Chapter 10

Detailed Measured Sections, Cross Sections, and Paleogeographic Reconstructions of the Upper Cretaceous and Lower Tertiary Nonmarine interval, Wind River Basin, Wyoming

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Volume Title Page

By Ronald C. Johnson

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Detailed Measured Sections, Cross Sections, and Paleogeographic Reconstructions of the Upper Cretaceous and Lower Tertiary Nonmarine interval, Wind River Basin, Wyoming

By Ronald C. Johnson

Abstract

Detailed measured sections and regional stratigraphic cross sections are used to reconstruct facies maps and interpret paleogeographic settings for the interval from the base of Upper Cretaceous Mesaverde Formation to top of lower member of the Paleocene Fort Union Formation in the Wind River Basin, Wyoming. The Mesaverde Formation spans the time during which the Upper Cretaceous seaway retreated eastward out of central Wyoming in Campanian time and the initial stages of the Lewis transgression in earliest Maastrichtian time. This retreat stalled for a considerable period of time during deposition of the lower part of the Mesaverde, creating a thick buildup of marginal marine sandstones and coaly coastal plain deposits across the western part of the basin.

The Lewis sea transgressed into the northeast part of Wind River Basin, beginning in early Maastrichtian time during deposition of the Teapot Sandstone Member of the Mesaverde Formation. The Meeteetse Formation, which overlies the Teapot, was deposited in a poorly-drained coastal plain setting southwest of the Lewis seaway. The Lewis seaway, at maximum transgression, covered much of the northeast half of the Wind River Basin area but was clearly deflected around the present site of the Wind River Range, southwest of the basin, providing the first direct evidence of Laramide uplift on that range.

Uplift of the Wind River Range continued during deposition of the overlying Maastrichtian Lance Formation. The Granite Mountains south of the basin also became a positive feature during this time. A rapidly subsiding trough during the Maastrichtian time formed near the present-day trough of the Wind River Basin in which more than 6,000 feet of Lance was deposited. The development of this trough appears to have begun before the adjacent Owl Creek Mountains to the north started to rise; however, a muddy facies in the upper part of Lance in the deep subsurface, just to the south, might be interpreted to indicate that the Cretaceous Cody Shale was being eroded off a rising Owl Creek Mountains in latest Cretaceous time.

The Paleocene Fort Union Formation unconformably overlies older units but with only slight angular discordance around much of the margins of the Wind River Basin. Pre-Fort Union erosion was most pronounced toward the Wind River Range to the southwest, where the Fort Union ultimately overlies strata as old as the upper part of the Cretaceous Cody Shale. The unconformity appears to die out toward the basin center. Coal-forming mires developed throughout the western part of the basin near the beginning of the Paleocene. River systems entering the basin from the Wind River Range to the southwest and the Granite Mountains to the south produced areas of sandy fluvial deposition along mountain fronts. A major river system appears to have entered the basin from about the same spot along the Wind River Range throughout much of the Paleocene, probably because it became incised and could not migrate laterally. The muddy floodplain facies that developed along the deep basin trough during latest Cretaceous time, expanded during the early part of the Paleocene. Coal-forming mires that characterize part of the lower Fort Union Formation reached maximum extent near the beginning of the late Paleocene and just prior to the initial transgression of Lake Waltman.

From the time of initial flooding, Lake Waltman expanded rapidly, drowning the coal-forming mires in the central part of the basin and spreading to near basin margins. Outcrop studies along the south margin of the basin document that once maximum transgression was reached, the lake was rapidly pushed basinward and replaced by fluvial environments.

Introduction

The Wind River Basin is a large structural depression formed during the Laramide orogeny in latest Cretaceous, Paleocene, and early Eocene time as the Rocky Mountain foreland basin, an extensive area of crustal downwarping stretching from the Arctic to the Gulf of Mexico, was gradually partitioned into much smaller basins by rising Laramide uplifts. Adjacent mountain ranges and anticlinal uplifts include the Wind River Range on the west, Owl Creek and southern Bighorn Mountains on the north, the Casper arch on the east, and Granite Mountains on the south (figs. 1 and 2).

Sedimentary strata dip 10º-20º basinward along the south and west margins of the basin; whereas, along the north and east margins the dips are commonly vertical to overturned. The basin floor is 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 (figs. 1, and 2). The basin interior is covered by nearly flat-lying lower Eocene rocks, that mask the structural features of the older rocks except along the mountain flanks and adjacent basin margins.

This paper summarizes stratigraphic investigations of Upper Cretaceous and lower Tertiary rocks in the Wind River Basin conducted primarily by the U.S. Geological Survey (USGS) beginning in 1990 and carried on intermittently until 2005. This work built on previous work by the USGS that began in the 1940s. During the early 1990s, these efforts were supported by (1) a Bureau of Indian Affairs (BIA)-funded project, administered by the Joint Business Council of the Shoshone and Arapahoe Tribes, to assess coalbed methane resources of the Wind River Indian Reservation; and (2) by a U.S. Department of Energy-funded project to characterize the basin-centered tight gas accumulation in Upper Cretaceous and lower Tertiary Rocks in the basin. Minor work was continued in the late 1990s under a USGS project to assess coal resources in Tertiary rocks in Rocky Mountain basins, and work was resumed in 2004 under the USGS National Oil and Gas Assessment Project.

Detailed measured sections, stratigraphic cross sections, and paleogeographic reconstructions for the interval from the base of the Upper Cretaceous Mesaverde Formation to the base of the Waltman Shale Member of Paleocene Fort Union Formation (fig. 3) are presented in this report. Similar studies of the Waltman Shale and younger rocks are discussed by Roberts and others (Chapter 5, this CD-ROM), and strata below the Mesaverde are discussed by Finn (Chapter 9, this CD-ROM and Kirschbaum and others (Chapter 3, this CD ROM). A detailed description of the structural development of the Wind River Basin also is presented in a report by Johnson and others (Chapter 4, this CD-ROM).

Many of the detailed measured sections (pls. 1, and 2) and accompanying descriptions presented here were published previously in a U.S. Geological Survey Open-File Report (Johnson and others, 1996), but newly measured sections at Castle Gardens and Coalbank Hills, along the south margin of the basin, also are included. The Castle Gardens section extends from the upper part of the sandy member of the Upper Cretaceous Cody Shale to the upper part of the Paleocene Fort Union Formation. Although the Fort Union strata had been previously measured—and dated using palynomorphs—by Flores and others (1992; 1994) and Nichols and Flores (1993), that part of the section was remeasured to obtain specific data for use in assessing the oil and gas resources of the Wind River Basin. However, a slightly different traverse was used, along which a thin tongue of Waltman Shale Member of the Fort Union Formation was discovered (pl. 1) that was not observed in previous studies. Of limited extent—the tongue is truncated beneath overlying fluvial sandstones a short distance in both directions. This indicated a broader extent of the late Paleocene Lake Waltman than earlier thought, the importance of which is discussed in a later section.

Two east-west cross sections (pls. 3, and 4) and two north-south cross sections in the western part of the basin (pls. 5, and 6) show lithologies and correlations of the Upper Cretaceous Mesaverde Formation and younger strata. Other cross sections by Finn (Chapter 9, this CD-ROM), were used to help construct some of the maps presented in this report. The lines of section for two east-west cross sections are similar to those of Keefer (1997, his A-A' and B-B') but the datum used is the base of the Waltman Shale Member of the Fort Union Formation and marginal lacustrine equivalents rather than the top of the Teapot Sandstone Member of the Upper Cretaceous Mesaverde Formation. Line of section for north-south cross section C-C' (pl. 5) is similar to Keefer and Johnson (1997, their C-C'); whereas, that for D-D' is new to this report but incorporates some of the same drill holes used in Keefer and Johnson (1997, their cross sections A-A' and B-B'). In addition, stratigraphic units have been subdivided into environments of deposition.

Correlations in marginal areas of the basin on the cross sections presented were modified from those of Keefer (1997) and Keefer and Johnson (1997) on the basis of new outcrop and subsurface studies showing that (1) Lake Waltman extended much farther toward the margins of the basin than previously thought, and (2) the lake transgressed rapidly into the marginal areas of the basin earlier. Lacustrine deltaic sequences deposited by Lake Waltman were identified by Keefer and Johnson (1997, their cross sections B-B' and C-C') in the western part of the basin and west of the pinchout of the Waltman Shale, but Keefer and Johnson (1997) interpreted the deltas to have been deposited much later in the history of Lake Waltman than the initial transgression.

Finding an approximate time line such as the base of Lake Waltman lacustrine rocks and equivalents in the largely homogeneous nonmarine Upper Cretaceous and Paleocene sequence was critical in the western part of the basin because most wells are not deep enough to penetrate the Teapot Sandstone Member of the Mesaverde Formation, which had previously been used as a stratigraphic cross section datum (Keefer, 1997). Using the base of Lake Waltman lacustrine rocks as a time line significantly changed regional correlation, and necessitated the redrawing of previously published isopach maps particularly of the lower member of the Paleocene Fort Union Formation below the Waltman Shale and the underlying Upper Cretaceous Lance Formation (Johnson and others, 1996). As a result, new paleogeographic reconstructions for five-time intervals in the interval below the Waltman Shale and marginal lacustrine equivalents were constructed: (1) lower part of the Meeteetse Formation, (2) upper part of the Meeteetse Formation-lower part of the Lance Formation, (3) lower part of the Lance Formation, (4) lower part of lower unnamed member of the Fort Union Formation, and (5) uppermost part of the lower unnamed member.

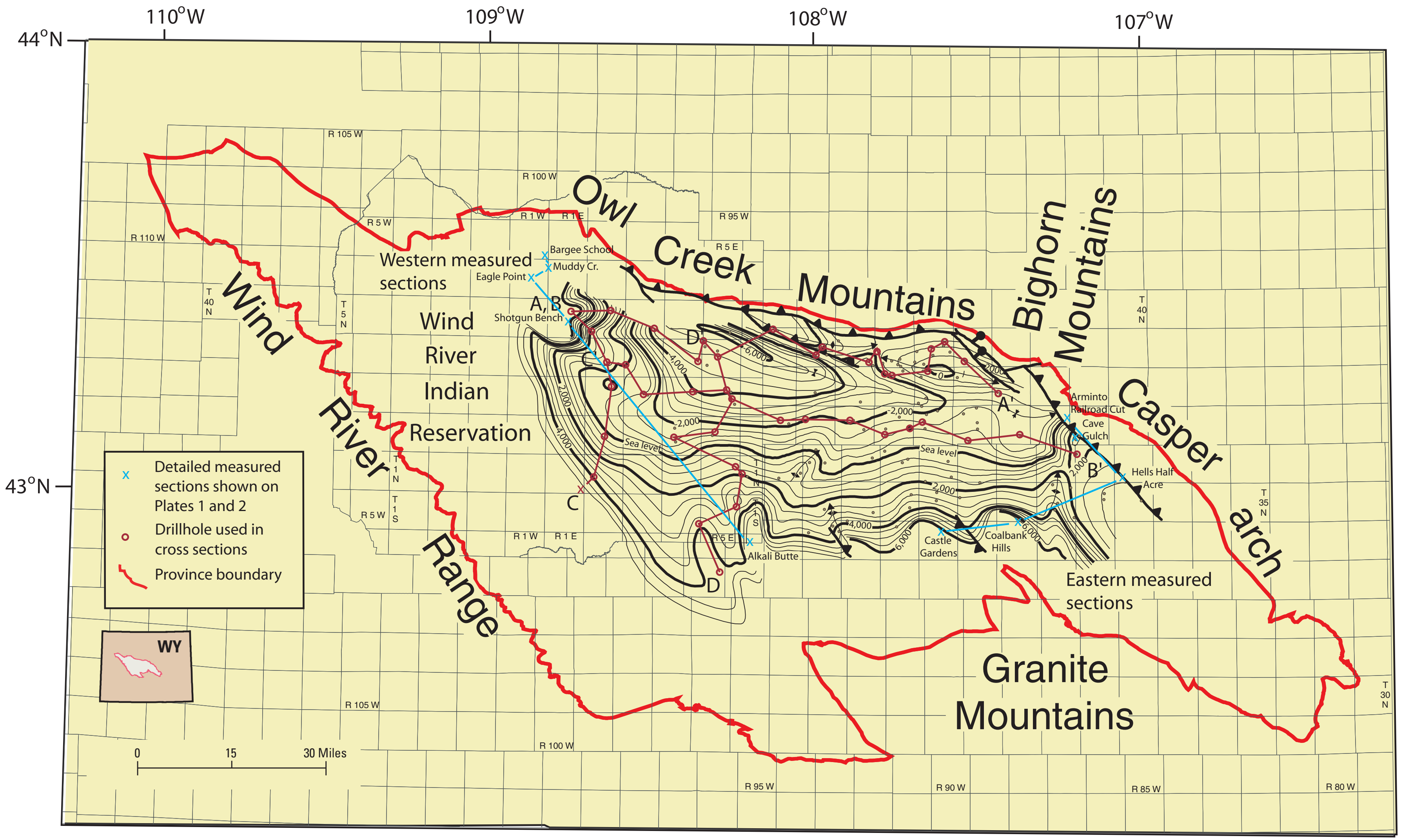

Figure 1. Map of Wind River Basin Province (outline in red) showing surrounding uplifts, and locations of cross sections. Structure contours drawn on base of Waltman Shale Member of Paleocene Fort Union Formation. Contour interval: 500 feet.

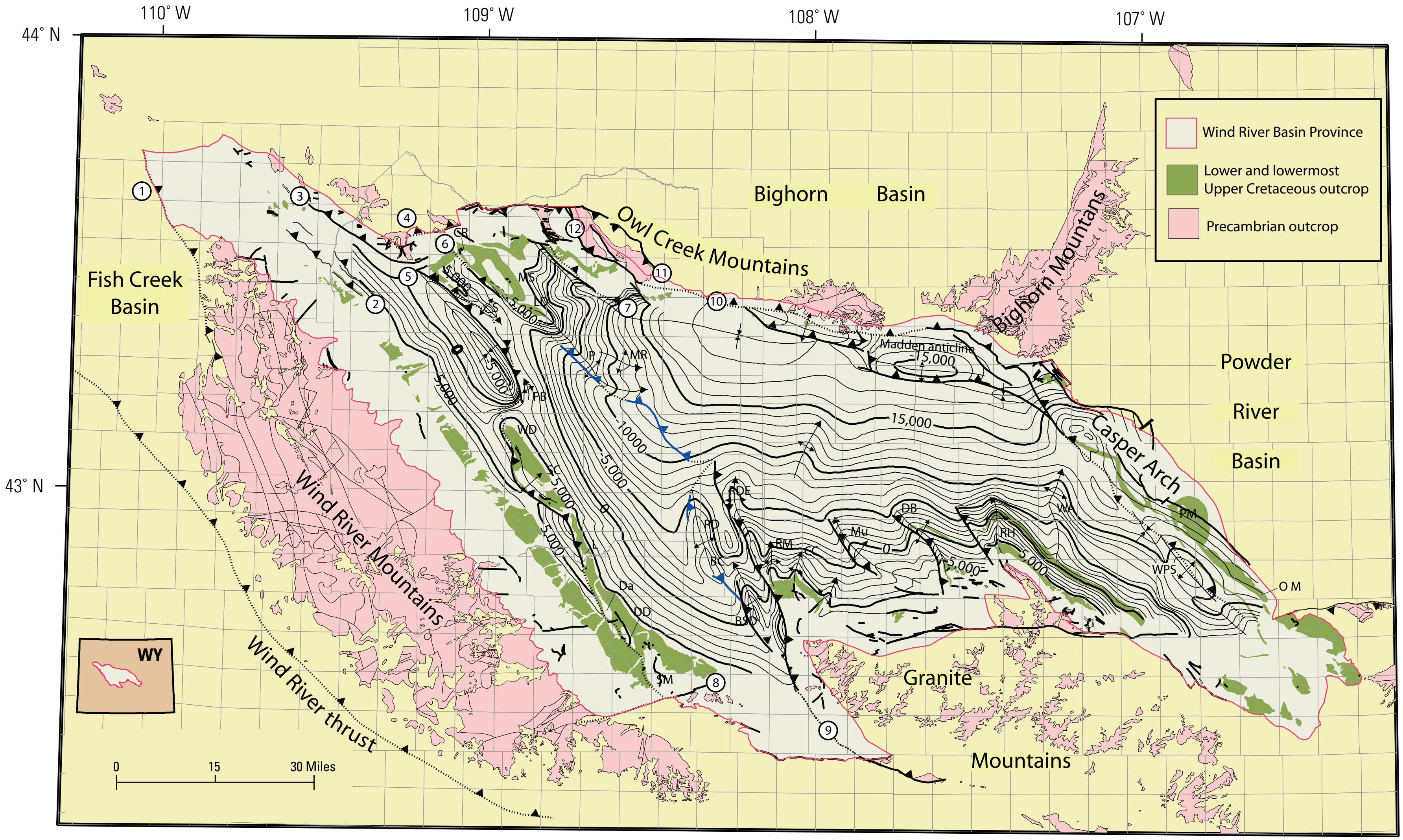

Figure 2. Generalized tectonic map of the Wind River Basin Province and adjoining areas showing major faults and anticlines. Structure contours drawn on the top of the Upper Cretaceous Frontier Formation are modified from Johnson and others (1996). [All structures are from Love and Christiansen (1985), unless otherwise stated, and are shown in black; dashed where inferred in subsurface.] 1) White Rock thrust; 2) Wind Ridge and Coulee Mesa thrust system; 3) Black Mountain thrust; 4) Red Creek thrust (see Blackstone, 1990); 5) Rolff Lake fault; 6) Circle Ridge/Maverick Springs thrust; 7) Shotgun Butte thrust; 8) Clear Creek fault; 9) Emigrant Trail fault; 10) south Owl Creek fault; 11) north Owl Creek fault; 12) Cottonwood Creek fault. Anticlines are abbreviated: BC, Beaver Creek, BSD, Big Sand Draw; CC, Conant Creek; CR, Circle Ridge; Da, Dallas; DB, Dutton Basin; DD, Derby Dome; L, Lander; LD, Little Dome; MS, Maverick Springs; Mu, Muskrat; MR, Muddy Ridge; OM, Oil Mountain; P, Pavillion; PB, Pilot Butte; PM, Pine Mountain; RD, Riverton Dome; RDE, Riverton Dome East, RH, Rattlesnake Hills; RM, Rogers Mountain; S, Sheldon; SC, Sage Creek; SM, Sheep Mountain; WA, Waltman arch; WD, Winkleman Dome; WPS, West Poison Spider.

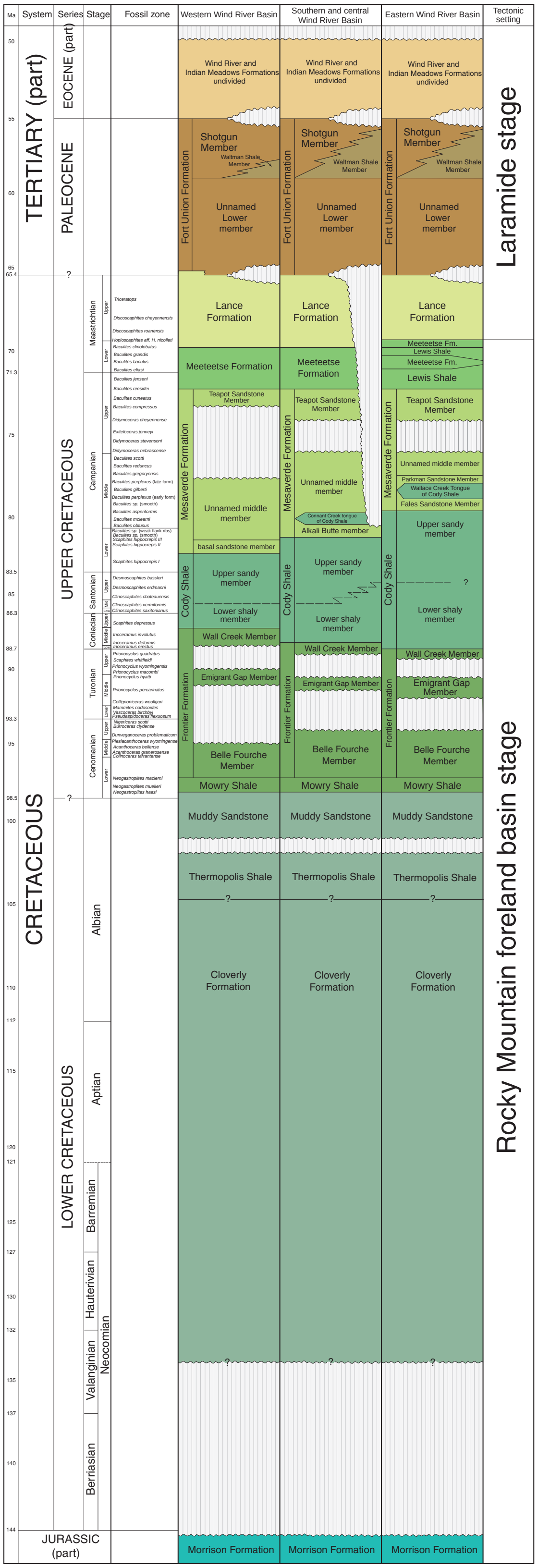

Figure 3. Generalized correlation chart for Jurassic Morrison Formation through Eocene Indian Meadows and Wind River Formations in the Wind River Basin, Wyoming. From Finn (Chapter 9, this CD-ROM). Click on image to view and print full size.

