Sedimentology and Depositional History of the Lower Paleocene Tullock Member of the Fort Union Formation, Powder River Basin, Wyoming and Montana

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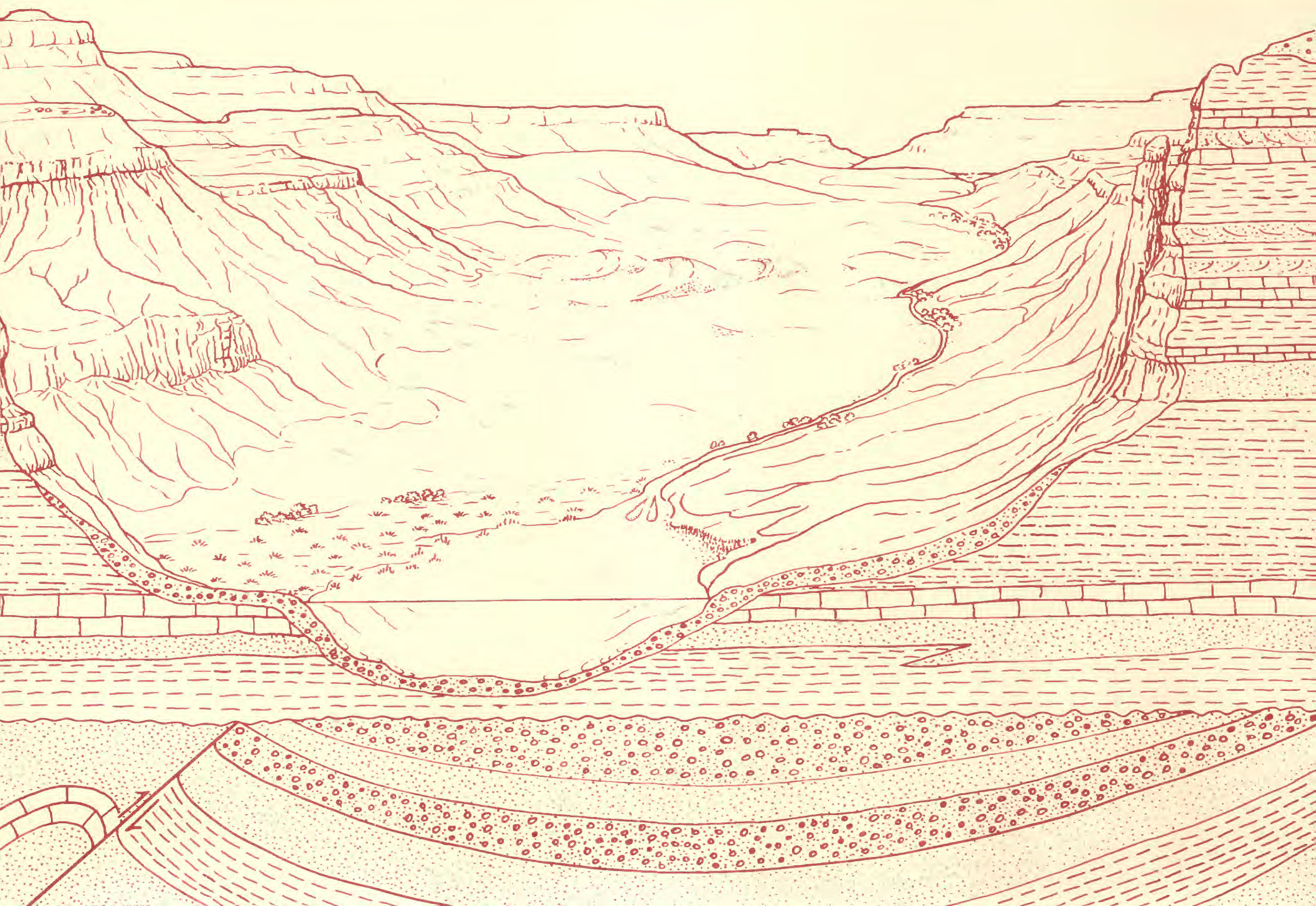

Chapter L

Sedimentology and Depositional History of the Lower Paleocene Tullock Member of the Fort Union Formation, Powder River Basin, Wyoming and Montana

By JANET L. BROWN

Depositional style of fluvial deposits during initiation of a Laramide foreland basin

U.S. GEOLOGICAL SURVEY BULLETIN 1917

EVOLUTION OF SEDIMENTARY BASINS—POWDER RIVER BASIN

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Sedimentology and Depositional History of the Lower Paleocene Tullock Member of the Fort Union Formation, Powder River Basin, Wyoming and Montana

By Janet L. Brown

Abstract

The Powder River Basin occupies a 22,000-mi^2 (35,000-km^2) area of northeastern Wyoming and southeastern Montana. Rocks of the Tullock Member (lower Paleocene) of the Fort Union Formation represent alluvial sedimentation in a Laramide intracratonic basin. The Cretaceous-Tertiary time line at or near the base of the Tullock provides temporal control for the timing and distribution of these basin infilling events. Tullock sediments have a maximum thickness of about 113 m (371 ft) in the north and 439 m (1,440 ft) in the south. The infilling Tullock clastic sediments merged eastward with distant delta-plain systems containing aggrading distributary channels that flowed into the Cannonball epicontinental sea.

The Tullock Member was deposited in a continental fluvial environment. Channel deposits (comprising about one-third of the sequence) contain mainly trough and tabular planar crossbedded and climbing-ripple laminated sandstone; reactivation surfaces, liquefaction fronts, and structures resulting from soft-sediment deformation are also common, suggesting episodic rapid deposition, saturation of sediments, and a high watertable. Fine-grained overbank deposits (making up about two-thirds of the sequence) show color mottling, contain plant, wood, and coal fragments, have obscure bedding or no apparent internal structure, and contain thin coal beds.

Tullock sandstone geometry and sedimentary structures suggest bankfull depths equal to paleochannel thickness, low fluvial gradient, low sinuosity, highly stable vegetated banks, and lenticular channel form. Channel systems carried predominantly suspended loads on mature low-gradient flood plains. Mud-dominated sediment moved through Tullock fluvial channels principally by downstream aggradation by bar construction, and build-up of the floodplain over low levees by overbank flooding, depositing mainly suspended material.

Sedimentary structures and geometry of Tullock sediments suggest deposition in anastomosed river systems. Carbonate clasts in the lowermost part of the Tullock in the northwestern part of the basin suggest the beginning of doming and stripping of Paleozoic and Mesozoic strata from the area of the future Bighorn Mountains. Contemporaneously, coal-forming environments indicated by carbonaceous zones and coal beds spread from the southeast to the northwest across the basin in early Paleocene time. A likely control of peat accumulation was a temporary readvance of the Cannonball sea (a part of the Western Interior Seaway), which raised base level and locally reduced the gradient in the southeastern part of the basin. The reduced gradient promoted river aggradation, ponding, and swamp formation, and created anastomosing river systems having low sinuosity.

INTRODUCTION

The Powder River Basin occupies a 22,000-mi^2 (35,000-km^2) area of northeastern Wyoming and southeastern Montana (fig. 1).

