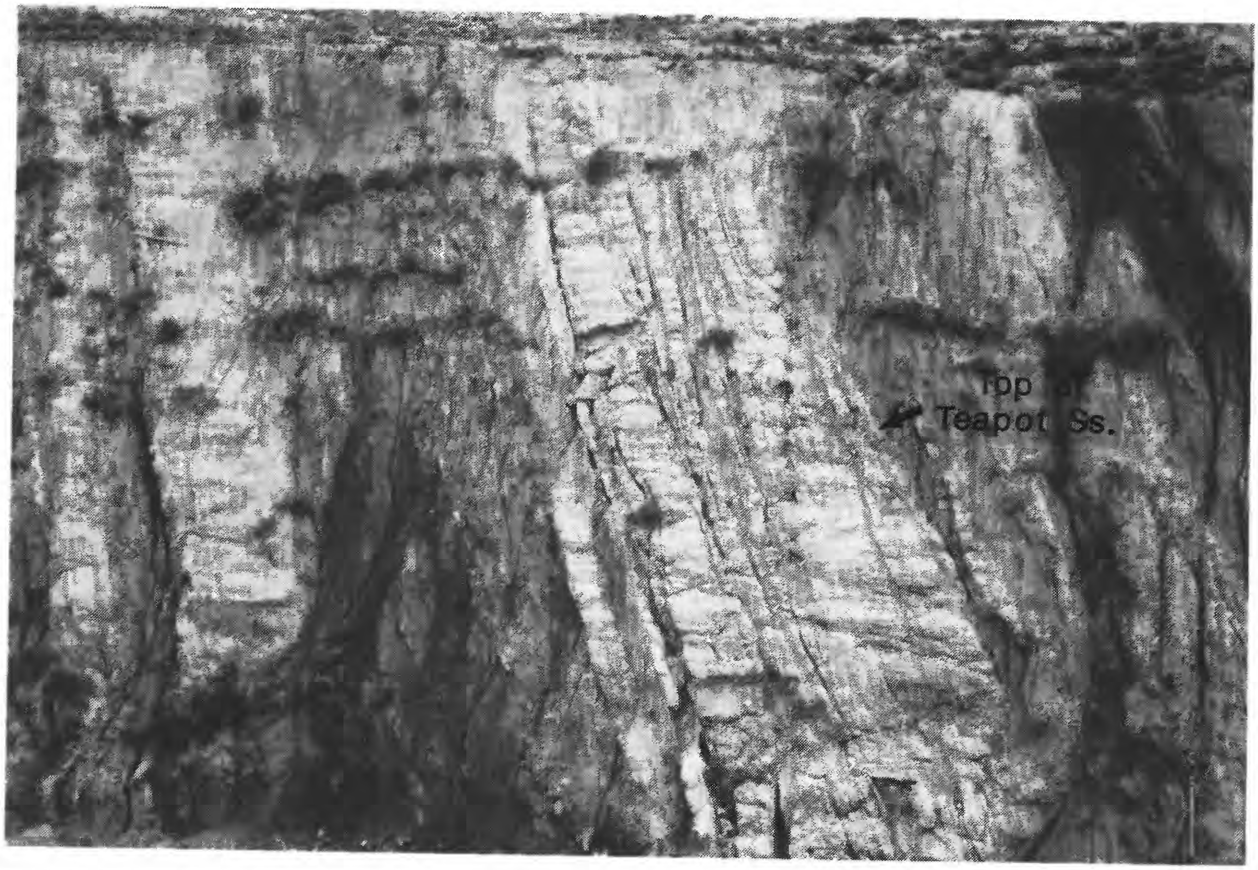


Figure 39: Photo of multiscoured sandstone in the Teapot Sandstone Member of the Upper Cretaceous Mesaverde Formation at the Armnto measured section in the northeast part of the basin (Plate 3; location on Plate 1c). Sandstone is from 25 to 30 ft thick.

Acre (Figure 2, Plate 3) about 12 miles southeast of the Arminto section in the eastern part of the basin. The Teapot at this locality is 150 ft thick and includes two sandstones, 70 and 69 ft thick separated by 11 ft of carbonaceous shale. A small scour-based lenticular channel sandstone occurs in the carbonaceous shale. Internally, the two sandstones are trough cross bedded with troughs as much as 5 ft high (Figure 40). Some horizontal bedding and hummocky bedding was also observed (Figure 41). The trough cross beds are bi-directional (Figure 42) with the majority of troughs indicating a due south flow direction and fewer troughs trending north-northwest (Plate 3). The bi-directional trough cross beds and hummocky beds suggest that the Teapot Sandstone at Hell's Half Acre is marginal marine. In addition, the Teapot is overlain by a tongue of the marine Lewis Shale, which is discussed with the discussion of the Meeteetse Formation.

Cave Gulch section: A detailed section beginning at the base of the Teapot Sandstone Member and ending in the lower part of the Fort Union Formation was measured near Cave Gulch in the northeast part of the basin about 6 miles southeast of the Arminto section (Figure 2, Plate 3). At this locality, the sandstone is a single, white, fine-to medium-grained, 35 ft-thick sandstone. Internally the sandstone has trough cross beds, horizontal and low-angle bedding, and irregular laminae. It is overlain by carbonaceous shale and thin channel sandstones of the Meeteetse Formation.

Hydrocarbon production and reservoir characterization of sandstones in the nonmarine interval of the Mesaverde Formation

To date, the nonmarine interval of the Mesaverde Formation has not been highly productive in the Wind River Basin. Production has occurred at Madden Anticline in the north-central part of the basin, at Muddy Ridge and Sand Mesa fields in the western part of the basin, and at West Poison Spider Field in the easternmost part of the basin (Figure 3). At Madden, the Mesaverde is highly overpressured and requires at least 14 lb mud to maintain balance while drilling (Dunleavy and Gilbertson, 1986, p. 115). Mesaverde production at Madden is confined to the Teapot Sandstone Member which has an average log porosity of 7.4 percent and a permeability from core of 0.03 md (Dunleavy and Gilbertson, 1986). At West Poison Spider field, the Teapot produces both oil and gas. Analysis from core of the Teapot at West Poison Spider averaged 12 percent porosity, with a range of 4.5 to 16.5 percent, and a permeability of 17.7 md (Gouger, 1989).

Total sandstone in the unnamed middle member and Teapot Sandstone Member in beds 10 ft thick or greater varies from over 1,200 ft in the western part of the Wind River Basin to less than 100 ft in the extreme eastern part (Figure 43). The percent sandstone in this interval varies from less than 10% to over 50% (Figure 44). The principal targets for hydrocarbon exploration in the unnamed middle member are fluvial channel sandstone. The much thinner crevass splay sandstones may also be exploration targets, particularly if several are perforated in the same drillhole. Single channel sandstones vary in thickness from as little as 5 ft at the Arminto section in the eastern part of the basin to a maximum of about 50 ft at the Muddy Creek section in the western part. Crossbeds in these sandstones were not studied in detail but stream flow direction was probably from west to east, or perpendicular to the north-south trending Upper Cretaceous shoreline. Many of the channel sandstones display well-developed lateral accretion. Clayey drapes, which commonly occur in association with the accretion units,

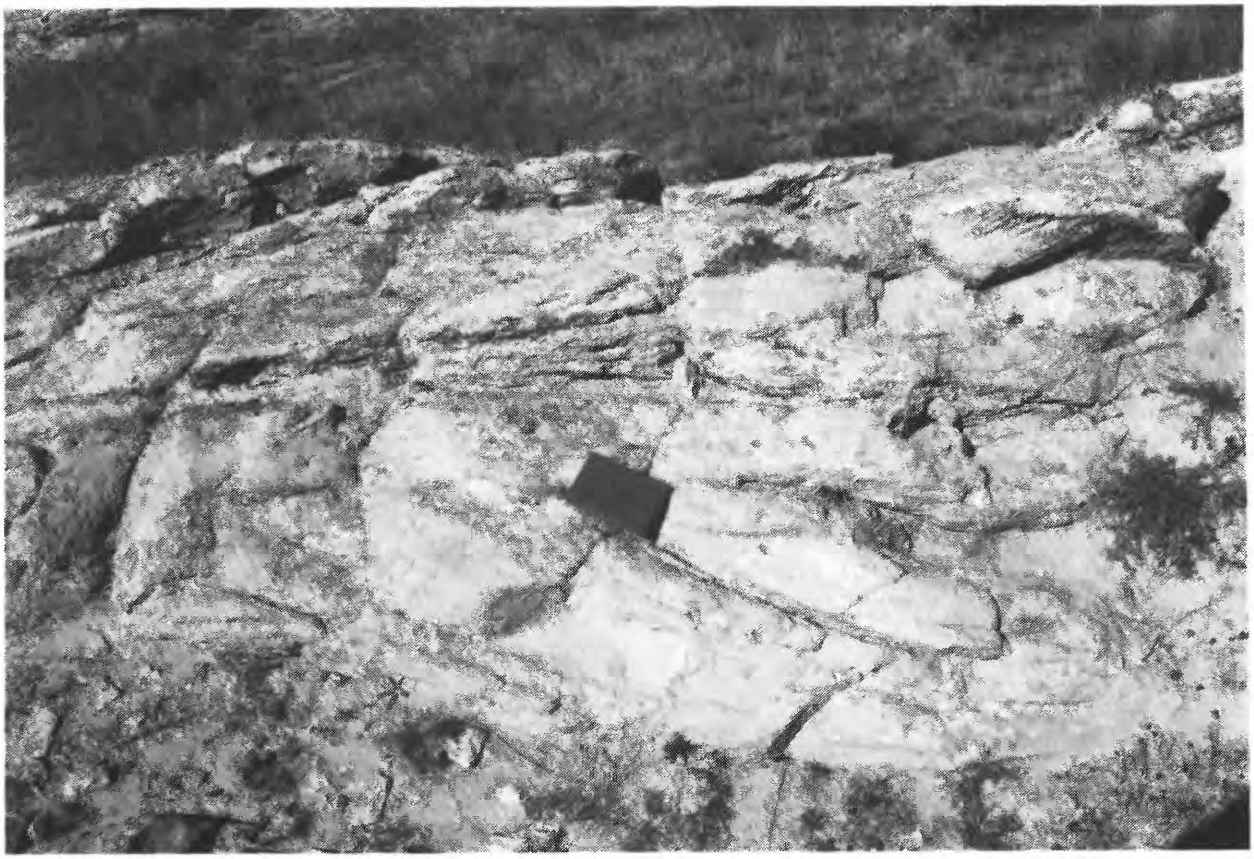


Figure 40: Photo of trough-cross beds as high as 5 ft in the Teapot Sandstone Member of the Upper Cretaceous Mesaverde Formation at Hell's Half Acre measured section in the northeast part of the basin (Plate 3; location on Plate 1c).

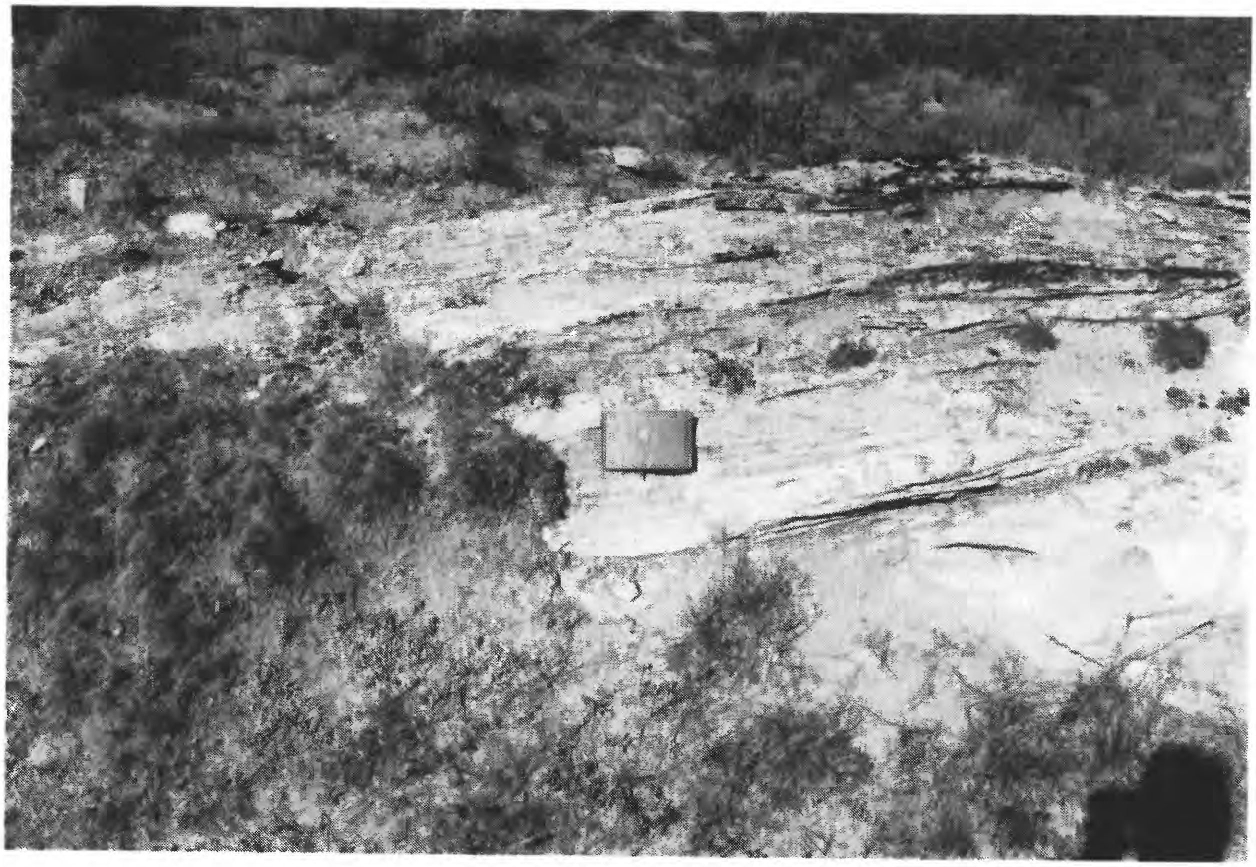


Figure 41: Photo of humocky bedding in the Teapot Sandstone Member of the Upper Cretaceous Mesaverde Formation at Hell's Half Acremeasured section in the northeast part of the basin (Plate 3; location on Plate 1c). Note 5 by 8 inch notebook for scale.

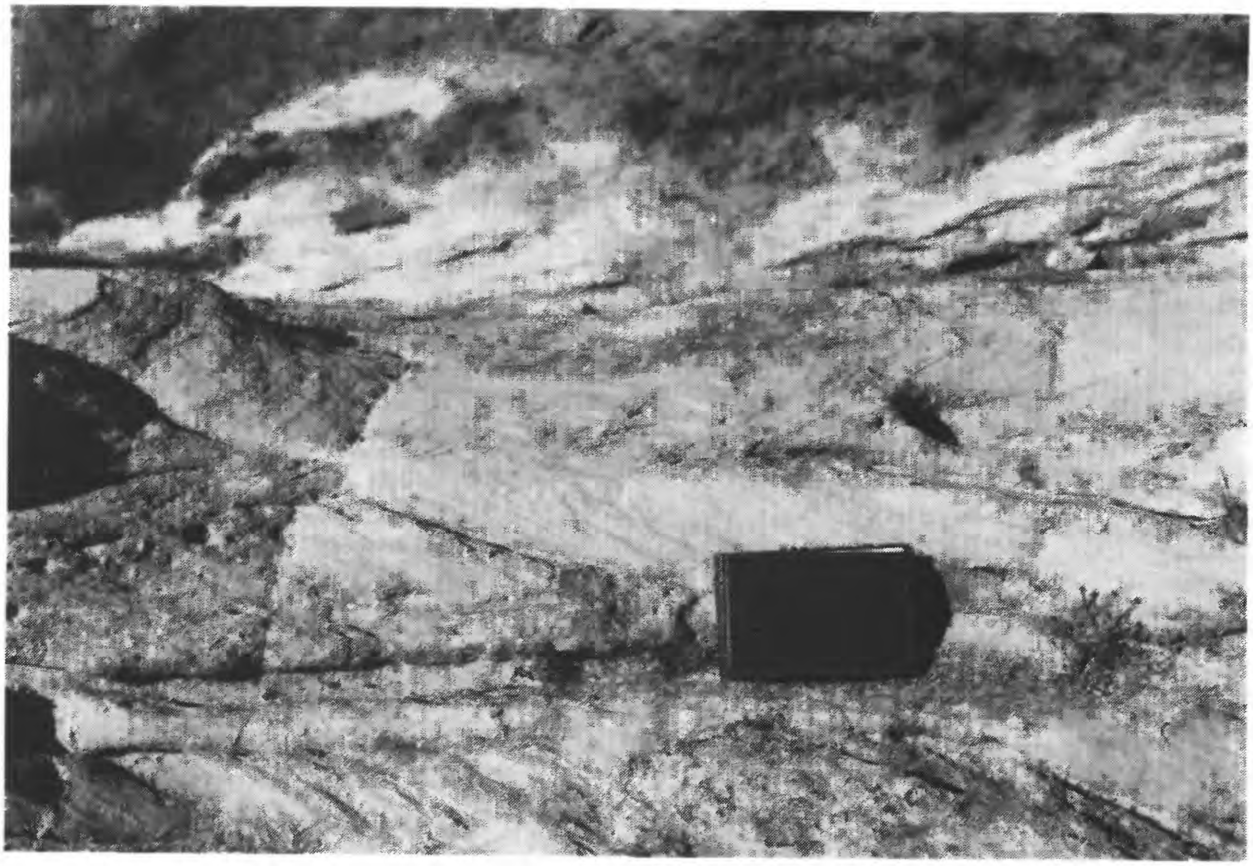


Figure 42: Photo of bidirectional trough-cross bedding in the Teapot Sandstone Member of the Upper Cretaceous Mesaverde Formation at Hell's Half Acre measured section in the northeast part of the basin (Plate 3; location on Plate 1c). Note 5 by 8 inch notebook for scale.

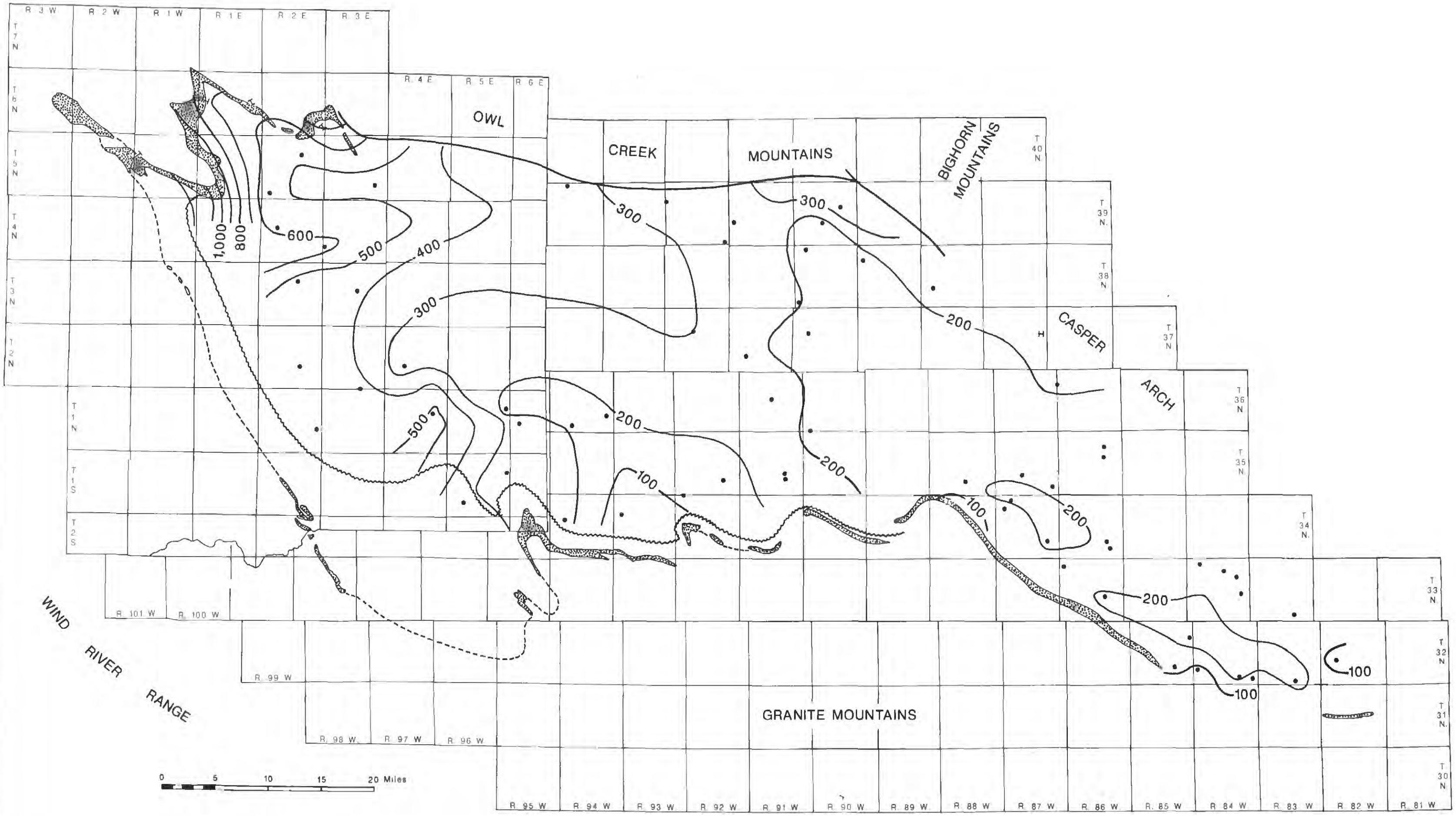


Figure 43: Isopach map of total sandstone in beds 10 ft thick or greater in the middle member and the Teapot Sandstone Member of the Upper Cretaceous Mesaverde Formation, Wind River Basin, Wyoming. Drillholes used for control are shown as black dots. Contour interval is 100 ft.