Stratigraphy of the Mesaverde Formation

The Mesaverde Formation in the Wind River Basin is a highly variable sequence of sandstone, siltstone, shale, carbonaceous shale, and coal that was deposited along the western margin of the Upper Cretaceous interior seaway as the seaway gradually receded eastward across central Wyoming in Late Cretaceous (Campanian) time and during the early stages of the Lewis transgression into central Wyoming in latest Cretaceous time. The formation thins eastward from more than 2,200 feet (ft) in the northwestern corner of the basin to less than 500 ft in the southeastern corner as the lower part progressively grades eastward into underlying marine Cody Shale (fig. 4). The Mesaverde can generally be subdivided into three parts: (1) a lower part consisting of marginal marine rocks deposited as the seaway receded across the area, (2) a middle nonmarine part that was deposited in coastal plain and fluvial setting once the seaway had retreated to the east, and (3) an upper part deposited in a highly sandy fluvial environment in the southwestern half of the basin and in fluvial and marginal marine settings in the northeastern half that was in part deposited during the Lewis transgression (fig. 3). The lower, marginal marine part is informally referred to as the basal sandstone member in the western part of the basin (Keefer, 1997; Keefer and Johnson, 1997) and the Parkman Sandstone Member in the eastern part (Rich, 1958). The Mesaverde intertongues with the underlying Cody Shale in some areas, and two major tongues, the “Alkali Butte member” and the Fales Sandstone Member, are recognized. The middle nonmarine part is generally called the middle member (Rich, 1958; Keefer, 1972), and the name Teapot Sandstone Member has been assigned to the upper part (Hares, 1916; 1946).

Mesaverde Tongues

The “Alkali Butte member” and the Fales Sandstone Member in the lower part of the Mesaverde Formation are separated from the main body of the formation by tongues of Cody Shale (fig. 3). By far the thickest tongue of the Mesaverde is the Alkali Butte member, which was informally named by Hogle and Jones (1991) for an interval as much as 1,000 ft thick in the west-central part of the basin. Alkali Butte member is just east of, and laterally equivalent to, the 1,200-ft-thick interval of marginal marine sandstones in the lower part of the Mesaverde that can be observed in exposures at Alkali Butte (fig. 5) and in wells northward across the basin. It is overlain by a marine shale as thick as 500 ft that was informally called the “Conant Creek tongue” of the Cody Shale (Szmajter, 1993). Conant Creek tongue, to the west, wedges out and Alkali Butte member merges with the main body of the Mesaverde Formation along a generally north-

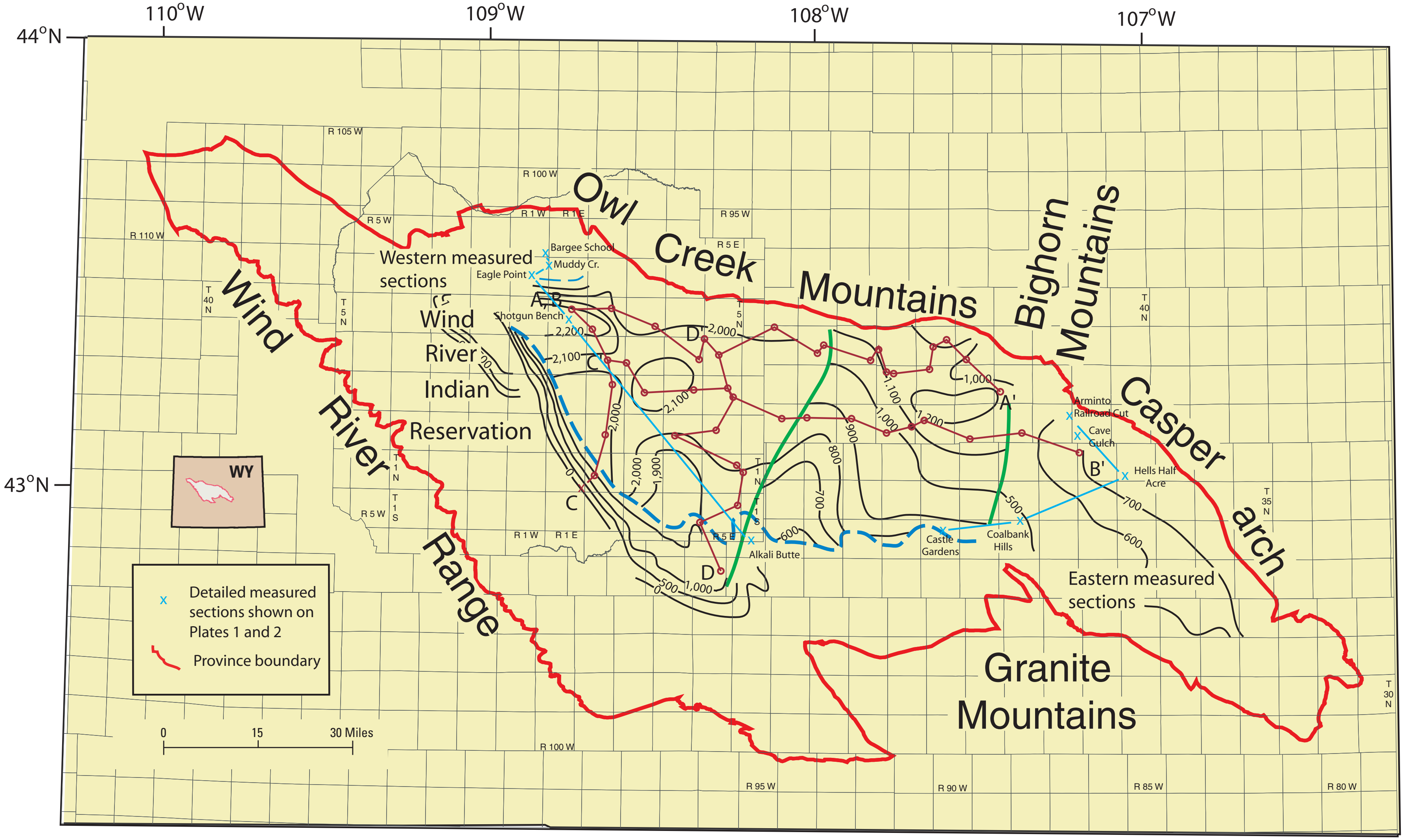

Figure 4. Isopach map of the Upper Cretaceous Mesaverde Formation, Wind River Basin, Wyoming. The Mesaverde is partially to completely truncated beneath younger units along the south margin of the basin, south of dashed blue line. The map does not include the "Alkali Butte member" in the west-central part or the Fales Sandstone Member in the eastern part. The heavy green lines represent the western limits of these two members. Modified from Johnson and others (1996). Contour interval: 100 feet.

northeast trend near the eastern margin of the Wind River Reservation (fig. 5). The unit pinches out to the east into a sandy zone in the upper sandy member of the Cody Shale (fig. 3) (see Finn, Chapter 9, this CD-ROM, his cross section B-B'). Herrero Fernandez (2000) presented evidence that these Mesaverde tongues were deposited during periods when base level dropped and deep valleys were incised in the nonmarine part of the Mesaverde to the west. Yenne and Pipiringos (1954, their 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 Alkali Butte member and Conant Creek tongue described here.

A thinner tongue of the Mesaverde Formation, the Fales Sandstone Member, is present in the eastern part of the basin (figs. 2, 5, and pl. 2). This tongue, which is as much as 350 ft thick, was originally named the Phayles Reef Member of the Mesaverde Formation by Barwin (1959; 1961a). Fales Sandstone 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, 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 *perplexus* zones of the Upper Cretaceous upper Campanian (Keefer, 1972, table 2). The Fales Sandstone Member was first studied in detail by Barwin (1959; 1961a; 1961b) who recognized three facies—in ascending order, littoral and nearshore marine, coastal swamp, and lagoonal. The basal marine sandstone is described by Barwin (unpub. master's thesis 1961a; 1961b) as weakly bedded but locally cross-bedded in the upper part. At the type section, in the Rattlesnake Hills (sec. 4, T. 33 N., R. 87 W., fig. 2), 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 (J.R. Barwin, unpub. master's thesis 1961a, p. 23). The upper lagoonal facies includes thin coquina beds with brackish-water pelecypods. According to J.R. Barwin (unpub. master's thesis 1961, p. 25), only the basal marine sandstone is present east of the type locality. A titanium-rich black sandstone deposit, as much as 5 ft thick, was described by J.R. Barwin (unpub. master's thesis 1961, p. 23) in the uppermost part of the basal marine sandstone in the Coalbank Hills (sec. 5, T. 34 N., R. 88 W., fig. 1). This sandstone, which also was studied by Houston and Murphy (1977), was traced into the Coalbank Hills measured section that is described in a later section. 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; unpub. master's thesis 1961), consists entirely of marine rocks.

Finn (1993), 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 east margin of the basin. The basal marine sandstone as defined by Finn (1993) and further refined by Finn (Chapter 9, this CD-ROM) is an interval of marginal marine sandstones as much 200 ft thick with individual sandstones as much as 107 ft thick.

Detailed Measured Sections of Fales Sandstone Member

Detailed sections of the Fales Sandstone Member were measured at two localities: (1) along a railroad cut east of Arminto (sec. 13, T. 37 N., R. 87 W.; fig. 1; pl. 2), and (2) Coalbank Hills near the titaniferous sandstone locality (sec. 5, T. 34 N., R. 88 W.; fig. 1, pl. 2). In addition, a section containing the probable equivalent of the Fales was examined at the Castle Gardens locality (fig. 1).

Cave Gulch Area

In the Arminto railroad cut (fig. 4), the Fales consists of a 34-ft-thick, horizontally bedded, in part trough-cross bedded, sandstone with carbonaceous and coaly laminae in the upper 4 ft (pl. 2). Above this unit is 35 ft of carbonaceous shale with coal beds as much as 2 ft thick overlain by an interbedded sequence of gray shale, siltstone, and sandstone with bioturbated zones and bivalves.

Coalbank Hills

In the Coalbank Hills section (fig. 4), the Fales, 355 ft thick, includes sandstones as much as 45 ft thick interbedded with carbonaceous shale. Many of the sandstones contain hummocky cross strata and low-angle cross bedding, and *Ophiomorpha* burrows that indicate a probable marginal marine in origin. One of the sandstones was rooted at the top and overlain by carbonaceous shale. The black titaniferous sandstone, described by J.R. Barwin (unpub. master's thesis 1961), was not present along the line of section but is present a short distance to the west where it was traced into the upper part of the sandstone in the interval 740 to 776 ft on the measured section, near the base of the Fales (pl. 2).

Castle Gardens

Correlation of the Fales Sandstone Member westward along the south margin of the basin from Coalbank Hills into the Castle Garden area is problematical. The Mesaverde Formation is not exposed continuously between the two areas, thus the Fales cannot be mapped with certainty. Although a highly sandy interval is present at Castle Gardens in approximately the stratigraphic position of the Fales, how this unit relates to the Fales is unclear (fig. 1, and pl. 2). The

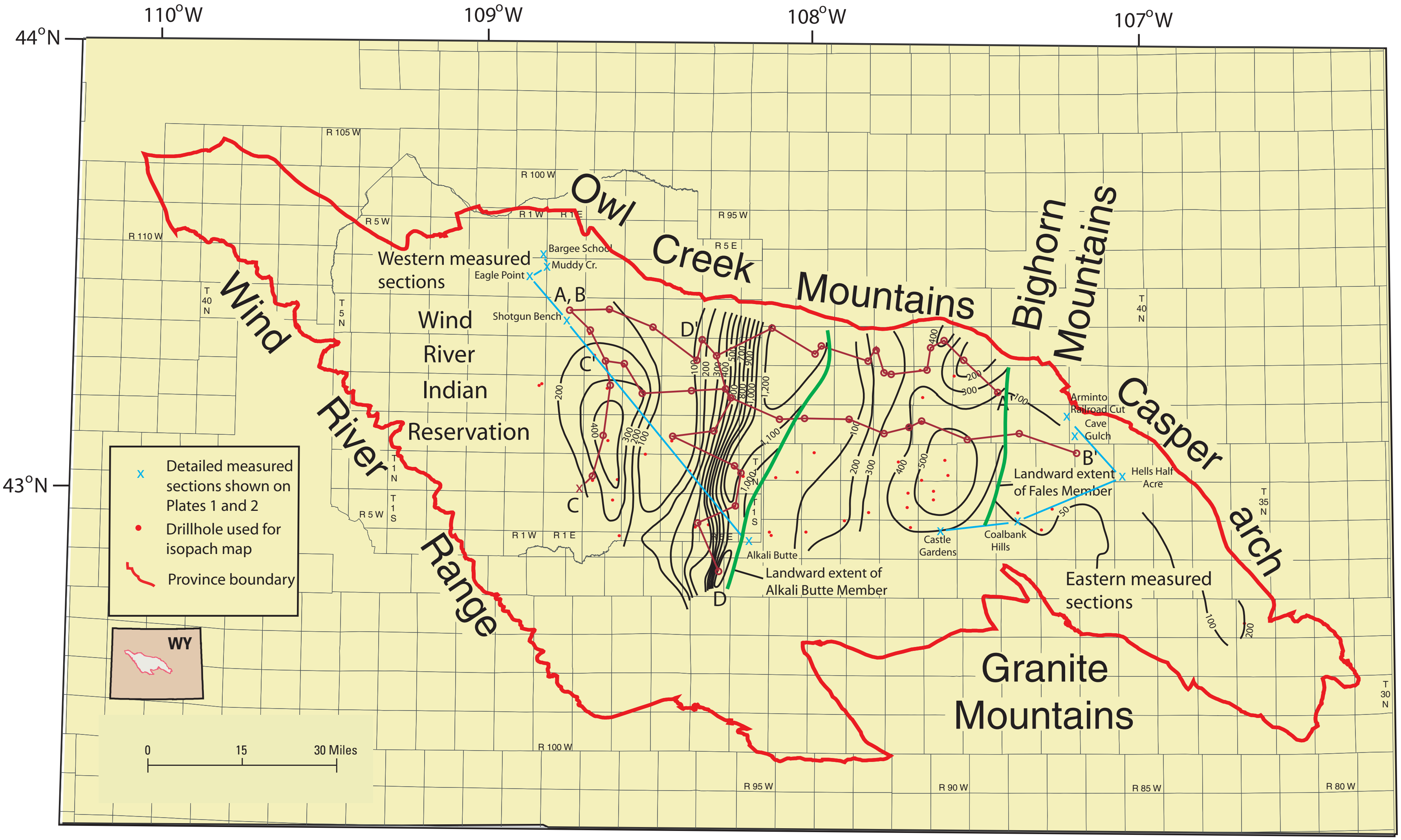

Figure 5. Isopach map of the marginal marine interval in the lower part of the Upper Cretaceous Mesaverde Formation. The map does not include the "Alkali Butte member" in the west-central part or the Fales Sandstone Member in the eastern part. The heavy green lines represent the western limits of these two members. Modified from Johnson and others (1996). Contour interval is 100 feet except in the eastern part of the basin where a 50-ft contour is included.

interval is 185 ft thick and consists of mainly very-fine to fine-grained sandstone with hummocky and low-angle cross strata.

Lower, Marginal Marine Part of the Mesaverde Formation

Sandstones in the lower marginal marine part commonly have sedimentary structures characteristic of shoreface sequences or partial shoreface sequences, including hummocky cross strata, low-angle cross strata, trough-cross strata, and *Ophiomorpha* burrows; one or two such sandstones are present throughout most of the basin. However, near the eastern boundary of the Wind River Indian Reservation in the western part of the basin, marginal marine sandstones as well as some fluvial channel and crevasse splay sandstones form an interval as much as 1,200 ft thick along a north-northeast trend where the shoreline oscillated within a 15-to 20-mile-wide zone for an extended period of time during an eastward retreat (fig. 5). Individual marginal marine sandstone units along this trend can commonly be traced in the subsurface between wells many miles apart in a north-south direction; whereas, correlation in an east-west direction between wells as little as a mile or two apart is generally difficult. The base of this thick 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, near the southeast corner of the Wind River Indian Reservation, by Yenne and Pipiringos (1954, their section no. 8).

Abundant coal is interbedded with these marginal marine sandstones; total coal thicknesses of as much as 124 ft of coal (fig. 6), by far the greatest total coal thickness for the Mesaverde Formation in the basin. West of this thick sandstone buildup, the total coal thickness decreases to between 20 and 60 ft, and to the east, total coal thicknesses are generally less than 20 ft. Individual coal beds appear to be generally continuous in a north-south direction or roughly parallel to the paleoshoreline and can commonly be traced between closely spaced wells aligned north-south as demonstrated by Keefer and Johnson (1993, p. 77) in their correlation of coal beds between two wells 5 miles apart. The coals were mined in the past where 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). This thick coal accumulation in the Wind River Basin 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 (Johnson and others 1996, fig. 66).

Detailed Measured Sections of Lower Marginal Marine Part

The marginal marine part of the Mesaverde Formation was described at (1) four localities near Shotgun Butte in the northwest part of the basin—Bargee School, Muddy Creek, Eagle Point, and Shotgun Bench (Johnson and Clark, 1993); (2) Alkali Butte in the southwest corner of the Wind River Indian Reservation (Johnson and others, 1996); (3) Castle Gardens (new section) and Coalbank Hills (Johnson and others, 1996) along the south margin of the basin; and (4) at Arminto railroad cut in the Cave Gulch area (Johnson and others, 1996) (fig. 1, pls. 1 and 2).

Shotgun Butte Area

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 (fig. 1, and pl. 1). The unit, which contains trough-cross, horizontal, and low-angle bar accretion bedding, was interpreted by Johnson and Clark (1993) as a shoreface sandstone. This sandstone is everywhere overlain by carbonaceous shale, coal beds, and channel sandstones of probable fluvial origin. A 74-ft-thick interval containing numerous channel features from 10 to 20 ft thick is present below the shoreface sandstone at the Muddy Creek section (pl. 1). These channel sandstones, which have mainly horizontal strata and contain basal lag deposits of siltstone and mudstone blocks as much as 6 ft across, were interpreted by Johnson and Clark (1993) as possible storm-surge channels.

Alkali Butte

The lower 646 ft of the thick buildup of marginal marine sandstones near the east boundary of the Wind River Indian Reservation is exposed at Alkali Butte (fig. 1, and pl. 1), where the upper part is truncated beneath the Paleocene Fort Union Formation. The section is dominated by thick (24 to 115 ft), relatively clean, very fine-to fine-grained sandstones of probable marginal marine origin. The sandstones are relatively persistent and several were traced along outcrop for about 1.2 miles to the southeast. These sandstones exhibit horizontal strata and low-angle cross strata for the most part, but some hummocky cross strata also are present. The sandstones are interbedded mainly with carbonaceous shale and coal beds as much as 8.5 ft thick (1,279 to 1,287.5 ft on measured section, pl. 1). An elongated body of carbonaceous shale 15 ft long and 1.5 ft thick is encased within one of the marginal marine sandstones (993 ft of the measured section, pl. 1); This shale 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 are in some of the carbonaceous shale and

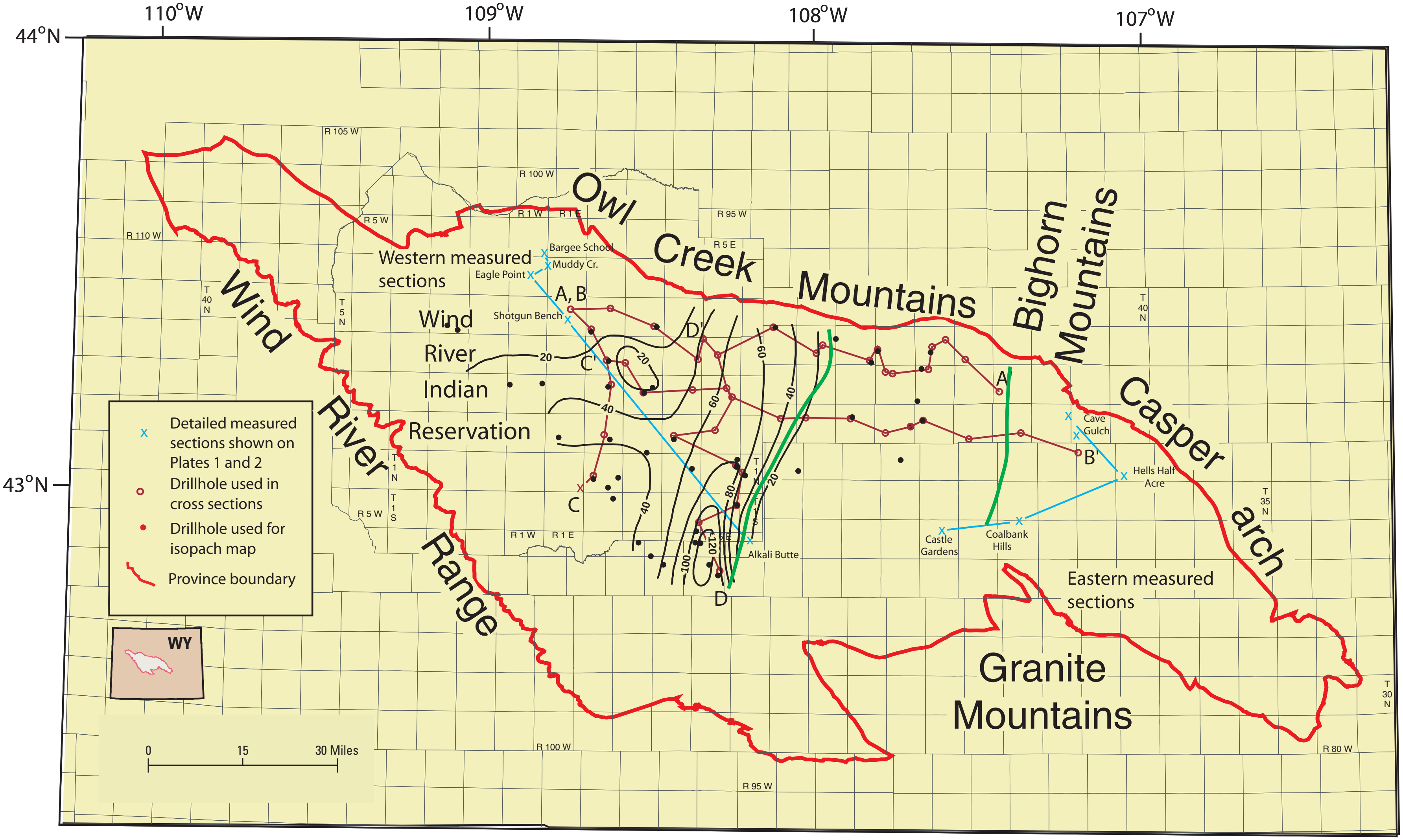

Figure 6. Isopach map of total coal in beds 2 feet thick or greater in the Upper Cretaceous Mesaverde Formation. Western limits of the "Alkali Butte member" and the Fales Sandstone Member are shown as heavy green lines. Drillholes used for control are shown as gray dots. Modified from Johnson and others (1996). Contour interval is 20 feet.

coal intervals. These were the only channel-form sandstones observed in the section. Oyster beds are present in one of these channel intervals near the base of the marginal marine interval (895 to 906 ft on the measured section, pl. 1). Both channel sandstones and associated oyster beds lie directly above a carbonaceous interval and below a thick sandstone of probable shoreface origin. Patchy dead oil is in one of the sandstones near the base of the interval (fig. 7), and dead oil was observed at several other outcrops nearby.