Terrigenous basin-fill of Tertiary age consists of clastic rocks of the Paleocene Fort Union Formation and the Paleocene and Eocene Wasatch Formation, which together attain a maximum thickness of 2,000 m (6,560 ft) along the basin axis. In the Powder River Basin, the Fort Union Formation includes, from oldest to youngest, the Tullock Member, the Lebo Member, and the Tongue River Member (Dobbin and Horn, 1949). In Wyoming, the sedimentary record of Laramide basins indicates that Laramide deformation began during Late Cretaceous time (65–75 Ma) (Dickinson and others, 1988; Perry and others, 1990). Rates of Laramide uplift varied from place to place through the latest Cretaceous and Tertiary, supplyng detritus to the Powder River Basin and other foreland basins. The Tullock Member represents part

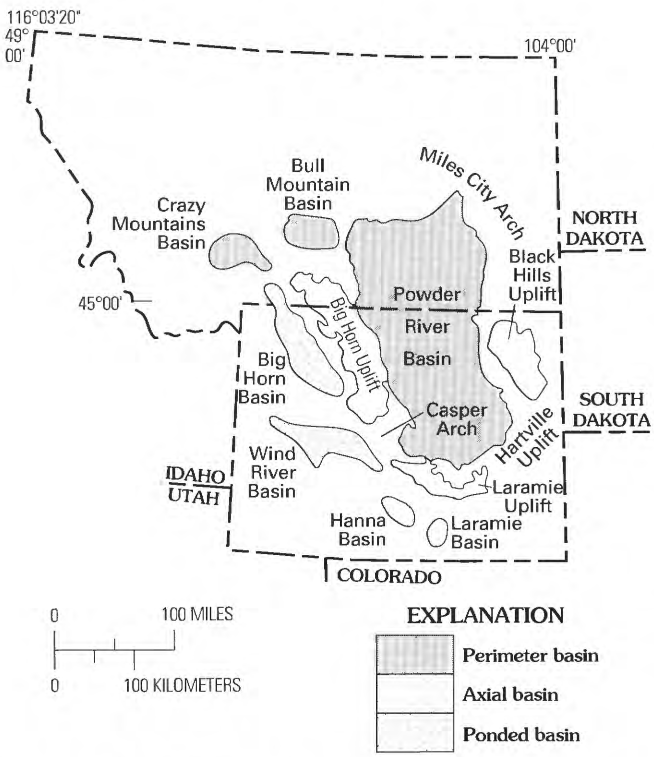


Figure 1. Index map of Powder River Basin showing structural setting, Laramide tectonic features, and classification of basins (modified from Dickinson and others, 1988). Outline of Powder River Basin is taken as base of Tullock Member of Fort Union Formation and Cretaceous-Tertiary boundary

of the deposits of an extensive alluvial system that existed during this time.

The purpose of this study is to reconstruct the history of Tullock deposition on the basis of sedimentological, palynological, stratigraphic, and petrologic data. These reconstructions can be used for hydrologic and resource predictions within the Powder River Basin and can provide an analogue for deposition in other foreland basins.

Acknowledgments.—The last year of field work was greatly enhanced by the assistance of D. J. Nichols and K.J. Franczyk. I thank Nichols for palynological analyses and P.L. Hansley for petrologic analyses. I thank C.T. Pierson for the structure contour map that appears as figure 2 of this report. I greatly appreciate the kindness and generosity of Jackie and Newell Redding, who allowed me to camp on their land and offered their friendship, and of Alice Hope, who gave permssion to work in the Burnt Creek area as well as sharing stories of first homesteading the land with her late husband. Nichols and I greatly appreciate the efforts of Corky Oldhorn, Crow Indian Reservation, who permitted us access to Indian lands for our field work. I am indebted to the kindness and hospitality of Jean Hough, who shared her friends and home with me while I was in Broadus, Mont.

REGIONAL STRUCTURAL SETTING

The Powder River Basin is bounded structurally on the northeast by the stable interior craton of North America. Elsewhere it is bounded by uplifts of the Late Cretaceous and Tertiary Laramide orogeny: the Miles City arch (Cedar Creek anticline) and Black Hills uplift on the east; the Hartville uplift, Laramie uplift, and Casper arch on the south and southwest; and the Bighorn uplift on the west (fig. 1). These structures generally reflect regional east-west shortening. The Basin is classified as a perimeter basin by Dickinson and others (1988). It is characterized by arcuate Laramide structural elements on the west and south and gentle structural relief along its eastern flanks, which merge into the stable continental craton. Previous studies have suggested that the structural development of the Powder River Basin and bounding Bighorn uplift began in early middle Paleocene time and continued through late Eocene time (Coney, 1972; Blackstone, 1975, 1986; Gries, 1983). By that time, the Sevier orogeny was waning in western Wyoming and on the eastern edge of the Great Basin in Utah, and the folding and eastward overthrusting of older strata over younger foreland rocks was largely completed (Armstrong, 1968). Laramide deformation commenced to the west and southwest of Wyoming before marine deposition had ended in the northeast. Large and deep structural basins formed concurrently with the Laramide uplifts through Eocene time (Tweto, 1975; Dickinson and others, 1988). New data from this study suggest that the uplift of the Bighorn block, which directly influenced down-warping and sediment infilling of the Powder River Basin, began in earliest Paleocene time (Brown, 1985; Brown and Hansley, 1989; Brown and Nichols, 1989). Basin fill derived from Laramide uplifts consisted mainly of stream deposits and included local paludal or lacustrine facies.

REGIONAL STRATIGRAPHY

The Tullock Member consists of fine-grained sandstone, sandy siltstone, shale, rare thin limestone, and coal. Analysis of structure contours constructed to show the top of the Lance Formation in the Powder River Basin shows asymmetrical foreland basin subsidence that suggests crustal shortening from west to east (fig. 2). The structure contours were computed by C.T. Pierson from unpublished well log data compiled by N.M. Denson, D.L. Macke, and R.R. Schumann, and they complement regional structure and thickness maps of selected Precambrian through Tertiary formations in the Powder River Basin (Crysdale,1990). The Tullock Member is an important regional aquifer for eastern Montana and Wyoming and also serves as a source of low-sulfur coal for local consumption. Figure 3, modified from Lewis and Hotchkiss (1981), is a regional isolith map showing cumulative sandstone thicknesses and serves to predict locations of