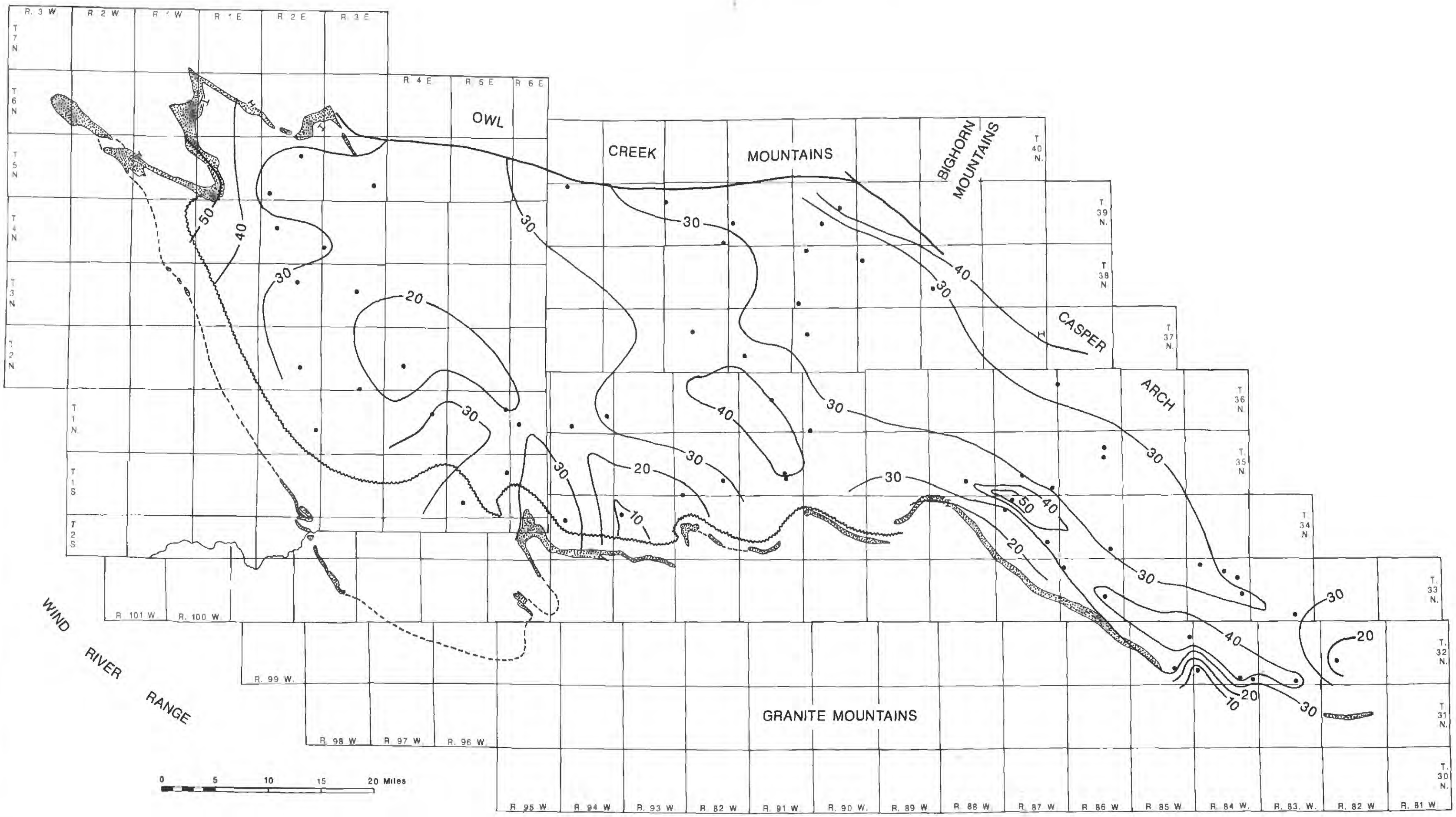


Figure 44: Percent sandstone map for sandstone beds 10 ft thick or greater in the middle member and the Teapot Sandstone Member of the Upper Cretaceous Mesaverde Formation, Wind River Basin, Wyoming. Drillholes used for control are shown as black dots. Contour interval is 10 percent.

could act as permeability barriers in the subsurface. Complex multistorey sandstone units with multiple scour surfaces as much as 76 ft thick occur in the Muddy Creek and Eagle Point sections in the western part of the basin. Windolph and others (1982) and Hickling and others (1989) reported sandstones as much as 100 ft thick in the unnamed middle member in the western part of the basin. These multistorey sandstones may be attractive targets for future hydrocarbon exploration. A multistorey sandstone body at the closely spaced sections at Eagle Point, however, had a very limited lateral extent in a north-south direction or perpendicular to the probable direction of stream flow.

The Teapot Sandstone Member appears to be present throughout the basin. The fluvial sandstones in the western part of the basin are complex multiscour, multistorey bodies. Some of these sandstones appear to be quite lenticular while others appear to have considerable lateral extent. Cross beds in the western part of the basin, where the Teapot is fluvial, were not studied in detail. Curry (1976) suggested that the Teapot Sandstone in the Powder River Basin to the East of the Wind River Basin was deposited in an eastward prograding delta a conclusion also supported by Coughlan (1983). This would suggest that the Teapot fluvial systems flowed generally eastward toward the open sea. In contrast, marginal marine Teapot sandstones in the eastern part of the basin may trend generally north-south or parallel to paleoshoreline

MEETEETSE FORMATION AND LEWIS SHALE

The Meeteetse Formation consists of interbedded nonmarine sandstone, siltstone, shale, carbonaceous shale, and coal deposited in poorly drained coastal environments to the west of the advancing Lewis seaway. The Meeteetse is generally much less sandy than the underlying unnamed middle member of the Mesaverde Formation. Resistivity and gamma-ray log, particularly in combination with sonic logs that help to define coaly intervals, serve to distinguish the Meeteetse in wells across the basin (Figure 45). In the southeastern corner of the basin, tongues of marine shale and sandstone of the Lewis Shale occur at the top and base of the Meeteetse interval (drillhole B, Figure 45), reflecting limited westward transgressions of the Late Cretaceous Lewis sea into this area. A thin shale unit also occurs at the base of the Meeteetse in wells drilled on the Madden anticline in the northeast corner of the basin (see drillhole C, Figure 22); this unit was considered to be the lower tongue of the Lewis Shale by Dunleavy and Gilbertson (1986). The thickness of Meeteetse-Lewis strata ranges from about 750 to 1,335 feet thick (Figure 46). The Meeteetse is progressively truncated by younger rocks toward the south margin of the basin.

Sandstones in the Meeteetse Formation are fine- to coarse-grained, and lenticular. The formation contains a higher proportion of coal and carbonaceous shale beds than any of the other Cretaceous formations in the region (see sonic log on drillhole A, Figure 45). The coal beds are commonly only a few inches to a few feet thick. The thickest beds are about 15 feet. Total aggregate thickness of coal in beds 2 ft thick or greater is about 50 ft in the central part of the basin (Figure 47). Nearly all of the shale beds in the Meeteetse are carbonaceous to some extent. Because of poor exposure, few directional readings on cross beds were measured in the fluvial sandstones.

Detailed measured sections of the Meeteetse Formation and Lewis Shale

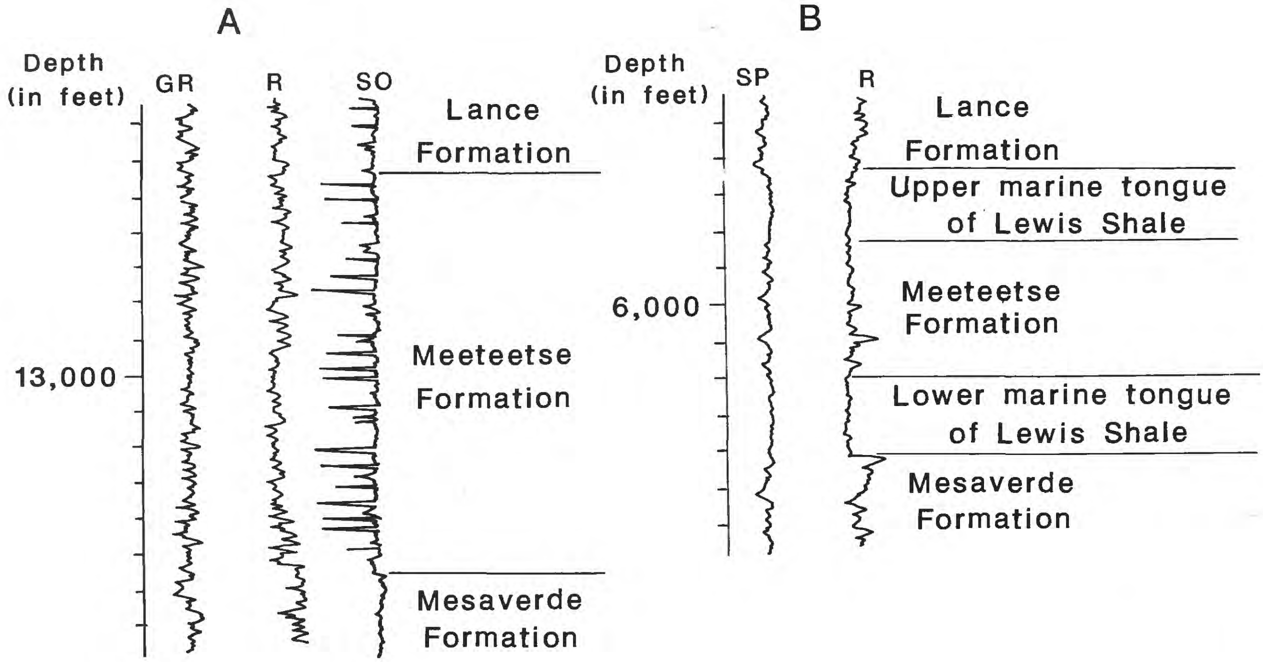


Figure 45: Geophysical logs (R - resistivity, GR - gamma-ray, SO - sonic, SP - self potential) of the Meeteetse Formation and Lewis Shale of Upper Cretaceous age. Drillhole A - Dome Petroleum Moneta no 1-29 (SW1/4 NE1/4 sec. 29, 37N., R. 91 W.); drillhole B - Union Oil of California Young Ranch no. 1-34 (NE1/4 SE1/4 sec. 34, T. 32N., R. 83W.).

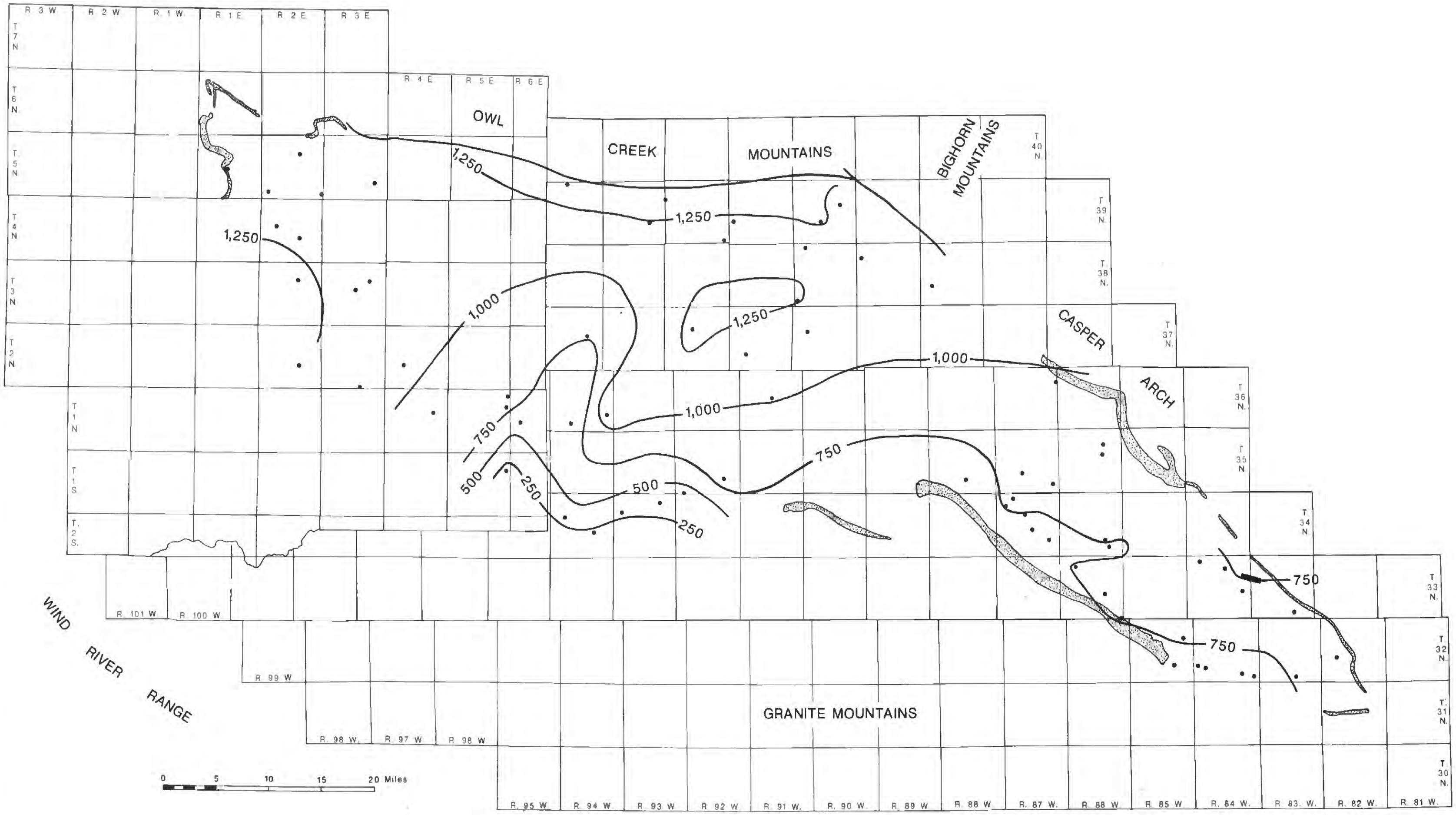


Figure 46: Isopach map of the Meeteetse Formation and Lewis Shale of Upper Cretaceous age. The Lewis Shale is present only in the eastern part of the basin. Drillholes used for control are shown as black dots. Contour interval is 250 ft.

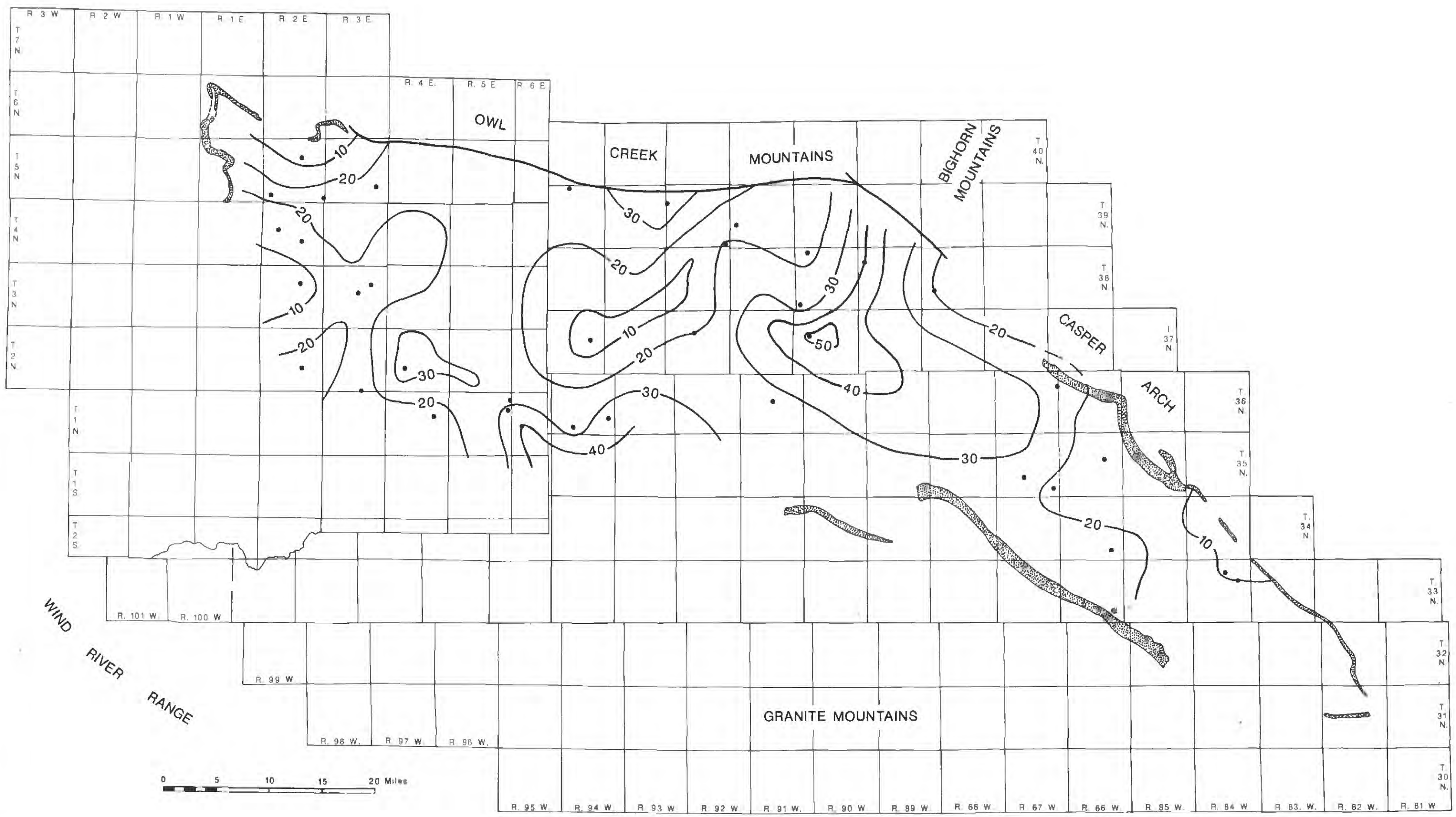


Figure 47: Isopach map of total coal in beds 2 ft thick or greater in the Upper Cretaceous Meeteetse Formation. Drillholes used for control are shown as black dots. Contour interval is 10 ft.

The Meeteetse Formation and Lewis Shale are generally nonresistant to weathering and typically form valleys between the resistant sandstones of the Mesaverde below and the resistant sandstones of the Lance above. As a result, well exposed sections of the Meeteetse Formation and Lewis Shale in the Wind River Basin are rare. Detailed sections were measured at Shotgun Bench in the western part of the basin and at Cave Gulch and Hell's Half Acre in the eastern part (Figure 2, Plates 2 and 3).

Shotgun Bench section: The Meeteetse Formation at Shotgun Bench (Figure 2, Plate 2) is 1,080 ft thick and contains a total of 507 ft of sandstone, or 47 percent of the total rock volume, in units 10 ft thick or greater. All of the sandstones appear to be highly contorted. The Meeteetse can be generally subdivided into four intervals, two coaly (2,620 to 3098 ft and 3,280 to 3,595 ft on the measured section, Plate 1) and two sandy intervals (3,098 to 3,280 ft and 3,595 to 3,700). The lower coaly interval contains six coal beds from 3 inches to 1 ft thick, and much of the shale is carbonaceous. Sandstone units in the lower coaly interval are as much as 31 ft thick, and many pinch out along outcrop. They have trough crossbeds as much as 3 ft high and ripple-drift laminae. The upper coal-bearing interval is similar to the lower, with six coal beds from 6 inches to 1.5 ft thick , and most of the shaly intervals are carbonaceous. The sandstones in the upper coaly interval are also similar to those in the lower interval, with a maximum thickness of 22 ft. The two sandy intervals of the Meeteetse contain sandstone units with a maximum thickness of 105 ft. They have trough crossbeds as much as 3 ft high and ripple-drift laminae; bedding characteristics, however, are generally difficult to see, particularly in the thick sandstone at the top of the formation. A clay ripup clast zone occurs in the middle of the lower sandstone in the lower sandy zone, suggesting that it may be a multistory sandstone.

Hell's Half Acre section: Approximately 400 ft of Lewis Shale strata occurs at the base of the Meeteetse-Lewis interval at the Hell's Half Acre section (Figure 2, Plate 3). The basal bed is a 20 ft thick fine-to very fine-grained white sandstone with abundant carbonaceous laminae and probably hummocky cross stratification (Figure 48). The next 91 ft consists of interbedded sandstone and gray fissile shale. The sandstones are horizontal and hummocky bedded and contain *Ophiomorpha* burrows, and some of the shaly sequences are streaky to lenticular bedded (Figure 49). Above this interbedded sequence is 142 ft of fine-to very fine-grained light gray to white sandstone that exhibits hummocky bedding and *Ophiomorpha* burrows, in the lower part and two distinct scour surfaces with clayey ripups in the upper part. Small trough cross beds also occur in the upper part.

The lower 747 ft of the overlying Meeteetse Formation is relatively well exposed at Hell's Half Acre, but the uppermost part is largely concealed. A 28 ft fine-to very fine-grained white sandstone, with bi-directional trough cross beds, occurs at the base. The remainder of the formation is interbedded sandstone, gray shale, and carbonaceous shale and coal. Fluvial channel sandstone beds are minor constituents, ranging from about 6 ft to 19 ft in thickness. Only four sandstones are 10 ft thick or greater for a total thickness of 60 ft. Some sandstones are small, cut and fill channels of limited dimensions while others are fairly extensive laterally. Crevasse splay sandstones to as much as 5 ft thick are scattered throughout the interval as are carbonaceous shale and coal. The thickest coal beds, 3 ft and 6 ft thick separated by a 2-ft-thick carbonaceous shale parting, occur between 1,266 and 1,277 on the measured section (Plate 3). An abandoned mine shaft occurs in this interval along the line of section.

Figure 48: Photo of hummocky bedding in interbedded carbonaceous shale and sandstone in the Upper Cretaceous Lewis Shale at Hell's Half Acre mesured section in the eastern part of the basin (Plate 3; location on Plate 1c). Note 5 by 8 inch notebook for scale.

Figure 49: Photo of streaky to lenticular bedding in the Upper Cretaceous Lewis Shale at Hell's Half Acre measured section in the eastern part of the basin (Plate 3; location on Plate 1c). Note 5 by 8 inch notebook for scale.

Cave Gulch section: The Meeteetse Formation at Cave Gulch is divided into two units by a tongue of the Lewis Shale (Figure 2, Plate 3). The lower unit, directly above the Teapot Sandstone Member of the Mesaverde Formation, is 94 ft thick and consists of carbonaceous shale with two thin channel sandstones 4 and 8 ft thick. These sandstones display well-developed lateral accretion with clayey drapes along accretion units. Above this lower Meeteetse unit is 464 ft of Lewis Shale which is poorly exposed except for a 79 ft thick fine-to very fine-grained, light-gray to white sandstone near the middle, and 58 ft of slightly fissile gray mudstone with three 1 ft thick hummocky cross stratified sandstones at the top. The 79 ft thick sandstone is horizontal and hummocky cross stratification with many types of burrows including *Ophiomorpha* burrows. Strata of Lewis Shale are of marine origin.