Cave Gulch Area

At the Arminto railroad cut (fig. 1, and pl. 2), the name Parkman Sandstone Member of the Mesaverde Formation is applied to a single 76-ft-thick marginal marine sandstone at the base of the main body of the Mesaverde Formation. This sandstone is in sharp contact with the underlying interbedded sandstone and shale of the Wallace Creek Tongue of the Cody Shale. The Parkman contains pelecypods near the base, is horizontally bedded, and has low-angle cross strata throughout all but the upper 7 ft where trough-cross strata to 3 ft high form the dominant sedimentary structures. Large-scale low-angle cross strata were observed in the upper part. The Parkman is overlain by carbonaceous shale and interbedded sandstone and gray shale.

Coalbank Hills

At Coalbank Hills (fig. 1, pl. 2), the marginal marine interval also is called the Parkman Sandstone Member and consists of a single 43-ft-thick shoreface sandstone with large-scale trough-cross bedding and hummocky cross strata. The Parkman is overlain by carbonaceous shale and is separated from the underlying Fales Sandstone Member of the Mesaverde Formation by 45 ft of poorly exposed Wallace Creek Tongue of the Cody Shale.

Castle Gardens

Correlation of the marginal marine interval westward from Coalbank Hills into Castle Gardens along the south margin of the basin is uncertain, as the basal sandstone of the Mesaverde at Castle Gardens cannot be reliably correlated

Figure 7. Marginal marine sandstone of the Mesaverde Formation saturated with bitumen or “dead oil” at 915 feet of the Alkali Butte measured section (pl. 1).

directly with the Parkman farther to the east. This basal sandstone, which is, however, tentatively assigned the name Parkman, is 85 ft-thick, very fine to fine grained, and displays hummocky cross strata, trough-cross bedding and low-angle bar accretion bedding (pl. 2).

Middle Member of the Mesaverde Formation

The middle member consists of interbedded sandstone, siltstone, shale, carbonaceous shale, and coal that accumulated in nonmarine, largely fluvial depositional environments. The sandstones typically display characteristics of having originated as flood plain, stream channel, and crevasse splay deposits. Individual channel sandstones are highly lenticular and can be traced only short distances laterally, but are commonly stacked or amalgamated into complex units as much as 100 ft thick. Shale units, many of which are 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. Coal beds are present at various horizons, but most commonly near the base where these beds probably represent coastal swamp and delta plain deposits on top of and interbedded with the marginal marine interval of the Mesaverde.

Detailed Measured Sections of Middle Member

The middle member of the Mesaverde Formation was described in detail at (1) Bargee School, Muddy Creek, Eagle Point, Shotgun Bench, and Alkali Butte in the western part of the basin (Johnson and Clark, 1993; Johnson and others, 1996) (fig 1, and pl. 1), (2) Castle Gardens (new section) and Coalbank Hills along the south margin of the basin (Johnson and others, 1996); and (3) the Arminto railroad cut in the Cave Gulch area, in the northeast part of the basin (Johnson and others, 1996) (fig. 1, pl. 2).

Bargee School

A 55-ft-thick, very fine-to fine-grained sandstone, containing several scoured surfaces overlain by clayey-ripup clast zones, is present a short distance above the top of the marginal marine sandstone interval (fig. 1, and pl. 1). This complex fluvial sandstone, which consists of two or possibly more individual fluvial channels, displays horizontal strata, climbing-ripple laminae, and trough-cross strata as much as 2 ft high; most trough-cross strata appear to trend about N. 65^{o} E. The unit pinches out along outcrop and is not present at the Muddy Creek section, 2.5 miles to the south-southeast

The remaining part of the middle member contains erosionally-based fluvial channel sandstones and much thinner sandstones of probable crevasse splay origin. Fluvial channel sandstones are about 10 to 20 ft thick, very fine to medium grained, and have horizontal strata, climbing ripples, and trough-cross strata to about 2 ft in height and are present in the intervals from 311 to 435 ft and from 538 to 560 ft on the measured section (pl. 1). Lateral accretion units, with mudstone and siltstone drapes, were observed in two of the sandstones suggesting that these sandstones were deposited by mixed load moderate to high sinuosity streams. Crevasse splay sandstones are from about 1 to 8 ft thick, and consist of small-scale trough-cross strata and climbing ripple laminations.

Seven coal beds from 0.5 to 2 ft thick are present in the Bargee School section. These coal beds are generally somewhat dirty and contain carbonaceous shale partings. Three of the beds are overlain by crevasse splay sandstones, two by channel sandstones, and two by carbonaceous shale.

Muddy Creek

The middle member is 1,321 ft thick at Muddy Creek (fig. 1 pl. 1), 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, are in this coal-bearing interval; these channel sandstones appear to be single channels, and display well-developed lateral accretion. Sandstones of probable crevasse-splay origin also are present; these beds are as much as 4.5 ft thick, fairly persistent laterally, and have small trough-cross beds and climbing ripple laminations.

The upper part of the member contains fluvial channel sandstones as much as 46 ft thick and two thin coal beds. The sandstones have scour bases, and several contain one or more scour surfaces above the base. Lateral accretion was observed in two bases. Thinner sandstones of probable crevasse splay origin are scattered throughout the section. In total, the middle member at Muddy Creek contains 15 fluvial channel sandstones 10 ft or more thick for a total sandstone thickness of 436 ft. All of the individual channel sandstones and coal beds in this section pinch out before reaching the Bargee School section about 2 miles to the north.

Eagle Point

Several multistory sandstone bodies with scour surfaces and associated clayey-ripup clasts are present in the 345 ft of section measured above the marginal marine sandstone interval of the Mesavede Formation (fig. 1, and pl. 1). 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 ft on measured section). Deformed laminations, interpreted as fluid escape structures, are common in this unit.

A second section at Eagle Point was measured 400 ft to the southwest to study the local variability in the fluvial sandstones. Only 185 ft of the middle member is exposed at the second locality (pl. 1). Two 0.4-ft-thick coals in the interval just above the base were not observed in the first Eagle Point section, possibly because of poor exposures. 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 at the second Eagle Point section (pl. 1, fig. 8). The exact relation 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 relatively poor exposures in an intervening gully. Basal lag deposits consisting of angular ripup clasts of coal, sandstone, siltstone, and mudstone as much as several feet across are in zones as much as 10 ft thick in the 64-ft-thick sandstone at the second locality. This sandstone has horizontal beds and trough-cross strata to as much as 2 ft high and is not highly contorted. This sandstone does not contain two coal beds that were observed in the same stratigraphic interval at the first Eagle Point section (pl. 1), but the presence of large coal ripup clasts in lag deposits may indicate that the peat accumulations, if originally there, were channeled out.

Shotgun Bench

The middle member at Shotgun Bench is 1,902 ft thick (fig. 1, and pl. 1). This member contains 19 sandstones 10 ft or more thick for a total thickness of 418 ft. Average bed thickness is 22 ft, and the maximum thickness observed was 45 ft. The member here can be generally divided into three zones—in ascending order, a coal-bearing interval 390 ft thick (215 to 605 ft on the plotted section, pl. 1), a 475-ft-thick sandy interval with abundant fluvial channel sandstones (605 to 1,080 ft), and an upper zone 1,037 ft thick with few fluvial channels (1,080 to 2,117 ft). No attempt was made to trace these zones laterally and, with the exception of the coaly zone above the basal marginal marine interval, these zones cannot be identified in the other measured sections in the area.

Nine coal beds from 0.5 to 2.0 ft thick are in the 390-ft-thick coal-bearing interval. Sandstones in this interval are mainly thin tabular beds interpreted as crevasse splays ranging

Figure 8. Complex stack of fluvial sandstones with several highly irregular zones of ripup clasts (outlined with dashed lines) in the nonmarine interval of the Upper Cretaceous Mesaverde Formation at the second Eagle Point measured section (pl. 1). Note 6-foot person (arrow).

from about 0.6 to 5.0 ft thick, with climbing ripple laminations and trough-cross strata as much as 1 ft high. Only four or possibly five fluvial channel sandstones, ranging from 4 to 25 ft thick, are in the coal-bearing interval. Well-developed lateral accretion, marked by mud drapes, can be observed in two of these sandstones, indicating deposition in moderate to high sinuosity streams. Sandstones 10 ft or more thick constitute only 15 percent of the rock in the coal-bearing interval.

The overlying sandy interval contains 183 ft of fluvial channel sandstones with only one 0.75 ft thick coal bed. The sandstones are as much as 45 ft thick, and exhibit trough-cross strata as much as 3 ft high, horizontal strata, and ripple-drift laminae. Lateral accretion with mud drapes was observed in three of the sandstones, two of which were only 8 ft and 9 ft thick indicating that some fluvial channels were relatively small and sinuous. A few probable crevasse splay sandstones also are present.

The upper 1,037 ft of the middle member is an alternating sequence of thin, very-fine to fine-grained fluvial channel sandstones and crevasse splay sandstones. Many of the lenticular sandstone bodies are 8 to 10 ft thick; only nine are more than 10 ft thick, and these total 176 ft of the interval, of which 41 ft of this total is a single lenticular sandstone bed near the top. Four thin coal beds, from 3 inches (in.) to 1 ft thick also are present.

Coalbank Hills

The middle member of the Mesaverde Formation is 407 ft thick at Coalbank Hills (fig. 1, and pl. 2). The lower 60 ft is carbonaceous but contains neither coal nor sandstone beds. The remaining 347 ft consists of four fluvial channel sandstones from 10 to 23 ft thick, thin splay sandstones as much as 2 ft thick, and gray mudstone. The channel sandstones, which do not appear to be “stacked” display cross bedding and climbing ripples, and have a combined thickness of 65 ft.

Arminto Railroad Cut

At the Arminto railroad cut, the middle member is 489 ft thick (fig. 1, and pl. 1). A carbonaceous interval is present at the base, but there are no coal beds. Individual channel sandstones vary from about 5 to 38 ft thick. Figure 9 is a photograph that shows an 81-ft-thick complex sequence of sandstones that occupies the interval 698 to 779 ft on the measured section (pl. 1) and contains three discrete sandstones 25 ft, 8 ft, and 35 ft thick, in ascending order. The upper and lower sandstones are mainly trough-cross bedded with multiple minor scour surfaces; the middle includes trough-cross strata and climbing ripples,

Figure 9. Photograph of fluvial channel sandstones in the nonmarine interval of the Upper Cretaceous Mesaverde Formation, Cave Gulch area measured section (pl. 2). This portion of the nearly vertical section was measured in the deep Arminto railroad cut in the overriding block of the Casper arch thrust (see fig. 4 for location). The two thickest sandstones are about 30 to 35 feet thick; up section is to left. The interval extends from about 834-919 feet on the measured section (pl. 2).

Figure 10. Photograph of fluvial channel sandstones in the nonmarine interval of the Upper Cretaceous Mesaverde Formation, Cave Gulch area measured section (pl. 2). This portion of the nearly vertical section was measured in the deep Arminto railroad cut in the overriding block of the Casper arch thrust (see fig. 4 for location). The sandstones are from 5 to 38 ft thick and display well-developed lateral accretion; up section is to left. The interval extends from about 923 to 975 on the measured section (pl. 2). Note 6-foot person for scale.

and a thick mud drape near the top. Figure 10 is a photograph of the upper part of the middle member, representing the interval between about 923 ft to 1,082 ft. Six fluvial channel sandstones from 5 to 38 ft thick are present in this interval; these channel sandstones are highly variable laterally and display well-developed laterally accreting sandstone units separated by mudstones. Six sandstones 10 ft thick or greater compose 160 ft of the total middle member at Arminto.

Castle Gardens

At Castle Gardens, the middle member is 455 ft thick, but only 195 ft is exposed (fig. 1, and pl. 2). A coaly and carbonaceous zone lies above what is considered to be Parkman Sandstone equivalent, with coals as much as 1 ft thick. This zone includes two thin persistent sandstones, 2 and 4 ft thick, that are probably crevasse splays. Two lenticular very fine-to medium-grained channel sandstones or channel sandstone complexes, 44 ft and 50 ft thick, are exposed in the overlying interval. These sandstones display trough-cross bedded and contorted laminae, and the lower one includes several bioturbated and rooted zones.

The Teapot Sandstone Member of the Mesaverde Formation

The Teapot Sandstone Member of the Mesaverde Formation is recognized in both outcrops and drillholes by the distinctive white color and coarser grain size than sandstones in the underlying and overlying units. 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 less than 50 ft in places near the east margin. The member commonly contains a few thin shale, siltstone, and carbonaceous shale beds in the thicker sections, but commonly consists of only a single sandstone unit in the thinner sections. The Teapot is entirely of nonmarine origin in the southwestern part of the basin but includes marginal marine rocks and intertongues with the Lewis Shale in the northeastern part. The contact with the middle member of the Mesaverde is typically sharp, and some investigators consider it to mark a regional disconformity that extends across central Wyoming (Gill and Cobban, 1966; Reynolds, 1966). No direct evidence of a disconformity was observed during the present study, and near the Muddy Creek section described below (pl. 1), the contact appears to be intertonguing.

Detailed Measured Sections of Teapot Sandstone Member

The Teapot Sandstone Member was described in detail at (1) Muddy Creek (Johnson and others, 1996) and Shotgun Bench (Johnson and Clark, 1993) in the western part of the basin, (2) Coalbank Hills (Johnson and others, 1996) and Castle Gardens (new section) in the southern part, and (3) Hells Half Acre and Cave Gulch (Johnson and others, 1996) in the eastern part (fig. 1, and pls. 1 and 2).

Shotgun Bench

The Teapot Sandstone Member at the Shotgun Bench locality is 503 ft thick (fig. 1, and pl. 1). The basal contact is distinct and sharp, with a thick fine-to medium-grained white sandstone overlying a thin very-fine to fine-grained gray sandstone of the middle member. Six prominent sandstones, 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-cross strata as much as 5 ft high and horizontal to subhorizontal strata can be observed, with climbing ripples on some of the trough surfaces. Possible erosion surfaces were observed in some of the sandstones, but with no clayey ripup clasts. One 0.5-to 1-ft-thick nonlaminated calcareous zone that may be paleosoil is within a thick sandstone at 2,444 ft on the plotted section (pl. 1). A distinctive crisscross pattern of tabular-shaped veinlets, as much as 2 in. thick and from about 2-6 in. apart, are present in abundance in many of these sandstones. These veinlets, first described here by Keefer and Troyer (1964), are noncalcareous, more resistant to weathering than the host sandstone, and are at oblique angles to both bedding and the horizontal. A single thin section of one of these veinlets from a somewhat weathered outcrop sample (C. W. Keighin, U.S.G.S. oral comm., 1996) revealed that clay cement is slightly more abundant and the porosity somewhat lower in the veinlet than in the host sandstone. Gray mudstone, carbonaceous shale, and thin, largely lenticular sandstones are present between the thick sandstone units. Many of the thin sandstones are bioturbated, but a few have small-scale trough-cross strata as much as 1 ft high and climbing ripples. The contact with the overlying Meeteetse Formation is placed at the top of the highest white sandstone.

Muddy Creek

The Teapot Sandstone Member is 330 ft thick at Muddy Creek (fig. 1, and pl. 1) and is distinguished from the underlying middle member by coarser grain size and white color. The basal contact was examined closely along outcrops in a north-south direction for about a half mile, and the white, medium-to coarse-grained sandstones of the Teapot were observed to be interbedded with the brown, very fine-to fine-grained sandstones of the middle member, and deposition of the lithologically different sandstones appears to overlap in time (fig. 11). Thus, the regional disconformity described by Gill and Cobban (1966) and Reynolds (1966) at the base of the Teapot is not in evidence here. The basal white sandstone of the Teapot is lenticular along outcrop; whereas, white sandstones above the basal sandstone appear to be relatively continuous laterally (fig. 12). Sandstones 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). These veinlets, where abundant, 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. These sandstones are trough-cross bedded with troughs as much as 4 ft high. The five major sandstones in the Teapot have a combined thickness of 272 ft. The contact with the overlying Meeteetse Formation is placed at the top of the highest white sandstone; only the lower 150 ft of Meeteetse strata are exposed at Muddy Creek.

Cave Gulch

The Teapot Sandstone Member was measured at two localities— at Cave Gulch and at Arminto railroad cut (fig. 1, and pl. 2). At Cave Gulch, the Teapot is a single white fine-to medium-grained 35-ft-thick sandstone exhibiting trough-cross, horizontal, low-angle, and irregular strata. Here the Teapot is overlain by carbonaceous shale and thin lenticular sandstones of the Meeteetse Formation. In the Arminto railroad cut, the member is 27 ft thick and consists of white medium-grained sandstone with small scale trough-cross strata, climbing ripples, and horizontal strata, interbedded with gray mudstone. Small, cut-and-fill channels with white clayey ripups above basal scour surfaces, and numerous clayey drapes are visible from a distance (fig. 13). Here the Teapot is overlain by about 48 ft of carbonaceous shale, thin coal beds, and thin sandstone of the Meeteetse Formation. The near-vertical exposures of the Mesaverde and Meeteetse Formations in the deep railroad cut (fig. 13) are truncated and overlain by gently dipping beds of the Eocene Wind River Formation.

Hells Half Acre

At Hells Half Acre (fig. 1, and pl. 2), the Teapot Sandstone Member is 150 ft thick and includes two sandstones, 70 and 69 ft thick, separated by 11 ft of carbonaceous shale that contains a small, scour-based lenticular channel sandstone. Internally, the two sandstones have trough-cross strata with troughs as much as 5 ft high. Some horizontal bedding and hummocky cross strata also were observed (fig. 14). The trough-cross strata are bi-directional (fig. 15), with the majority of troughs indicating

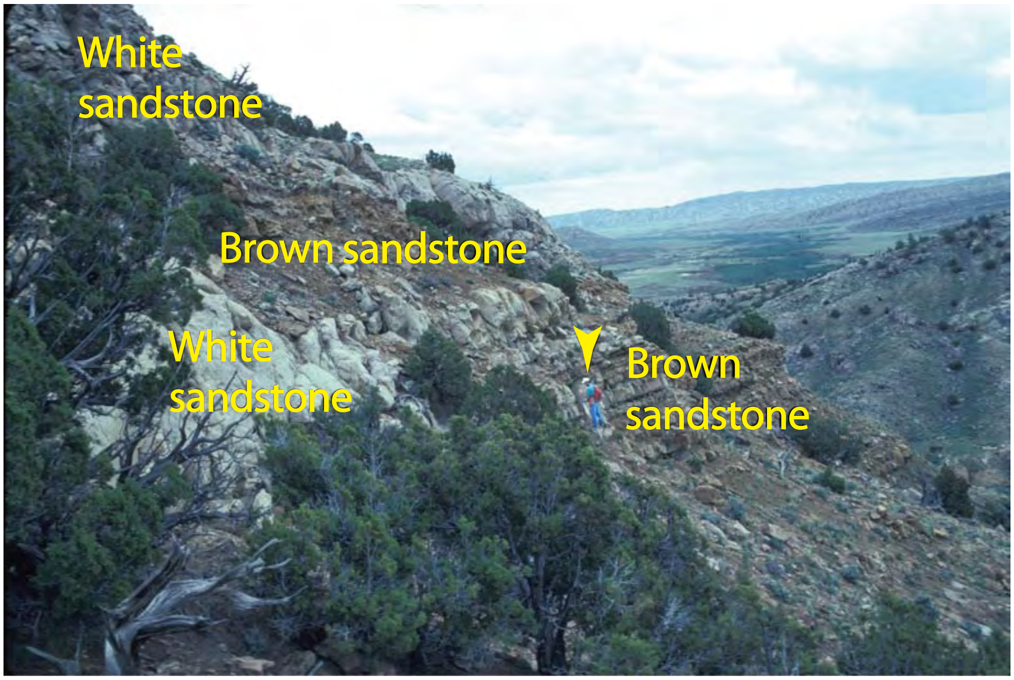

Figure 11. Photograph of the base of the Teapot Sandstone Member of the Upper Cretaceous Mesaverde Formation at the Muddy Creek measured section pl. 1), showing intertonguing of white, medium-grained sandstones typical of the Teapot and brown, very fine-grained sandstone typical of the underlying middle member of the Mesaverde Formation. Note 6-foot person for scale.