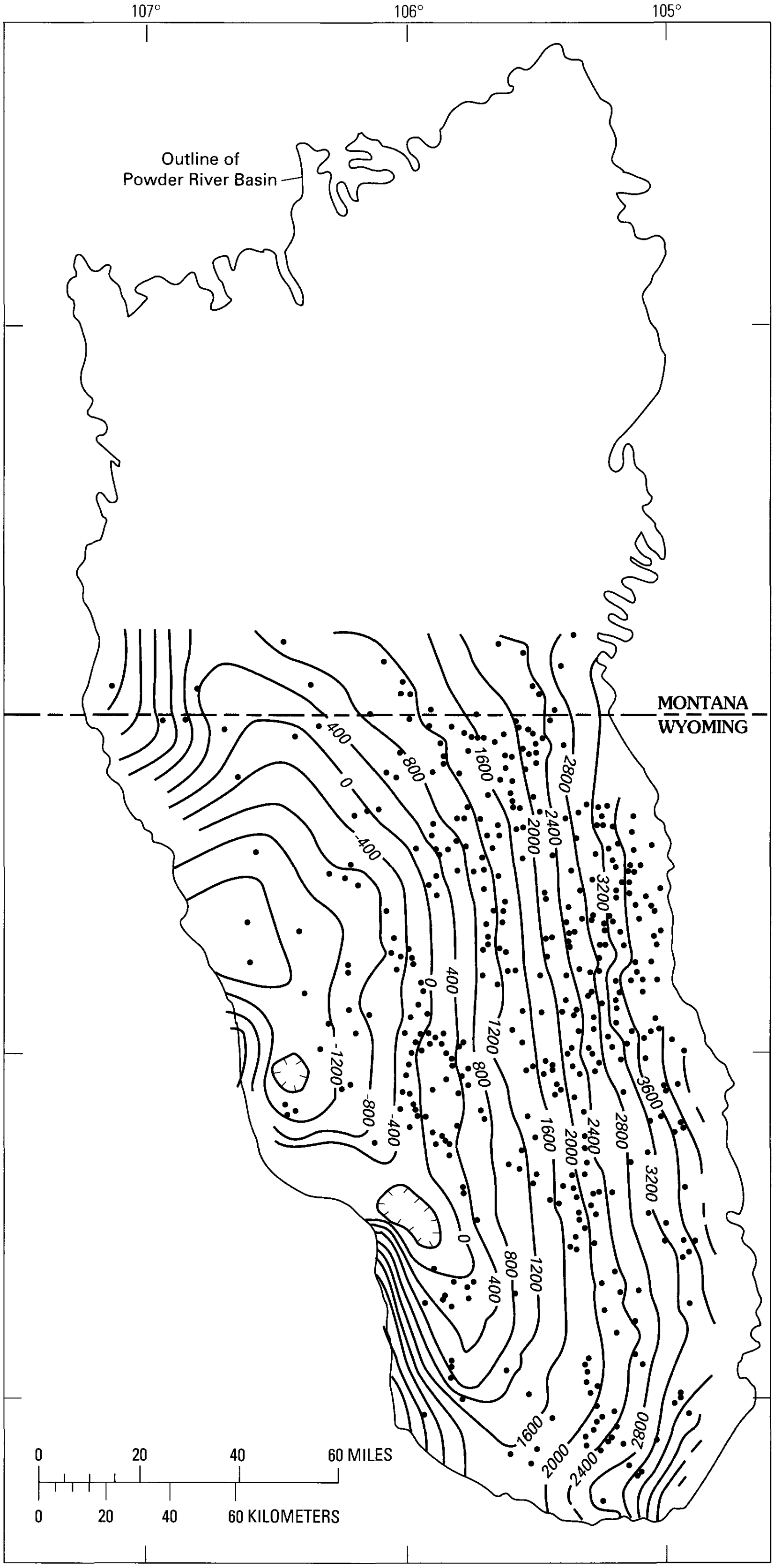


Figure 2. Regional structure-contour map showing top of Lance (Hell Creek) Formation (base of Tullock Member of Fort Union Formation). Map by C. T. Pierson from unpublished borehole data (dots) of N. M. Denson. Contour interval is 400 ft.

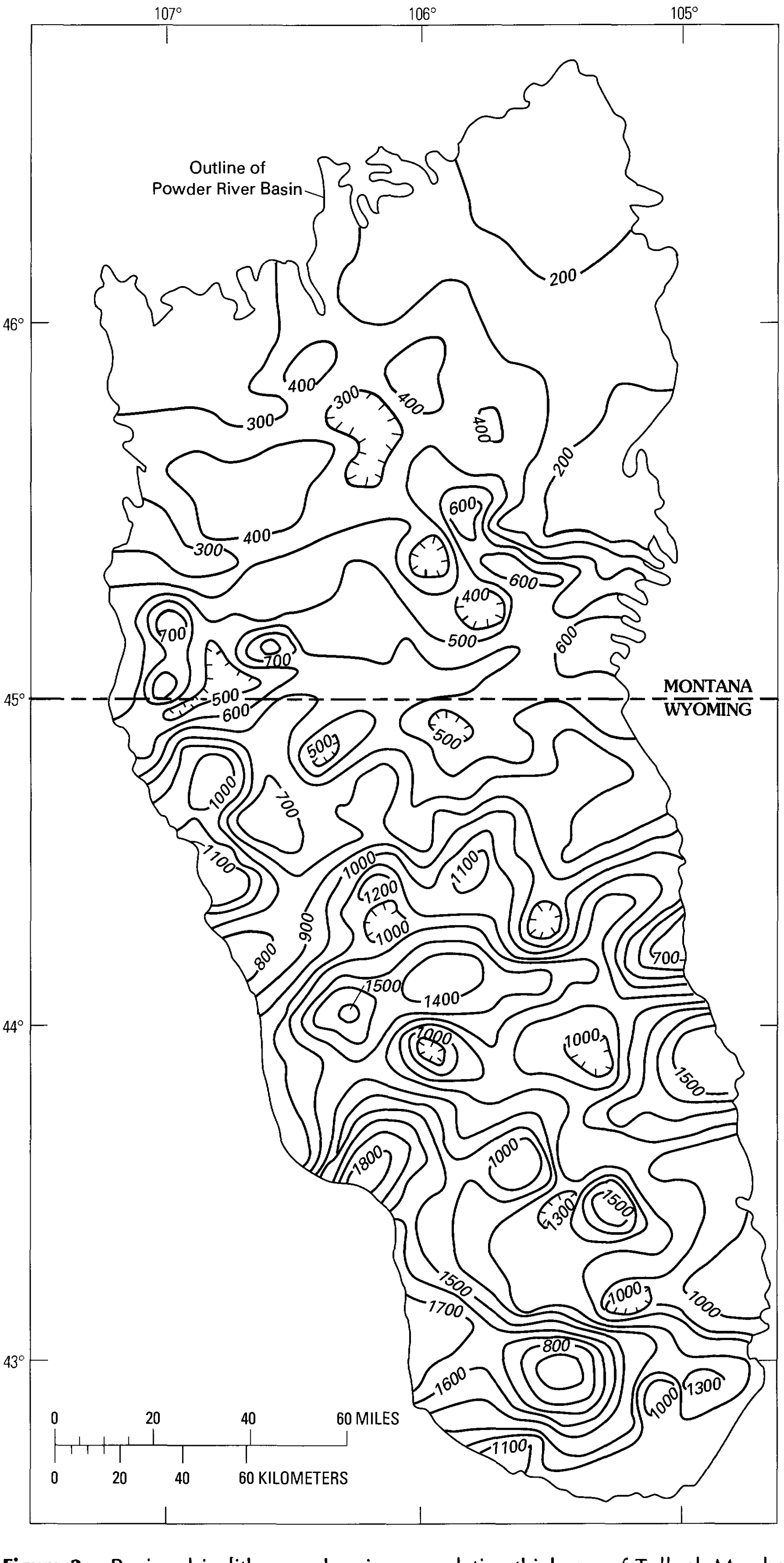


Figure 3. Regional isolith map showing cumulative thickness of Tullock Member sandstone in Powder River Basin (modified from Lewis and Hotchkiss, 1981). Contour interval is 100 ft.

aquifers and coal zones in the subsurface. The Tullock Member ranges in thickness from 113 m (370 ft) in the northwestern part of the basin to 439 m (1,440 ft) in the southeast (appendix 1).

The Tullock overlies the Upper Cretaceous and locally Paleocene Hell Creek Formation in Montana and the equivalent Lance Formation in Wyoming. It underlies the Lebo Member of the Fort Union Formation in both States (fig. 4). The three members of the Fort Union Formation are difficult to distinguish from one another everywhere in the basin owing to changes in lateral facies or contact relationships.