The Lewis Shale tongue is overlain by carbonaceous shale of the overlying tongue of the Meeteetse Formation. Typical Meeteetse lithology of carbonaceous shale and coal interbedded with relatively thin fluvial channel sandstones extends up to the base of a 214-ft sandstone that begins at 1,623 ft on the measured section (Plate 3). Carbonaceous shale and thin coal beds are scattered throughout, with a maximum coal bed thickness of 2.5 ft. The fluvial channel sandstones vary from small cut and fill channels as little as 3 ft thick to more laterally extensive channels to as much as 25 ft thick. All channels appear to be simple or non-stacked channels, and many of these channels display well-developed lateral accretion with clay drapes along accretion units.

The 214 ft sandstone, occurring at 1,623 ft on the measured section (Plate 3) is thought to mark the base of the Lance Formation. If this is a valid interpretation, then the total thickness of the Meeteetse-Lewis interval at this locality is 1,588 ft , or about 600 ft greater than the thickness based on well data from adjacent areas to the west. The cause of this thickness variation was not determined..

Hydrocarbon production and reservoir characterization of sandstones in the Lewis Shale and Meeteetse Formation

Although the Meeteetse Formation is overpressured in the deeper areas of the basin (see Dunleavy and Gilbertson, 1989) it is seldom tested and has produced minor amounts of gas at only one field in the Wind River Basin, the Muddy Ridge field in the northwest part of the basin.

Figure 50 is a map of total sandstone in beds 10 ft thick or greater in the combined Lewis Shale and Meeteetse Formation, and Figure 51 is a percent sandstone map for the same interval. These maps were constructed from limited well data. Total sandstone thickness in beds 10 ft thick or greater varies from less than 100 ft to over 500 ft and percent sandstone varies from less than 10 percent to over 40 percent. Potential hydrocarbon reservoirs include fluvial channel sandstones in the Meeteetse and marginal marine sandstones in the Lewis. Fluvial channel sandstones are typically single channels with a maximum thickness of about 35 to 40 ft, but some “stacking” of individual channels into thicker units occurs in the subsurface (see Keefer, in press; Szmajter, in press). Thin scour-based channels are also common but these do not appear to be thick or extensive enough to be significant hydrocarbon reservoirs. Clayey drapes, associated with lateral accretion units in many fluvial sandstone in the Meeteetse Formation may form permeability barriers to fluid flow in the subsurface. The greatest

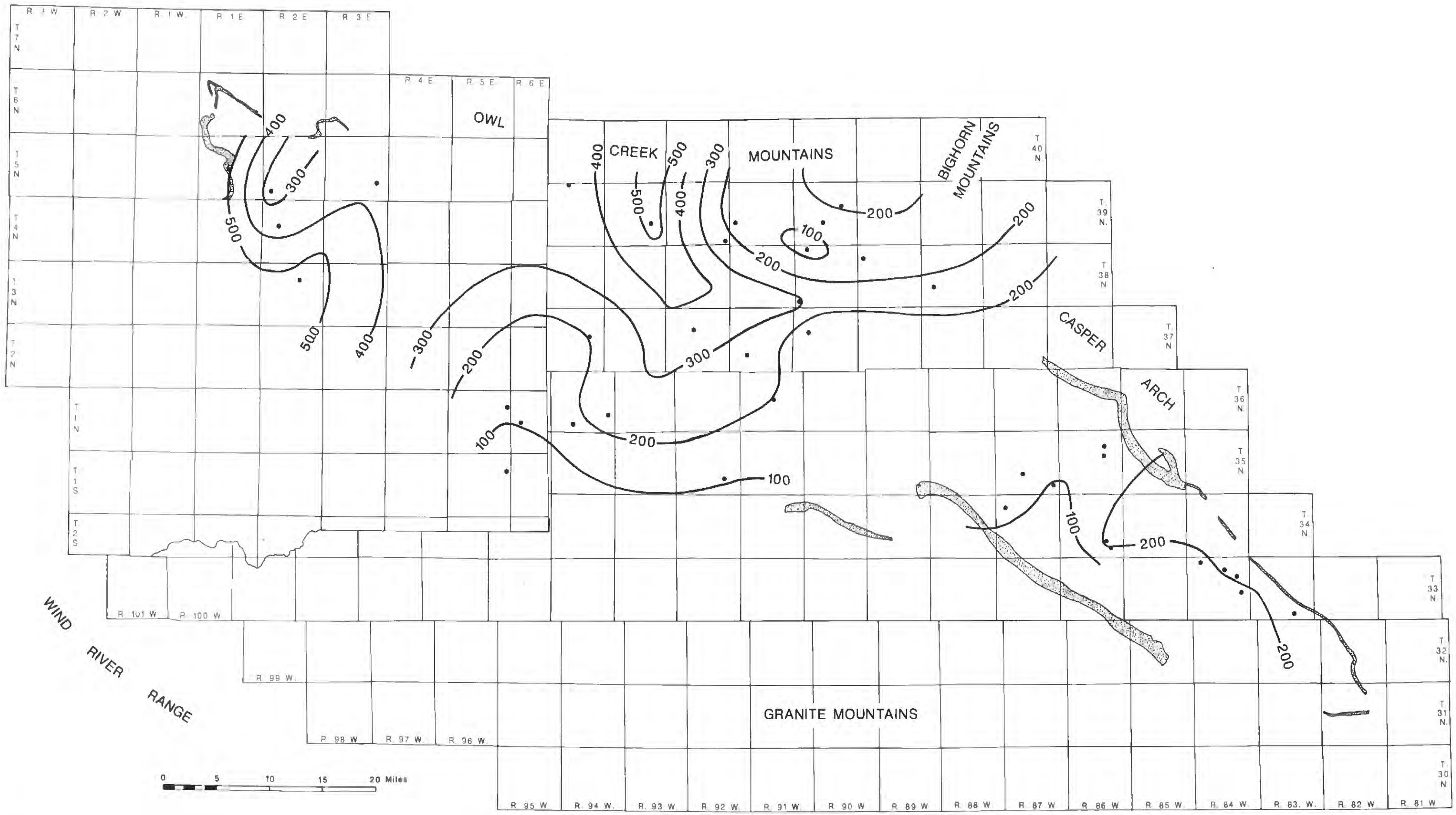


Figure 50: Isopach map of total sandstone in beds 10 ft thick or greater in the Meeteetse Formation and Lewis Shale of Upper Cretaceous age, Wind River Basin, Wyoming. Outcrops of the Meeteetse Formation and Lewis Shale are shown as stipple pattern. Drillholes used for control are shown as black dots. Contour interval is 100 ft.

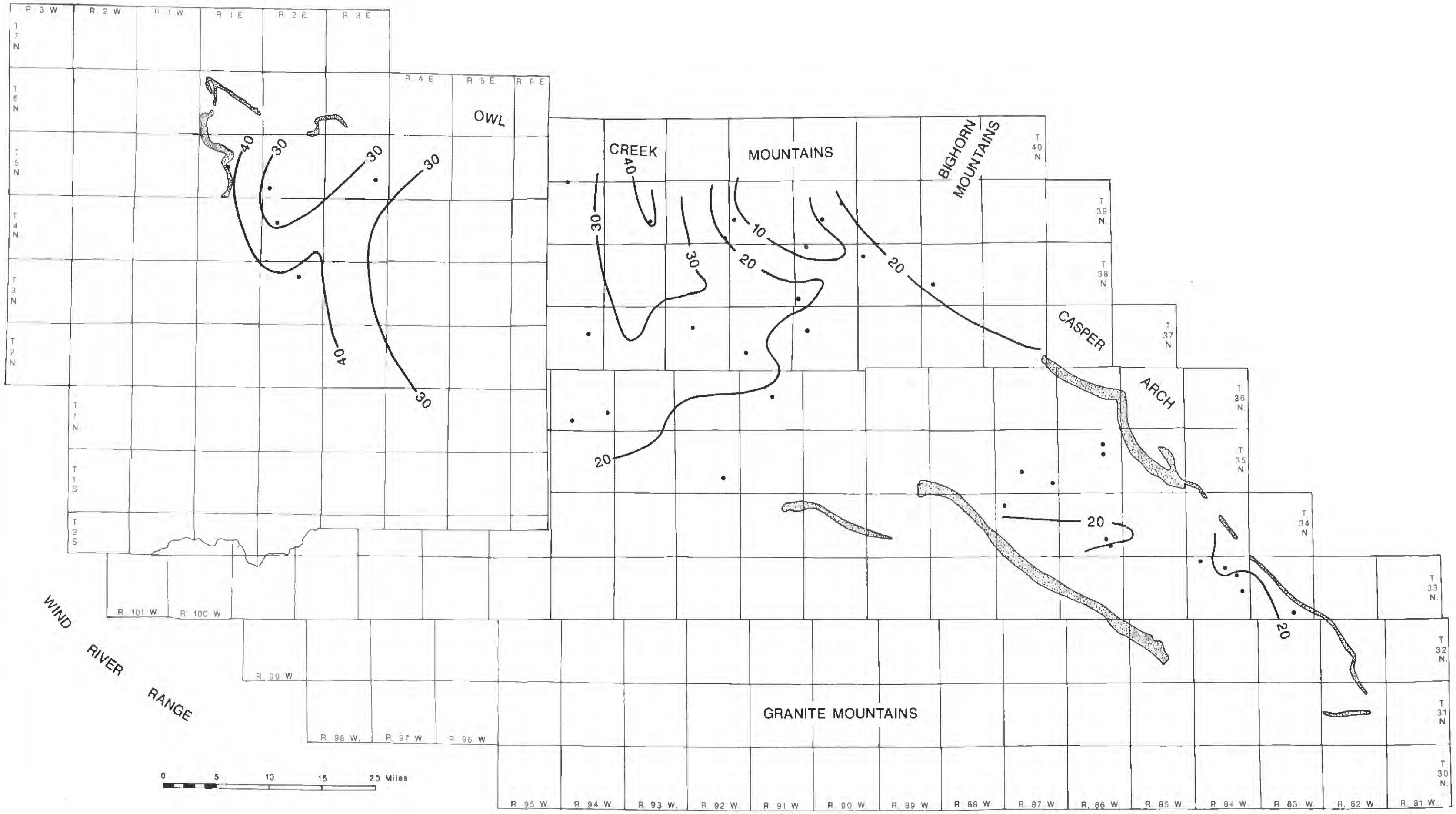


Figure 51: Map showing percent sandstone in beds 10 ft thick or greater in the Meeteetse Formation and Lewis Shale of Upper Cretaceous age, Wind River Basin, Wyoming. Outcrops of the Meeteetse Formation and Lewis Shale are shown as stipple pattern. Drillholes used for control are shown as black dots. Contour interval is 10 percent.

thickness and greatest percentage of sandstone in the Lewis-Meeteetse interval occurs in the north-central part of the basin at Bonneville and Howard Ranch gas fields (Figure 3) where the Meeteetse occurs at depths of from 11,500 to 13,500 ft. At these localities, stacks of fluvial sandstone are more common than in the Meeteetse in other parts of the basin.

LANCE FORMATION

The distribution, thickness, and character of strata assigned to the Lance Formation, the uppermost unit of Cretaceous age in the Wind River Basin, are indicative of deposition during the initial stages of Laramide deformation in the region. The Lance ranges in thickness from a wedge-edge where it is truncated beneath younger rocks along the south margin of the basin to a maximum of 6,860 ft in the northeast part of the basin (Figure 52). Despite its great thickness the Lance has been studied far less intensely than other much thinner Upper Cretaceous and Lower Tertiary formations in the basin. The rocks consist of interbedded fine- to coarse-grained, in part conglomeratic sandstone, shale, mudstone, carbonaceous shale, and thin coal beds. Sandstone generally predominates in the lower part of the formation (for example, interval 10,875-12,425 feet in drillhole A, Figure 53) and finer grained strata in the upper part (Keefer, 1965). Very coarse to conglomeratic sandstones occur in the western part of the basin, reflecting local uplift and erosion of highlands adjacent to the subsiding Wind River Basin trough (Keefer and Troyer, 1964), but no conglomerates have been observed in exposures along the south and east basin margins.

The Lance was studied in detail in the eastern part of the Wind River Basin by Gillespie and Fox (1991) who defined several facies in the formation including a previously unrecognized deltaic facies in the lower part and an extensive paludal lacustrine facies along the basin trough in the upper part. Their paludal-lacustrine facies approximately corresponds to the banded shale and claystone unit of Keefer (1965). The deltaic facies of Gillespie and Fox occurs in the lower 400 ft of the Lance exposed near Waltman (Figure 2) and is characterized by cycles of claystone and sandstone averaging about 25 ft thick. Each cycle is capped by a thin (3 to 6 ft thick) laterally persistent sandstone which they interpret as crevasse splay sandstones. The underlying claystone is interpreted as interdistributary bay deposits. Along the southern basin margin of the basin, Gillespie and Fox (1991) described the Lance as being deposited by large, low-sinuosity river systems. Thin coal beds are scattered throughout the Lance Formation but appear to be most numerous in the upper part based on sonic log interpretations.

The contact between the Lance Formation and the overlying lower member of the Fort Union Formation is difficult to distinguish in most drillholes, because all of these strata in the structurally deeper parts of the Wind River Basin were deposited under similar depositional conditions that persisted from latest Cretaceous into Paleocene times. The correlations established during the present study (and the resulting gas resource evaluations for each formation) were based on: (1) measurements and descriptions of the two stratigraphic units in outcrops along the basin margins; (2) palynological determinations from both surface and subsurface samples (see Nichols and Flores, 1993); and (3) structure sections drawn transverse (north-south) to the basin axis, on which the Lance-lower Fort Union rocks can be bracketed between the more readily recognizable strata of the Meeteetse Formation below and the Waltman Shale Member of the Fort Union above, to show the influence of basin subsidence on stratigraphic thicknesses. In most drill holes, the Lance-Fort Union contact is placed at the

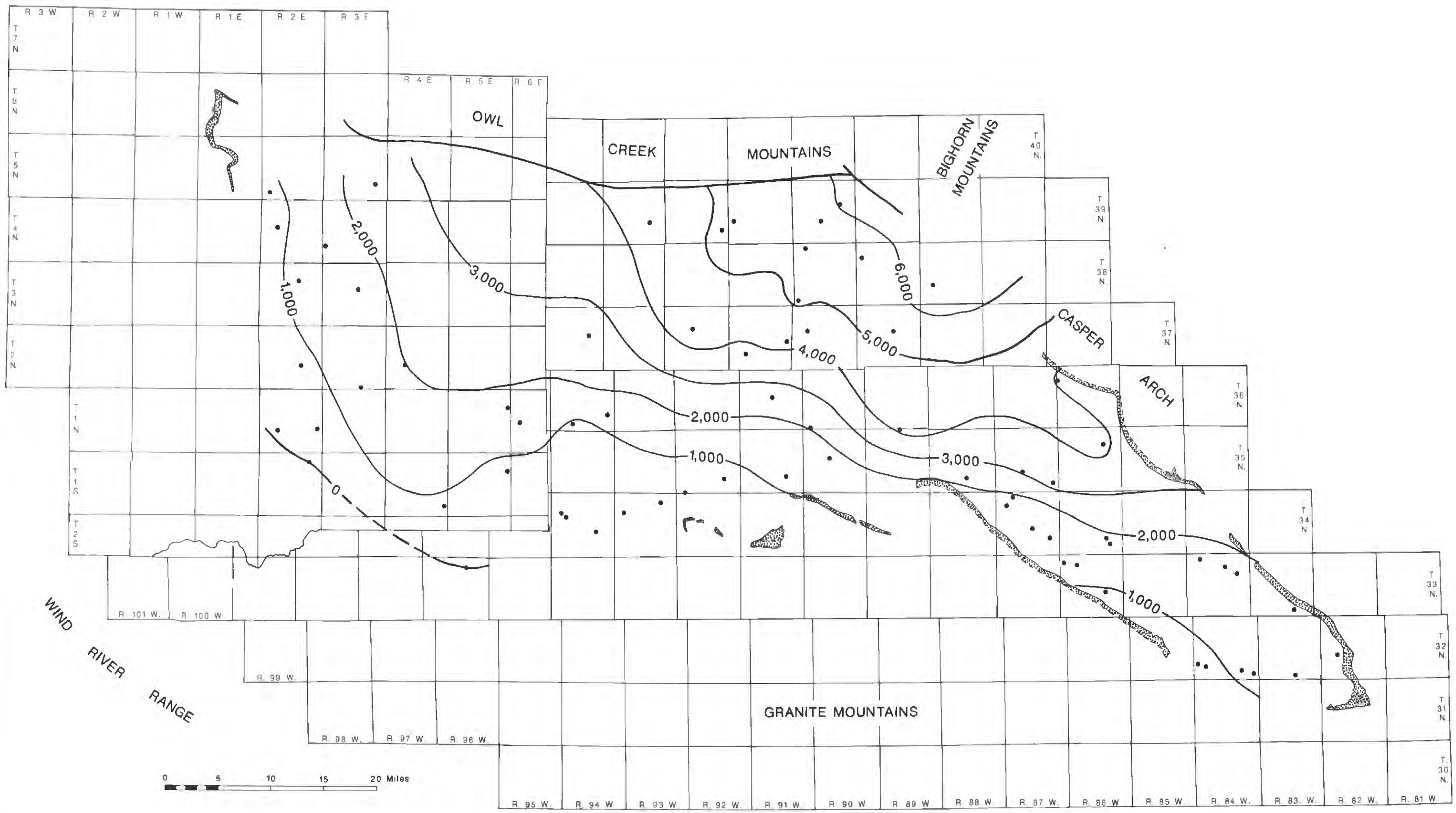


Figure 52: Isopach map of the Lance Formation, Wind River Basin, Wyoming. Outcrops of the Lance Formation are shown as stipple pattern. Drillholes used for control are shown as black dots. Contour interval is 1,000 ft.

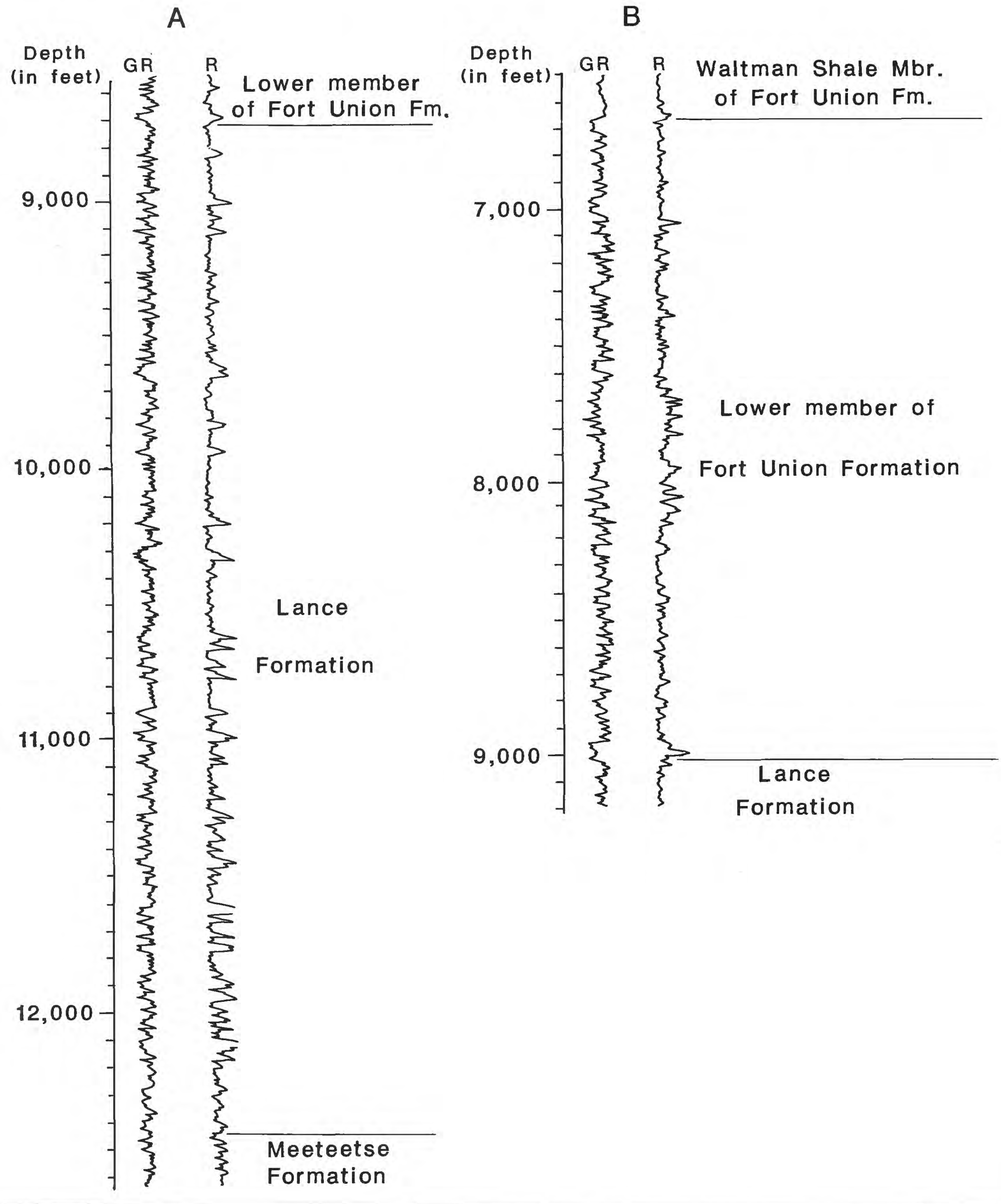


Figure 53: Resistivity (R) and gamma-ray (GR) logs of the Lance Formation and lower member of the Fort Union Formation, Wind River Basin, Wyoming. Drillhole A - Dome Petroleum Moneta no. 1-29 (SW 1/4 NE1/4 sec. 29, T. 37N., R. 91W.); Drillhole B - Dome petroleum Dome-Hardwick no. 1-24 (SW1/4 NE1/4 sec. 24, T. 37N., R. 91W.).

change from interbedded shale, mudstone and thin sandstones that characterizes the upper part of the Lance Formation in many surface sections, to the thicker and more prominent sandstone units that characterizes the lower part of the lower member of the Fort Union (Figure 53). This contact, defined in lithologic terms, does not always correspond to the Cretaceous-Tertiary boundary. This will be discussed more fully with the discussion of the Fort Union Formation. The distinction between the Lance and Fort Union is an important economic consideration in cases where oil and gas lease arrangements are dependent upon which formation is being produced.