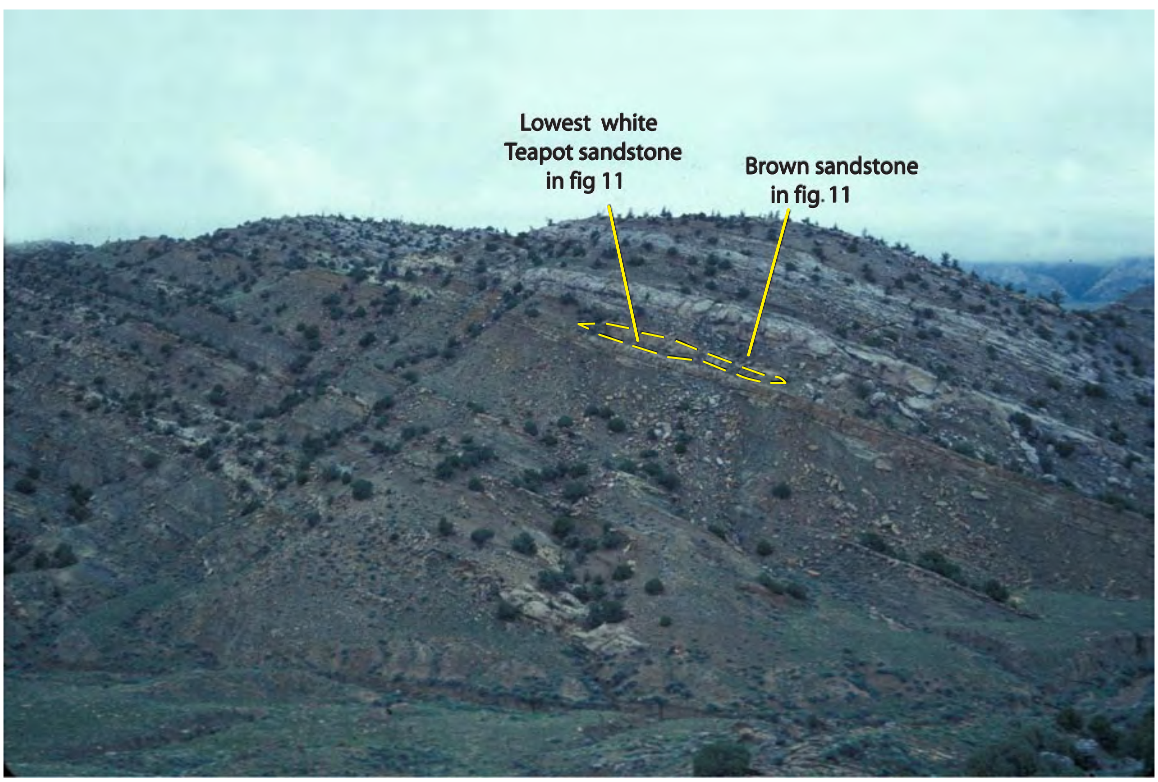

Figure 12. Distant view of white sandstones of Teapot Sandstone Member of the Upper Cretaceous Mesaverde Formation at the Muddy Creek measured section (pl. 1). Note lenticular nature of the basal white sandstone and the much more persistent nature of sandstones above the basal sandstone.

Figure 13. Photograph of channels in the nearly vertical Teapot Sandstone Member of the Upper Cretaceous Mesaverde Formation exposed in the deep Arminto railroad cut in the Cave Gulch area. The Teapot is 27 ft thick and overlain by the carbonaceous Meeteetse Formation. Up section is to right.

Figure 14. Photograph of hummocky cross strata in the Teapot Sandstone Member of the Mesaverde Formation at the Hells Half Acre measured section (pl. 2). Note 5-by 8-inch notebook for scale.

Figure 15. Photograph of bidirectional trough-cross bedding in the Teapot Sandstone Member of the Mesaverde Formation at Hells Half Acre measured section (pl. 2). Note 5-by-8 inch notebook for scale.

a south-southwest flow direction and fewer troughs trending north-northwest (pl. 2). These sedimentary features indicate a probable marginal marine origin in this area; furthermore, the Teapot is overlain here by a tongue of the marine Lewis Shale (see later discussion).

Coalbank Hills

At Coalbank Hills (fig. 1, and pl. 2), the Teapot Sandstone Member consists of a single 20-ft-thick, very fine-to 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 strata, trough-cross strata, and climbing ripples. This sandstone also has some of the crisscross veinlets that characterizes the Teapot in many areas of the basin.

Castle Gardens

The unit believed to represent the Teapot Sandstone Member at Castle Gardens, which is atypical of the member in other parts of the basin, is a 75-ft-thick sandy interval consisting of three, very fine-to fine-grained lenticular sandstones, 5, 15, and 30 ft thick, interbedded with medium-gray mudstone (pl. 2). This sandstone is overlain by a covered interval 63 ft thick, then fairly well exposed coaly and carbonaceous strata typical of the overlying Meeteetse Formation. The three sandstones are trough-cross bedded and drift-ripple laminated.

Stratigraphy of the Meeteetse Formation and Lewis Shale

The Meeteetse Formation and Lewis Shale were deposited in late Campanian and early Maastrichtian time (fig. 3) during a period in which depositional patterns appear to have become influenced by tectonic movements in portions of the Wind River Range and Granite Mountains. Figure 16 is a regional paleogeographic reconstruction of the Maastrichtian, modified from Johnson and others (2004), that shows the Lewis seaway, at the maximum westward extent, to deflect around the present sites of the southern Wind River Range and western Granite Mountains. This configuration of the paleoshoreline is interpreted to indicate that there was incipient uplift possibly representing initial stages of the oncoming Laramide orogeny in those areas. This interpretation is supported by the westward and southwestward thinning of all the stratigraphic units (Meeteetse Formation, Lewis Shale, Lance Formation) deposited during latest Cretaceous time across the present site of the Wind River Basin (figs. 17, 18,

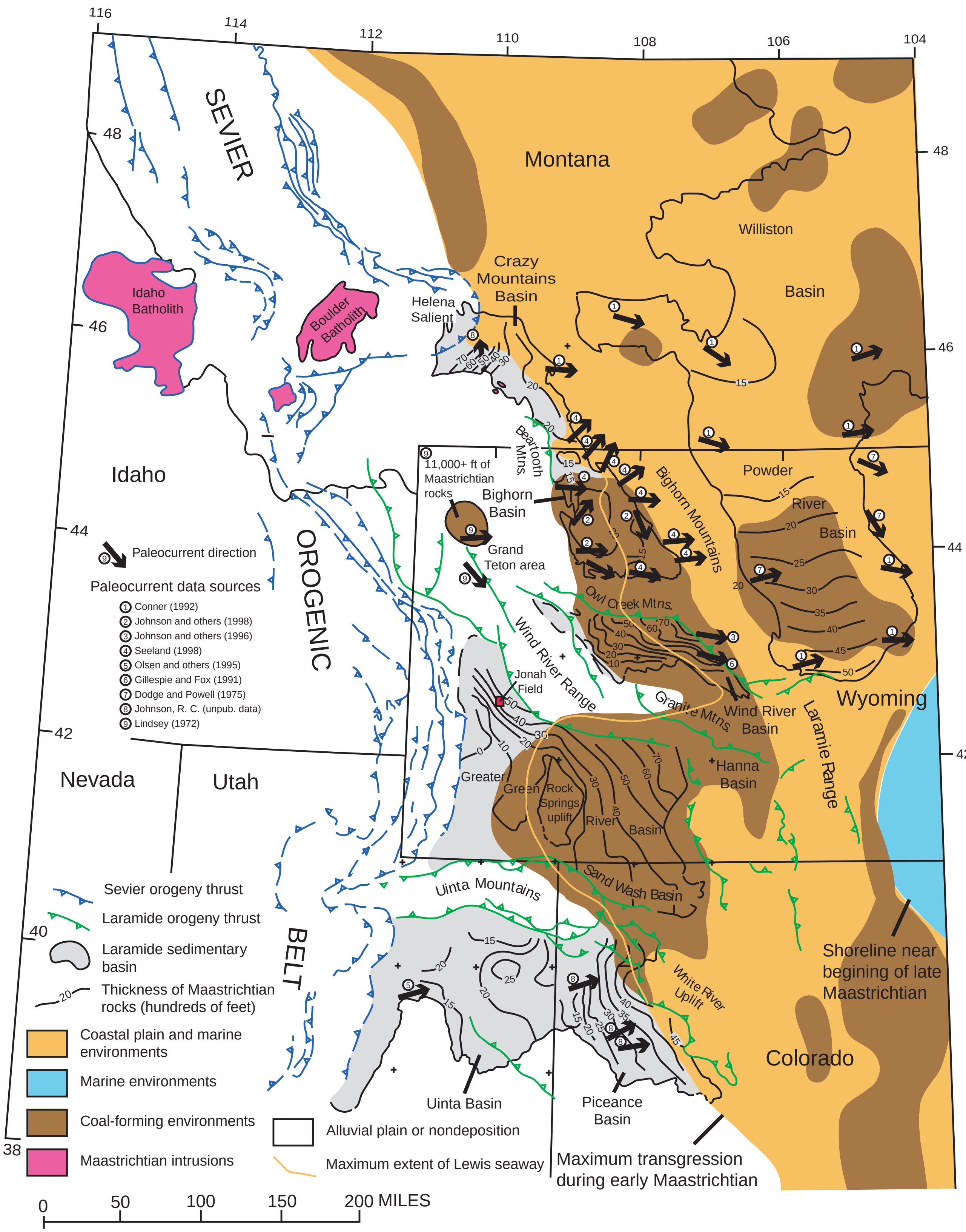

Figure 16. Paleogeographic map of the central Rocky Mountain region showing approximate thickness of Maastrichtian rocks, Sevier orogeny and Laramide orogeny thrust faults, environments of deposition (including coal-forming environments during the Maastrichtian), and paleocurrent directions in Maastrichtian rocks. Thicknesses in hundreds of feet. Sources of paleocurrent data are listed on the figure. Modified from Johnson and others (2004).

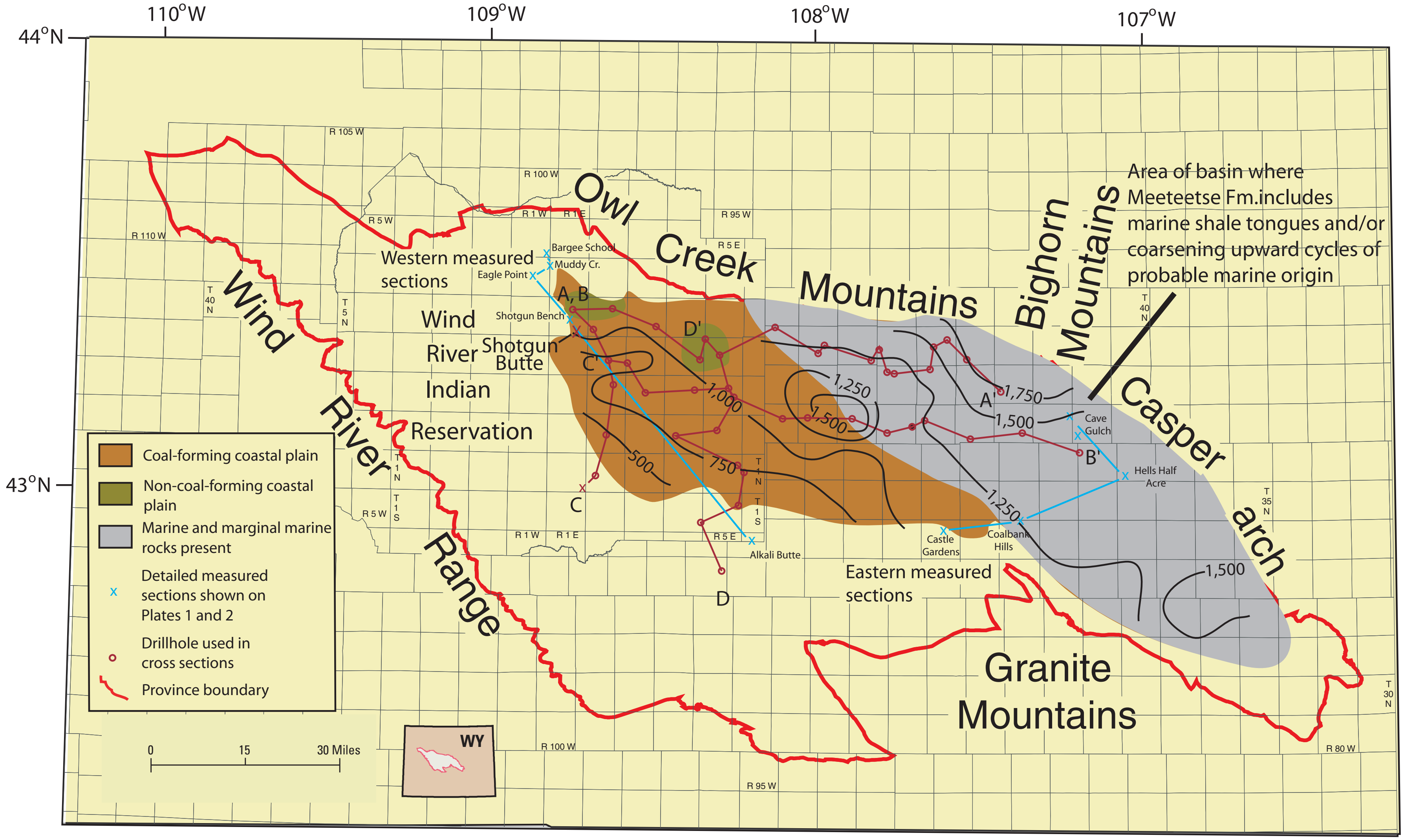

Figure 17. Facies map during maximum incursion of the Lewis seaway into the Wind River Basin area during deposition of the lower part of the Upper Cretaceous Meeteetse Formation. Area shown in gray is where marine tongues are present in the lower part of the Meeteetse. Isopach map is of total thickness of the combined Meeteetse Formation and Lewis Shale. Contour interval is 250 ft.

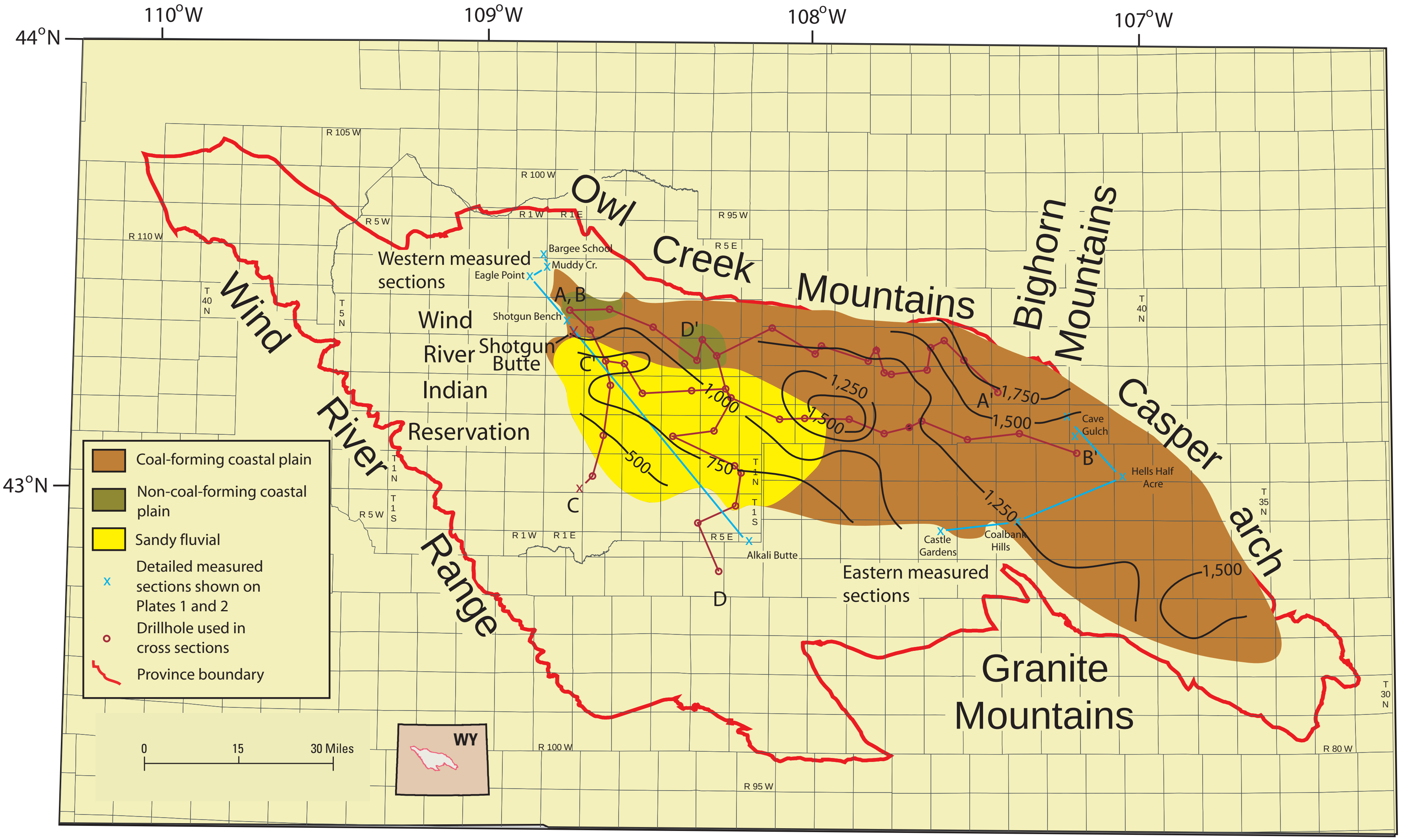

Figure 18. Facies map during deposition of the upper part of the Meeteetse Formation. Isopach map is of the Meeteetse Formation. Contour interval is 250 feet.

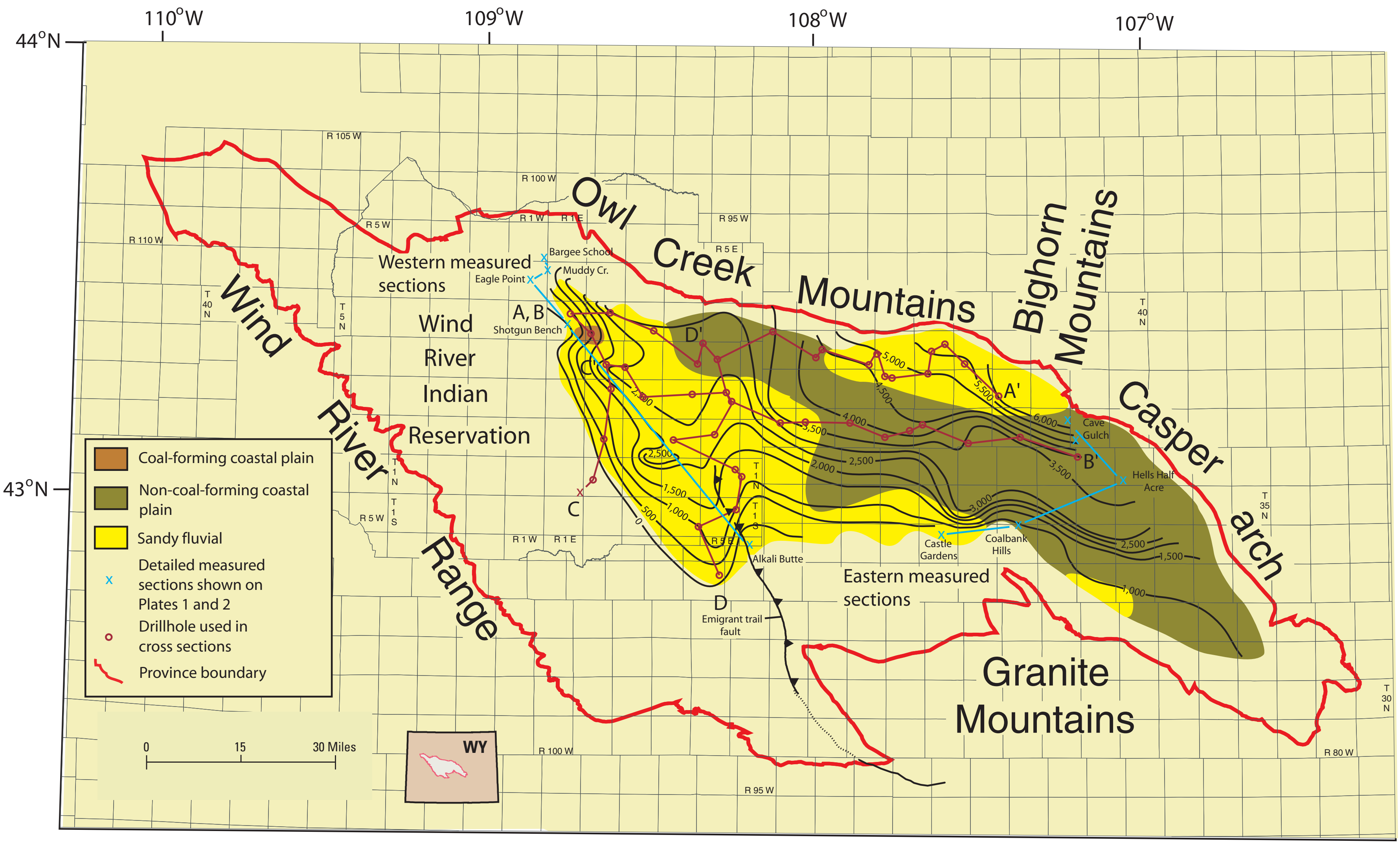

Figure 19. Facies map during deposition of the lower part of the Lance Formation. Isopach map is of the total Lance Formation. Contour interval is 500 feet.

and 19), as well as the multiple unconformities that formed in these rocks toward the west and southwest margins of the basin (pls. 5, and 6).