Pertinent regional studies of the Tertiary stratigraphy of the Powder River Basin are found in Denson and Pipiringos (1969), Lewis and Hotchkiss (1981), Ayers and Kaiser (1984), Flores and Ethridge (1985), and Ayers (1986). The Lance Formation was named by Stone and Calvert (1910). Brown (1907) named the "Hell Creek beds" and Thom and Dobbin (1924) assigned the Hell Creek to the Lance Formation as its lower member. In 1923, the Tullock Member was named for outcrops on Tullock and Sarpy Creeks, Treasure County, Mont., by Rogers and Lee (1923). They divided the Lance Formation into two parts: an upper coal-bearing member named the Tullock Member and a lower, undifferentiated part that contained no coal. Simpson (1937), using land-mammal biostratigraphy, assigned beds that were the true dinosaur-bearing Hell Creek to the Cretaceous; he designated as Tertiary the overlying beds that contained no dinosaurs but did contain mammals of Tertiary type. He also supported the acceptance of the Paleocene as a separate Tertiary epoch distinct from the Eocene. However, until the early 1940's it remained uncertain whether the Tullock Member was Late Cretaceous or Paleocene in age. Dorf (1942) assigned a Paleocene age to the Tullock Member on the basis of fossil flora of typical Paleocene Fort Union aspect by correlation from the nearby Gillette coal field. Related Tertiary studies conducted in the Lance Creek area for the purpose of classifying public lands and evaluating possible economic coal fields include Shaw (1909), Winchester (1912), Dobbin and others (1957), Sharp and Gibbons (1964), Denson (1974), and Denson and others (1978).

Underlying the Tullock Member are the nonmarine, mostly Upper Cretaceous Lance (Wyoming) and Hell Creek (Montana) Formations. The Lance is characterized by thick sandstone, carbonaceous shale, sandy shale, siltstone, and mudstone, its lithologic character varying greatly from place to place. In the northern part of the Powder River Basin, the Hell Creek was deposited in alluvial plain and large-scale fluvial systems. In much of the rest of the basin, the units are characterized by numerous dark carbonaceous shale beds and thin coal seams, indicating deposition in ephemeral lakes and peat swamps or mires in interfluve areas. In the type area of the Lance Formation, located in the southeastern part of the Powder River Basin, ceratopsian dinosaur

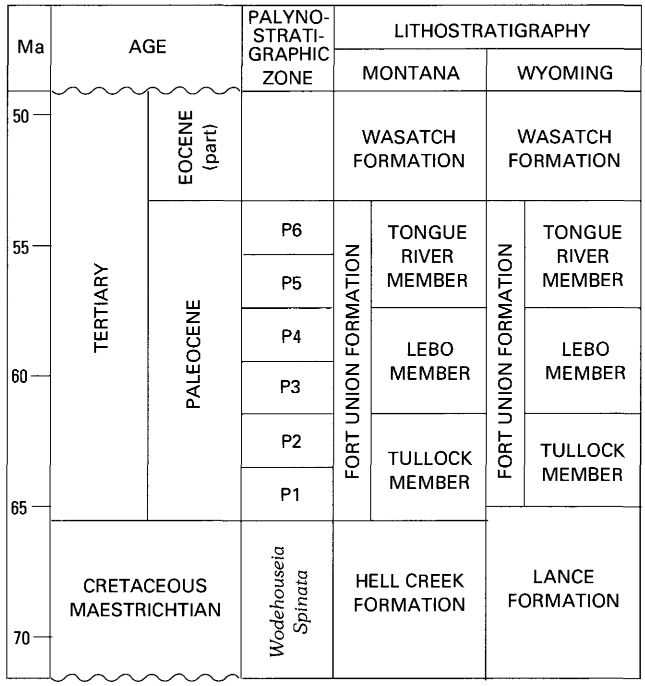


Figure 4. Generalized stratigraphic chart for the latest Cretaceous and early Tertiary, Powder River Basin, Wyo. and Mont., showing formations, members, and palynostratigraphic zones. Zones are from Nichols and Ott (1978) and Nichols and others (1982).

remains and important Lancian land mammals (Clemens, 1963) were found.

The contact of the Tullock Member with the underlying Lance and Hell Creek Formations in the Powder River Basin is gradational through a predominantly shaley interval, but there are coal zones in the interval in many places. Tullock sandstone bodies do not differ greatly from those in the Lance and Hell Creek Formations except that they are yellowish, thinner, and more lenticular, and they contain no conglomeratic layers. The lithologic base of the Tullock Member in the Powder River Basin is close to, but only in some places coincident with, the Cretaceous-Tertiary (K-T) time boundary. The biostratigraphically defined boundary is characterized in the Powder River Basin by abrupt disappearances of characteristic Upper Cretaceous palynofloral species and changes in the relative abundances of major groups within the palynoflora (Nichols and Brown, 1989b; Nichols and others, 1992). The formation contact is characterized by the "lowermost persistent coal bed" or a subtle color change from greenish of the Lance Formation to yellowish of the Tullock Member (Rogers and Lee, 1923). A unique clay layer at the K-T boundary, first decribed by Orth and others (1981) as found in nonmarine rocks in the Raton Basin, N. Mex., has been found in three places in the Powder River Basin. The boundary clay layer contains an anomalous concentration of iridium, shock-metamorphosed minerals, and sparse goyazite spherules (Bohor and others, 1987; Wolfe and Izett, 1987; Nichols and others, in press). The abrupt disappearance of characteristic palynofloral species defines the K-T boundary, but neither the clay layer, nor the change in color, nor the lowermost persistent coal bed provides reliable markers for identifying the time line in the absence of biostratigraphic evidence. In the Tullock reference section of the northwestern Powder River Basin, the K-T boundary is about 4.3 m (14 ft) below the lowermost persistent coal bed of Rogers and Lee (1923) and 3.3 m above the color change (Brown and Nichols, 1988).

In the Lance type area in the southeastern Powder River Basin, Simpson (1929) collected, described, and interpreted new specimens of Lance mammals. This work on the mammal faunas was then enlarged and detailed by Clemens (1963), who placed the formation contact at the base of the first persistent coal bed above the highest dinosaur bones. Leffingwell (1970), searching for a reliable means of identifying the boundary, restudied Clemens' section and found a change in palynomorph assemblages from Cretaceous to Tertiary about 9.5 m (31 ft) below Clemens' contact. Bohor and others (1987) precisely located the change in palynomorph assemblages 4–7 cm below a thin coal bed near the area studied by Leffingwell (1970).

In the southwestern Powder River Basin, Wolfe and Izett (1987) reported a K-T boundary clay layer in the Teapot Dome area (see the measured section for the Teapot Dome area, pl. 3, this report). Nichols and Brown (1989a) discovered a fourth K-T boundary site that contained a very high concentration of iridium and shocked quartz. This site is described in detail by Nichols and others (in press). The boundary clay layer and abrupt change in palynomorph assemblages occurs together at the base of the lowermost persistent coal bed in the Sussex area. This is the only location in the basin where the coal bed, the K-T boundary layer, and the abrupt change in composition of palynomorph assemblages are congruent.