Detailed measured sections of the Lance Formation

The Lance Formation was measured and described in detail near Cave Gulch along the Casper Arch in the eastern part of the basin (Figure 2, Plate 3). The upper part of the formation was truncated beneath the overlying Eocene Wind River Formation at this locality, and only the lower 1,850 ft of Lance is present. The upper part was measured along a ridge about 3,500 ft to the southeast where the upper part of the Lance and about 500 ft of the overlying lower member of the Fort Union Formation are preserved beneath the Wind River. Areal photos were used as an aid in this offset. Estimated maximum error in thickness from this offset is about 300 ft. The top of the Lance is placed at 5,232 ft on the measured section where there is a subtle increase in grain size from fine-to very fine-grained sandstone to fine -to medium-grained sandstone. The contact used here corresponds approximately to the mapped contact between the Lance and the overlying Fort Union Formation (Keefer, 1970, Plate 1), and appears to be similar to the contact used by Flemings and Nelson (1991) further to the southeast along the Casper arch. Although sandstones in the lower part of the Fort Union, as defined in this study, are somewhat coarser grained than sandstones in the underlying Lance, the buildup of thick sandstones, found in the lowermost Fort Union in many parts of the basin, was not present along the line of section.

A total of 3,582 ft of Lance was measured, using the base of the 214-ft-thick sandstone beginning at 1,623 ft as the basal formation contact (Plate 3). This compares with a thickness for the Lance of 3,970 ft at the Coastal 2-7-36-86 Bullfrog well in sec. 7, T. 36N., R., 86W about 1 mile to the west. It should be emphasized, however, that the surface section was measured on the hanging wall of the Casper arch thrust. The exact horizontal displacement on the thrust is unknown but the sedimentary section continues under the thrust for from 5 to 15 miles (Skeen and Ray, 1983). The Coastal well, in contrast, penetrated the Lance on the footwall. The Lance appears to contain much more sandstone at the Cave Gulch locality (1,713 ft in beds 10 ft thick or greater) than in the nearby Coastal well (778 ft in beds 10 ft thick or greater). Part of the difference in total measured sandstone thicknesses could be because sandstone may be easier to detect on the surface than on geophysical logs, particularly if the sandstones are clayey; the tendency is to minimize thicknesses of individual beds on the logs. If there is a distinct difference in total sandstone thickness, however, the indication is that the muddy facies, as described in the upper Lance along the trough of the basin by Keefer (1965) and Gillespie and Fox (1991), was replaced to the north along the Casper arch by a much sandier facies. This sandier facies was subsequently thrust to the southwest over the top of the muddy facies.

Calcareous cemented nodular bodies occur in sandstones throughout Lance Formation as well as the Meeteetse Formation exposed at Cave Gulch. These bodies are typically somewhat flattened along the bedding planes, have bulbous exteriors, can be as much as 10 ft thick and 30 ft or more in length, and form resistant ridges above less resistant sandstone and mudstone. Thin, persistent, ripple-drift laminated crevasse splay sandstones, common in the underlying Meeteetse Formation, are rare in the Lance. The splay deposits described in the lower part of the Lance near Cave Gulch by Gillespie and Fox (1991) were not observed; they may have placed the contact between the Meeteetse and the Lance somewhat lower stratigraphically than is shown on Plate 3.

The basal Lance unit, 214 ft thick, is the thickest individual sandstone unit measured in the formation. It directly overlies a 1-ft coal bed at the top of the underlying Meeteetse Formation. The lower 28 ft of sandstone is fine-to very fine-grained and displays well-developed lateral accretion with clayey drapes along accretion surfaces. This sandstone is similar to sandstones in the underlying Meeteetse Formation. The top of this sandstone is scoured, and overlain by a stack of at least four fine-to medium-grained sandstone units with scour bases and ripups along scour surfaces (Figure 54). Internally these scour-based sandstones have trough cross beds as much as 5 ft high (Figure 55) but bedding is commonly highly contorted (Figure 56).

Fluvial sandstones are scattered throughout the upper part of the Lance Formation. Maximum measured thickness of individual units above the basal sandstone is 130 ft (4,341 to 4,471 ft on the measured section, Plate 3). Three different types of fluvial channel sandstones were recognized in the Lance at Cave Gulch: 1) cut and fill channel sandstones; 2) laterally migrating high sinuosity channel sandstones; and 3) medium to low sinuosity channel sandstones, commonly with multiple scour surfaces. All three general types of channels can be "stacked" to form thick sandstone bodies, and some of the stacked sandstone bodies, such as the basal Lance sandstone, include more than one type of sandstone channel. The lateral extent of most of these complex multistorey sandstones was not thoroughly investigated during this study. Cut and fill channels vary from the 3 to 9-ft-thick channels that occur from 2,696 to 2,725 on the measured section to those that are 15 to 20 ft thick in the interval 1,593-1,621. Three individual channels are vertically stacked in this latter interval to form a single sandstone to as much as 40 ft thick that extends for about 500 ft along outcrop. High sinuosity channel sandstones range to as much as 40 ft thick and typically include shale breaks along lateral accretion units. Medium to low sinuosity sandstones contain numerous scour surfaces which typically have clayey ripup zones just above them.

Paleocurrent measurements on eight troughs within the basal sandstone suggest a north-northeast flow direction (Plate 3). Paleocurrent measurements were taken from sandstones in four other intervals in the Lance Formation at Cave Gulch, and in all these cases, a southeast flow direction is indicated (Plate 3). In addition, paleocurrent readings on the lowermost sandstones in the overlying Fort Union Formation also indicate a southwest flow direction. Flemings and Nelson (1991) in their studies further to the southeast along the Casper arch, in contrast, measured an northward paleoflow direction for the uppermost Lance and a north-northwest paleoflow direction for the lower member of the Fort Union Formation. Gillespie and Fox (1991), in a study of paleocurrent indicators in the Lance at Castle Gardens in the south-central part of the basin, determined a southeast flow direction for the lower Lance and a northeast flow direction for the upper Lance. Flemings and Nelson (1991) determined a

Figure 54: Photo of scour surface with clayey ripups in basal sandstone of the Lance Formation at Cave Gulch measured section (Plate 3; location on Plate 1c) in the northeast part of the basin. Scour surface is at 1,760 ft on measured section (Plate 3). Up section is to the left. Note six inch pencil for scale.

Figure 55: Photo of trough-cross beds to as much as 5 ft high in basal sandstone of the Lance Formation at the Cave Gulch measured section (Plate 3; location on Plate 1c) in the northeast part of the basin. Up section is to left. Note 26 inch pick for scale.

Figure 56: Photo of highly contorted bedding in well-cemented calcareous zone in basal sandstone of the Lance Formation at Cave Gulch measured section in the northeast part of the basin (Plare 3; location on Plate 1c). Note 26 inch pick for scale. Up section is to the left.

northeast flow direction for the lower part of the Fort Union Formation at Castle Gardens, however, Nichols and Flores (1993, p. 184) question the placement of the Lance-Fort Union contact by Flemings and Nelson at Castle Gardens.

Hydrocarbon production and reservoir characterization of sandstones in the Lance Formation

The Lance has produced gas at Sand Mesa and Muddy Ridge fields in the western part of the basin and at Bonneville and Madden fields in the north-central part of the basin (Figure 3, Table 1). Barrett Resources of Denver Co. has recently drilled several successful Lance gas wells at Waltman field in the eastern part of the basin (Figure 3) with initial production rates for individual wells ranging to as much as 11 million cubic feet of gas per day. The Lance is cut by the Casper arch thrust at Waltman field with the plane of the thrust progressively cutting through deeper levels of the Lance toward the northeast across the field. This discovery has sparked considerable interest in the potential for gas in the Lance throughout the basin. The Lance Formation has produced minor gas from moderately overpressured rocks (fluid pressure gradient: 0.55 psi/ft) at Bonneville field (Figure 3, Plate 1) near the basin trough in the north-central part of the basin (Gilbert, 1989). The Lance Formation at Madden anticline also appears to be slightly overpressured with a pressure gradient of around 0.50 psi/ft (Brown and Shannon, 1989). Lance sandstones at Madden have very low permeabilities, and there is some indications that fractures play a more important role in production than in the shallower lower Fort Union sandstones (Dunleavy and Gilbertson, 1986, p. 113). Brown and Shannon (1989) reported a permeability for the Lance at Madden anticline of .0087 md measured on core under 6,000 pounds per square inch pressure. Core studies of the Lance Formation from several deep drillholes at Madden anticline show that the Lance sandstones are moderately well sorted and are cemented with quartz overgrowths, carbonate, and illite (Dunleavy and Gilbertson, 1986, p. 113).

The architecture of sandstones in the Lance in the Wind River Basin is still poorly understood. The few outcrop studies that have been made, coupled with the available but scattered drillhole data available (spacing between wells is commonly several miles) limits understanding of this complex unit that thickens across the basin from less 1,000 ft near the south margin to nearly 7,000 ft near the basin trough in the northeast part of the basin (Figure 52). This dramatic thickening, which occurs over a distance of less than 25 miles, represents the earliest evidence of partitioning of the Cretaceous foreland basin and downwarping along the Laramide Wind River Basin trough. Total thickness of sandstone in the Lance in beds 10 ft thick or greater varies from less than 100 ft along the south margin of the basin to over 2,000 ft west of Madden anticline (Figure 57), whereas the percent of sandstone in beds two feet thick or greater in the Lance varies from nearly 60 percent in the western part of the basin to less than 10 percent along the Casper Arch in the northeast part (Figure 58). The shaly facies, which previous workers suggested was best developed along the trough of the basin (Keefer, 1965; Gillespie and Fox, 1991), is best developed in the northeast part of the basin south of the Casper Arch where the Lance includes less than 20 percent sandstone (Figure 58). The shaly facies is not as well developed further to the west where the thickest amount of total sandstone in the Lance occurs near the basin axis west of Madden anticline (Figure 57).

The thickest sandstones in the Lance Formation are the multistorey bodies composed of several medium to low sinuosity fluvial channels. In general, the stacking of these fluvial

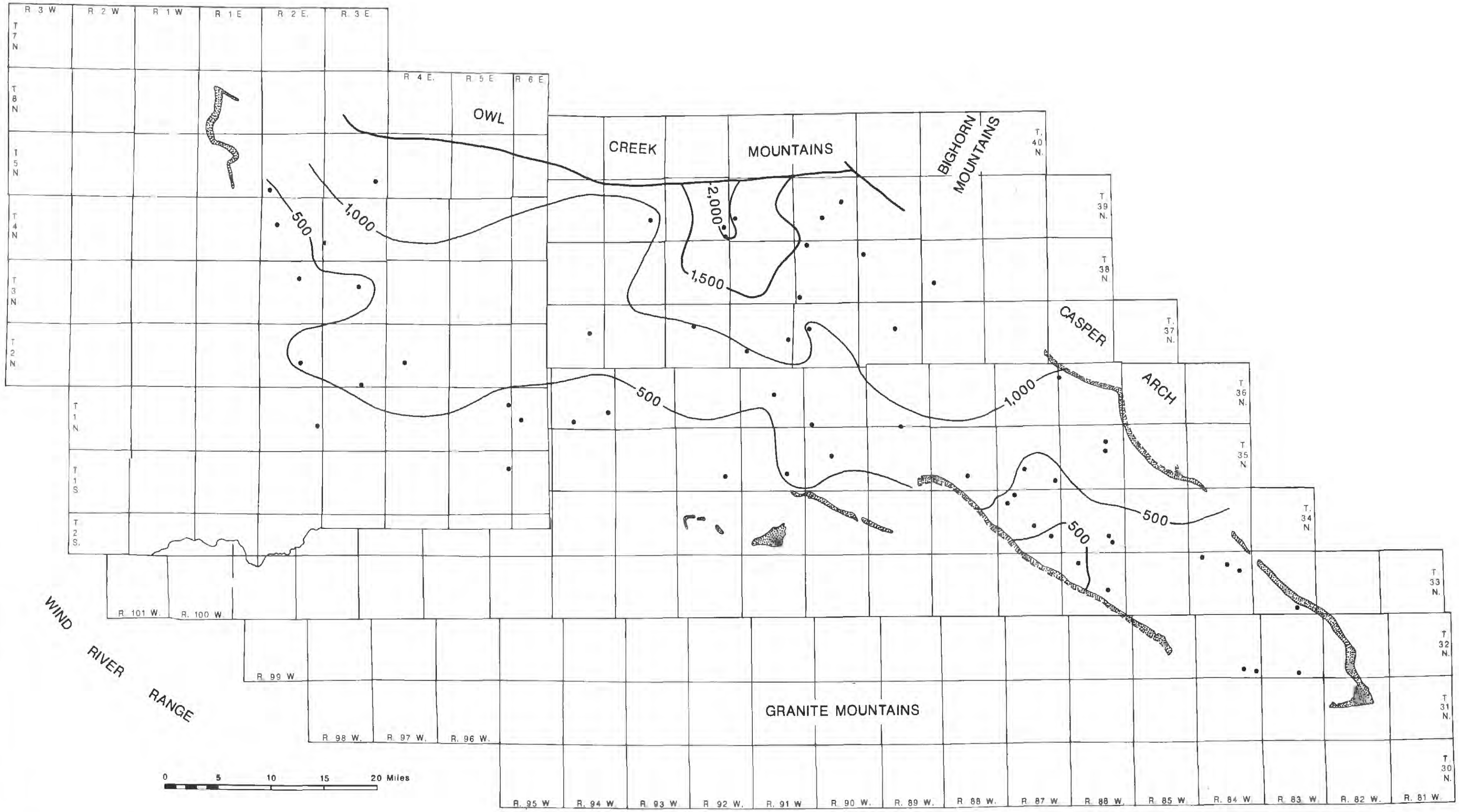


Figure 57: Isopach map of total sandstone in beds 10 ft thick or greater in the Lance Formation, Wind River Basin, Wyoming. Outcrops of Lance Formation are shown in stipple pattern. Drillholes used for control are shown as black dots. Contour interval is 500 ft.

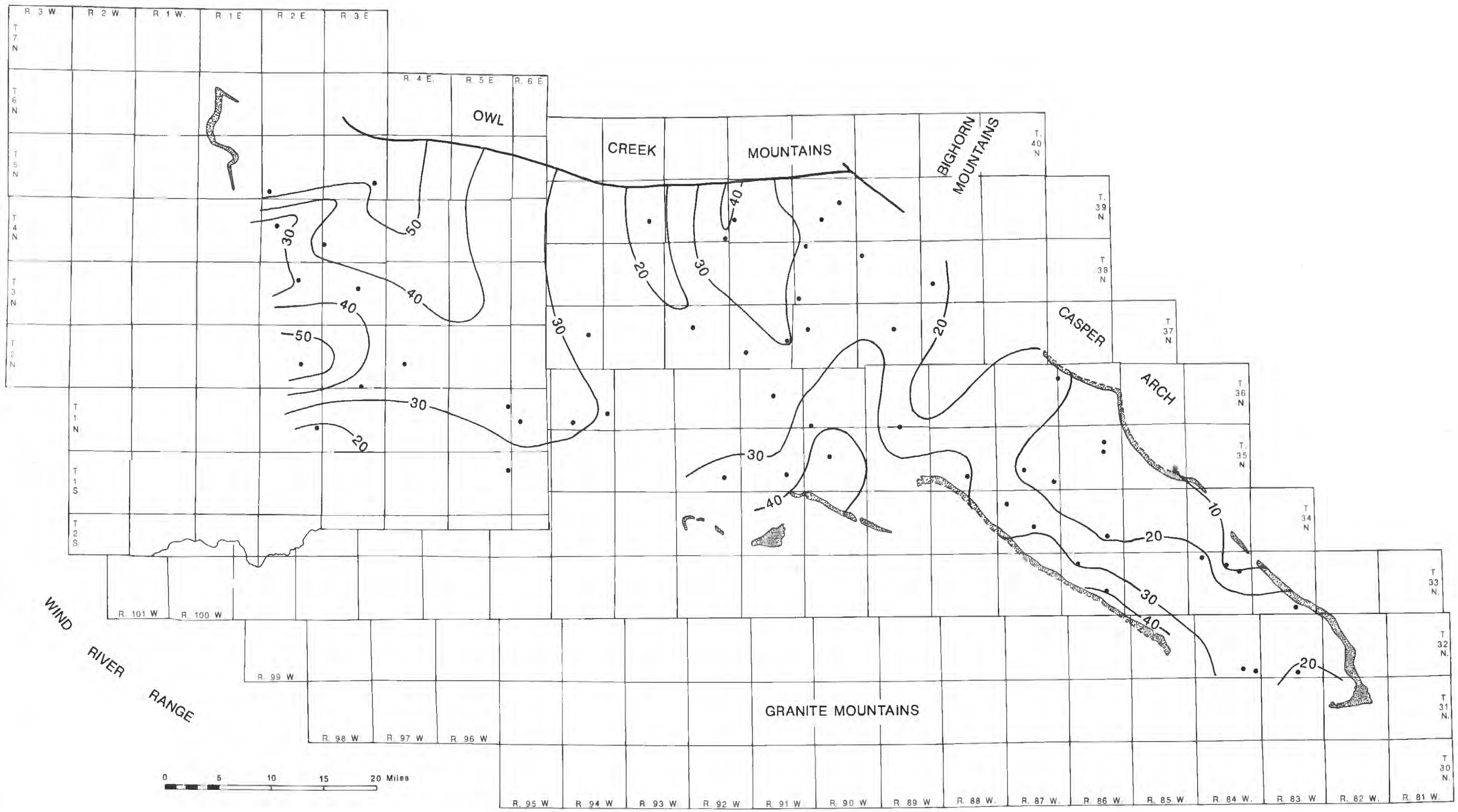


Figure 58: Percent sandstone map in beds 10 ft thick or greater in the Lance Formation, Wind River Basin, Wyoming. Outcrops of Lance Formation are shown in stipple pattern. Drillholes used for control are shown as black dots. Contour interval is 10 percent.

sandstones to form thick units increases as the percent of sandstone increases. The thickest multistorey sandstone found in this study occurs in the Moncrief 19-1 Steffen Hill well in sec. 19, T. 39N.-R. 91W. west of Madden anticline in an area where the Lance is 5,220 ft thick and contains more than 40 percent sandstone. In this well. a 250-ft-thick sandstone is present in the middle part of the Lance between 13,570 and 13,820 ft (Szmajter, in press). Channel sandstones at Cave Gulch vary widely from relatively narrow cut and fill channels to amalgamated more laterally persistent, bodies. The geometry of these thick multistorey bodies, however, is as yet largely unknown over much of the basin area.

The limited paleocurrent data available for the Lance Formation in the Wind River Basin indicate a general easterly flow direction. Paleoflow directions measured in the Lance on the hanging wall of the Casper thrust varies from northeast in the basal sandstone to southeast for the remainder of the Lance. These results indicate a general flow to the east across the Casper Arch, suggesting that either the arch was not actively rising during Lance deposition or that Lance stream systems were able to downcut through the rising arch. Paleogeographic reconstruction's by Flores and others (1994) for the Paleocene of central and northwest Wyoming also indicate that at the beginning of the Paleocene or near the end of Lance deposition, a major trunk stream flowed generally eastward along the trough of the Wind River Basin and exited at some point across the present location of the Casper Arch. The Wind River Basin was therefore an area of rapid subsidence during this time. Flores and others (1993) suggest that subsidiary drainages flowed generally northeastward off the rising Wind River Range into the trunk stream near the basin trough. The northeast paleocurrent direction measured by Gillespie and Fox (1991) at Castle Gardens for the upper Lance is consistent with this interpretation.

FORT UNION FORMATION

The Fort Union Formation in central Wyoming was deposited during a time of transition, when the Rocky Mountain foreland basin was gradually being partitioned by rising uplifts into smaller Laramide structural and sedimentary basins. In the Wind River Basin, Keefer (1961a; 1961b; 1965) included all rocks of Paleocene age in the Fort Union Formation. The contact between the Fort Union Formation and the underlying Lance Formation in the Wind River Basin is generally marked by a change from shale, claystone, and minor sandstone in the uppermost part of the Lance to predominantly sandstone and conglomerate in the lowermost part of the Fort Union, however, Keefer (1961a, p. 183) noted that beds above and below the contact were lithologically similar at some surface localities and in many drillholes. The Fort Union Formation unconformibly overlies older formations (angular and/or erosionally) in outcrops along the southern margin of the basin (Keefer, 1961a; 1965). This unconformity appears to die out a short distance downdip from outcrop. Although the contact with the underlying Lance Formation was picked on the basis of a lithologic change, Keefer (1965, p. A21) cited paleontological evidence which indicated that the contact coincided closely with the Cretaceous-Tertiary boundary. An exception was noted at the Waltman locality, where the uppermost few feet of the Lance Formation contained spores and pollen of earliest Paleocene age.

The Fort Union Formation appears to be locally conformable with the underlying Lance where it crops out in a series of anticlines and synclines in the Shotgun Butte area

(Figure 59) in the northwest part of the basin. Keefer and Troyer (1964) determined that these structures began to form during deposition of the Upper Cretaceous Meeteetse Formation, and that deformation continued through deposition of the Fort Union. They believed that the Fort Union was conformable with the underlying Lance Formation in the structural troughs while disconformities occurred over the crests of the anticlines. The base of the Fort Union in the Shotgun Butte area occurs at the base of an interval of conglomerate and conglomeratic sandstones as much as 100 ft (30 m) thick.

The Fort Union Formation was divided into three members in the Wind River Basin by Keefer, (1961a; 1961b; 1965; 1969); these are in ascending order (Figures 4 and 5), the lower unnamed member, the Waltman Shale Member, and the Shotgun Member. The lower member is of mainly fluvial origin and is recognized on the surface and in the subsurface throughout most of the basin. The Waltman Shale Member is composed mainly of lacustrine shale and lacustrine mudstone deposited in offshore areas of Lake Waltman, a large lake that, at its maximum extent, covered most of the central part of the ancestral Wind River Basin. The Waltman Shale Member occurs largely in the subsurface and crops out only in the Waltman area in the northeast part of the basin. This outcrop was designated by Keefer (1961) as the type section. The Shotgun Member is a complex unit that is thought to be largely time equivalent to the Waltman Shale Member (Keefer, 1961a; 1961b; Keefer and Troyer, 1969). It consists of fine-to coarse-grained, in part conglomeratic, fluvial and marginal lacustrine rocks deposited around the margins of Lake Waltman as the lake was gradually filled in. The Shotgun Member was named for Shotgun Butte in the western part of the basin, where it is best exposed.