The Meeteetse Formation consists of interbedded fine- to coarse-grained sandstone, siltstone, shale, carbonaceous shale, and coal deposited in a poorly drained coastal plain setting to the west and southwest of the Lewis seaway. Generally the Meeteetse is much less sandy and more coaly and carbonaceous than the underlying Teapot Sandstone Member of the Mesaverde Formation and overlying Lance Formation. Coal beds are common with some beds to about 15 feet thick; total aggregate thickness in beds 2 ft thick or more varies from less than 10 ft to more than 50 ft (fig. 20).

The Lewis Shale was deposited in a nearshore to offshore marine setting as the Lewis seaway transgressed and regressed across the northeast half of the Wind River Basin and consists of gray, poorly exposed fissile shale with some bentonitic beds and very fine-to fine-grained sandstone units that typically contain *Ophiomorphia* and other types of burrows.

The contact between the Meeteetse and Lance Formation appears conformable throughout the deeper areas of the basin, and is generally placed at the change from mud-dominated, coaly and carbonaceous strata of the upper Meeteetse to the much sandier and less coaly strata that characterizes the lower part of the Lance. The thick sandstones generally wedge out into finer grained rocks toward the basin trough (fig. 19) and the contact is difficult to define there. Poor well control in many parts of the basin adds to this difficulty. Where the sandstones are missing in the western part of the basin trough, the stratigraphic position of the contact can, in places, be approximately located using a thick, laterally persistent coal bed in the uppermost part of the Meeteetse (pl. 3, wells 4-6). Along the eastern part of the deep basin trough, the position of the contact is placed at the top of a coaly interval that varies stratigraphically from place to place (for example: pl. 4, wells 11 and 12).

A massive, lenticular sandstone unit from 0 to 300 ft thick was included in the uppermost part of the Meeteetse Formation in an outcrop in the northwest part of the basin by Keefer and Troyer (1964). The sandstone is from 3,595 to 3,700 ft in the Shotgun Bench measured section described later (pl. 1). Troyer and Keefer (1955); and Keefer and Troyer (1956) had originally assigned the sandstone to the Lance Formation believing it was the uppermost Cretaceous unit in the area, but subsequent studies of spore and pollen assemblages identified a considerable thickness of Cretaceous strata above. A disconformity is locally present above the sandstone, and Keefer and Troyer (1964) believed the disconformity should be placed between the Meeteetse and Lance Formations, and thus the massive sandstone was included in the Meeteetse. The upper Meeteetse sandstone as defined by Keefer and Troyer (1964), however, appears to trace basinward into the lower part of the Lance Formation (pl. 4). A possible explanation for this sandstone is it represents the initial period of uplift on Laramide structures in the Shotgun Bench area while the overlying local disconformity formed as uplift progressed and expanded outward.

Detailed Measured Sections of Meeteetse Formation and Lewis Shale

The Meeteetse Formation and Lewis Shale are generally easily eroded and typically form valleys between the resistant sandstones of the Mesaverde below and the Lance above. As a result, well exposed sections are rare, but detailed sections were measured at Shotgun Bench in the western part of the basin and at Cave Gulch and Hells Half Acre in the eastern part (fig. 1, pls. 1, 2).

Shotgun Bench

The Meeteetse Formation was described along the south rim of Shotgun Bench in secs. 20, and 21, T. 5 N. R. 1 E. and about 3 ½ miles south-southeast of the Meeteetse section measured by Keefer and Troyer (1964, their pl. 2, measured sec. no. 2). The top of the Meeteetse is placed at the top of the massive sandstone that comprises the upper part of the Meeteetse as defined by Keefer and Troyer (1964), although, as previously discussed, this sandstone might trace basinward into the lower part of the Lance Formation. The Meeteetse is 1,180 ft thick, which is comparable to the 1,103 ft of Meeteetse measured by Keefer and Troyer (1964, p. 65-68) to the northwest and consists of very fine-to coarse-grained, light-gray sandstone, gray shale, carbonaceous shale, and numerous coal beds that are less than 2 ft thick (fig. 1, and pl. 1). Medium-and coarse-grained sandstones are confined to the lower 400 ft. Lenticular channel sandstones are typically less than about 30 ft thick and exhibit trough-cross, horizontal, and ripple-drift lamina. Two sandstones 87 and 80 ft thick lie between 3,098 and 3,280 ft and are very fine-to fine-grained, with contorted trough-cross and horizontal lamina, and internal scour surfaces. The sandstones might be equivalent to the basal sandstone of the Lance Formation farther basinward (pl. 4).

Hells Half Acre

Approximately 400 ft of Lewis Shale is present at the base of the Meeteetse-Lewis interval at the Hells Half Acre section (fig. 1, pl. 2). A 44-ft-thick interval of interbedded gray shale and very fine-to fine-grained sandstone overlies the Teapot Sandstone Member, which appears to be marginal marine here. Sandstone beds vary from single laminae to about 2 in. thick, have horizontal and hummocky cross strata, and decrease in abundance upwards. Overlying strata include a 5-ft-thick very fine-to fine-grained sandstone with horizontal and trough-cross strata, 33 ft of dark-gray shale, and 176 ft

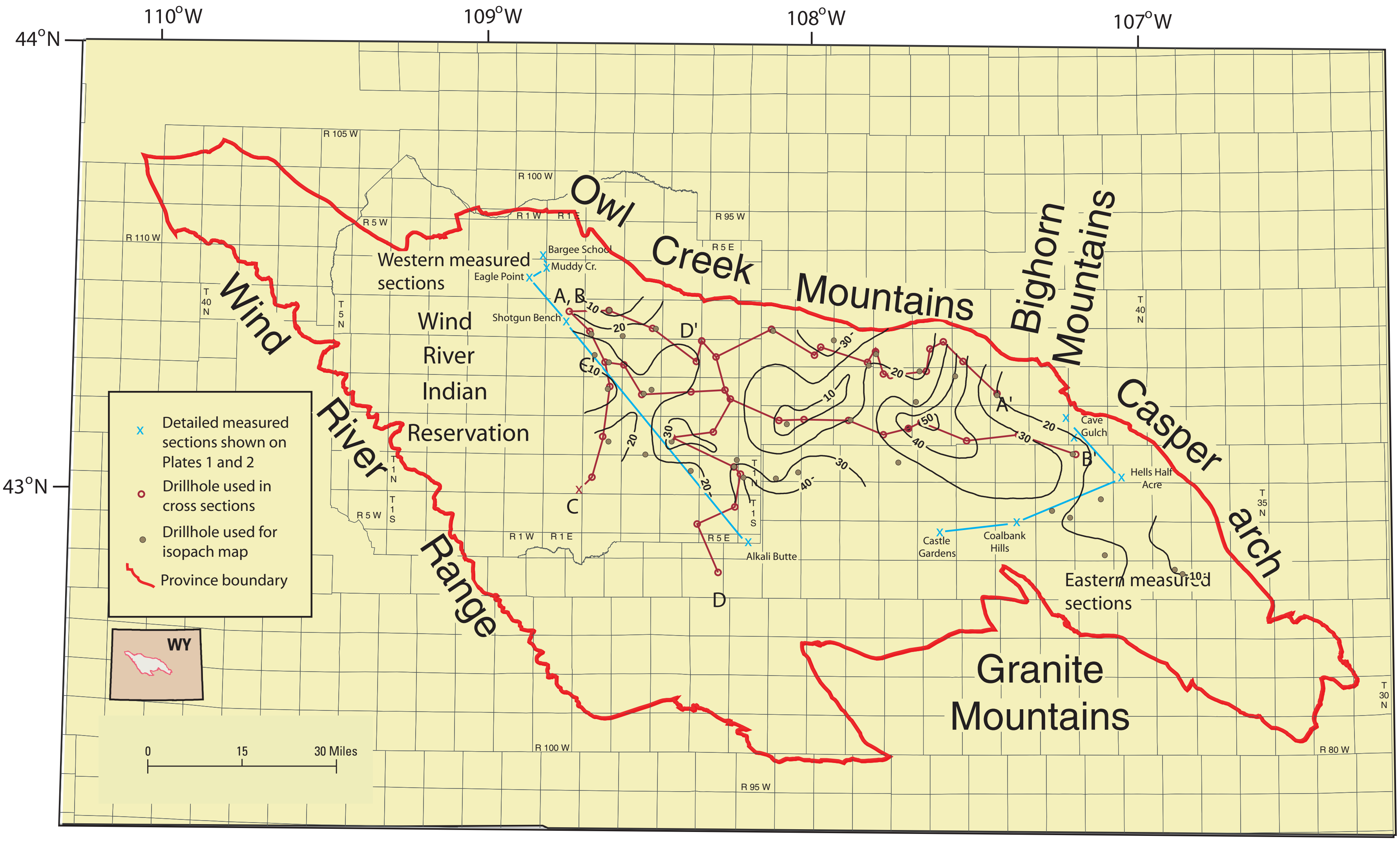

Figure 20. Total thickness of coal in beds 2 feet thick or greater in the Meeteetse Formation, Wind River Basin. Contour interval is 10 feet.

of predominantly very fine-to medium-grained sandstone that exhibits hummocky cross strata and *Ophiomorpha* burrows in the lower part and two distinct scour surfaces with clayey ripups in the upper part. Small trough-cross strata also are present in the upper part. The uppermost 142 ft of the section is largely covered, with the exception of one 5-ft sandstone that displays horizontal strata and trough-cross strata to 2 ft high. A sandy soil developed on this covered interval indicates this interval may consist mainly of sandstone and is possibly part of the Meeteetse Formation.

Overlying strata are in the Meeteetse Formation, of which 747 ft is relatively well exposed, but the uppermost part is largely concealed and was not described. A-28-ft thick very fine-to fine-grained white sandstone, with bi-directional trough-cross strata and of probable marginal marine origin, is present at the base of the exposed interval; the remainder is interbedded sandstone, gray shale, and carbonaceous shale and coal deposited in a poorly-drained coastal plain setting. Fluvial channel sandstone beds are minor constituents, ranging from about 6 ft to 19 ft in thickness for a total thickness of 60 ft. Only four sandstones are 10 ft thick or greater. Some sandstones are small cut-and-fill channels of limited dimensions; whereas, others are fairly extensive laterally. Laterally persistent 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, are present between 1,266 and 1,277 ft on the measured section (pl. 2). An abandoned mine shaft is along the line of the section.

Cave Gulch

The Meeteetse Formation at Cave Gulch is divided into upper and lower parts by a tongue of the Lewis Shale (fig. 1, pl. 2). The lower part, directly above the Teapot Sandstone Member of the Mesaverde Formation, is 65 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. The overlying Lewis Shale tongue, which is 458 ft thick, is poorly exposed except for a 79-ft-thick very fine-to 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 stratified with many types of burrows including *Ophiomorpha* burrows. Carbonaceous shale and thin coal beds are scattered throughout the 1,065-ft-thick upper part of the Meeteetse Formation with a maximum coal bed thickness of 2.5 ft. Fluvial channel sandstones vary from small cut-and-fill channels as thin as 3 ft to more laterally extensive channels as much as 25 ft thick. All channels appear to be simple (not stacked), and many display well-developed lateral accretion units of alternating sandstone and mudstone.

Total thickness of the Meeteetse-Lewis interval at Cave Gulch is 1,588 ft, which is 600 ft greater than the thickness in nearby drillholes. The measured section is on the upper plate of the Casper arch thrust, (fig. 1); whereas, the wells are located on the lower plate. A plausible explanation for the difference in thicknesses is that the Meeteetse and Lewis strata at Cave Gulch were originally deposited farther to the northeast where rates of subsidence and sediment accumulation were greater prior to thrusting. The isopach map of the two formations shows the thickening in that direction (fig. 17).

Castle Gardens

At Castle Gardens the Meeteetse Formation is 1,066 ft thick and relatively well exposed. The Meeteetse is composed of shale, carbonaceous shale, coal, thin sandstones of probable splay origin, and a few relatively small channel sandstones (pl. 2). Tongues of Lewis Shale and related marginal marine rocks were not identified, although these may be present in some covered intervals in the lower and middle parts of the Meeteetse. The section is near the southwestern limit of the Lewis seaway (fig. 17). Twenty-two coals are exposed in the section, varying from 4 in. to 4 ft thick for a total thickness of about 27 ft. Sandstones are fine to-very fine-grained. Thin sandstones of probable splay origin vary from 1 to 5 ft thick, are persistent along outcrop, and have horizontal and small-scale trough-cross strata and climbing ripples. Two probable fluvial channel sandstones, 22 ft and 26 ft thick, in the lower part of the Meeteetse have horizontal and trough-cross strata, and the upper bed contains carbonaceous ripups. Another probable channel, 9 ft thick and containing mud drapes and trough-cross bedding, is in the uppermost part of the Meeteetse.

Coalbank Hills

A poorly exposed tongue of Lewis Shale, 280 ft thick, directly overlies the Teapot Sandstone Member here, but the upper contact is not well defined. Shales in this interval contain *Ophiomorpha* burrows and bentonite beds. The overlying Meeteetse strata are 1,267 ft thick (fig. 1, pl. 2). The contact with the overlying Lance is poorly exposed, and is placed at the base of a10-ft-thick sandstone because (1) the contact is the only sandstone exposed in a 700-ft+ covered interval (pl. 2); and (2) the sandstone overlies a 20-ft interval of well-exposed carbonaceous shale, which is typical of the Meeteetse. A 465-ft-thick covered interval overlies this sandstone and 265 ft of covered interval underlies the 20-ft-thick carbonaceous shale. About two-thirds of the Meeteetse Formation is exposed and consists of sandstone, shale (much of which is carbonaceous), and coal. Twenty-one coal beds have a combined thickness of 31.7 ft; individual beds range from 0.5 ft to 4.5 ft thick (pl. 2). Sandstones are very fine to medium grained. A laterally persistent, 60-ft-thick white sandstone that can be easily traced on aerial photos is present from 687 ft to 747 ft on the measured section. This sandstone, of probable fluvial origin, is fine to medium grained with commonly contorted trough-cross strata to 3 ft high. Five lenticular fluvial channel sandstones, from 4.5 to 20 ft thick, with trough-cross strata and drift ripples, are present from 477 to 632 ft. Other sandstones are as much as 33 ft thick, and also display predominantly trough-cross stratification and drift ripples; these are assumed to be fluvial channel and crevass splay sandstones, but the lateral continuity could not be determined due to poor exposures.

Stratigraphy of the Lance Formation

The Lance Formation is characterized by fine- to coarse-grained, in part conglomeratic sandstone, shale, mudstone, carbonaceous shale, and thin coal beds deposited in nonmarine settings during and after the eastward retreat of the Lewis seaway from central Wyoming. The formation was deposited in a rapidly subsiding trough that extended southeast from the south boundary of Yellowstone Park through the present site of the Wind River Basin (Keefer and Love, 1963). In the depocenter just south of the present-day Owl Creek Mountains, the Lance is more than 6,000 ft thick (fig. 19). North of this rapidly subsiding trough, the Lance Formation is only about 1,000 to 1,500 ft in the southern part of the Bighorn Basin north of the Owl Creek Mountains (Keefer and others, 1998; Johnson and others, 1998; Johnson and others, 2004).

In the southwestern part of the Wind River Basin, there is clear evidence of continued uplift of parts of the Wind River Range and Granite Mountains (Keefer and Love, 1963). The Meeteetse Formation is truncated beneath the main part of the Lance along the southwest margin of the basin, adjacent to the Wind River Range (pl. 6; Keefer and Johnson, 1993, fig. 4), and the Lance thins and wedges out towards the Wind River Range (fig. 20) due to a combination of a decrease in the rate of subsidence and progressive truncation beneath the overlying Paleocene Fort Union Formation (pl. 5). The lowest part of the Lance is sandy and conglomeratic toward both the Wind River Range and Granite Mountains (fig. 20, pls. 5 and 6), indicating that these uplifts were providing abundant coarse clastic sediments by this time. In addition, the Lance thins markedly along a north-northwest trend roughly paralleling, but a few miles to the east of the northwest-trending, westward-thrusting, Emigrant Trail thrust fault (figs. 3 and 20), a fault in the southwestern part of the basin related to the uplift of the Granite Mountains (Berg, 1961; Keefer, 1970). The thinning indicates probable movement on the fault during deposition of the Lance; the eastward offset in the thinning trend might be expected as the fault plane has migrated westward through time.

The paleogeographic reconstruction of early Lance deposition (fig. 19) shows a predominantly sandy fluvial facies in the deep subsurface of the Wind River Basin just south of the Owl Creek Mountains, indicating the Owl Creeks may have been a sediment source at that time. However, cross bed readings from the lower part of the Lance at Cave Gulch on the Casper arch, east of this sandy facies shows an easterly flow direction (pl. 2), indicating possible sediment transport and accumulation in a large, east-flowing trunk stream that occupied the most rapidly subsiding part of the trough at this time.

The lower Lance, in the Bighorn Basin to the north, is predominantly a sandy and conglomeratic fluvial facies and, based on cross-bedding studies (Johnson and others, 1998), streams there also flowed generally eastward parallel to the present Owl Creek Mountains. Pebbles consist of chert and porcellanite similar to those found in the contemporaneous Harebell Formation in nearby Yellowstone National Park to the northwest (Johnson and others, 1998). Such pebbles are unlikely to have been derived from the Owl Creeks, as the first sediments to be eroded off of a newly uplifted Owl Creek Mountains would have been derived from sandstones and shales of the Mesaverde and Meeteetse formations and the marine Cody Shale.

Johnson and others (2004) compiled paleocurrent readings for Maastrichtian streams throughout most of the central Rocky Mountain region and concluded that these streams still flowed generally eastward off of the Sevier highlands as the streams had throughout the Cretaceous. This eastward flow was not greatly disrupted by rising Laramide uplifts during the Maastrichtian. Thus, as Keefer and Love (1963) suggested, there is little evidence for a positive feature in the nearby Owl Creek Mountains during deposition of the Lance but there was clearly a deep trough forming just south of where the Owl Creeks would rise in Paleocene time.

Detailed Measured Sections of 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 and at Castle Gardens and Coalbank Hills along the south margin (fig. 1, and pl. 2).

Cave Gulch Area

The Lance Formation in the Cave Gulch area was measured at two areas: the lower 1,850 ft was measured along the upper part of Cave Gulch; the upper 1,727 ft was measured along a ridge about 3,500 ft to the southeast. Upper Cretaceous strata, where exposed along the hanging wall of the Casper arch thrust, are progressively truncated beneath the Eocene Wind River Formation toward the northwest, which accounts for the absence of the upper part of the Lance at Cave Gulch. Areal photos were used as an aid in this offset, and the estimated maximum error in thickness from this offset is about 300 ft. The top of the Lance is placed at 1,727 ft on the second measured section segment where there is a subtle increase in grain size from very fine-to fine-grained sandstone to fine -to medium-grained sandstone. This contact corresponds approximately to the mapped contact between the Lance and the overlying Fort Union Formation (Keefer, 1970, pl. 1), and appears to be similar to the contact used by Flemings and Nelson (1991) farther 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 in the lowermost Fort Union in many parts of the basin, was not present here.

A total of 3,577 ft of Lance was measured in the Cave Gulch area (pl. 2), compared with a thickness of 3,970 ft penetrated in the Coastal 2-7-36-86 Bullfrog well in sec. 7, T. 36 N., R., 86 W. about 1 mi to the west. Note the surface section was measured on the hanging wall of the Casper arch thrust; whereas, the Coastal well penetrated the Lance on the footwall. The amount of horizontal displacement on the thrust is unknown but the sedimentary section continues under the thrust for 5 to 15 mi (Skeen and Ray, 1983). 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), indicating that the muddy facies, as described in the upper part of Lance along the trough of the basin by Keefer (1965), Gillespie and Fox (1991), and Johnson and others (1995) was replaced to the northeast by a much sandier facies.

Calcareous cemented nodular bodies are present in sandstones throughout Lance 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 crevasse splay sandstones with climbing ripples, 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. 2.

The 214-ft-thick basal Lance sandstone is the thickest individual sandstone unit in the formation. The Lance Sandstone directly overlies a 1-ft coal bed at the top of the underlying Meeteetse Formation. The lower 28 ft of this sandstone is very fine to fine grained and displays well-developed laterally accreting sandstone and mudstone units and is similar to sandstones in the underlying Meeteetse Formation. The remainder consists of a stack of at least four fine-to medium-grained sandstone units with scour bases and ripups along scour surfaces. Internally, these scour-based sandstones have trough-cross strata as much as 5 ft high, but bedding is commonly highly contorted.

Fluvial sandstones are scattered throughout the Lance Formation above the basal sandstone. Individual channel sandstones vary from 3 to about 40 ft thick, but these channel sandstones are commonly stacked into complex units that are as much as 130 ft thick (841 to 971 ft on the upper part of Cave Gulch measured section, pl. 2). These complex sandstones commonly contain numerous scour surfaces with clayey ripup zones. Laterally accreting sandstone and mudstone units were observed in some of the channel sandstones.

Paleocurrent measurements on eight troughs within the basal sandstone indicate a north-northeast flow direction; whereas, measurements taken from sandstones in four stratigraphically higher intervals in the Lance Formation at Cave Gulch indicate a southeast flow direction (pl. 2). Paleocurrent readings on the lowermost sandstones in the overlying Fort Union Formation also indicate a southeast flow direction.

Coalbank Hills

The Lance Formation at the Coalbank Hills locality is 1,138 ft thick, with only a little more than one-third of the interval exposed (pl. 2). The Lance-Fort Union contact was mapped in the area by Weitz and others (1954), and the same contact was subsequently used by Rich (1962) and Keefer (1970). The contact is placed slightly higher in the present study, at the base of a 92-ft-thick sandstone (pl. 2) that is interpreted as correlating with the thick sandstone at the base of the Fort Union in outcrops throughout much of the basin (Keefer, 1965). Sandstones in the Lance in the Coalbank Hills section are very fine to fine grained and can be divided into: (1) probable fluvial channel sandstones from 20 to 42 ft thick that are commonly channel-form, with trough-cross bedding to 3 ft high; and (2) low angle bar accretion, and thinner sandstones 5 ft thick or less that probably represent mainly crevasse splays that are fairly persistent and have smaller trough-cross strata to about 1 ft high and ripple-drift laminae. Gray mudstones with little carbonaceous debris are interbedded with the sandstones.