The contact of the Tullock Member with the overlying Lebo Member was first described from its occurrence in the Crazy Mountains 201 km (125 mi) west of the Tullock type area (Stone and Calvert, 1910). The Lebo of the northern Powder River Basin is generally represented by dark-gray to olive-gray shale containing rare beds (as thick as 3 m, or 10 ft) of gray arkosic sandstone. Many calcareous paleosol horizons are present in the Lebo as indicated by discontinuous but distinctive zones of white banding. Some coal beds, a few thicker than 0.5 m (2 ft), occur in the Lebo and form clinker horizons in the southern Powder River Basin. The Lebo Member ranges in thickness from 152 m (499 ft) in the northwestern basin to about 518 m (1,700 ft) in the southwestern basin (Law, 1975; Lewis and Hotchkiss, 1981). In outcrop, the Lebo is represented by rolling grassland interrupted by small areas of badlands.

METHODS OF STUDY

Methods of study included well-log analysis, outcrop observations and data from measured sections, palynological investigations, and petrologic analyses of selected thin-sections from sandstone beds of the Tullock.

Analysis of Log Profiles

This study emphasizes subsurface data because of the generally poor quality of outcrop of the Tullock Member in the Powder River Basin. The objectives of the subsurface analyses were to identify and correlate basin-wide facies of the Tullock (pls. 1–3). The subsurface data helped in selection of specific outcrop sites for field studies. The basal contact of the Tullock Member was identified in selected logs, which were then arranged in four subsurface transects oriented perpendicular to the inferred paleoslope of Cherven and Jacob (1985). The subsurface transects were selected by analysis of the isolith map of Lewis and Hotchkiss (1981); where the individual sandstone beds as determined from well-log interpretation are added together cumulatively and the total percent sand shown by contours. In this study, the four transects were located along the highest total percent sand. However, the isolith contours do not necessarily represent a single thick, continuous sandstone body, but rather overall percent sand in the section irrespective of individual bed thickness.

Published studies of the subsurface by Curry (1969, 1971), Lewis and Hotchkiss (1981), and Ayers (1986) served as useful guides for study of the Tullock. Logs penetrating the Tullock showed spontaneous potential and short normal-induction resistivity calibrated for oil and gas exploration. The fast sond speed used for this type of exploration cannot accurately detect the highly variable lithologic changes typical of continental systems. No gamma logs are available for rocks younger than Cretaceous.

The well-log signature used to mark the base and top of the Tullock is a wide separation between components of the short normal-induction curve of the resistivity trace. The base of the Tullock within each transect, as determined by log signature, is assigned a common datum elevation. Uncertainties about the absolute elevations of surfaces on which the Tulllock was deposited and lack of subsurface geochronologic control during the accumulation of Tullock sediments in the Powder River Basin makes it difficult to establish a subsurface datum that reliably reflects pre-Tullock topography.

The lower and upper contacts of the Tullock Member in outcrop do not coincide with the subsurface contacts. The lithologic contacts as shown by the well logs represent only the boundaries between fine-grained strata and sandstone bodies of high porosity and permeability that serve as freshwater aquifers. Coal beds mark the base and top of the

Tullock in outcrop, but coal beds are not accurately identifiable in the subsurface in the absence of gamma logs. No cores, cuttings, or lithologic logs are available for the Tullock interval of the Powder River Basin. A type log was generated showing well-log signatures that identify the Tullock Member in the Powder River Basin (fig. 5).

There is no separation of components of the resistivity curve between the log signatures for the Lebo Member above, or the Lance Formation below, the Tullock. In contrast, logs of the Tullock show a wide separation of components in the resistivity curve and this is related to the presence of freshwater. A diagrammatic lithologic section was derived from the interpretation of each log showing rock type and relative amounts of inferred channel sandstone and overbank mudstone. The resolution of the subsurface analyses was limited by sparse areal log coverage, which proved inadequate in detailing fluvial geometry. The subsurface transects supplement the regional Powder River Basin framework studies developed by Fox (1988) and Crysdale (1990).

Outcrop Studies and Sampling

The field data for this study consisted of observations and measurements from measured sections in four selected sites correlated directly to adjacent subsurface log profile transects (fig. 6): the northwestern Powder River Basin (Tullock Creek), the northeastern Powder River Basin (Little Powder River), the southeastern Powder River Basin (Lance Creek), and the southwestern Powder River Basin (Teapot Dome).

The stratigraphic interval studied includes the uppermost part of the Lance and Hell Creek Formations, the Tullock Member, and the lowermost part of the overlying Lebo Member of the Fort Union Formation. Stratigraphic sections were measured with a Brunton compass, Jacob's staff, Abney level, and steel tape. Sedimentary structures offering reliable paleocurrent trends were rare, but, where possible, measurements were made from axes of large trough cross-beds. These data are shown on the graphic logs of the measured sections (figs. 11, 14, 18, and 23). Although limited exposure prevented more than one measurement per set and, at most, three to five measurements per exposure, I consider the paleocurrent data to be reliable.

In general, outcrops are unconsolidated and discontinuous, preservation of sedimentary structures is poor, lateral trends of lithofacies are difficult to follow, and less than 30 percent of the total vertical section is exposed. It was not possible to measure closely spaced sections or to describe higher resolution, three-dimensional facies relationships in detail. Terminology for thickness of beds follows McKee and Weir (1953), and that for stratification and bedding follows Blatt and others (1980). Graphic logs of the measured sections in each of the four areas illustrate lithofacies types, architectural elements, and inferred depositional environments. Lithofacies classification (fig. 7) was adapted from Allen (1965) and Miall (1985). Eleven lithofacies were identified.

Megafossils are not abundant in the Tullock Member, but palynomorphs are, and palynological analysis proved useful for biostratigraphy in this study. Sampling for palynology included 146 samples from 16 localities. Locations of sections and samples for palynological data are listed in appendix 3. Detailed analyses are presented in Nichols and Brown (1992). In addition to the samples from the Tullock Member, about 50 samples were collected from the underlying Hell Creek and Lance Formations and a few from the overlying Lebo Member of the Fort Union Formation.

Although identifying the source of Tullock clastic sediments was not the primary objective of this study, the study included reconnaissance sampling for petrologic analysis. Changes in sandstone mineral composition reflecting distance and timing of uplifts that bounded the basin were plotted using the K-T boundary as a time line. Nine thin sections were prepared from samples collected from measured sections in three of the four study areas in the Powder River Basin: the northwestern, southwestern, and southeastern. Samples from the three areas were taken from channel sandstone of the lower, middle, and upper parts of the Tullock Member. Localities of thin section samples in the measured sections are noted in appendix 2. Figure 8 shows the vertical and lateral compositional changes as determined from thin-section analyses (Hansley and Brown, in press).

Tullock sandstone is very friable; large samples were collected and all required impregnation with epoxy. The thin sections were then stained with sodium cobaltinitrate to aid in identification of potassium feldpar and with Alizarin Red-S to aid in identification of calcite. The Gazzi-Dickinson method of point counting was used for determination of petrographic modes because fine-grained sandstone predominates and the method maximizes information regarding source rocks in tectonically active terranes (Dickinson, 1970; Ingersoll and others, 1984). Greater than 300 point counts were performed on each thin section to determine modal mineralogy, and 100 point counts were performed on each thin section to determine grain size and sorting.