The lower unnamed member of the Fort Union is well exposed in the Shotgun Butte area in the northwest part of the basin and near Waltman in the northeast part (Figure 59). The Shotgun Butte area is west of the pinchout of the Waltman Shale, and here the lower unnamed member is overlain by the Shotgun Member (Keefer and Troyer, 1964). Keefer and Troyer (1964) described the lower unnamed member near Shotgun Butte as predominantly conglomerate and sandstone with some gray shale and brown carbonaceous shale. Pebbles and cobbles are described as well-rounded to subrounded and composed of chert, quartzite, porcelanite, siliceous shale, petrified wood, and quartz. Keefer (1965, p. A22) described the lower unnamed member as 2,325 ft thick and composed of white fine- to very coarse-grained sandstone, and siltstone in a surface section near Waltman, in the northeast part of the basin. From drillholes in the southern and eastern parts of the basin, Keefer (1961a, p. 183) described the lower unnamed member as consisting of white fine- to coarse-grained, in part glauconitic, sandstone interbedded with dark-gray to black shale, claystone, siltstone, carbonaceous shale and coal. The coarse sandstone contains abundant quartz and chert, but no feldspar.

The Waltman Shale Member crops out only in limited areas along the Casper Arch in the northeast part of the basin (Keefer, 1961b) but has been extensively studied in the subsurface by Keefer (1961a; 1961b); Ray (1982); Liro and Pardus (1990); and Katz and Liro (1993). The Waltman Shale attains a maximum thickness of over 2,500 ft thick near the basin trough and progressively thins toward the south and west margins of the basin (Keefer, 1965, fig. 14). The contact with the underlying lower unnamed member is sharp and well defined on geophysical logs (Keefer, 1961b). Liro and Pardus (1990), in a seismic stratigraphic study of the Waltman Shale Member in the central and eastern part of the basin, found that the contact between the Waltman and the underlying unnamed member occurs over a limited stratigraphic thickness indicating that Lake Waltman transgressed across the area relatively rapidly. Jorjorian and others (1989) estimated the depth of the lake at at least 500 ft based on relief on clinoform units around the margins of the lake. The contact between the Waltman Shale and the overlying Shotgun Member is gradational in some areas while interfingering occurs between the Waltman Shale and the Shotgun in others (Keefer, 1961a, p. 184). The Waltman Shale is organic-rich and thought to be the source of the waxy oil produced from deltaic sandstones in the Shotgun Member at Haybarn and Fuller Reservoir fields (Katz and Liro, 1993).

The Shotgun Member, which is thought to be largely equivalent to the Waltman shale, was named for exposures in the Shotgun Butte area in the northwest part of the basin by Keefer (1961b). The Shotgun Member near Shotgun Butte is from 1,190 to 2,830 ft thick and was described by Keefer and Troyer (1964, p. 32) as "a remarkably even bedded sequence of soft, easily eroded claystone, siltstone, shale, and sandstone." The Shotgun is conformable here with the underlying lower unnamed member, and the contact is marked by sharp lithologic and topographic change from resistant conglomerates and sandstones below to nonresistant finer-grained strata above. The Shotgun Member exposed in the Shotgun Butte area does not appear to include any lacustrine rocks. The closest lacustrine rocks appear to be coarsening upward deltaic cycles in the subsurface about 15 miles southeast of the Shotgun Butte outcrops (Keefer and Johnson, in press). Deltaic intervals of the Shotgun crop out in the vicinity of Waltman, and these intervals were interpreted by Phillips (1983) to be fan delta deposits. The only other known exposure of the Shotgun Member is an isolated outcrop along Badwater Creek north of Madden Anticline in the north-central part of the basin (Turtelot (1953). The Shotgun Member is widespread in the subsurface in the basin where it ranges to as much as 2,200 ft thick (Keefer, 1965, p. A29). It is fine-grained in the subsurface in the northern part of the basin and similar lithologically to the type section. To the south, however, it becomes progressively coarser and includes conglomerate and arkosic material.

Outcrop studies of the Fort Union Formation

Detailed outcrop studies of the Fort Union were recently completed under the DOE Western Tight Gas Sands Program near Waltman in the northeast part of the basin (Flores and others, 1990; Nichols and Flores, 1993), in the Castle Gardens area in the south-central part of the basin (Flores and others, 1991), near the town of Hudson in the southwestern part of the basin (Flores and others, 1992), and in the Shotgun Butte area in the northwestern part (Flores and Keighin, 1993) (see Figure 2). Investigations in the Shotgun Butte area were also supported in part by a Bureau of Indian Affairs and the Shoshone and Arapahoe Tribes. These recent investigations included detailed palynomorph studies by Flores and Keighin (1992; 1993) and Nichols and Flores (1993) who used the six-fold subdivision of the Paleocene, P1 through P6, that was developed by Nichols and Ott (1978). In addition, palynomorphs were investigated in one drillhole in the western part of the basin by Nichols and Flores (1993). The six Paleocene biozones are defined primarily by various species of *Momipites* and *Caryappollenites* which are ancient relatives of the modern family that includes walnuts and hickories. According to Nichols and Flores (1993, p. 184-184) the palynomorph zones are only loosely correlated to the American land mammal ages for the Paleocene, however, Nichols and Flores (1993) generally correlate the P1 and P2 biozones to the early Paleocene, the P3 and P4 biozones to the middle Paleocene, and the P5 and P6 biozones to the late Paleocene.

Waltman area: Nichols and Flores (1993) identified all six Paleocene biozones, P1 through P6 in outcrops of the Fort Union Formation near Waltman (Figure 2) and designated this section as the reference section for the Paleocene biozones. The lower unnamed member here is 1,946 ft thick and occurs within theP1 through P4 biozones. It consists of both fining upwards and coarsening upwards sandstones, carbonaceous shale and thin coal beds. The Waltman Shale is variably truncated beneath Eocene strata in the Waltman area and was about 540 ft thick where measured by Nichols and Flores (1993). The Waltman Shale occurs within the P5 and P6 biozones and consists of organic-rich shale and thin sandstone beds.

Shotgun Butte area: In the vicinity of Shotgun Butte (Figure 2), the Fort Union Formation occurs in a series of southeast plunging anticlines and synclines that were actively forming during Upper Cretaceous and Paleocene time. Keefer and Troyer (1964) believed that the Fort Union was conformable with the underlying Lance Formation along synclinal axes. Flores and Keighin (1993), in a study of Fort Union fluvial architecture in the Shotgun Butte area, concluded that Paleocene river systems flowed southeast along a paleovalley that formed in the synclines as a result of rapid subsidence rates. They defined four types of fluvial sandstones in the lower unnamed member, and concluded that the fluvial systems were largely anastamosed and meandering in the early stages of lower Fort Union deposition and later evolved into braided systems.

Nichols and Flores (1993) were able to identify biozones P2, P3 and P5 in the Shotgun Butte area, but poor recovery of spores and pollen prevented the identification of zones P1, P4, and P6. Palynomorphs collected from uppermost part of the Lance Formation, as mapped by Keefer and Troyer (1964), suggested an early Paleocene age. If true, then the lithologic break, mapped as the Lance-Fort Union contact in the Shotgun Butte area, does not correspond exactly to the Cretaceous-Paleocene boundary. The lower unnamed member of the Fort Union is within biozones P2 and P3, while P5 pollen was collected from the overlying Shotgun Member. The uppermost, possibly Paleocene part of the Lance Formation in the Shotgun Butte area, consists mainly of sandstones, siltstones, and mudstones and rare carbonaceous shales and coal beds. This interval was interpreted by Flores and Keighin (1993) as deposited by mixed suspended load and bedload braided, meandering, and anastomosed stream systems. The comparatively thin (39 ft thick or less) sandstones in the Shotgun Member are interpreted by Flores and Keighin (1993) to have been deposited by low-to high-sinuosity, meandering and anastomosed streams confined by floodplain sediments that were partially covered by poorly drained, low-lying mires.

Castle Gardens area: The Fort Union Formation is difficult to distinguish from the underlying Lance Formation at Castle Gardens in the south-central part of the basin (Figure 2) and cannot be subdivided into members. Flores and others (1992) used palynomorphs to determine that the Paleocene section here is about 2,300 ft thick. All six Paleocene biozones are present at Castle Gardens. They found Paleocene pollen in the upper few hundred feet of what had previously been mapped as the Lance Formation (Keefer, 1970, Gillespie and Fox, 1991) and redefined the Fort Union to include this Paleocene interval. About two-thirds of the Fort Union or 1,450 ft (442 m) was deposited during just the P5-P6 biozones when Lake Waltman was present farther north in the basin. Flores and others (1992) suggested a relationship between this rapid rate of subsidence and the development of the lake. The Fort

Union sandstones were deposited by sinuous bedload streams that varied from deep and wide to shallow and narrow. The lithology of pebbles in the sandstones changes upwards in the Fort Union section from mudstone in the P1 biozone, to chert and some granite in the upper part of the P4 and lower part of the P5 biozone and finally to abundant granite in the upper part of the P5 and the P6 biozones. These changes seem to record the progressive unroofing of the Granite Mountains to the south. Coal beds occur in the P4 and P5 biozones and are most commonly found above the larger fluvial channel and crevasse-splay complexes. The thickest coal bed observed was about 12 ft; this coal was dated as in the P5 biozone.

Hudson area: Near Hudson, along the southwest flank of the Wind River Basin (Figure 2), the Fort Union Formation is only a few hundred feet thick, and the member subdivisions cannot be recognized. Palynomorphs indicating a P3 biozone age were recovered from the middle part of the interval. The formation is largely conglomeratic, and unconformably overlies the lower part of the Mesaverde Formation in this area. The outcrops occur on the northeast limbs of a series of northwest-trending, sharply folded and faulted anticlines that parallel the nearby flank of the Wind River Range (Plate 1). Flores and others (1993) believed that the anticlinal folding, as well as uplift on the Wind River Range, resulted in removal of the Upper Cretaceous Meeteetse and Lance Formations and much of the Upper Cretaceous Mesaverde Formation Formation in this area creating a 15-mile-wide northeast-trending paleovalley which was filled by Fort Union sediments.

Flores and others (1993) informally divided the Fort Union Formation near Hudson into three parts. The lower part is about 115 ft thick and consists mainly of conglomerate and conglomeratic sandstone. Individual conglomerate beds are as much as 110 ft thick and 1.7 mi in lateral extent. Conglomeratic sandstones are as much as 45 ft thick and 1.4 mi in lateral extent. The middle part is 170 ft thick and consists mostly of siltstone and mudstone with subordinate conglomeratic sandstone and rare carbonaceous shale and coal beds. The upper part is composed of 115 ft of conglomeratic sandstone and subordinate siltstone and mudstone and rare carbonaceous shale and coal beds. Conglomerates form lenses in the sandstones that are as much as 10 ft thick and 0.4 mi in lateral extent. The upper and lower parts of the Fort Union were deposited by low-sinuosity braided streams while the middle part reflects deposition in poorly drained to well-drained floodbasins and low-lying mires.

Subsurface studies of the Fort Union Formation

Subsurface studies of the Fort Union Formation conducted under the U.S. Department of Energy Western Tight Gas Sands Program include detailed cross sections (Finn, 1993; Finn, in press; Keefer and Johnson, 1993: Keefer and Johnson, in press; Keefer, in press; and Szmajter, 1993), palynomorph investigations (Nichols and Flores, 1993), coal investigations (Johnson and Flores, 1993; Johnson and others, 1994c), and paleogeographic reconstructions (Johnson and Flores, 1994).

Johnson and others (1994c) constructed paleogeographic maps for three different time periods in the Fort Union Formation: 1) lower part of lower unnamed member; 2) upper part of lower unnamed member; and 3) maximum extent of Waltman Shale Member. Figure 59 shows the distribution of lithofacies in the lower part of the lower unnamed member of the Fort Union Formation. Two facies are shown: 1) a sandy fluvial facies which covered most of the basin at this time; and 2) an unusual mud-dominated facies which was present mainly

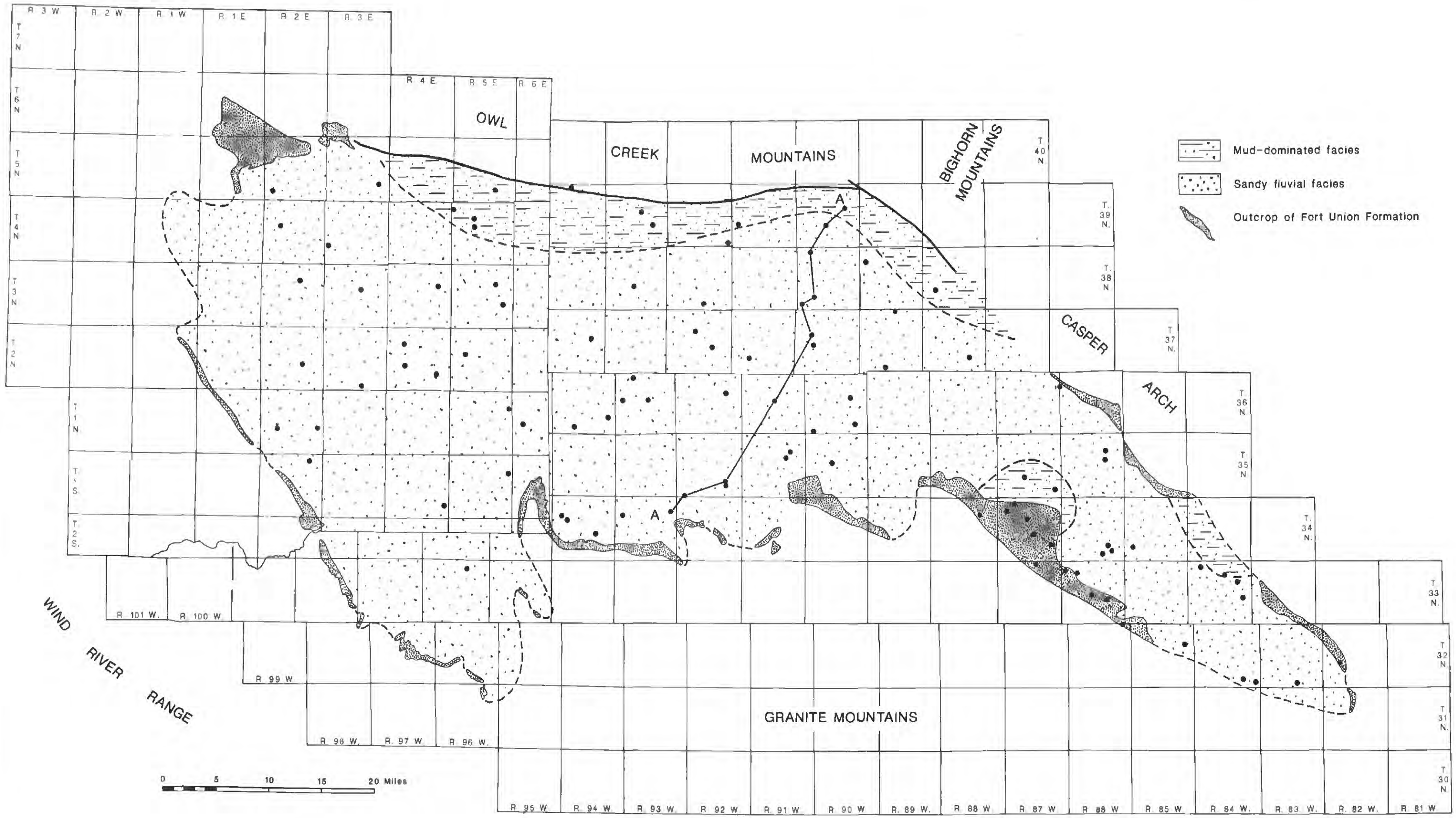


Figure 59: Generalized lithofacies map for the lower part of the lower unnamed member of the Fort Union Formation. Location of cross section A-A' (Figure 61) is shown. Drillholes used for control are shown as black dots.

along the rapidly subsiding trough of the basin. A study of geophysical logs indicates that the mud-dominated facies consists primarily of interbedded sandy mudstone and thin (<10 ft thick) muddy sandstones. It is easily distinguished on geophysical logs from the overlying lacustrine Waltman Shale which is predominantly shale. In addition, the mud-dominated facies lacks the laterally persistent, correlatable shale marker beds which characterize the lacustrine Waltman Shale. Keefer (1961b, p. 131) noted that these marker beds can be traced between wells many miles apart. Keefer was unsure what caused the distinctive marker beds but suggested that they may be related to slight changes in carbonate content or some other matrix material. Flores and others (1994) suggest that the fine grained rocks found in the mud-dominated facies were sourced by Cretaceous marine shales that were stripped off of rising Laramide uplifts during the Paleocene. They suggest that this facies was deposited on floodplains and in floodplain lakes of mudstone-dominated fluvial systems that formed along the basin trough in response to rapid downwarping.

The mud-dominated facies of the lower unnamed member occurs predominantly in the subsurface but may crop out in the vicinity of Twin Buttes, just south of the Owl Creek Mountains in the northern part of the Wind River Reservation (Figure 2). The Fort Union Formation is exposed here on the upturned south flank of the Owl Creek Mountains. The mud-dominated faceis occurs in the Shotgun Member (Keefer and Troyer, 1964, measured section no. 7) and hence it may not correlate preciesly with the mud-dominated faceis in the lower unnamed member in the subsurface. The Shotgun at Twin Buttes consists mainly of gray shale and carbonaceous shale with thin coaly partings and minor red, purple and olive-gray shale. Sandstones are all less than 10 ft thick with the exception of the sharktooth locality sandstone mentioned above which is 19 ft thick. The 1,265 ft of Shotgun measured by Keefer includes only 90 ft of sandstone or about 7% of the total thickness. Age of the Shotgun Member at Twin Buttes, based on abundant mammal, crocodile and shark fossils collected from a channel-like sandstone 217 to 236 ft above the base of the Shotgun Member is Torrejonian or early Tiffanian (middle or early late Paleocene). This is approximately equivalent to the age of the Waltman Shale and possibly the upper part of the lower unnamed member further to the east along the basin trough. The varicolored shales suggest soil-forming processes, and the channel-like sandstone suggest fluvial channels. These features are consistent with the mud-dominated fluvial floodplain interpretation for this facies by Flores and others (1994).

Figure 60 is a lithofacies map modified from Johnson and others (1994c) of the upper part of the lower unnamed member with isopachs showing total coal in beds 2 ft thick or greater. An isopach map of total coal in beds 2 ft thick or greater in the Fort Union Formation in the Wind River Reservation in the western part of the basin was published by Johnson and Flores (1993); this isopach map was extended to include the rest of the basin by Johnson and others (1994c). Three facies are shown on the map: 1) mud-dominated facies, which has expanded to cover a broader area along the basin trough than during the previous time period; 2) coaly facies which occurs along a broad belt in the western two-thirds of the basin; and 3) sandy fluvial facies which is now confined to the southern and western margins of the basin. Coal in the Fort Union Formation in the basin has only recently been documented in detail (Johnson and Flores, 1993; Johnson and others, 1994c). Prior to these studies Fort Union coals in the basin had recieved very little attention primarily because they

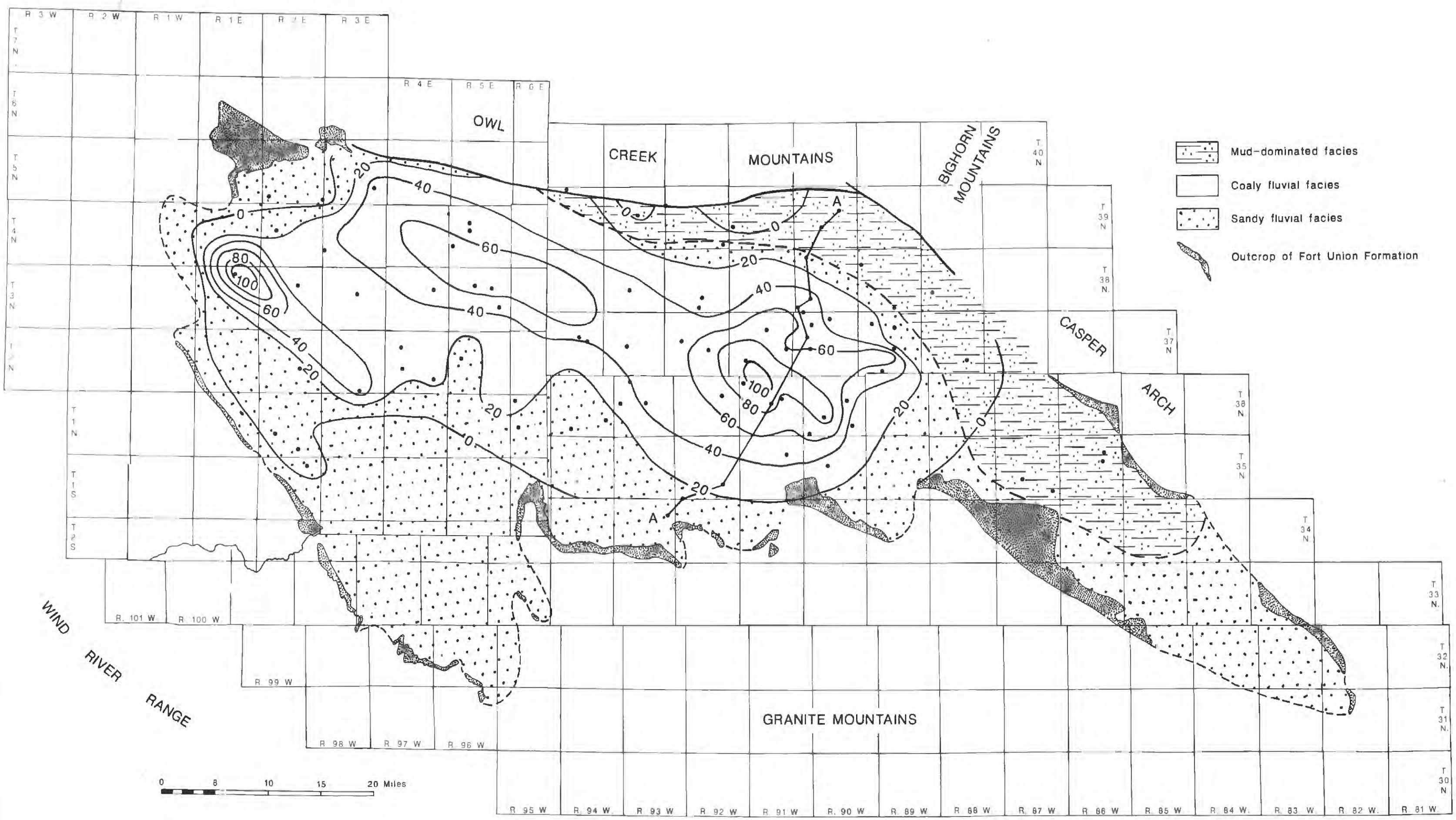


Figure 60: Generalized lithofacies map during maximum extent of the coaly fluvial facies in the upper part of the lower member of the Paleocene Fort Union Formation. Drillholes used for control are shown as black dots. An isopach map of total coal in the coaly facies in beds 2 ft thick or greater is shown. Contour interal is 20 feet. Modified from Johnson and others (1994).

occur mainly in the subsurface. Some of the coal beds in the P4 and P5 biozones at Castle Gardens (Flores and others, 1992) may be correlative to this facies.