Castle Gardens

The Lance Formation at Castle Gardens is 499 ft thick and consists of a series of distinctive white cliff-forming sandstones locally famous for Indian petroglyphs and pictographs. Flores and others (1994), using palynomorphs, dated a coal 80 ft above the base of the sandstone sequence as Maastrichtian (pl. 2), but four coals higher in the section were barren of pollen (R. Flores, U.S.G.S. oral commun., 2004). A coal bed in the lowermost part of the overlying Fort Union Formation contained pollen representing the early Paleocene palynomorph zone P1 (Flores and Keighin, 1992; Flores and others, 1994; Nichols, 1994). Flores and Keighin (1992) and Flores and others (1994) interpreted much of this undated part of the white cliff-forming sandstones to be the basal part of the Paleocene Fort Union Formation. Thus, in their interpretation little of the Lance is present at Castle Gardens.

Flemings and Nelson (1991) similarly obtained a Maastrichtian age for two coal beds in the lower part of this 499-ft-thick white sandstone and also determined that the upper part of this interval was barren of pollen; they believed that this distinctive white sandstone interval was Paleocene Fort Union Formation and that the Maastrichtian pollen were reworked. Lithologically, this interval is similar to the sandy and conglomeratic lower part of the Lance along much of the southwest margin of the basin so, on that basis, also is considered to be Lance at Castle Gardens. Using this interpretation, the upper part of the Lance was eroded before the overlying Paleocene Fort Union was deposited, and the white color might be due to feldspars in the sandstone weathering to kaolinite during this period of erosion. In the southwest part of the Piceance Basin of western Colorado, a similar weathered zone with kaolinized sandstones developed in the uppermost part of the Cretaceous Mesaverde Formation during an extended period of exposure and erosion prior to deposition of the overlying Paleocene strata there (Johnson and May, 1980; Johnson, 1989). At Castle Gardens and in the southwest part of the Piceance Basin, the precise location of the unconformity is difficult to pick because of reworking of kaolinite into sediments in the lowermost part of the overlying Paleocene strata.

The white cliff-forming sandstone sequence consist of very fine-to medium-grained white sandstone, gray to dark gray shale and carbonaceous shale, and coal. The strata are distinctive from the overlying Fort Union Formation, which is much less sandy, and the sandstones are predominantly gray. An exception is the lenticular white sandstone in the lowermost part of the Fort Union Formation that is interpreted to represent reworking of underlying white Lance sandstones. Sandstones in the Lance, from 30 to 140 ft thick, are mainly complex amalgamations of fluvial channel sandstones (figs. 21, and 22) with trough-cross beds to 3 ft high, low-angle bar accretion bedding, and multiple scour surfaces. Three individual lenticular channel sandstones from 6 to 12 ft thick are present between 2,410 and 2,469 ft in the measured section (pl. 2). Individual channel widths for both the isolated channels and for the channels in the complex stacks vary from about 300 to 600 ft in these west-northwest-trending outcrops. A paleocurrent study by Flemings and Nelson (1991, p. 49, fig. 13A) indicate a northeast flow direction. Thus the outcrop trend is roughly perpendicular to flow direction and the observed channel widths are probably close to true widths. Two coal beds 4 ft and 3 ft thick were observed in the Lance Formation along the line of section.

Stratigraphy of the Fort Union Formation

The Fort Union Formation is a highly variable unit that can be generally subdivided into two intervals: a lower interval deposited in poorly-drained fluvial and paludal settings; and an upper interval deposited in fluvial, marginal lacustrine, and lacustrine settings in and adjacent to a major lake, Lake Waltman (Keefer 1961a; 1961b; 1965; 1969). The lower interval, consisting of sandstone, gray shale, carbonaceous shale and coal, was called the lower unnamed member. The upper interval was divided into two members: the Waltman Shale Member, consisting mainly of offshore lacustrine shale, and the Shotgun Member, consisting of fine-to coarse-grained, in part conglomeratic, fluvial and marginal lacustrine rocks. The Waltman Shale Member was named for exposures in the Waltman area in the northeastern part of the basin, and the Shotgun Member was named for Shotgun Butte in the western part of the basin, where the unit is best exposed (Keefer, 1961b). The Fort Union Formation is well exposed in many marginal areas of the basin, but the Waltman Shale Member crops out only in limited areas (Keefer, 1961b). The Waltman has been extensively studied in the subsurface, however, by Keefer (1961a; 1961b); Ray (1982); Liro and Pardus (1990); Katz and Liro (1993), and Roberts and others (Chapter 5, this CD-ROM).

The Fort Union Formation unconformably overlies older units, but only with slight angular discordance around much of the margins of the basin; these unconformities appear to die out toward the basin center (Keefer, 1965). Keefer (1965, p. A19) described the contact with the underlying Lance Formation thusly: "In most outcrops the contact is marked by a lithologic change from dull-gray and tan, banded soft shale, claystone and sandstone below to white sandstone and siltstone interbedded with thin conspicuous ledgy red-brown ironstone beds above." The Lance-Fort Union contact in outcrops has been generally well defined throughout the basin using the aforementioned variations in lithology; and in conjunction with palynomorphs investigations (Flores and others, 1992; 1994, Nichols and Flores, 1993). However, in many of the deeper parts of the basin there is no sandstone buildup at the contact, and similar depositional conditions persisted from latest Cretaceous into Paleocene times. In these areas, there is not a good lithologic criterion to pick the contact, and only a few pollen dates are available for the subsurface (Schmitt, 1975; Nichols and Flores, 1993). Likely the Lance-Fort Union contact shown on the subsurface cross sections (pls. 1-4) does not correspond closely everywhere to the Cretaceous-Paleocene boundary.

Erosion of older units beneath the Fort Union is most pronounced toward the Wind River Range to the southwest where the Fort Union ultimately overlies strata as old as the upper part of the Cody Shale (pl. 5). Flores and others (1993) interpreted the conglomeratic Fort Union Formation exposed near Hudson, along the southwest margin of the basin as deposited by fluvial systems in a 15-mile-wide, northeast-trending paleovalley incised into hogbacks that formed adjacent to the Wind River Range to the southwest. A coal bed about 210 ft above the base of the Fort Union there was dated in the palynomorph Zone P3 of the Paleocene (Nichols and Flores, 1993).

Keefer and Troyer (1964) described the Fort Union Formation in the Shotgun Butte area where it crops out in a series of anticlines and synclines: they (1) determined

Figure 21. Photograph of white sandstone in the Lance Formation at Castle Gardens measured section (pl. 2), consisting of a complex amalgamation of fluvial channel sandstones.

Figure 22. Photograph of white sandstone in the Lance Formation at Castle Gardens measured section (pl. 2), consisting of a complex amalgamation of fluvial channel sandstones. This view is to the left of figure 21; the blocky sandstone face to the right of center is common to both figures.

that these structures began to form during deposition of the Upper Cretaceous Meeteetse Formation, and that deformation continued throughout deposition of the Fort Union, and (2) interpreted the Fort Union as being conformable with the underlying Lance Formation in the structural troughs and unconformable over the crests of anticlines. The lower unnamed member in this area varies in thickness from 520 to 1,200 ft, and is predominantly conglomerate and sandstone with some gray shale and brown carbonaceous shale. 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 Member is conformable 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. Although the Shotgun includes lacustrine and marginal lacustrine rocks elsewhere in the basin, at the type locality the Shotgun appears to be all fluvial (R. M. Flores, U.S.G.S. oral commun., 2006).

Flores and Keighin (1993) studied the fluvial architecture of sandstones in the lower member of Fort Union in the Shotgun Butte area and concluded that Paleocene river systems flowed southeast along a paleovalley that formed in the synclines as a result of rapid subsidence. They interpreted these sandstones as being deposited by braided, meandering, and anastomosed streams; whereas, sandstones in the overlying Shotgun Member were deposited by meandering, moderately sinuous fluvial channels. They defined four types of fluvial sandstones in the lower member, and concluded that the fluvial systems were largely anastamosed and meandering in the early depositional stages and later evolved into braided systems.

Nichols and Flores (1993) identified palynomorph Zones P2 and P3 in the lower member and Zone P5 in the Shotgun Member in the Shotgun Butte area. Palynomorphs collected from uppermost part of the Lance Formation, as mapped by Keefer and Troyer (1964) in the Shotgun Butte area, also were of early Paleocene age, indicating that the lithologic break, mapped as the Lance-Fort Union contact in the Shotgun Butte area, does not correspond precisely to the Cretaceous-Paleocene boundary.

The contact between the Lance and Fort Union Formations along the Casper arch, in the northeast part of the basin, appears to be gradational and is placed at the change from predominantly shaly strata below to predominantly sandy strata above (Keefer, 1965). The Lance and Fort Union in this area are exposed in near vertical outcrops on the hanging wall of the Casper arch thrust that has uplifted the formations over 10,000 ft and thrusted several miles to the southwest. Keefer (1965, p. A21) reported spores and pollen of earliest Paleocene age from the upper few feet of the Lance near Waltman along the Casper arch, so this lithologic shift only approximately marks the Cretaceous-Tertiary contact here as was noted for the Shotgun Butte area. The lowermost part of the Fort Union as defined by Keefer (1965) in the Casper arch area was dated by Nichols and Ott (1978) and Nichols and Flores (1993) as in the palynomorph Zone P1(earliest Paleocene), thus supporting the hypothesis of continuous deposition from Lance to Fort Union.

Keefer (1965, p. A22) in his measured section near Waltman, along the Casper arch (fig. 23) in the northeast part of the basin, described (1) the lower member as 2,325 ft thick of white fine- to very coarse-grained sandstone and siltstone, and (2) the Waltman Shale Member (type section) as 643 ft of chocolate-brown and gray shale and silty shale with a few thin ledge-forming sandstone beds. Nichols and Ott (1978) identified all six Paleocene biozones, P1 through P6 in the Casper arch exposures, and designated a section there as the reference section for the Paleocene biozones in the Rocky Mountains. They determined that the lower unnamed member is within the P1 through P4 biozones, and the Waltman Shale Member that is variably truncated beneath Eocene strata along the arch is within palynomorph zones P5 and P6.

Flores and others (1992; 1994) conducted a detailed sedimentological study of the Fort Union Formation at Castle Gardens, along the south margin of the basin, and dated the entire formation using palynomorphs. The Fort Union in that area is about 2,300 ft thick, and all six Paleocene biozones are present, with the P1-P2 interval about 225 ft thick, the P3-P4 interval about 600 ft thick, and the P5-P6 interval about 1,450 ft thick. About two-thirds of the formation was deposited during the latter period, which Flores and others (1992) attributed to a rapid rate of basin subsidence and the development of Lake Waltman. Lenticular Fort Union sandstones were deposited by sinuous bedload streams that varied from deep and wide to shallow and narrow; whereas, coarsening-upward, lenticluar and tabular sandstones represent crevasse splays (Flores and others, 1992). Coal beds are in the P4 and P5 biozones, and lie most commonly above the larger fluvial channel and crevasse-splay complexes. The thickest coal bed observed was about 12 ft and dated in the P5 biozone.

Figure 23 is a facies map of early Fort Union time. The map probably spans palynomorph Zones P-1 and P2, and possibly part of Zone P3, based on previously discussed palynomorph studies. The paleovalley in the Hudson area described by Flores and others (1993) is manifested as a sandy fluval facies that extends northeastward from outcrops near Hudson to the central part of the basin where the sandy facies dies out into less sandy fluvial rocks. This major Paleocene drainage system appears to have exited the ancestral Wind River Range close to the present-day junction of the Popo Agie River and Little Wind River at the base of the Wind River Range (fig. 23), indicating that the course of these rivers may have remained largely unchanged from Paleocene time to the present. Changing course may have been difficult for these rivers once they became incised into the rising Wind River Range. The present-day Little Wind River flows into the Wind River a few miles farther to the north, and the Wind River then flows northward across the basin and through Wind River Canyon that is incised in the Owl Creek Mountains, but during

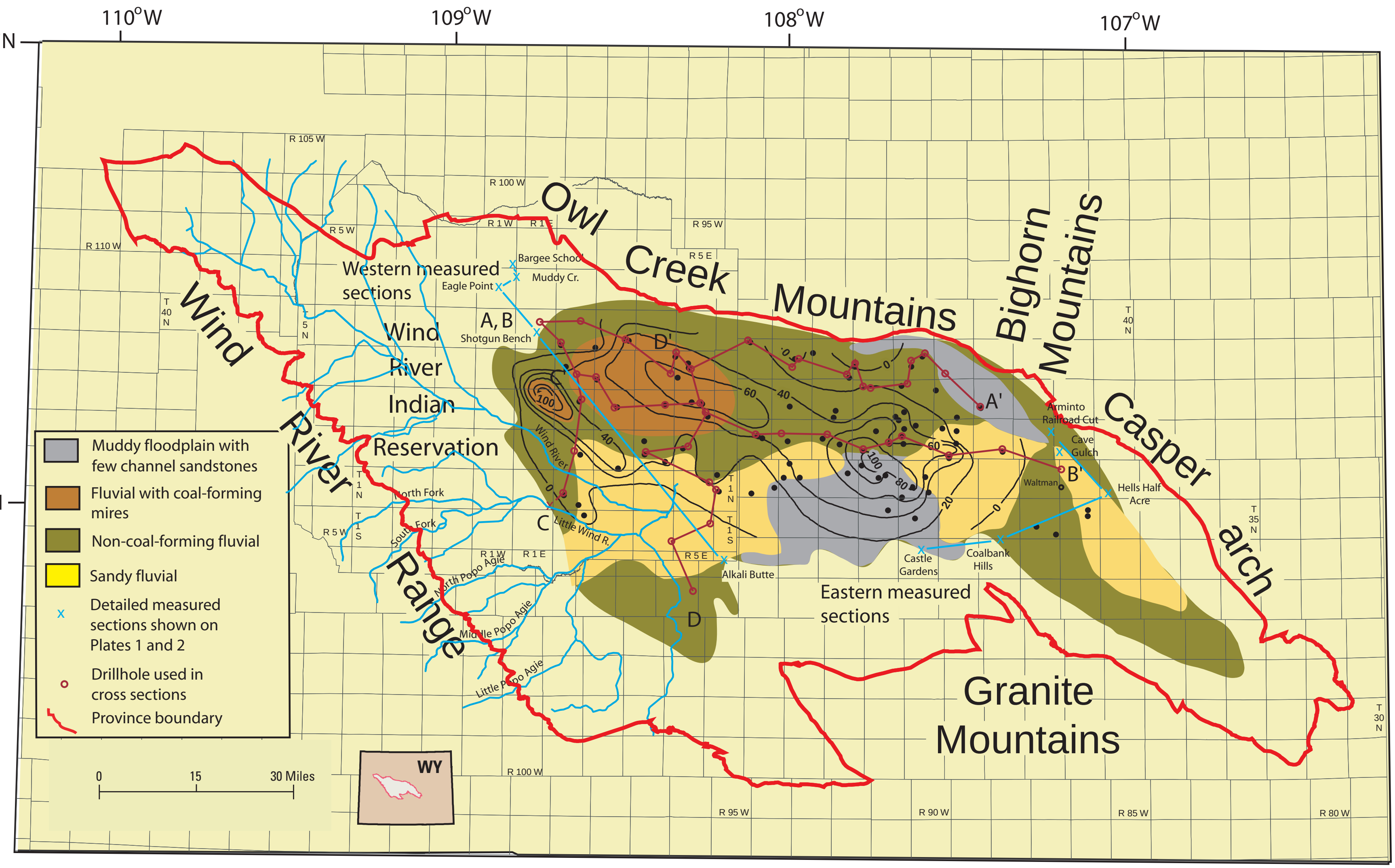

Figure 23. Facies map during deposition of the lower part of the lower unnamed member of the Paleocene Fort Union Formation. Isopach map is of the lower unnamed member. Contour interval is 500 feet. Present-day Wind River and Popo Agie river systems are shown in blue.

Paleocene time the ancestral Wind River probably flowed northeastward and exited the basin in the area of the Casper arch.

Another area of sandy fluvial rocks extended northward from the Granite Mountains; whereas, a muddy floodplain area, with only minor thin fluvial channels, occupied a 25-mile wide area between these two sediment sources. Coal-forming mires occupied the western part of the rapidly subsiding trough on the Wind River Reservation. Coals from these mires, named "C coals" by industry, form an important, widespread marker bed at the base of the Fort Union Formation.

Predominantly mudstone accumulated in the most rapidly subsiding part of the basin, just south of the Bighorn Mountains (fig. 23), a depositional environment that had existed there since Lance deposition and then persisted at least until the development of Lake Waltman (Johnson and others, 1994). On geophysical logs, the mud-dominated facies of the lower part of the Fort Union is shown to consist primarily of interbedded sandy mudstone and thin (<10 ft thick) muddy sandstones and is easily distinguished from the overlying Waltman Shale Member, which is predominantly shale. In addition, the mud-dominated facies lacks the laterally persistent, correlatable shale marker beds that characterize the lacustrine Waltman (Keefer (1961b). Flores and others (1994) suggested that the fine-grained rocks in the mud-dominated facies were (1) sourced by Cretaceous marine shales that were stripped off rising Laramide uplifts during the Paleocene, and (2) deposited on flood plains and in flood-plain 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 is known primarily from subsurface data. However, 1,265 ft of predominantly gray shale and carbonaceous shale with thin coal partings, and minor sandstones, and red, purple, and olive-gray shales was measured in exposures of the Shotgun Member of the Fort Union Formation (fig. 24) by Keefer and Troyer (1964) along the north margin of the basin within the Wind River Indian Reservation (E½ sec. 31,T. 6 N., R. 3 E., fig. 25). Very fine-to medium-grained sandstone constitute only about 90 ft of the total section, in beds less than 10 ft thick except for one channel-like 19-ft bed 217-236 ft above the base. This sandstone contains an abundant and varied mammalian fauna dated as Torrejonian or early Tiffanian (Keefer and Troyer, 1964), an age range (in terms of North American land-mammal ages) that corresponds closely with Paleocene palynological Zones P2 and P3 (D. J. Nichols, U.S.G.S. oral commun., 2006) that characterizes the upper part of the lower unnamed member of the Fort Union Formation elsewhere in the basin. No samples were collected for palynological study in the section, but the upper 1,000 ft most probably contains strata equivalent to the Waltman Shale Member, as the western shoreline of Lake Waltman was nearby (fig. 25). The rare 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 25 is a facies map for the uppermost part of the lower unnamed member of the Fort Union Formation, for the period just prior to the development of Lake Waltman. The drainage system that entered the basin from the direction of the Wind River Range continued in about the same position as earlier during the Paleocene. For an idea of what incised drainages may have looked like on the flanks of the Wind River Range, see the 3-dimmensional block diagrams constructed by Keefer (1965, figs. 32 and 33) and Flores and others (1993, fig. 16). The mud-dominated floodplain that had previously occupied the area east of this drainage was replaced by fluvial and sandy fluvial environments that developed along much of the south margin of the basin, north of the Granite Mountains. The coaly facies reached maximum extent at this time. Total coal thicknesses in the lower member are included in figure 25; thickest accumulations are (1) in the central part of the Wind River Reservation (more than 100 ft), (2) near the east margin of the Wind River Reservation (fig. 3), just south of the trough of the basin (more than 60 ft), and (3) north of Castle Gardens in the central part of the basin (more than 100 ft). Individual coal beds commonly can be traced between wells in areas with closely spaced well control such as in the Muddy Ridge and Pavillion fields in the westen part of the basin. In these areas, oil and gas operators have informally assigned names such as "A" coal and "B" coal to persistent coal beds in the upper part of the lower unnamed member. The accumulation south of Little Dome is in a syncline that was subsiding rapidly during the Paleocene (Johnson and Flores, 1993).

The maximum extent of the initial transgression of Lake Waltman also is shown in figure 25. In marginal areas, the transgressions of Lake Waltman are typically marked by coarsening-upward deltaic sequences; many of these are marked on the cross sections in plates 1, 2, and 4. The lake expanded much farther than previously thought, based on new data resulting from the present investigation.

The base of the Waltman Shale is sharp and well defined on geophysical logs (Keefer, 1961b) and in seismic logs(Liro and Pardus 1990; Gilbert, 2000), suggesting that the initial transgression of Lake Waltman occurred rapidly in geologic terms. The base of the Waltman Shale where it crops out near Waltman, Wyoming, along the Casper arch in the northeast margin of the basin, was dated by Nichols and Flores (1993) as in the lowest part of the Paleocene palynological P5 zone.

A tongue of the Waltman Shale that was discovered during the present study in exposures near Castle Gardens, demonstrated that Lake Waltman extended farther south than previously thought. This tongue was correlated into the more detailed section of Flores and others (1992; 1994), and was precisely dated as being in the lowest part of the P5 Paleocene palynomorph zone (pl. 1). Because the base of the Waltman is in the lowest part of the P5 zone at both Castle Gardens and Casper arch localities on the margins of the basin, if the base also could be dated as being in the P5 zone near where Lake

Waltman first began to form, it would prove that the initial transgression of the lake was rapid. To pursue this reasoning, samples were collected from a coal bed directly beneath the Waltman Shale from three wells in Frenchie Draw field a few miles south of the basin trough, near where Lake Waltman is likely to have first formed. Two of these samples yielded palynomorphs indicative of the P5 zone (Johnson and others, 2005). A surface sample 19 ft above the lowest Waltman tongue at the Coalbank Hills site also yielded palynomorphs indicative of the P5 zone. These results proved that Lake Waltman formed in the early part of P5 palynomorph zone and expanded rapidly into marginal areas of the basin.