DESCRIPTIONS OF THE FOUR STUDY AREAS

Northwestern Powder River Basin—Tullock Creek and Lodgegrass Areas

The Tullock Member was named by Rogers and Lee (1923) and a reference section established from exposures in Tullock Creek and Sarpy Creek in Treasure County, Mont., in the northwestern Powder River Basin. Recent studies in the area include Thom and others (1935), Lewis and Roberts (1978), Mapel and Griffith (1981), Kanizay (1986), and

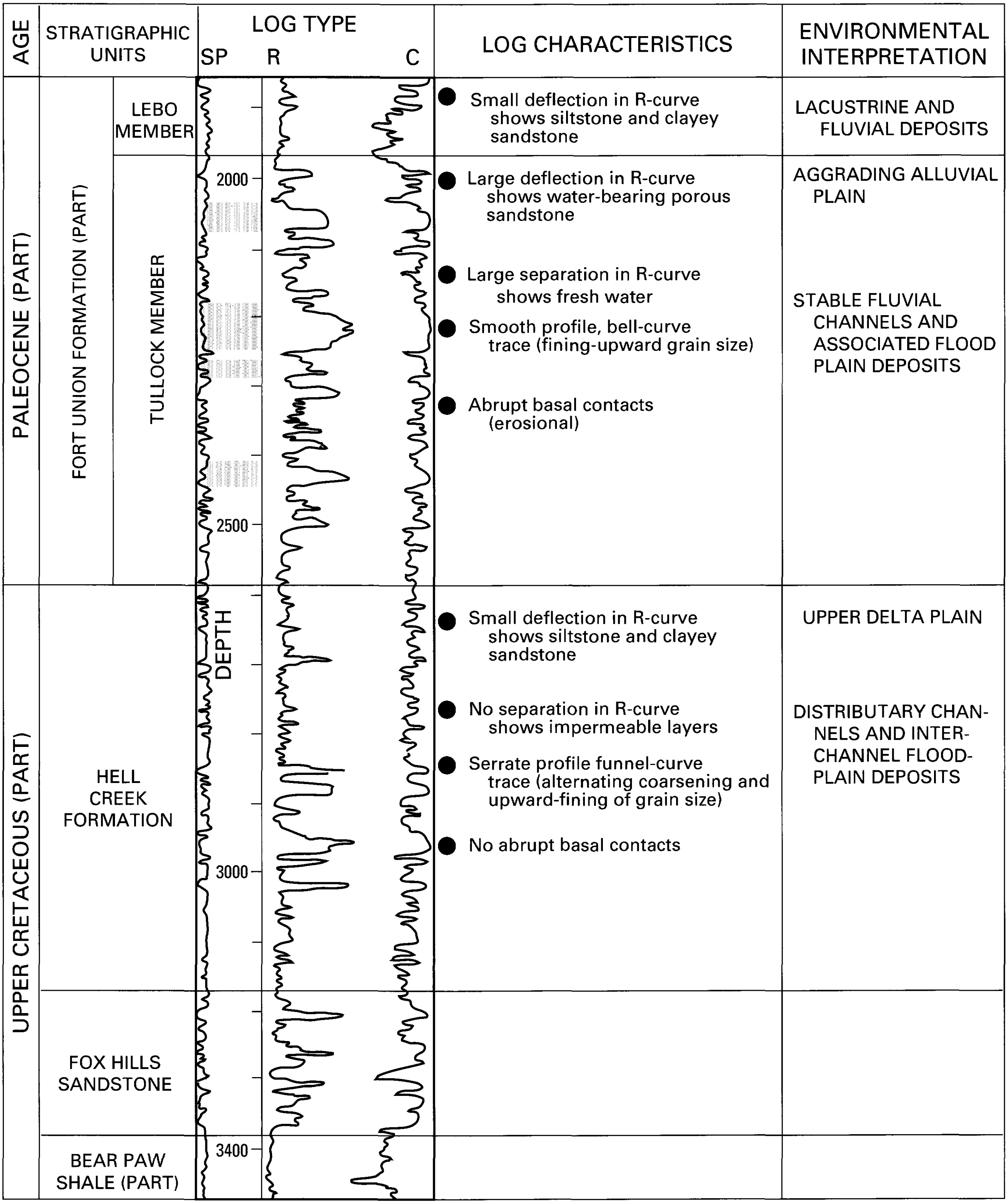


Figure 5. Type log of Tullock Member, Fort Union Formation, showing identifying characteristics of the sequence in northern Powder River Basin. SP, spontaneous potential; R, resistivity; C, conductivity. Depth in feet. Gray shading indicates water-bearing, porous sandstone.

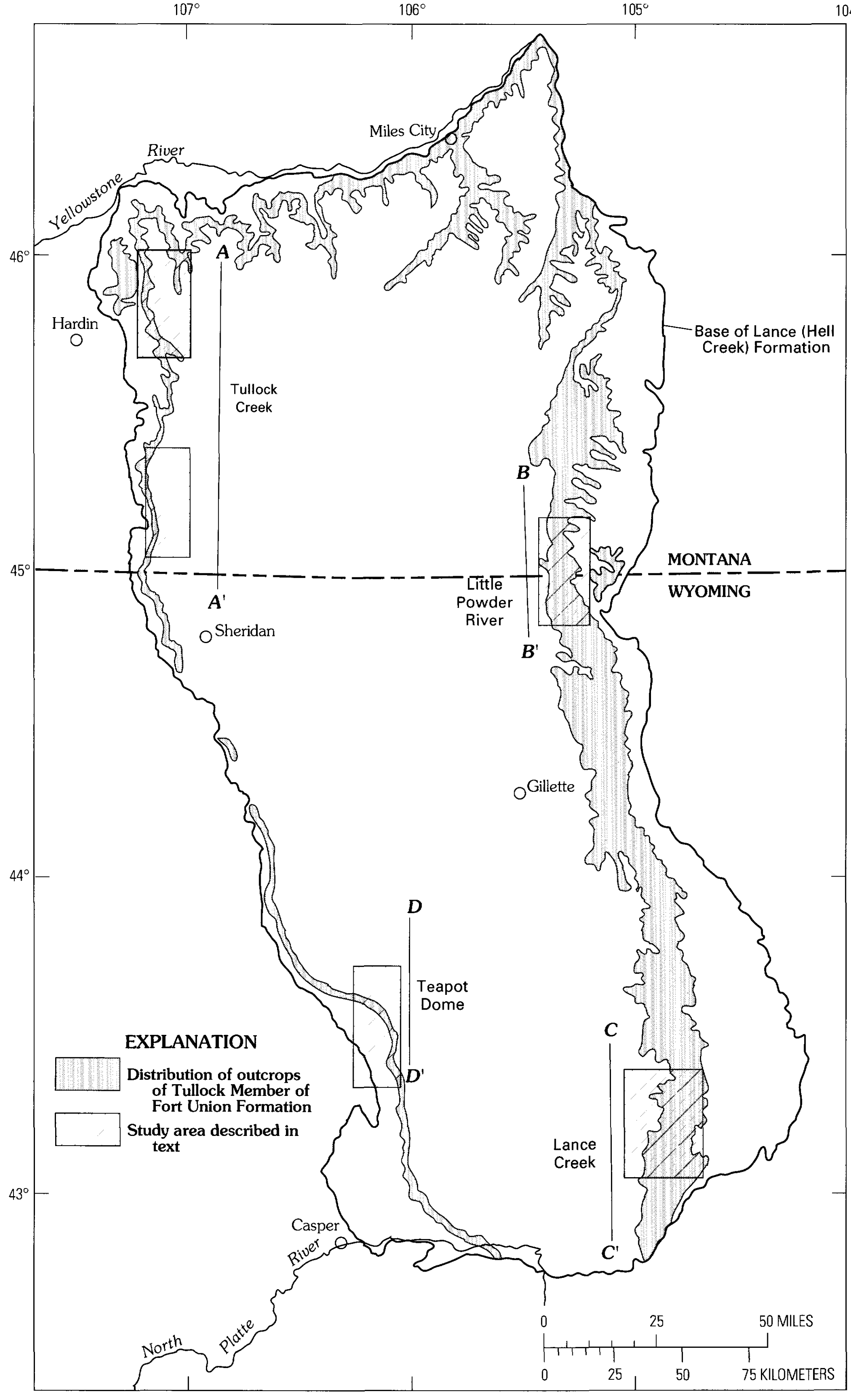
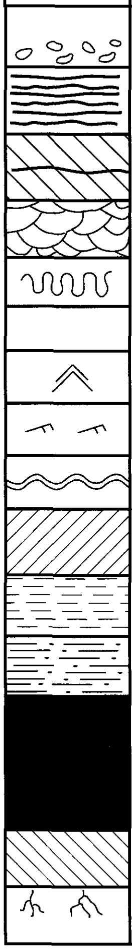