The coaly facies reached its maximum extent during deposition of the uppermost part of the lower unnamed member and immediately prior to the beginning of Lake Waltman. The stratigraphically highest coal bed typically occurs just below the base of the Waltman Shale. Individual coal beds can commonly be traced between wells in areas with closely spaced well control such as in the the Muddy Ridge and Pavillion fields area in the westen part of the basin. Here, oil and gas companies have informally assigned names "A" coal, "B" coal, and "C" coal to persistent coal beds (see Nichols and Flores, 1993, Figure 3). Total coal accumulations are greatest in three areas: 1) south of Little Dome Anticline in the western part of the basin, where over 100 ft of total coal is present; 2) east of the Pavillion-Muddy Ridge gas field (Figure 3), just south of the trough of the basin, where over 60 ft of coal occurs; and 3) north of Castle Gardens in the central part of the basin, where over 100 ft of coal is present. According to Johnson and Flores (1993), the accumulation south of Little Dome occurs in a syncline that was subsiding rapidly during the Paleocene, whereas the accumulation east of the Pavillion-Muddy Ridge Field occurs near the fluctuating shoreline of Lake Waltman in an area located roughly between two mapped river systems.

Figure 61 is a north-south cross section across the central part of the Wind River Basin which shows lateral facies relationships in the Fort Union Formation. The cross section is from Johnson and others (1994c). Individual coal beds are shown but are not correlated. The mud-dominated facies extends down into the upper part of the Lance along the basin trough. The south to north progradation of the lacustrine delta facies as Lake Waltman was gradually filled in is apparent on the cross section. Another possible deltaic facies occurs in the extreme northern part of the cross section, adjacent to the Owl Creek Mountains. This possible deltaic system does not appear to prograde with time.

Figure 62 is a paleogeographic map of Lake Waltman at its maximum extent shortly after the lake formed. Lacustrine rocks are divided into lacustrine shale and lacustrine deltaic facies. The deltaic facies includes relatively thin (.50 ft thick) tongues of lacustrine shale. Data are sparse in the eastern part of the basin, and the extent of the two facies are very approximately located. The lacustrine shale facies extends far to the south in a broad area between two deltaic systems, one near the eastern margin of the Wind River Reservation and the other near Castle. The two deltaic systems are apparent on an isopach map of the thickness from the base of the Waltman Shale to the base of the lowest deltaic sandstone of the overlying Shotgun Member (Figure 62). The distribution of coal in the underlying lower unnamed member suggests the presence of two river systems in approximatly the same positions. The thick coal accumulation in the central part of the basin occurs between the two deltaic systems in the overlying Waltman Shale. If these rivers became incised in the rising highlands to the south, they could have remained largely stationary through time. Flores and others (1993) describe a broad paleovalley incised in the flank of the Wind River Range during Paleocene time in the Hudson area, near the southeast margin of the Wind River Reservation.

Hydrocarbon production and reservoir architecture of sandstones in the lower member of the Fort Union Formation

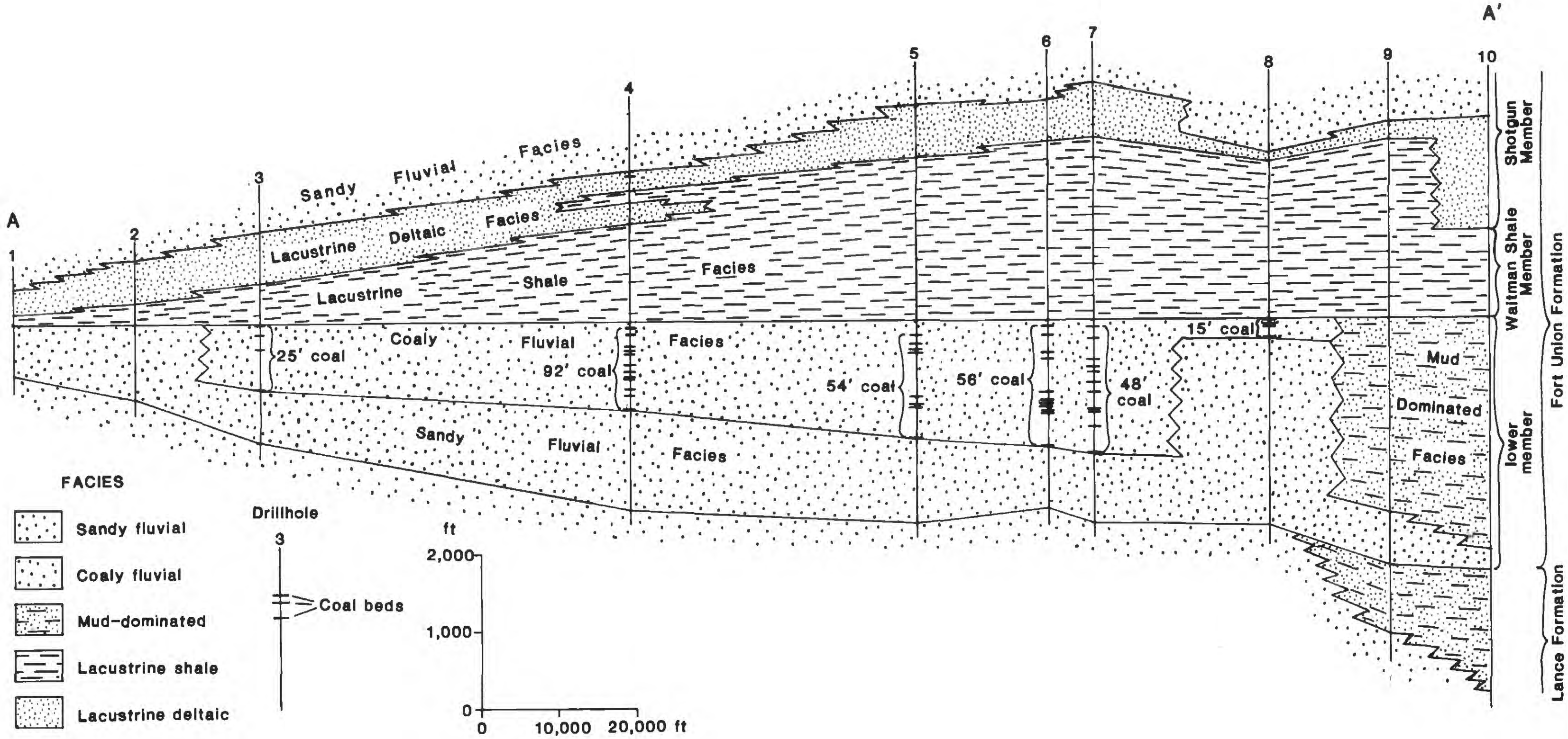


Figure 61: Generalized north-south cross section A-A' from the southern margin of the basin to the basin trough showing lithofacies in the Paleocene Fort Union Formation. Datum is the base of the Waltman Shale Member of the Fort Union Formation. The Lance-Fort Union contact shown is the base of the sandy interval at the base of the Fort Union as defined by Keefer and Troyer (1964) in the Shotgun Butte area. Location on Figure 59. From Johnson and others (1994).

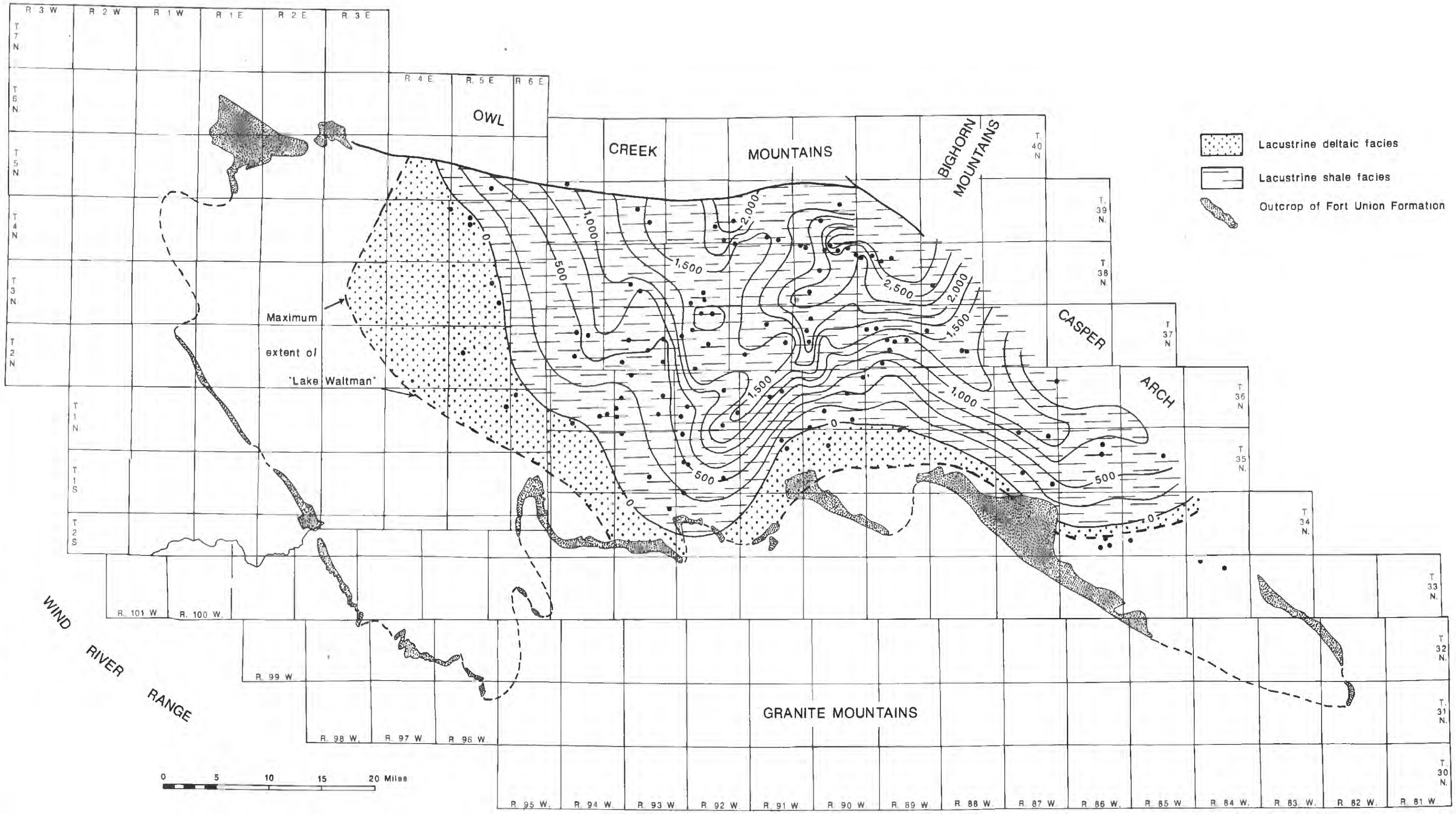


Figure 62: Generalized lithofacies map during maximum extent of Paleocene Lake Waltman. Two different facies are shown: 1) maximum extent of the lacustrine shale facies; and 2) maximum extent of the lacustrine deltaic facies. Isopach map is the interval from the base of the lowest lacustrine shale to the base of the lowest deltaic sandstone in the Waltman Shale Member of the Paleocene Fort Union Formation is shown. Contour interval is 250 ft.

Most hydrocarbon production from the Fort Union Formation in the Wind River Basin is from the lower member, with only minor amounts of gas and heavy waxy oil being produced from deltaic sandstones in the Waltman Shale and from fluvial sandstones in the Shotgun Member above the Waltman Shale (Table 1, Figures 4 and 5). The potential for tight gas accumulations in strata of the Waltman Shale and Shotgun Members is considered low. Major producing fields from the lower unnamed member of the Fort Union Formation include Frenchie Draw, Fuller Reservoir, Madden, Muddy Ridge, and Waltman (Figure 3, Table 1). At Frenchie Draw field the lower unnamed member has produced over 43 bcf of gas, with production accompanied by over 7 million barrels of water (Table 1). Porosity from core ranges from 6 to 12 percent and permeability ranges from 0.1 to 0.2 md (Mueller, 1989a). At Waltman, porosity and permeability from core ranges from 15 to 20 percent and 0.6 to 6 md respectively (Ptasynski, 1989). The lower unnamed member has not been cored at Fuller Reservoir, Madden, and Muddy Ridge fields (Specht, 1989; Brown and Shanon, 1989; Mueller, 1989b), and no reliable porosity and permeability data are available. Johnson and Rice (1993) and Johnson and others (1994a) presented considerable evidence that the Waltman Shale acts as a fairly efficient seal, inhibiting the vertical migration of hydrocarbons in the basin. The Waltman Shale may have also played a role in the development of overpressuring at relatively shallow depths at Madden field by providing an effective seal against vertical migration of gas generated in the lower member and underlying Cretaceous rocks (Johnson and Rice, 1993).

The lower unnamed member varies in thickness from less than 1,000 ft along the west, south, and east margins of the basin to over 4,500 ft near the basin trough in the west-central part of the basin (Figure 63). The isopach map in Figure 63 uses the Lance-Fort Union contact as defined by Keefer (1965). As previously discussed, the contact may not everywhere correspond to the Cretaceous-Tertiary boundary. Figure 64 is an isopach map of total sandstone in the lower member of the Fort Union Formation in beds 10 ft thick or greater, and Figure 65 is a percent sandstone map for the member in beds 10 ft thick or greater. Total sandstone varies from less than 250 ft along the northern and southern margins of the basin to more than 1,250 ft in the west-central part. Percent sandstone is lowest along the north margin of the basin, where the mud-dominated facies occurs, and in the south-central part of the basin, between the east margin of the Wind River Reservation and Castle Gardens where a thick accumulation of coal occurs. The sandy fluvial facies contains about 30 to 50% fluvial sandstones and little coal. Most individual fluvial sandstones in this facies are from 15 to 35 ft thick, and become finer-grained upward. These sandstone commonly stack into complex multistorey bodies from 50 ft to over 300 ft thick. The coaly fluvial facies is somewhat less sandy than the sandy fluvial facies, with about 25 to 40% fining upwards sandstone units from 15 to 35 ft thick, and rarely contains complex multistorey sandstone bodies.

Fluvial sandstones near the south margin of the basin are likely to be elongate in a north-south direction or parallel to stream flow from the highlands to the south. These fluvial sandstones may be subject to some recharge from outcrops along the south margin of the basin and, as a result, may be water wet for considerable distances downdip toward the trough of the basin. Based on the paleogeographic reconstruction's of Flores and others (1994), these generally north-flowing fluvial systems may have joined a generally east-flowing trunk stream system near the basin axis.

SUMMARY DISCUSSION

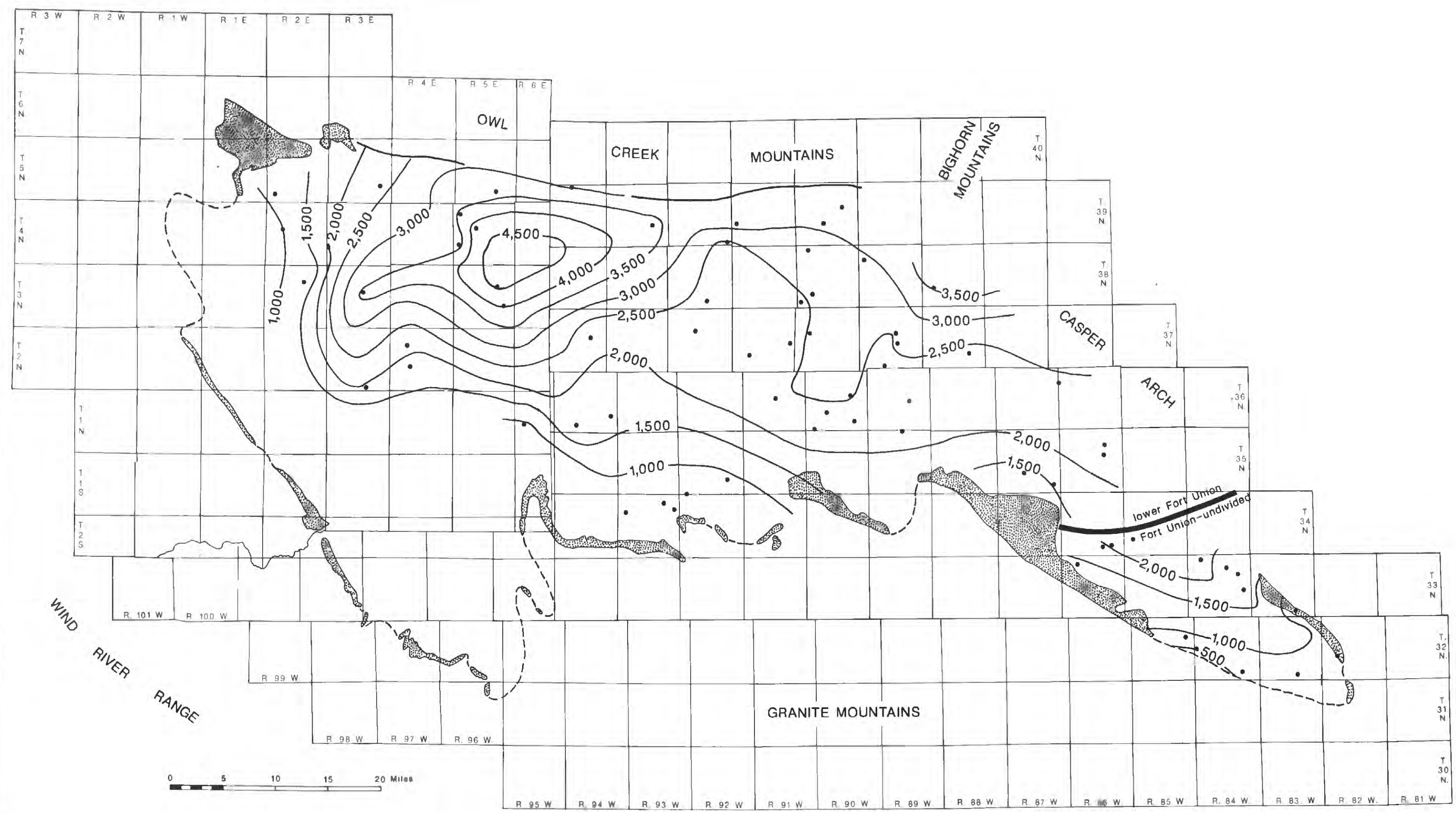


Figure 63: Isopach map of the lower unnamed member of the Paleocene Fort Union Formation. Contour interval is 500 ft.

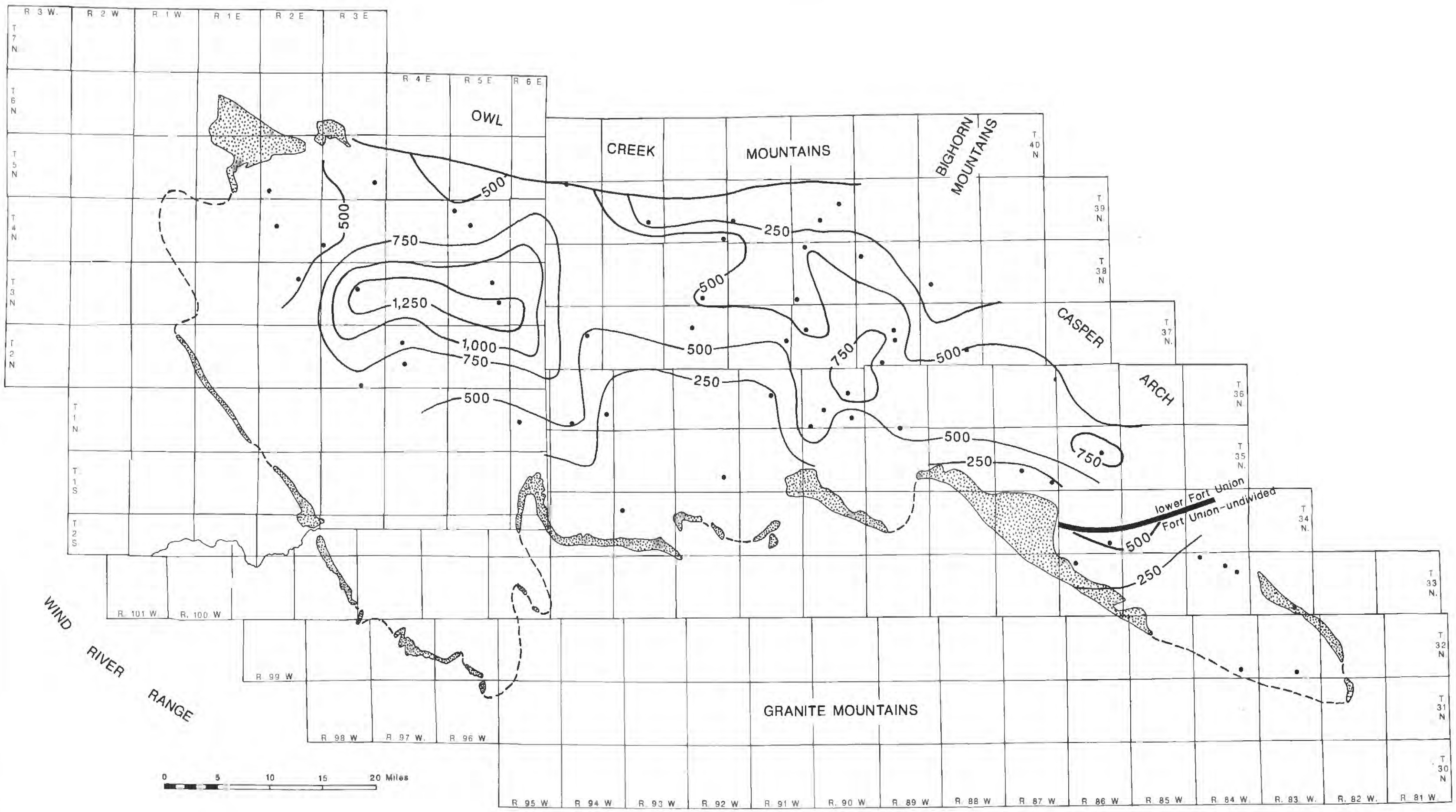


Figure 64: Isopach map of total sandstone in beds 10 ft thick or greater in the lower member of the Paleocene Fort Union Formation, Wind River Basin. Contour interval is 250 ft.