Outcrop Studies of the Fort Union Formation

Castle Gardens

Excellent outcrops of the Fort Union Formation and the Cretaceous-Tertiary boundary sandstone are present in a belt about 3 miles wide and 6 miles long in the Castle Gardens area. There, the Fort Union Formation is at least 2,325 ft thick (Flores and others, 1992; 1994) and is underlain by the Upper Cretaceous Lance Formation. Flores and others (1992; 1994) measured a detailed stratigraphic section showing lithology, depositional facies characteristics, and palynologic (spores and pollen) biozones (pl. 2), and conducted a detailed sedimentological analysis. The K/T boundary is within a poorly dated, distinctive, white-weathering sandy unit about 500 ft thick that is considered to be entirely Lance.

Part of Castle Gardens section was remeasured along a slightly different traverse than the one used by Flores and others (1992; 1994), resulting in the discovery of the thin tongue of the Waltman Shale Member (fig. 26) described earlier; the tongue was apparently scoured out by overlying fluvial rocks along the traverse taken by Flores and others (1992; 1994).

The lower 478 ft of Fort Union at Castle Gardens above the distinctive white sandstone of the Lance Formation, consists almost entirely of dark gray mudstones with a few small scour-and-fill channel sandstones and a few tabular sandstones (pl. 2) interpreted by Flores and others (1992) as splay sandstones. This interval is within the Paleocene palynomorph Zones P1 through P3 and is roughly equivalent in time to the highly sandy and conglomeratic lower unnamed member of the Fort Union Formation at Shotgun Butte (Shotgun Butte locality shown in fig. 18). The Castle Gardens area during this period was apparently in an interfluvial area between major streams one originating in the Wind River Range to the southwest, and the other originating in the Granite Mountains to the south (fig. 24; Flores and Keighin, 1993, fig. 24).

Figure 24. Photograph of muddy floodplain facies with few channel sandstones in the Shotgun Member of the Paleocene Fort Union Formation in the north-central part of the Wind River Basin (E1/2 sec. 31, T. 6 N., R. 3 E); buttes capped by Eocene rocks in background.

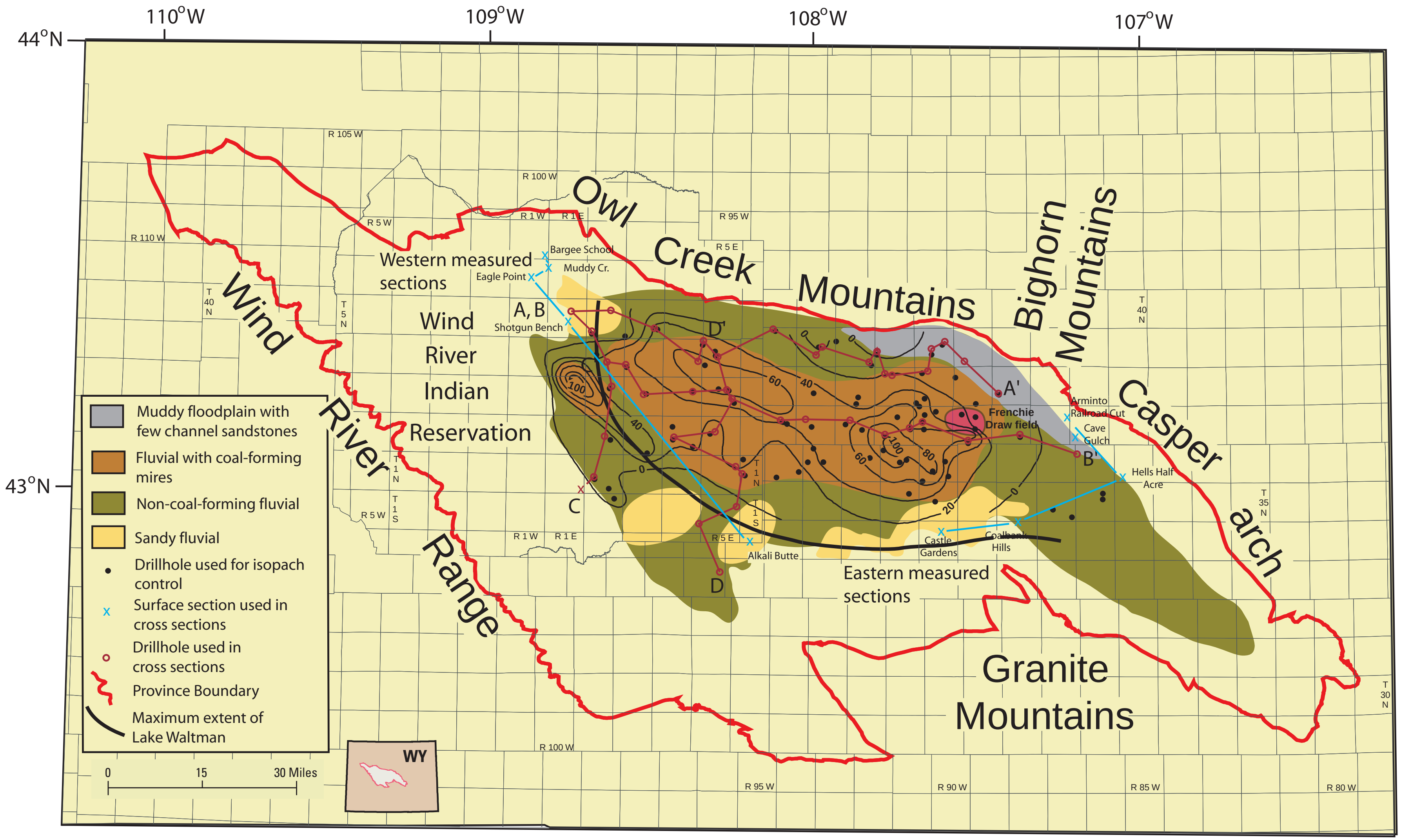

Figure 25. Facies map during deposition of the uppermost part of the lower unnamed member of the Paleocene Fort Union Formation, just below the Waltman Shale Member. Isopach map is total thickness of coal in beds 2 feet thick or greater in the lower unnamed member.

Above the mudstone interval, from 478 to 860 ft on the measured section, is an interval containing distinctive tabular sandstones, interpreted by Flores and others (1992; 1994) as splay sandstone (pl. 2) that display trough-cross laminae, horizontal strata, and ripple-drift laminae. The base of this interval is in the upper part of palynomorph Zone P3, and the top is near the boundary between Zones P4 and P5, about 125 ft below the tongue of the Waltman Shale Member described later. At least 10 of these tabular sandstones, from 5 to 19 ft thick, were identified in this interval, and interestingly, the interval contains no channel sandstones (pl. 2). Crayfish burrows are abundant in some of the splay sandstones, and chert pebbles as large as 1.5 in. are present from 782-820 ft in a conglomeratic unit that crops out just south of the Castle Gardens road for a considerable distance.

The first fluvial channel sandstone is at 871 ft, in the lowermost part of the palynomorph Zone P5, and fluvial channel sandstones are the dominant type of sandstone in the remaining part of the Fort Union. Flores and others (1992) interpreted the channel sandstones to have been deposited by bedload streams that varied from deep and wide to shallow and narrow.

The thin tongue of Waltman Shale Member (also lower Zone P5) is present from 985 to 1,000 ft (figs. 26, 27, 28; pl. 2); the thin tongue is fissile, dark-brown in color, and contains fish scales. The tongue sharply overlies a trough-cross bedded, coarse-grained and conglomeratic sandstone of probable fluvial origin and is scoured out by another coarse-grained conglomeratic sandstone a short distance along outcrop in both directions. At the outcrop studied, the lacustrine shale grades up into silty shale through a 2-ft-thick interval. The presence of an offshore lacustrine shale tongue between two coarse-grained probable fluvial units indicates that there may have been marked fluctuations in lake level early in the history of Lake Waltman.

The section overlying the Waltman tongue consists of coarse-grained and conglomeratic sandstones as much as 41 ft thick, interbedded with gray shales, carbonaceous shales, and thin coal beds. Pebbles consist of varicolored chert, quartzite, and porcellanite as large as 2 in. Disaggregated rounded granite cobbles as large as 1 ft were observed at about 1,300 ft in the measured section, but none were found in place. Many of these cobbles surrounded an old fire pit and were probably brought in from elsewhere. The remeasured section was stopped at 1,637 ft, at the end of reasonably good exposures and in strata representing the upper part of the P5 palynomorph zone; this was about 650 ft stratigraphically below the end of the section measured by Flores and others (1992; 1994).

Coalbank Hills

A thickness of 1,841 ft of Fort Union was measured at Coalbank Hills (fig. 1, pl. 2), that did not include, because of poor exposures, approximately the uppermost 300 ft of the formation as mapped by Keefer (1970). The lower part of the section was measured in 2005 and the upper part was measured in 2004; an overlap of about 65 ft was measured both years and is shown on plate 2.

The lower member of the Fort Union at Coalbank Hills is 1,319 ft thick. A 92-ft-thick very fine- to fine-grained nonresistant white weathered sandstone, with troughs to 2 ft high and multiple zones of clayey ripups, marks the base of the formation. Overlying sandstones are mainly less than 32 ft thick and appear to consist of individual trough-cross bedded fluvial channel sandstones and much thinner, more persistent sandstones that are probably mostly crevass splay sandstones. An exception is a 78-ft nonresistent sandstone 127 ft below the top of the lower unnamed member, which has poorly developed bedding and forms a conspicuous white band along outcrop.

A Waltman Shale tongue is clearly visible in a gulley bottom on the east side of Dry Creek Road near SW ¼ sec. 2, T. 34 N., R. 88 W. (fig. 29, pl. 2, location map for Coalbank Hills). The section was measured on the west side of the road, because the Fort Union is better exposed there. Six thin tongues of probable Waltman Shale Member, 2 ft to 10 ft thick, are between 637 ft and 1,108 ft along the line of section. These tongues consist of fissile, fairly well-laminated dark gray to dark-brown organic-rich shale, similar lithologically to that at Castle Gardens and at the type section (Keefer, 1965), and are interbedded with sandstone, mudstone, and carbonaceous shale with thin coal beds (pl. 2). The 10-ft-thick Waltman tongue between 659-669 ft on the measured section (pl. 2) is probably the same tongue that is exposed on the east side of the Dry Creek Road, as both have sandstones both above and below. The underlying sandstone is very fine- to fine-grained with trough-cross strata as much as 1.5 ft high, and the overlying sandstone is highly bioturbated; these and other similar sandstones associated with the Waltman tongues may be both fluvial and marginal lacustrine. Other Waltman tongues in the section have mainly mudstone and carbonaceous shale above and below (pl. 2). A 14-ft conglomerate composed entirely of subangular to subrounded chert and quartzite pebbles as much as 0.25 in. in diameter is near the top of the measured interval. The interval is designated as Waltman Shale Member and Shotgun Member undivided, and contains both offshore lacustrine shales characteristic of the Waltman and marginal lacustrine and fluvial intervals characteristic of the Shotgun Member.

New Palynomorph Dates for the Fort Union Formation

The poorly drained fluvial and paludal conditions that had persisted throughout deposition of the lower unnamed member of the Fort Union Formation appear to have ended abruptly with the development of Lake Waltman. Jorjorian

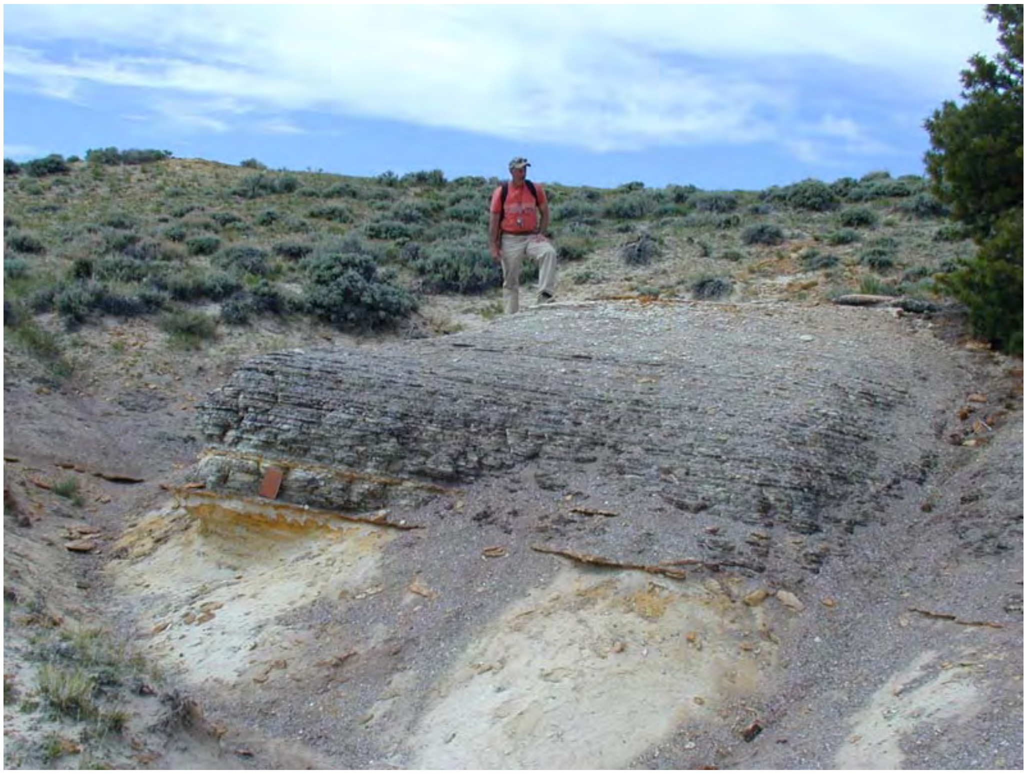

Figure 26. Photograph of thin tongue of Waltman Shale Member of the Paleocene Fort Union Formation at Castle Gardens measured section (pl. 2). Note 6-foot person and 5-by 8-inch notebook for scale

Figure 27. Photograph of thin tongue of Waltman Shale Member of the Paleocene Fort Union Formation at Castle Gardens measured section (pl. 2) showing sharp contact with underlying conglomeratic fluvial sandstone. Note 5-by 8-inch notebook for scale.

Figure 28. Photograph of thin tongue of Waltman Shale Member of the Paleocene Fort Union Formation at Castle Gardens measured section (pl. 2) showing overlying conglomeratic fluvial sandstone. Note 5-foot Jacob Staff for scale.

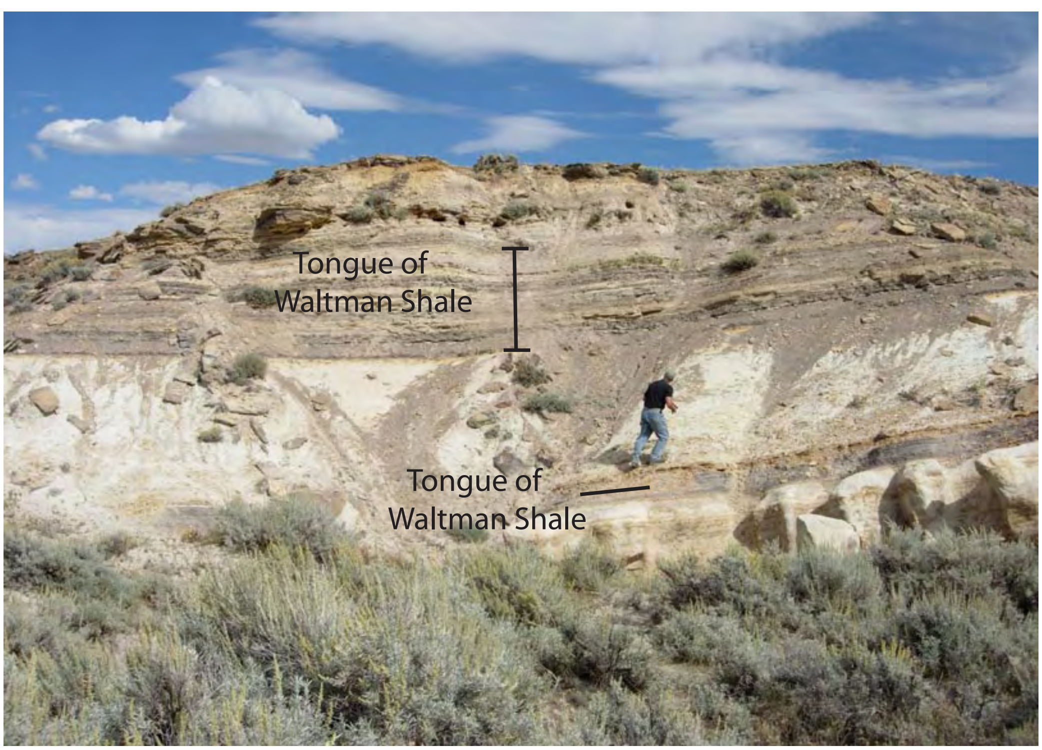

Figure 29. Photograph of tongues of Waltman Shale exposed in gulley bottom on east side of Dry Creek Road near Coalbank Hills (C-SW ¼ sec. 2, T. 34 N., R. 88W.).

and others (1989) estimated the depth of the lake to be at least 500 ft based on the relief of clinoform units around the lake margins. Prior to the present investigation, the base of the Waltman Shale Member had only been dated in outcrops near Waltman in the northeast part of the basin where the base of the Waltman is in the lowest part of palynomorph Zone P5 (Nichols and Ott, 1978). The discovery of the thin Waltman tongues as far south in the Wind River Basin as Castle Gardens provides evidence that Lake Waltman probably began and then expanded rapidly to near the basin margins during a fairly brief period early in Zone P5 time.

The above interpretation is supported by palynological studies of drill cuttings collected from coal beds in the uppermost part of the lower unnamed member of the Fort Union Formation from several wells in the Frenchie Draw Field (fig. 25). Analysis of palynomorphs by D. J. Nichols (written commun., U.S.G.S., 2004) indicate a Zone P5 for these strata (table 1). Frenchie Draw field is just south of the basin trough, near where the Waltman Shale is thickest (see Johnson and others, 1996, their fig. 62), and thus probably near where Lake Waltman first began to form. In addition, palynomorphs indicative of Zone P5 were identified from a 6 in. thick dirty coal 19 ft above the lowest Waltman tongue in the Coalbank Hills measured section (pl. 2, table 1). Thus the base of the Waltman Shale Member is in Zone P5 everywhere that has been dated thus far in the basin. Furthermore, at Castle Gardens, the base of the Waltman tongue is in the lowermost part of palynomorph Zone P5, about 120 ft above the base of the zone, which is about 950 ft thick here.

Summary Discussion

The buildup of marginal marine sandstones in the lower part of the Upper Cretaceous Mesaverde Formation along the east margin of the Wind River Indian Reservation, and the associated thick coal accumulation (locally over 120 ft), formed when the eastward retreat of the Cretaceous seaway stalled there for an extended period of time beginning in the earliest Campanian. Roehler, (1990, cross section H-H'; pl. 1) documented a similar, approximately correlative buildup of coal-bearing marginal marine sandstones in the Rock Springs Formation in the Green River Basin to the south, that trends generally northeast and appears likely to have extended across the present Wind River Range into the Wind River Basin (Johnson and others, 1996, fig. 66); (Tyler and Hamilton, 1994).

The Teapot Sandstone Member is considered a blanket sandstone, being nearly everywhere in the basin. Internally, the Teapot is a highly complex unit, consisting of fluvial sandstone in the western and southwestern parts of the basin and mixed fluvial and marginal marine rocks in the northeastern part. The apparent intertonguing of the middle member of the Mesaverde Formation and overlying Teapot Sandstone Member in the western part of the basin on the Wind River Indian Reservation, first described by Johnson and others (1996), indicates that the hypothesis by Gill and Cobban (1966) that a regional unconformity is present at the base of the Teapot may not apply in that area. Alternately, the intertonguing might be the result of reworking of sandstones from the middle member into the lower part of the Teapot Sandstone Member. Clearly, more work is needed to resolve this.

Reconstruction of the depositional setting of the Meeteetse Formation and the contemporaneous Lewis Shale indicates that the Lewis seaway was clearly deflected around the Wind River Range in response to early Laramide uplift. The Meeteetse Formation was deposited in a poorly-drained coastal plain setting southwest of the Lewis seaway; whereas, a sandier, better-drained fluvial setting developed immediately adjacent to the range.

Uplift of the Wind River Range continued during deposition of the Lance, and the Granite Mountains south of the basin also were a positive feature at that time. A rapidly subsiding trough formed near the present-day trough of the Wind River Basin, just south of the Owl Creek Mountains, where more than 6,000 ft of Lance was deposited. The initial development of this trough predated the onset of uplift on the adjacent Owl Creeks, but a mud-dominated facies that developed just south of the range late during Lance deposition might indicate that of the Cretaceous Cody Shale was then being eroded off the rising uplift.

The Paleocene Fort Union Formation unconformably overlies older units but with only slight discordance around much of the margins of the Wind River Basin; erosion was most pronounced toward the Wind River Range to the southwest, where the formation overlies progressively older strata and in places rests directly on the Cody Shale (pl. 5). The unconformities appear to die out toward the basin center. Coal-forming mires developed throughout the western part of the basin. A major river entered the basin from an apparent point source from the Wind River Range to the southwest and one or more rivers entered the basin from the Granite Mountains to the south; a muddy floodplain facies occupied the intervening area. A similar muddy facies developed along the deep basin trough during latest Cretaceous time, and expanded during the early part of the Paleocene.

Coal-forming mires reached maximum extent near the end of deposition of the lower member of the Fort Union Formation and just prior to the development of Lake Waltman. The drainage system off the Wind River Range continued during this period in about the same position, and the mud-dominated floodplain to the east was replaced by fluvial environments.