Figure 6. Map of Powder River Basin and Tullock Member outcrop showing locations of four study areas and adjacent subsurface profiles *A–A'*, *B–B'*, *C–C'*, and *D–D'*.



Symbols	Architectural element	Lithofacies code		Distinguishing features	Inferred Depositional Evironment
	CHANNEL (CH)	GM		Conglomerate containing intraformational clay rip-up clasts; matrix is fine to coarse sand; massive or crudely bedded; includes bankside slumps	ACTIVE CHANNEL-FILL
		SH		Sandstone; fine to coarse grained; parallel or horizontal lamination	
		SP		Sandstone; fine to coarse grained; solitary or grouped tabular planar crossbeds	
		ST		Sandstone; fine to coarse grained; solitary or grouped trough crossbeds	
		SL	SL-c	Sandstone; fine grained; convolute or distrubed bedding	
			SL-m	Sandstone; fine grained; structureless or massive bedding	
		SR	SR-cl	Sandstone; fine grained; climbing ripple lamination	
			SR-c	Sandstone; fine grained; current ripple lamination	
			SR-w	Sandstone; fine grained; wavy lamination	
	OVERBANK FINES (OF)	FSC		Mudstone; clay composition, indurated, obscurely bedded or no apparent internal structure; massive; (symbol), mudcrack	BACKSWAMP
		FM		Shale; silt and clay composition, massive; desiccation cracks	FLOODPLAIN
		FL		Siltstone; clay, silt, very fine sand composition, fine lamination, very small ripples	
		C		Coal bed	SWAMP
				Carbonaceous shale; containing unidentifiable fragments of leaves (symbol), stems, and woody material	
		FR		Rooted zones or rhizoliths suggesting possible soil horizons	RHIZOLITH

Figure 7. Architectural elements and associated lithofacies codes for Tullock Member, indicating sedimentary structures and environmental interpretations (using classification system of Miall, 1985).

Robinson and Van Gosen (1986). Figure 9 shows the locations of measured sections and the subsurface transect for the northwestern part of the basin.

Five partial sections of the Tullock Member were measured and paleocurrent trends determined in this area (Brown, 1985). These sections were also sampled for palynological zonation and age determinations (appendix 3, this report; Nichols and Brown, 1992). The Tullock ranges in thickness from 113 m (371 ft) to 236 m (774 ft) in this part of the Powder River Basin (appendix 1). In outcrop, isolated sandstone bodies form large buttes and rim rocks (fig. 10), but much of the area is either grassland in the lowlands or ponderosa pine forest at higher altitudes.

According to outcrop criteria, the basal contact of the Tullock Member is considered to be the base of the lowermost persistent coal bed, which is about 0.5 m (1.6 ft) thick, and is associated with a subtle color change in the siltstone and shale from olive green in the Hell Creek to buff yellow in the Tullock Member (Rogers and Lee, 1923). Palynological analyses (Nichols and Brown, 1992) of the Tullock sequence at Burnt Creek place the K-T boundary in a mudstone more than 4 m (13 ft) below coal bed A of Rogers and Lee (Brown and Nichols, 1988). Sandstone samples for petrologic analyses of the lower part of the Tullock Member were collected at the Reno Creek section on the Crow Indian Reservation. The upper contact of the Tullock Member with the Lebo Member in the northwestern Powder River Basin is marked by a thin, persistent sandstone that weathers to a dark-brown, well-defined rimrock.

Analysis of well logs suggests that the Tullock in this area comprises more than 70 percent fine-grained material of inferred overbank origin and less than 30 percent sandstone interpreted as fluvial channel deposits (Tullock Creek and Lodgegrass transect shown on plate 1). Estimates of

OUTCROP LOCATION		ROCK FRAGMENTS				
		Igneous	Metamorphic	Clastic (Not including chert)	Carbonate	Diagnostic Heavy Minerals
Tullock Creek and Lodgegrass areas (northern Powder River Basin)	Lower part of the Tullock Member	▲	●	●	●	Epidote
Sussex and Teapot Dome areas (southwestern Powder River Basin)	Upper part of the Tullock Member	●	■	■	None	Epidote, staurolite
	Middle part of the Tullock Member	●	■	■	■	Amphiboles
	Lower part of the Tullock Member	●	■	▲	None	Epidote group
Lance Creek and Leverette Butte areas (southeastern Powder River Basin)	Upper part of the Tullock Member	●	■	■	■	Sphene, epidote group
	Middle part of the Tullock Member	▲	■	■	■	Sphene, hornblende
	Lower part of the Tullock Member	●	■	▲	■	Epidote, sphene, olivine

EXPLANATION

■ <1 percent ▲ 1–10 percent ● >10 percent

Figure 8. Compilation of petrologic data organized by basin location and lower, middle, and upper parts of Tullock Member, Fort Union Formation. Vertical and lateral compositional changes as determined from petrologic analysis (Hansley and Brown, in press).

fine-grained strata based on subsurface data are more reliable than estimates from outcrops because the complete sequence is represented. Analysis of the subsurface data indicates the sandstone bodies are 5–20 m (16–66 ft) thick, have sharp lower contacts, are isolated, and show an upward fining of grain size (bell-shaped log signature). Coal beds and (or) carbonaceous shale is common, although in the absence of gamma logs it is not possible to differentiate coal from carbonaceous shale.

Figure 11*A–E* shows five measured sections: *A*, Burnt Creek #1; *B*, Burnt Creek #2; *C*, Minnehaha Creek North #1; *D*, Minnehaha Creek North #2; and *E*, Reno Creek in the northwestern Powder River Basin.

Burnt Creek #1 section consists of 86 percent overbank fine-grained sediment and is the only measured section in this study that includes the entire thickness of the Tullock Member. The other four sections include, at most, two-thirds of the Tullock and were measured from coal bed A of Rogers and Lee (1923). The Burnt Creek #2 section contains about 60 percent fine-grained strata. These five sections represent the lower part of the Tullock Member, and Minnehaha Creek North #2 corresponds to the representative Tullock section of Rogers and Lee (1923, p. 32). Their representative section consists of about 94 percent overbank lithofacies. In contrast, nearby Minnehaha Creek North #1, of this report, contains about 66 percent overbank sediments in the exposed section, suggesting large lateral variability. The Reno Creek section is within the present boundaries of the Crow Indian Reservation, Big Horn County, Mont., and contains about 70 percent fine-grained overbank sediment.