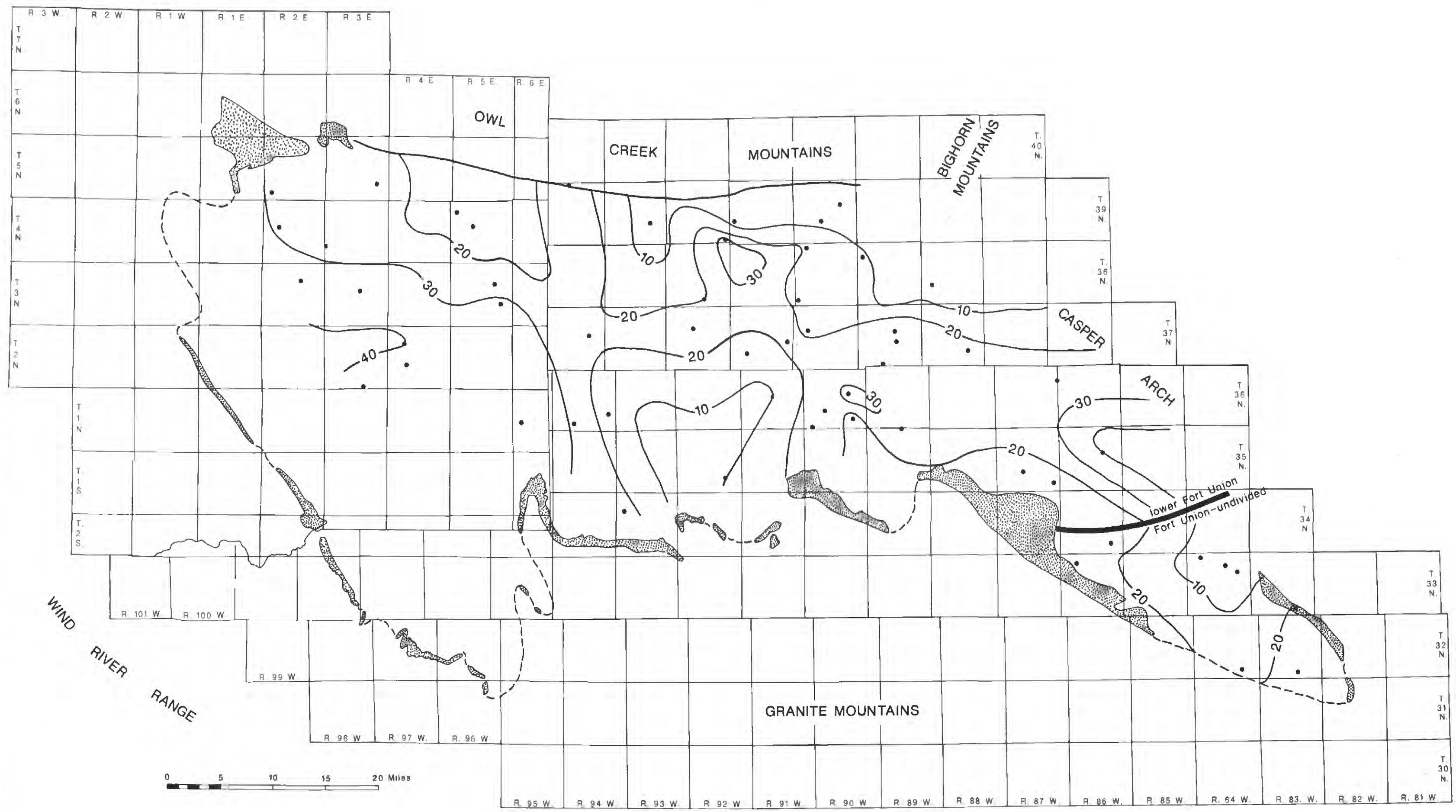


Figure 65: Percent sandstone map for beds 10 ft thick or greater in the lower member of the Paleocene Fort Union Formation, Wind River Basin. Contour intervalis 10 percent.

The purpose of these investigations, conducted under the DOE tight gas program, has been to characterize the geology of the all Upper Cretaceous through lower Tertiary formations that are included in the basin-centered tight gas accumulation. This interval is at its maximum thickness near the basin trough where the basin centered accumulation extends from about the top of the lower unnamed member of the Paleocene Fort Union Formation to at least the base of the Upper Cretaceous Frontier Formation for a total thickness of over 15,000 ft. The basin-centered tight gas accumulation in the Wind River Basin is under drilled when compared to basin-centered accumulations in many other Rocky Mountain basins, and available drillhole information is comparatively sparse. The results of these investigations are being published at a time of increasing drilling activity in the Wind River Basin, and it is hoped that these results will prove to be useful to the companies conducting these exploration efforts. We have concentrated our efforts on acquiring a better understanding of the distribution, lithologic character, and geometry of potential sandstone reservoirs within the basin-centered gas accumulation. Delineation of various types of facies in each of the formations studied, although based on limited stratigraphic data in many areas, is a valuable aid in predicting sandstone distribution, reservoir characteristics, and resource potential.

The lithology and environments of deposition of the Frontier has been previously studied by many workers, and our study of the Frontier was limited to constructing a detailed structure contour map (Plate 1) and a map showing total thickness of sandstone in beds 10 ft thick or greater (Figure 9). Total sandstone ranges from about 250 ft in the western part of the basin to less than 100 ft in the southwestern and southeastern parts (Figure 9). The overlying Shaly member of the Cody Shale varies from 1,150 to 2,250 ft across the basin. It contains no significant hydrocarbon reservoirs but may be an important source for hydrocarbons. The Sandy Member of the Cody Shale includes several relatively clean sandstones that have been called the “Sussex” and “Shannon” sandstones by drillers in the Wind River Basin. These sandstones produce gas from significantly overpressured reservoirs at Madden Anticline, but are largely untested elsewhere. They are similar to the Sussex Member and Shannon Member of the Cody Shale in the Powder River Basin to the east, but they are probably not correlative. The “Sussex” and “Shannon” sandstones comprise most of the sandstone in the Sandy Member of the Cody Shale in the Madden area. The isopach map of total sandstones 10 ft thick or greater in the sandy member (Figure 20) indicates that the “Sussex” and “Shannon” sandstones thin both to the north and south of Madden Anticline and that the source of sand may be southwest of Madden. The updip pinchout of sandstones in this interval toward the south margin of the basin may produce stratigraphic traps.

The buildup of marginal marine sandstones in the lower part of the Upper Cretaceous Mesaverde Formation along three north-south trends in the basin is described in detail for the first time in this report. These buildups are associated with thick coal accumulations and were produced when the eastward retreat of the Cretaceous seaway stalled for extended periods of time. The thickest of these buildups extends along the east boundary of the Wind River Reservation. The base of this buildup is probably in the *Scaphites hippocrepis* zone of the earliest Campanian. Roehler, (1990, cross section H-H', Plate 1) documents a similar approximately correlative buildup of marginal marine sandstones in the Upper Cretaceous Rock Springs Formation in the Green River Basin to the south. The generally northeast trend of this marginal marine sandstone buildup in the Rock Springs Formation appears to connect across the

Wind River Range to the marginal marine sandstones along the east margin of the Wind River Reservation (Figure 66). As in the Wind River Basin, a thick accumulation of coal is associated with the buildup of marginal marine sandstones in the Rock Springs Formation (Tyler and Hamilton, 1994). Maximum coal thickness is over 100 ft along a northeast-trending belt that aligns closely with the thick coal accumulation along the eastern boundary of the Wind River Reservation (Figure 66).

Total sandstone in the nonmarine interval of the Mesaverde Formation decreases from over 1,000 ft in the westernmost part of the basin to less than 100 ft along the southern and eastern margins (Figure 43). Much of this decrease is due to the lower part of the nonmarine interval grading eastward into first marginal marine rocks and then into marine rocks. These fluvial sandstones tend to "stack" into thick bodies, and one of these stacks of channel sandstones was studied in outcrop at Eagle Point in the western part of the basin. The thick stack of fluvial sandstones at Eagle Point was found to trend generally eastward or perpendicular to paleoshoreline, and it is suggested that many of the fluvial channel sandstones in the nonmarine interval may share this trend.

The Meeteetse Formation varies from 750 to 1,335 ft thick across the basin (Figure 46) and is almost totally untested for hydrocarbons. A major concern for drillers has been the general lack of potential sandstone reservoirs in the Meeteetse. Total sandstone in beds 10 ft thick or greater is less than 20 percent throughout most of the eastern half of the basin and less than 30% throughout most of the western half. Many of the sandstones present in the Meeteetse are thin, relatively persistent crevass splay sandstones which are thinner than the 10 ft minimum used in the sandstone isopach map. A area in the north-central part of the basin with higher than average thicknesses of sandstone in the Meeteetse is identified for the first time in this study. This sandstone buildup occurs at depths of from 11,500 to 13,500 ft and has not been tested for hydrocarbons.

Several significant gas discoveries have recently occurred in the Lance Formation, which is as much as 6,000 ft thick along the basin trough. The Lance contains over 2,000 ft of total sandstone in beds 10 ft thick or greater locally near the basin trough north of Madden Anticline (Figure 57). Sandstone percentages in the Lance, however, are less than 20% in some parts of the basin, particularly south of the Casper Arch were the mud-dominated facies is well-developed in the upper part of the Lance (Figure 58). This general lack of sandstone in the upper part of the Lance and the overlying lower unnamed member of the Fort Union Formation (Figures 64 and 65) was first recognized by Barett and Hubley (1969) and is a major concern for drillers. The maps presented here help better define the limits of the mud-dominated facies.

Sandstone reservoirs which persist to outcrop in potential recharge areas tend to be water-bearing further downdip into tight gas accumulations than sandstones which pinch out before reaching outcrop. The regionally persistent Rollins or Trout Creek Sandstone in the Piceance Basin of western Colorado, for example, appears to be water-bearing even in the deepest part of the basin-centered accumulation. Sandstones in the upper part of the Cody Shale and in the marginal marine interval of the overlying Mesaverde Formation in the Wind River Basin are elongate in a north-south direction and subject to recharge from outcrops along the south margin of the basin. Artesian systems were encountered at shallow depths in the marginal marine sandstone buildup along the east margin of the Wind River Reservation while coring for a coalbed methane evaluation. Further to the north and deeper in the basin, these marginal marine sandstones produced large amounts of water and little gas. Recent work by Kaiser and

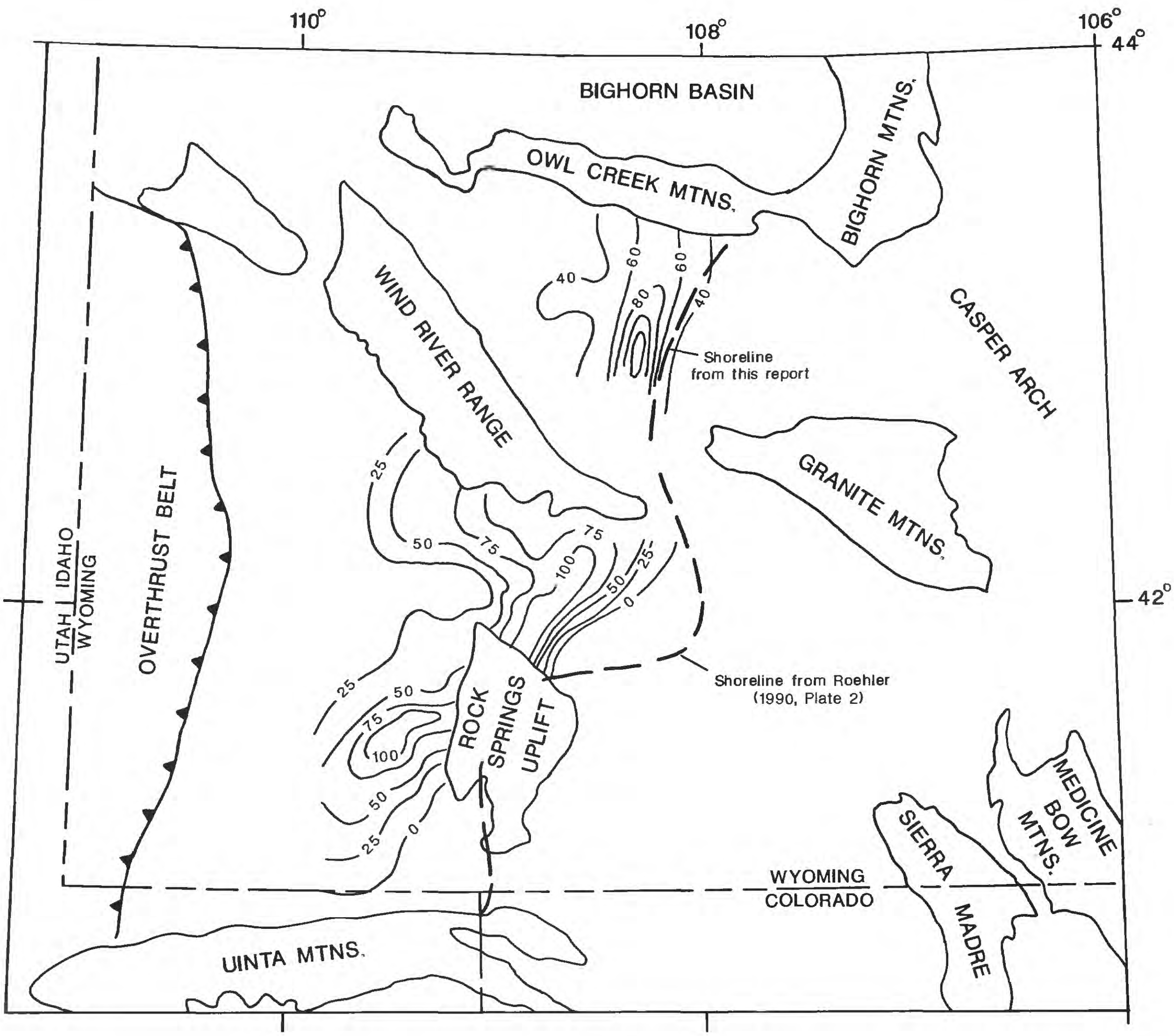


Figure 66: Generalized paleogeographic map of of western Wyoming during earliest Campanian time showing approximate shoreline trend. The shoreline remained close to this position for an extended period of time. Shoreline trend in the Greater Green River Basin is during *Baculites maclearni* time and is from Roehler (1990). Shoreline trend in the Wind River Basin is from this report. Thick coal accumulations are assiciated with this stillstand in both the Greater Green River Basin and the Wind River Basin. Total coal isopach map for the Greater Green River Basin is from Tyler and Hamilton (1994). Contour interval for the Greater Green River Basin: 25 ft. Total coal isopach map for the Wind River Basin is from this report. Contour interval for the Wind River Basin: 20 ft.

Scott (1994) in the San Juan Basin of New Mexico and Colorado, and the Greater Green River Basin of Wyoming, Colorado, and Utah suggests that artesian overpressuring is common around the margins Rocky Mountain basins.

The fluvial sandstones in the lower unnamed member of the Fort Union Formation may be another example where sandstone geometry aided the invasion of surface water. The Fort Union Formation crops out along much of the south margin of the basin. Sandstones in the Fort Union in this part of the basin were deposited by north-flowing streams and would tend to be elongate in a north-south direction. Although the architecture of these fluvial channel sandstones is far more complex than that of the more blanket-like marginal marine sandstones in the Mesaverde Formation and marine shelf sandstones in the upper part of the Cody Shale, they nonetheless may be subject to surface water recharge from these outcrops. Sandstone geometry in the Fort Union may; also be aiding surface water recharge in the western part of the basin. The Fort Union Formation crops out in the Shotgun Butte area in the western part of the basin, and sandstones in the Fort Union Formation in this part of the basin were deposited by generally east-flowing streams. This orientation would favor surface water movement from outcrop near Shotgun Butte into the subsurface to the east.

In summary, the Wind River Basin contains significant resources of natural gas in tight and near tight Upper Cretaceous and lower Tertiary reservoirs. This resource is underdeveloped when compared to similar resources in many other Rocky Mountain basins, and available drillhole information is comparatively sparse. It is hoped that timely publication of these studies will be an aid to the future development of this huge resource.

REFERENCES

Anderson, G. P., 1994, A field study of the Hay Reservoir area, an analog for exploration of Lewis Reservoirs: Natural Gas in the Western United States, First Biennial Conference: Rocky Mountain Association of Geologists and Colorado Oil and Gas Association, Oct. 17-18, Lakewood, Colorado, 2 p.

Barrett, W. J., and Hubley, M. D., 1969, The Madden Gas Field, Fremont County, Wyoming; in Barlow, J. A., Jr., ed., Symposium on Tertiary Rocks of Wyoming: Wyoming Geological Association 21st Field Conference Guidebook, p. 115-120.

Barwin, J. R., 1959, Facies of the Mesaverde Formation, east-central Wyoming: American Association of Petroleum Geologists Rocky Mountain Section Geological Record, Feb., 1959. p. 139-142.

Barwin, J. R., 1961a, Stratigraphy of the (Cretaceous) Mesaverde Formation in the southeastern part of the Wind River Basin, Fremont and Natrona Counties, Wyoming: University of Wyoming, Laramie Wyoming, unpublished MS thesis, 78 p.

Barwin, J. R., 1961b, Stratigraphy of the Mesaverde Formation in the southern part of the Wind River Basin, Wyoming: Wyoming Geological Association, 16th Annual Field Conference, p. 171-179.

Blackstone, 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., Forty-First Field Conference: Wyoming Geological Association, p. 151-165.

Brenner, R. L., and Davis, D. K., 1973, Storm-generated coquinoid sandstones: genesis of high-energy marine sediments from the Upper Jurassic of Wyoming and Montana: Geological society of America Bulletin, vol. 84, p. 1685-1698.

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

Cobban, W. A., and Kennedy, W. J., 1989, The ammonite Metengonoceras Hyatt, 1903, from the Mowry Shale (Cretaceous) of Montana and Wyoming: U. S. Geological Survey Bulletin 1787-L, 11 p.

Clark, Charles, 1978, West Poison Spider field, Natrona County, Wyoming: in Boyd, R. G., Boberg, W. W., and Olson, G. M., eds, Wyoming Geological Association Thirtieth Annual Field Conference Guidebook; Resources of the Wind River Basin, p. 261-271.

Coughlan, J. P., 1983, Depositional environment and diagenesis of the Teapot Sandstone (Upper Cretaceous) Converse and Natrona Counties, Wyoming: University of Wyoming, Laramie, Wyoming unpublished MS Thesis, 116 p.

Curry, W. H., 3ed, 1976, Late Cretaceous Teapot delta of southern Powder River Basin, Wyoming: in Curry, W. H. 3rd., and Runge, J. S., eds., Geology and Energy Resources of the Powder River Basin; Wyoming Geological Association 28th Annual Field Conference Guidebook, p. 21-32.

De Bruin, R. H., and Hostetler, S. D., 1991, Oil and gas fields map of the Wind River Basin, Wyoming: Wyoming Geological Survey Map Series MS-37, scale: 1:316,800.

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 Association 1986 Symposium, Casper, WY, p. 107-157.

Finn, T.M., 1993, Subsurface stratigraphic cross section of Lower and Upper Cretaceous rocks in the southeastern Wind River Basin, Wyoming: in Keefer, W.R., Metzger, W. J., and Godwin, L.H., eds., Oil and gas and other resources of the Wind River Basin, Wyoming: Wyoming Geological Association Special Symposium, 1993, Casper, WY, p. 91-94.

Flemings, P. B., and Nelson, S. N., 1991, Paleogeographic evolution of the Latest Cretaceous and Paleocene Wind River Basin: The Mountain Geologists, vol. 28, no. 2/3, p. 37-52.

Flores, R, M., Keighin, C. W., and Keefer, W. R., 1990, Reservoir-sandstone paradigms, Paleocene Fort Union Formation, Wind River Basin, Wyoming (abs.): American Association of Petroleum Geologists Bulletin, vol. 74, p. 1323.

Flores, R. M, Keighin, C. W., and Nichols, D. J., 1992, Sedimentology, conglomerate petrology, and palynostratigraphy of the Fort Union Formation (Paleocene), Castle Gardens, Wind River Basin, Wyoming: in Sundell, K A., and Anderson, T. C., eds., Road Log Volume for Rediscover the Rockies: Wyoming Geological Association, Casper Wy., p. 21-27.

Flores, R.M., Clark, A.C., and Keighin, C.W., 1993, Architecture of Fort Union paleovalley conglomerates related to aquifer potential in the western Wind River Basin: in Keefer, W.R., Metzger, W. J., and Godwin, L.H., eds., Oil and gas and other resources of the Wind River Basin, Wyoming: Wyoming Geological Association Special Symposium, 1993, Casper, WY, p. 143-162.

Flores, R. M., and Keighin, C. W., 1992, Facies and stratigraphic framework of the lower member of the Fort Union Formation (Paleocene), Shotgun Butte area, Wind River Basin, Wyoming, in Sundell, K A., and Anderson, T. C., eds., Road Log Volume for Rediscover the Rockies: Wyoming Geological Association, Casper Wy., p. 48-52.

Flores, R.M., and Keighin, C.W., 1993, Reservoir anisotropy and facies stratigraphic framework in the Paleocene Fort Union Formation, western Wind River Basin, Wyoming: in Keefer, W.R., Metzger, W. J., and Godwin, L.H., eds., Oil and gas and other resources of the Wind River Basin, Wyoming: Wyoming Geological Association Special Symposium, 1993, Casper, WY, p. 121-142.

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, The Society for Organic Petrology Eleventh Annual Meeting, Jackson, Wyoming: Wyoming State Geological Survey Public Information Circular no. 33, p 1-16.

Forster, J. A., and Horne, J. C., 1994, Controls on natural gas reservoir distribution: Frontier Formation, Green River Basin, Wyoming: Natural Gas in the Western United States, First Biennial Conference: Rocky Mountain Association of Geologists and Colorado Oil and Gas Association, Oct. 17-18, Lakewood, Colorado, Extended Abstracts vol., 11 p.