Lake Waltman first formed early in the period represented by Paleocene palynomorph Zone P5 time and expanded rapidly, in a geologic sense, across the coal-forming mires in the central part of the basin to near the basin margins. A thin tongue of Waltman Shale Member exposed near the south basin margin marks the maximum extent of Lake Waltman in that area. Elsewhere, the lake margins can only be extrapolated from subsurface data. As the lake retreated, lacustrine sedimentation was followed by marginal lacustrine and fluvial conditions.

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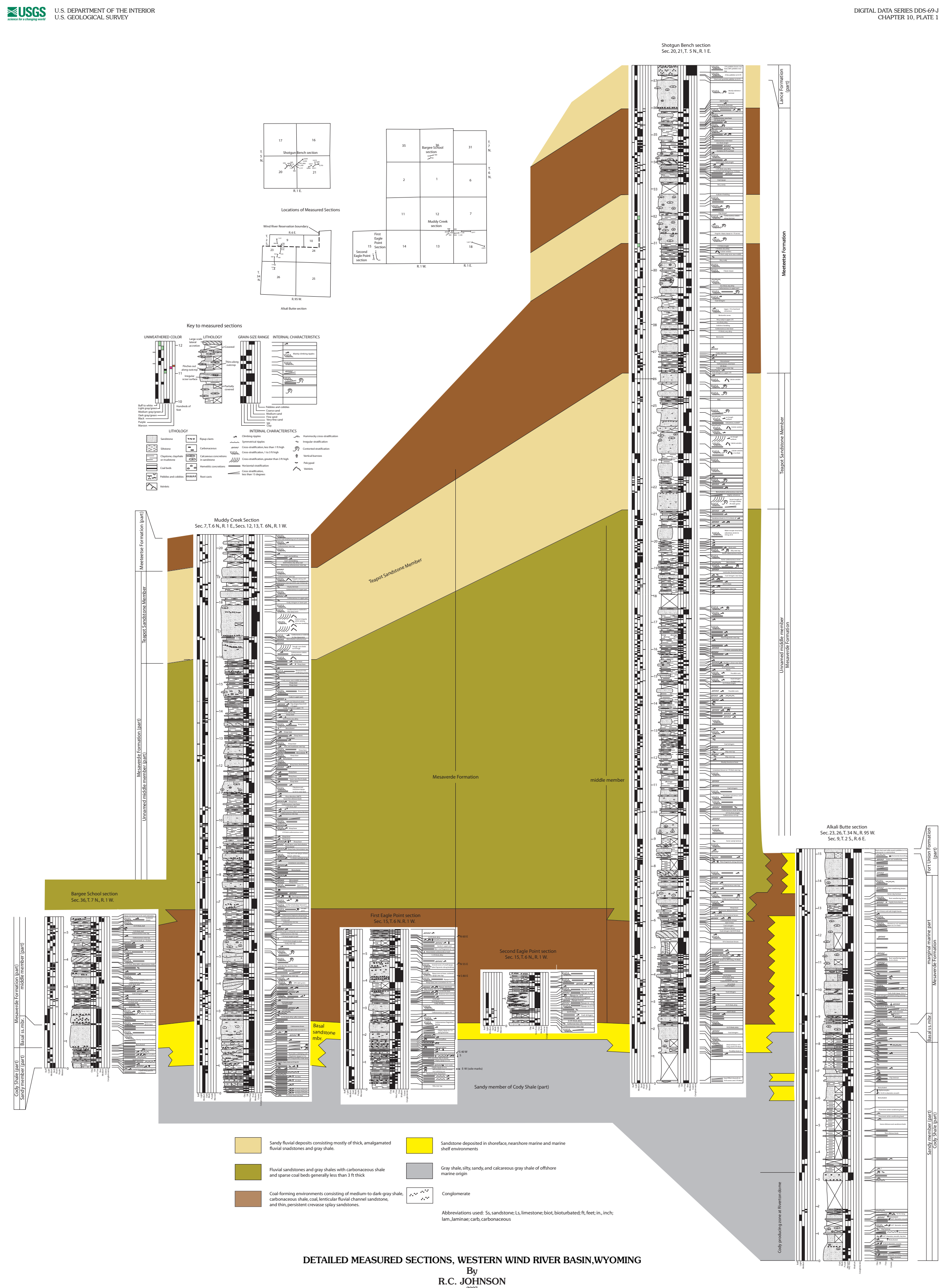

Plate 1. Detailed measured sections in the western part of the Wind River Basin. (Click on image to view and print full size).

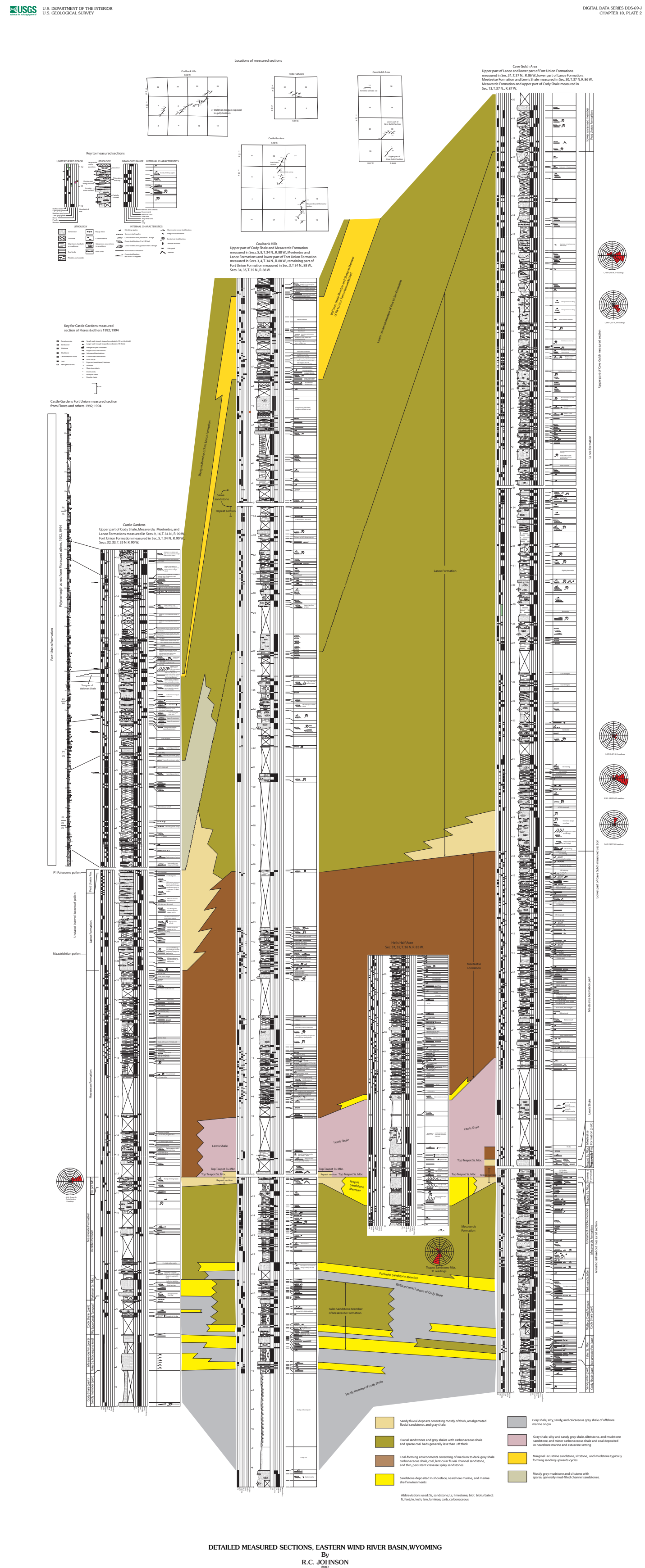

Plate 2. Detailed measured sections in the eastern part of the Wind River Basin. (Click on image to view and print full size).

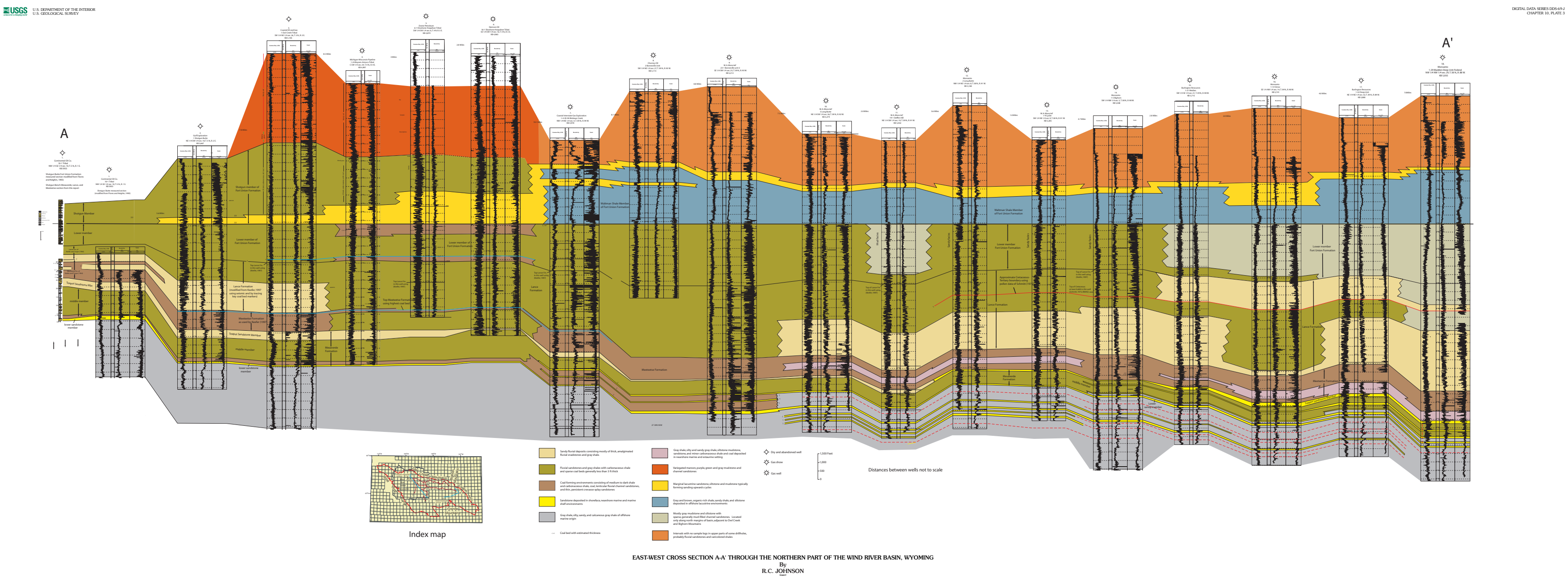

Plate 3. East-west cross section A-A′ through the northern part of the Wind River Basin. (Click on image to view and print full size).

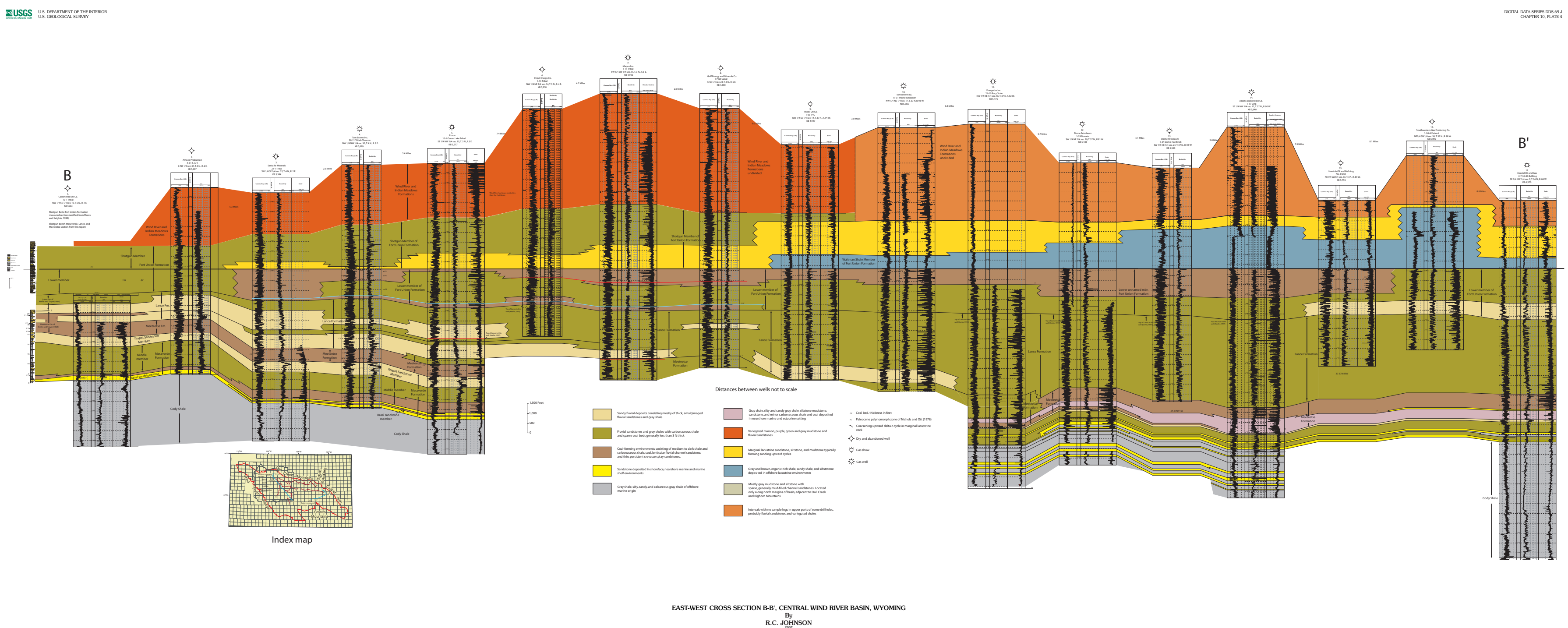

Plate 4. East-west cross section B-B′ through the central part of the Wind River Basin. (Click on image to view and print full size).

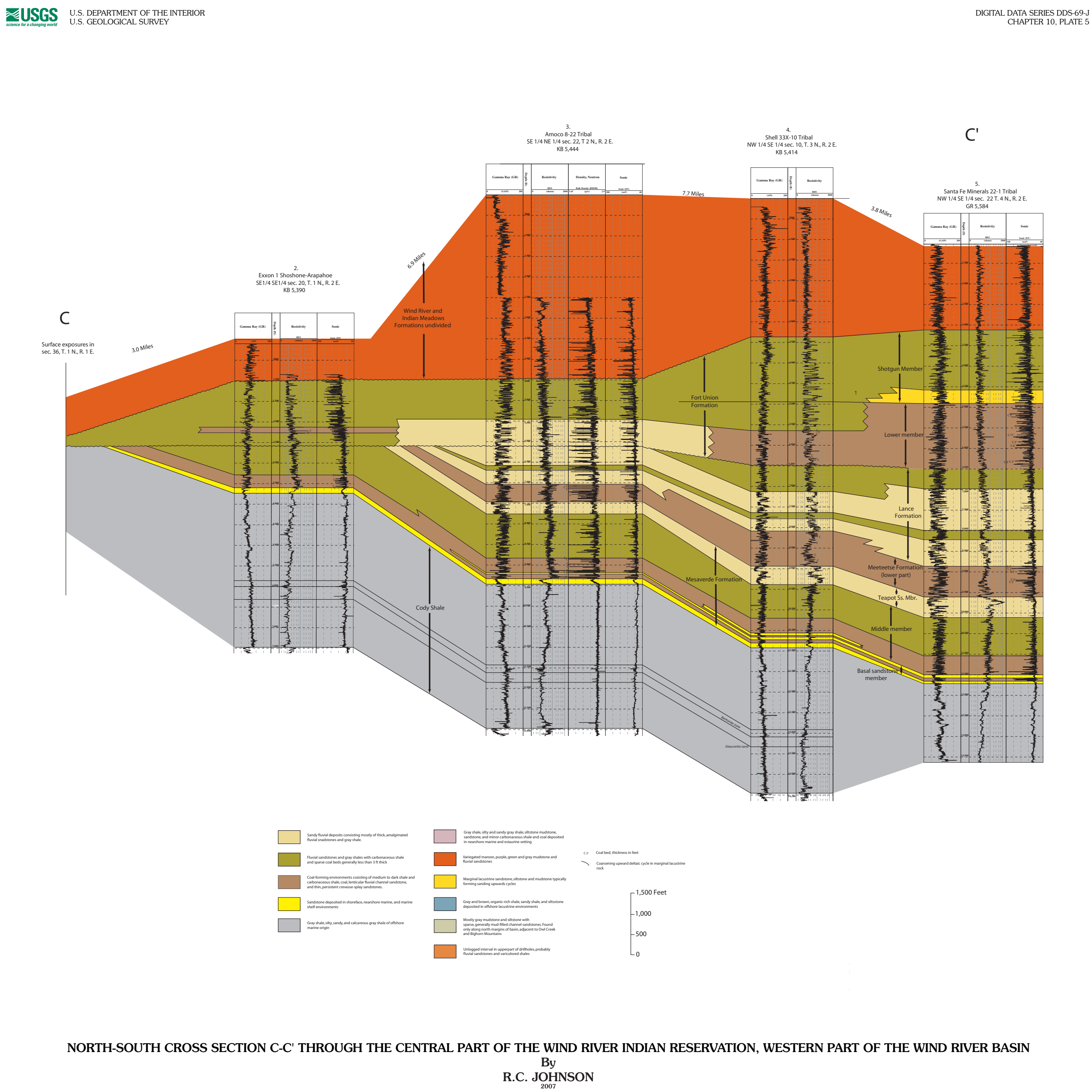

Plate 5. North-south cross section C-C′ through the central part of the Wind River Indian Reservation, western part of the Wind River Basin. (Click on image to view and print full size).

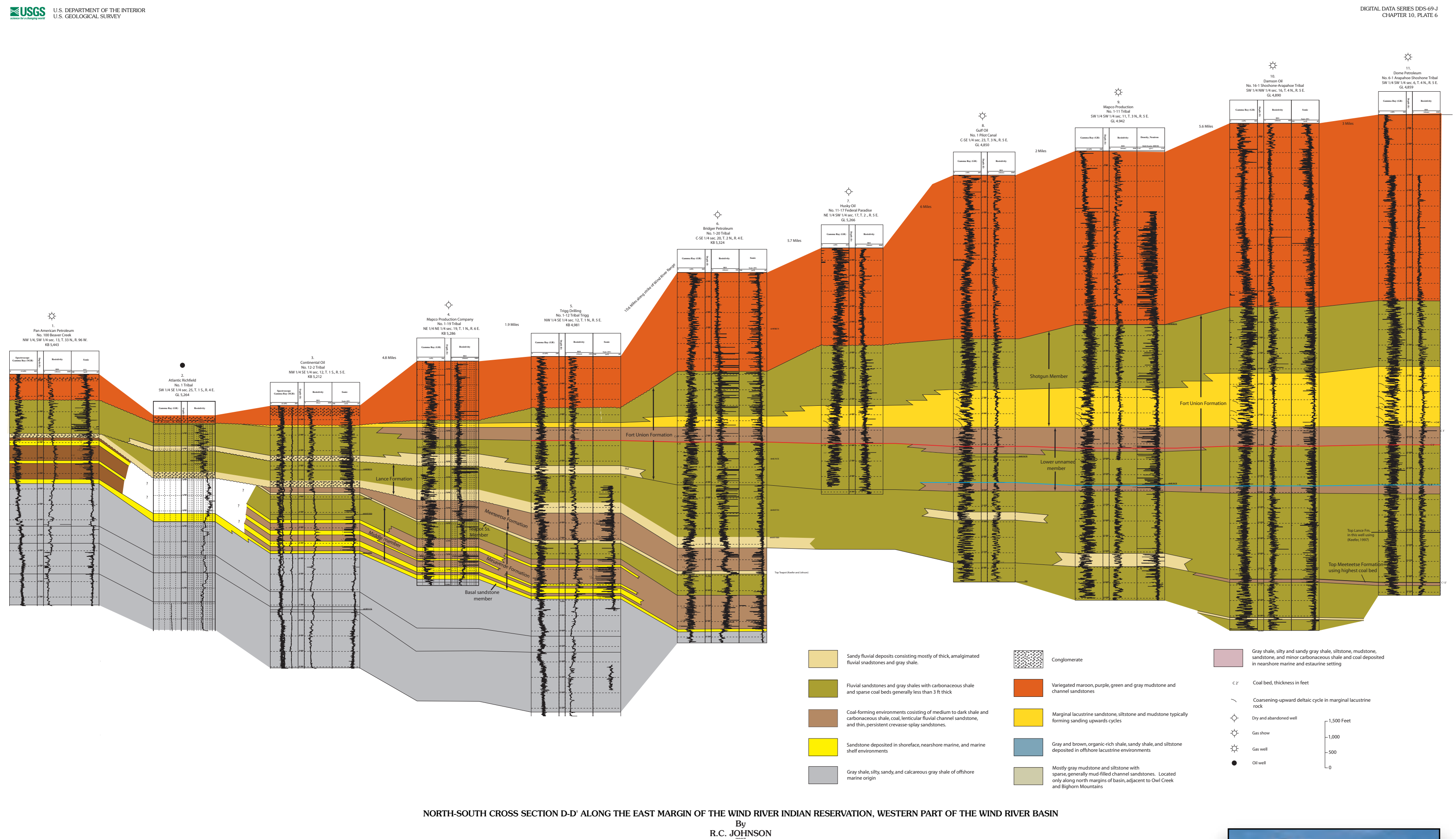

Plate 6. North-south cross section D-D′ along the east margin of the Wind River Indian Reservation, western part of the Wind River Basin. (Click on image to view and print full size).

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