Fouch, T.D., Wandrey, C.J., Pitman, J.K., Nuccio, V.F., Schmoker, J.W., Rice, D.D., Johnson, R.C., and Dolton, G.L., 1992, Natural gas accumulations in low-permeability Tertiary, and Cretaceous (Campanian and Maastrichtian) rock, Uinta Basin, Utah: U.S. Department of Energy DOE/MC/20422-3051, 81 p.

Gaskill, C. H., 1989, Tepee Flats: in Cardinal, D. F., Miller, Terry, Stewart, W. W., and Trotter, J. F., eds., Wyoming Oil and Gas Fields Symposium Bighorn and Wind River Basins: Wyoming Geological Association, p. 501-502.

Gautier, D. L., 1983, Chapter 8- Marine shales, in Rice, D. D., and Gautier, D. L., Patterns of Sedimentation, Diagenesis, and Hydrocarbon Accumulation in Cretaceous Rocks of the Rocky Mountains: Society of Economic Paleontologists and Mineralogists Short Course no. 11, p. 8-1 to 8-41.

Gilbert, N. M., 1989, Bonneville: in Cardinal, D. F., Miller, Terry, Stewart, W. W., and Trotter, J. F., eds., Wyoming Oil and Gas Fields Symposium Bighorn and Wind River Basins: Wyoming Geological Association, p. 68-69.

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

Gillespie, J. M., and Fox, J. E., 1991, Tectonically influenced sedimentation in the Lance Formation, eastern Wind River Basin, Wyoming: The Mountain Geologists, vol. 28, no. 2/3, p. 53-66.

Gouger, B. L., 1989, Poison Spider West: in Cardinal, D. F., Miller, Terry, Stewart, W. W., and Trotter, J. F., eds., Wyoming Oil and Gas Fields Symposium Bighorn and Wind River Basins: Wyoming Geological Association, p. 381-383.

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

Hickling, N. L., Warlow, R. C., and Windolph, J. F., Jr., 1989, Geology of the Upper Cretaceous and Tertiary coal-bearing rocks in the western part of the Wind River Basin, Wyoming: U.S. Geological Survey Bulletin 1813, 128 p.

Hogle, D. G., and Jones, R. W., 1991, Subsurface geology of Upper Cretaceous and lower Tertiary coal-bearing rocks, Wind River Basin, Wyoming: The Mountain Geologist, vol. 28, no. 2/3, p. 13-35.

Houston, R. S., and Murphy, J. F., 1977, Depositional environment of Upper Cretaceous black sandstones of the Western Interior: U.S. Geological Survey Professional Paper 994-A, 29 p.

Jiao, Z. S., and Surdam, R. C., 1993, Low-permeability rocks, capillary seals, and pressure compartment boundaries in the Cretaceous section of the Powder River Basin: in Stroock, Betty and Andrew, Sam, eds, Wyoming Geological Association Guidebook, Jubilee Anniversary Field Conference, p. 297-310.

Johnson, R. C., Crovelli, R. A., Spencer, C. W., and Mast, R. F., 1987, As assessment of gas resources in low-permeability sandstones of the Upper Cretaceous Mesaverde Group, Piceance Basin, Colorado: U.S. Geological Survey Open-File Report 87-357, 165 p.

Johnson, R. C., and Flores, R. M., 1993, Sratigraphy, areal distribution, and paleodepositional environments of Fort Union Formation coal beds, Wind River Reservation, Wyoming: in Keefer, W.R., Metzger, W. J., and Godwin, L.H., eds., Oil and gas and other resources of the Wind River Basin, Wyoming: Wyoming Geological Association Special Symposium, 1993, Casper, WY, p.281-294.

Johnson, R.C., and Clark, A.C., 1993, Environments of deposition of the uppermost part of the Cody Shale and the Mesaverde and Meeteetse Formations of Late Cretaceous age, Shotgun Butte area, Wind River Reservation, Wyoming: in Keefer, W.R., Metzger, W. J., and Godwin, L.H., eds., Oil and gas and other resources of the Wind River Basin, Wyoming: Wyoming Geological Association Special Symposium, 1993, Casper, WY, p. 95-109.

Johnson, R. C., Clark, A. C., Barker, C. E., Crysdale, B. L., Higley, D. K., Szmajter, R. J., and Finn, T. M., 1993, Coalbed Methane potential of the Upper Cretaceous Mesaverde and Meeteetse Formations, Wind River Reservation, Wyoming: in Keefer, W.R., Metzger, W. J., and Godwin, L.H., eds., Oil and gas and other resources of the Wind River Basin, Wyoming: Wyoming Geological Association Special Symposium, 1993, Casper, WY, p.215-242.

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., Oil and gas and other resources of the Wind River Basin, Wyoming: Wyoming Geological Association Special Symposium, 1993, Casper, WY, p. 319-335.

Johnson, R. C., Rice, D. D., and Fouch, T. D., 1994a, Evidence for gas migration from Cretaceous basin-centered accumulations into lower Tertiary reservoirs in Rocky Mountain basins: Rocky Mountain Association of Geologists and Colorado Oil and Gas Association First Biennial Conference, Natural Gas in the Western United States Proceedings, Oct. 17-18,1994, Lakewood, Colorado, Extended Abstracts vol. 8 p.

Johnson, R. C., Rice, D. D., and Fouch, T. D., 1994b, Gas migrating from basin-center low-permeability hydrocarbon accumulations in the Rocky Mountain basins-where does it go?: American Association of Petroleum Geologists Annual Meeting, Denver Colorado, June 12-15, 1994, Abstracts With Program. p. 181-182.

Johnson, R. C., Flores, R. M., Szmajter, R., and Finn, T. M., 1994c, A preliminary study of coal-forming environments during deposition of the Paleocene Fort Union Formation, 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, The Society for Organic Petrology Eleventh Annual Meeting, Jackson, Wyoming: Wyoming State Geological Survey Public Information Circular no. 33, p. 69-81.

Johnson, R. C., Finn, T. M., Keefer, W. R., Flores, R. M., Keighin, C. W., Szmajter, R. J., and Nuccio, V. F., 1995, Preliminary geologic characterization of Upper Cretaceous and Lower Tertiary low-permeability (tight) gas bearing rocks in the Wind River Basin, Wyoming: Proceedings of the Natural Gas RD&D Contractors Review Meeting, U.S. Department of Energy Office of Fossil Energy, Morgantown West Virginia, DOE/METC-95/1017, vol. 1, p. 87-101.

Jorjorian, T., 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: (abstract) American Association of Petroleum Geologists Bulletin, vol. 73, p. 1162.

Kaiser, W. R., and Scott, A. R., 1994, Abnormal pressure in the San Juan and Greater Green River Basins: Natural Gas in the Western United States; Rocky Mountain Association of Geologists and Colorado Oil and Gas Association First Biennial Conference, Oct. 17-18, Lakewood Colorado, Extended Abstracts vol., 5 p.

Katz, B.J., and Liro, L.M., 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., Oil and gas and other resources of the Wind River Basin, Wyoming: Wyoming Geological Association Special Symposium, 1993, Casper, WY, p. 163-174.

Keefer, W. R., 1961a, The Meeteetse, Lance, and Fort Union Formations, southern Wind River Basin, Wyoming: in Wiloth, G. J. ed., Symposium on Late Cretaceous Rocks, Wyoming and Adjacent Areas: Wyoming Geological Association Sixteenth Annual Field Conference, p. 180-186.

Keefer, W. R., 1961b, Waltman Shale and Shotgun Members of Fort Union Formation (Paleocene) in Wind River Basin, Wyoming: American Association of Petroleum Geologists Bulletin no 45, p. 1,310-1,323.

Keefer, W. R., 1965, Geologic history of Wind River Basin, central Wyoming: American Association of Petroleum Geologists Bulletin, vol. 49, no. 11, p. 1878-1892.

Keefer, W. R., 1969, General stratigraphy and depositional history of the Fort Union, Indian Meadows, and Wind River Formations, Wind River Basin, Wyoming: Wyoming Geological Association Twenty-First Annual Field Conference Guidebook, p. 19-28.

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., 1972, Frontier, Cody and Mesaverde Formations in the Wind River and southern Bighorn Basins, Wyoming: U.S. Geological Survey Professional Paper 495-E, 23 p.

Keefer, W. R., and Troyer, M. L. 1964, Geology of the Shotgun Butte area, Fremont County, Wyoming: U.S. Geological Survey Bulletin 1157, 123 p.

Keefer, W. R., Stratigraphy and correlation of Cretaceous and Paleocene Rocks, northern Wind River Basin, Wyoming: U.S. Geological Survey Oil and Gas Investigations Chart OC-146A (in press).

Keighin, C.W., 1993, Petrography of some Upper Cretaceous Mesaverde Formation sandstones, Wind River Basin, Wyoming: in Keefer, W.R., Metzger, W. J., and Godwin, L.H., eds., Oil and gas and other resources of the Wind River Basin, Wyoming: Wyoming Geological Association Special Symposium, 1993, Casper, WY, p. 111-119.

Law, B. E., and Dickinson, W. W., 1985, Conceptual model for the origin of abnormally pressured gas accumulations in low-permeability reservoirs: American Association of Petroleum Geologists Bulletin, vol. 69, no. 8, p. 1295-1304.

Law, B. E., Spencer, C. W., and Bostick, N. H., 1980, Evaluation of organic matter, subsurface temperature, and pressure with regard to gas generation in low-permeability Upper Cretaceous and lower Tertiary sandstones in Pacific Creek area, Sublette and Sweetwater Counties, Wyoming: The Mountain Geologists, vol., 12, p. 23-35.

Law, B. E., Spencer, C. W., and Bostick, N. H., 1979, Preliminary results of organic maturation, temperature, and pressure studies in the Pacific Creek area, Sublette County, Wyoming: in 5th DOE Symposium on Enhanced Oil and Gas Recovery and Improved Drilling Methods, Tulsa, Oklahoma, Proceedings, vol. 3 - Gas and Drilling: Tulsa, Oklahoma, Petroleum Publishing, p. 1-13.

Law, B. E., Spencer, C. W., Charpentier, R. R., Corvelli, R. A., Mast, R. F., Dolton, G. L., and Wandrey, C. J., 1989, Estimates of gas resources in overpressured low-permeability

Cretaceous and Tertiary sandstone reservoirs, Greater Green River Basin, Wyoming, Colorado, and Utah: in Eisert, J. L. ed, Gas Resources of Wyoming: Wyoming Geological Association Fortieth Field Conference Guidebook, p. 39-61.

Little, Laird, 1989, Riverton Dome East: in Cardinal, D. F., Miller, Terry, Stewart, W. W., and Trotter, J. F., eds., Wyoming Oil and Gas Fields Symposium Bighorn and Wind River Basins: Wyoming Geological Association, p. 410-412

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.

MacGowan, D. B., Garcia-Conzalez, M., Britton, D. R., and Surdam, R. C., 1993, Timing of hydrocarbon generation, organic-inorganic diagenesis, and the formation of abnormally pressured gas compartments in the Cretaceous of the Greater Green River Basin: a Geochemical Model: in Stroock, Betty, and Andrew, Sam, eds., Wyoming Geological Association Guidebook, Jubilee Anniversary Field Conference, p. 325-348.

Mann, R. L., and Malinowsky, M. S., 1993, Slant hole completion test, Cozzette and paludal production testing: in Malone, R. D., ed., Proceedings of the Fuels Technology Contractors Review Meeting, U.S. Department of Energy, Office of Fossil Energy, Morgantown West Virginia, DOE/METC-94/1002, p. 186-199.

Masters, J. A., 1979, Deep basin gas trap western Canada: American Association of Petroleum Geologists Bulletin, vol. 63, no. 2, p. 151-181.

Masters, J. A., 1984, Lower Cretaceous oil and gas in western Canada: in Masters, J. A., ed., Elmworth - Case Study of a Deep Basin Gas Field: American Association of Petroleum Geologists Memoir 38, p. 1-33.

McPeek, L. A., 1981, Eastern Green River Basin--a developing giant gas supply from deep, overpressured Upper Cretaceous sandstone: American Association of Petroleum Geologists Bulletin, vol. 65, p. 1078-1098.

Merewether, E.A., 1983, The Frontier Formation and mid-Cretaceous orogeny in the foreland of southwestern Wyoming: The Mountain Geologist, vol. 20, p. 121-138.

Meissner, F. F., 1980, Examples of abnormal fluid pressure produced by hydrocarbon generation (abstract): American Association of Petroleum Geologists Bulletin, vol. 65, p. 749.

Meissner, F. F., 1981, Abnormal pressures produced by hydrocarbon generation and maturation and their relation to processes of migration and accumulation (abstract): American Association of Petroleum Geologists Bulletin, vol. 65, p. 2467.

Meissner, F. F., 1984, Cretaceous and Lower Tertiary coals as sources for gas accumulations in the Rocky Mountain area: in Woodward, Jane, Meissner, F. F., and Clayton, J. L., eds., Hydrocarbon Source Rocks of the Greater Rocky Mountain Region; Rocky Mountain Association of Geologists Symposium, Denver Co. 1984, p. 401-432.

Mercer, J. C., and Frohne, K. H., 1986, Production characterization of tight lenticular gas sands in the Rulison area of western Colorado: SPE Paper 15248, 6 p.

Mueller, Clark, 1989, Frenchie Draw: : in Cardinal, D. F., Miller, Terry, Stewart, W. W., and Trotter, J. F., eds., Wyoming Oil and Gas Fields Symposium Bighorn and Wind River Basins: Wyoming Geological Association, p.174-175.

Mueller, Clark, 1989, Muddy Ridge: in Cardinal, D. F., Miller, Terry, Stewart, W. W., and Trotter, J. F., eds., Wyoming Oil and Gas Fields Symposium Bighorn and Wind River Basins: Wyoming Geological Association, p.312-315.

Nichols, D. J., and Ott, H. L., 1978, Biostratigraphy and evolution of the *Momities-Caryapollenites* lineage in the early Tertiary in the Wind River Basin, Wyoming: Palynology, v. 2, p. 93-112.

Nichols, D. J., and Flores, R. M., 1993, Palynostratigraphic correlation of the Fort Union Formation (Paleocene) in the Wind River Reservation and Waltman area, Wind River Basin, Wyoming: in Keefer, W. R., Metzger, W. J., and Godwin, L. H., eds, Oil and Gas and Other Resources of the Wind River Basin, Wyoming, Wyoming Geological Association Special Symposium, p. 179-189.

Nuccio, V. F., Finn, T. M., and Pawlewicz, M. J.,1993, Surface vitrinite reflectance study of the Wind River Basin, central Wyoming: in Keefer, W.R., Metzger, W. J., and Godwin, L.H., eds., Oil and gas and other resources of the Wind River Basin, Wyoming: Wyoming Geological Association Special Symposium, 1993, Casper, WY, p. 307-317.

Pawlewicz, M., 1993, Vitrinite reflectance study of the Wind River Basin, central Wyoming: in Keefer, W.R., Metzger, W. J., and Godwin, L.H., eds., Oil and gas and other resources of the Wind River Basin, Wyoming: Wyoming Geological Association Special Symposium, 1993, Casper, WY, p. 295-306.

Peterson, R. E. ,1984, Geological and porduction charactersistcs of the nonmarine part of the Mesaverde Group, Rulison Field area, Piceance Basin, Colorado: SPE/DOE/GRI Paper 12835, 10 p.

Phillips, S. T., 1983, Tectonic influence on sedimentation, Waltman Member, Tout Union Formation, Wind River Basin, Wyoming: in Lowell, J. D. ed., Rocky Mountain Foreland Basins and Uplifts, Rocky Mountain Association of Geologists Field Conference, p. p. 149-160.

Ptasynski, H., 1989, Waltman Bullfrog Unit: in Cardinal, D. F., Miller, Terry, Stewart, W. W., and Trotter, J. F., eds., Wyoming Oil and Gas Fields Symposium Bighorn and Wind River Basins: Wyoming Geological Association, p. 522-526.

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.

Ray, R. R., and Keefer, W. R., 1985, Wind River Basin, central Wyoming: in Gries, Robbie and Dyer, R. C. eds., Seismic Exploration of the Rocky Mountain Region: Rocky Mountain Association of Geologists and the Denver Geophysical Society, p. 201-212.

Reinecke, K. M., Rice, D. D., and Johnson, R. C., 1991, Characteristics and development of fluvial sandstone and coalbed reservoirs of Upper Cretaceous Mesaverde Group, Grand Valley Field, Garfield County, Colorado: in Schwochow, S. D., Murray, D. K., and Fahy, M. F. eds., Coalbed Methane of Western North America: Rocky Mountain Association of Geologists 1991 Guidebook, p. 209-225.

Reynolds, M.W., 1966, Stratigraphic relations of Upper Cretaceous rocks, Lamont-Baroil area, south-central Wyoming: in Geological Research, 1966: U.S. Geological Survey Professional Paper 550-B, p. B69-B76.

Rice, D. D., and Shurr, G. W., 1983, Patterns of sedimentation and paleogeography across the Western Interior Seaway during time of deposition of Upper Cretaceous Eagle Sandstone and equivalent rocks, Northern Great Plains: in Reynolds, M. W., and Dolly, E. D., eds., Mesozoic Paleogeography of the West-Central United States, Rocky Mountain Paleogeography Symposium 2: The Rocky Mountain Section, Society of Economic Paleontologists and Mineralogists, p. 337-358.

Rich, E. I., 1958, Stratigraphic relations of latest Cretaceous rocks in parts of Powder River, Wind River, and Big Horn basins, Wyoming: American Association of Petroleum Geologists Bulletin, vol. 42, no. 10, p. 2424-2443.

Roehler, H. W., 1990, Stratigraphy of the Mesaverde Group in the central and eastern Greater Green River Basin, Wyoming, Colorado, and Utah: U.S. Geological Survey Professional Paper 1508, 52 p.

Schmoker, J. W., 1995, Method for assessing continuous-type (unconventional) hydrocarbon accumulations: in Gautier, D. L., Dolton, G. L., Takahashi, K. I., and Varns, K. L., eds., 1995 National assessment of United States oil and gas resources on CD-ROM: U. S. Geological Survey Digital Data Series 30.

Schrayer, G.J., and Zarella, W.M., 1963, Organic geochemistry of shale I, Distribution of organic matter in the siliceous Mowry Shale of Wyoming: Geochim. et Cosmochim. Acta, vol. 27, p. 1033-1046.

Skeen, R. C., and Ray, R. R., 1983, Seismic models and interpretation of the Casper Arch Thrust: application to Rocky Mountain Foreland Structure: in Lowell, J. D., and Gries, Robbie eds., Rocky Mountain Foreland Basins and Uplifts: Rocky Mountain Association of Geologists, p. 99-124.

Specht, R. W., 1989, Fuller Reservoir: in Cardinal, D. F., Miller, Terry, Stewart, W. W., and Trotter, J. F., eds., Wyoming Oil and Gas Fields Symposium Bighorn and Wind River Basins: Wyoming Geological Association, p. 178-180.

Spencer, C. W., 1985, Geologic aspects of tight gas reservoirs in the Rocky Mountain region: Journal of Petroleum Technology, July, p. 1308-1314.

Spencer, C. W., 1987, Hydrocarbon generation as a mechanism for overpressuring in the Rocky Mountain Region: American Association of Petroleum Geologist Bulletin, vol. 71, p. 368-388.

Spencer, C. W., and Law, B. E., 1981, Overpressured, low-permeability gas reservoirs in Green River, Washakie, and Great Divide basins, southwestern Wyoming (abs.): American Association of Petroleum Geologists Bulletin, vol. 65, p. 569.

Szmajter, R. J., 1993, Subsurface stratigraphic cross section of Lower and Upper Cretaceous rocks in the south-central Wind River Basin, Wyoming: in Keefer, W.R., Metzger, W. J., and Godwin, L.H., eds., Oil and gas and other resources of the Wind River Basin, Wyoming: Wyoming Geological Association Special Symposium, 1993, Casper, WY, p. 87-90.

Thomas, J. B., 1979, Reservoir characterization of the Shannon Sandstone by scanning electron microscopy (SEM), x-ray diffraction (XRD) and thin-section analysis of drill cuttings; Michigan-Wisconsin Lysite 1-9 well: Reservoirs, Inc. service report prepared for Michigan-Wisconsin Pipeline Company, November, 1979, Monsanto Oil Company files.

Thompson R. M., and White, V. L., 1954, Geology of the Riverton area, central Wyoming: U.S. Geological Survey Oil and Gas Investigations Map OM-127.

Turtelot, H. A., 1953, Geology of the Badwater area, central Wyoming: U.S. Geological Survey Oil and Gas Investigations Map OM-124.

Tyler, R., and Hamilton, D. S., 1994, Tectonic and stratigraphic setting and coal occurrence of the Upper Cretaceous Mesaverde Group and lower Tertiary Fort Union Formation, Greater Green River Basin: in Geologic and Hydrologic Assessment of Natural Gas From Coal Seams in the Mesaverde Group and Fort Union Formation, Greater Green River Basin, Wyoming and Colorado: Topic Report, prepared for the Gas Research Institute, under contract no. 5091-214-2261, p. 8-68.

Tyler R., Kaiser, W. R., Scott, A. R., Hamilton, D. S., and Ambrose, W. A., 1995, Geologic and hydrologic assessment of natural gas from coal: Greater Green River, Piceance, Powder River, and Raton Basins, Western United States: Bureau of Economic Geology and the Gas Research Institute Report of Investigations No. 228, 219 p.

Windolph, J. F., Jr., Warlow, R. C., and Hickling, N. L., 1982, Coal resources assessment of the Wind River Indian Reservation, Fremont and Hot Springs Counties, Wyoming: U.S. Geological Survey Administrative Report to the Bureau of Indian Affairs, 186 p.

Woodruff, E. G., 1911, The Lander oil field, Fremont County, in The Lander and Salt Creek oil fields, Wyoming: U.S. Geological Survey Bulletin 452, p. 7-36.

Yenne, K. A., and Pipiringos, G. N., 1954, Stratigraphic sections of Cody Shale and younger Cretaceous and Paleocene rocks in the Wind River Basin, Fremont County, Wyoming: U.S. Geological Survey Oil and Gas Investigations Chart OC-49.

Yin, P., and Surdam, Diagenesis and overpressuring in the Almond Sandstones, Mesaverde Group: Wyoming Geological Association Guidebook, Jubilee Anniversary Field Conference, p. 349-357.