In outcrop, the sandstone bodies that show a channel geometry range in thickness from 3.0 m to 11.0 m (9.8 ft to 36.1 ft), although most are less than 5.0 m (16 ft) thick. No extremely thick sandstone bodies (>50 m, or 160 ft) were noted from the subsurface data, but this is probably related to the wide borehole spacing, which averages 5.3 km (3.3 mi), not to the actual absence of other large sandstone bodies. In the measured section, which is perpendicular to the inferred paleoslope, the sandstone bodies are lenticular and exhibit erosional bases that are incised into, and surrounded by, floodplain mudstone and siltstone. In almost all of the exposed sandstone bodies, the channel margins pinch out abruptly into horizontally laminated, fine-grained cohesive mudstone that contains plant fragments and thin carbonaceous layers. Where traceable, the sandstone bodies pinch out abruptly in about 300–600 m (984–1,970 ft). The scale of sedimentary structures and grain size of sediments within the sandstone bodies decrease upwards in the sections. Medium-scale trough cross sets (ST) are the predominant sedimentary structure and in three sections provided

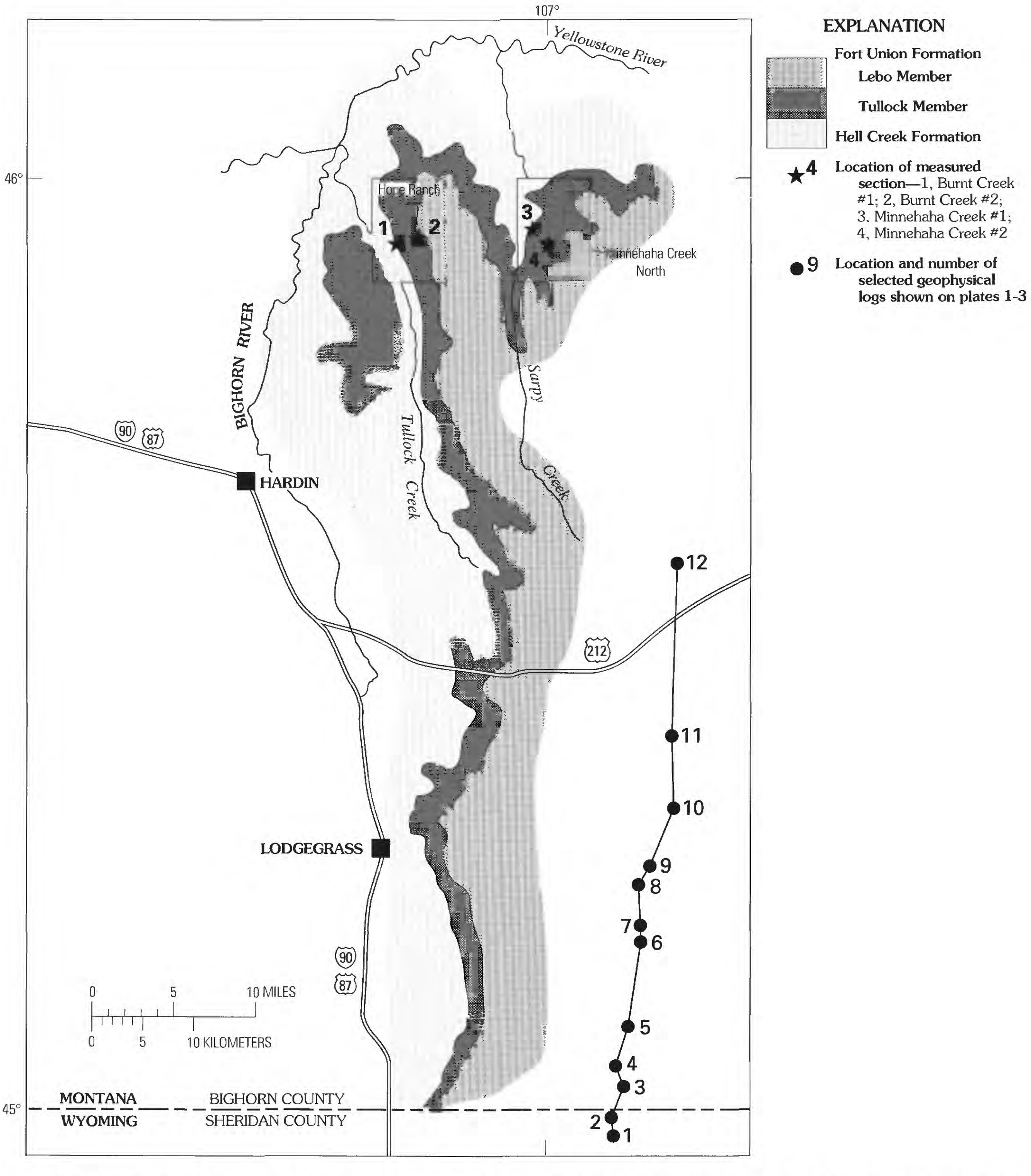


Figure 9. Detailed index map of northwestern Powder River Basin (Tullock Creek area) showing locations of measured sections and well-log transect. Solid line shows boundary of 7.5-minute quadrangles.

paleocurrent trends of east to southeast (Brown, 1985). Convolute bedding (SL–c) is the second most common sedimentary structure, followed by climbing-ripple lamination (SR–cl). The lowermost sandstone body in the Minnehaha Creek North #1 section is about 11 m (36 ft) thick and displays multiple parallel, low-angle surfaces within the

Figure 10. The Pinnacles, Mont., showing typical outcrop form of isolated Tullock Member sandstone bodies in northwestern Powder River Basin. Maximum thickness of this sandstone body is 72 m (237 ft), and it thins to 4 m (1.5 ft) through a horizontal distance of 600 m (1,969 ft).

main channel-form sandstone interpreted as lateral accretion surfaces (fig. 12).

Two paleocurrent measurements on axes of medium-scale trough crossbeds in the upper part of the sandstone body trended north and were oriented perpendicular to the dip of the inferred lateral accretion surfaces. These surfaces were the only ones observed in the Tullock Member in this study. The channel margins of the sandstone body were not abrupt, but gradually wedged out into floodplain sediments in a distance of about 5 m (16 ft). The erosional base of the channel-form sandstone contained clay rip-up clasts, mean grain size decreased upwards, and sets of crossbedding decreased in size from 1.0 m to 0.5 m (3.3 to 1.7 ft). The clay rip-up clasts, which are relatively uncommon in the Tullock Member, appear to be derived from large bankside slumps, or are clay chips scoured from the stream floor.

Most of the exposed sections were composed of organic-rich siltstone and claystone that contained coal beds, leaf-fossil horizons, carbonaceous shale, and rooted zones (FR). Depositional units that make up these facies range in thickness from a few centimeters to a few meters. Rooted zones (FR) not associated with coal beds are also present. Sand-filled desiccation cracks 5 cm (2 in.) in diameter were found in association with the organic-rich siltstone and claystone, but appear to be rare sedimentary structures in the Tullock Member.

A summary of the proportions of major rock fragments in these rocks determined from thin-section analyses is shown here in figure 8 and discussed more fully by Hansley and Brown (in press). Petrographic analysis reveals greater than 10 percent of large, angular carbonate clasts from a nearby source in early Tullock time. Other constituents include metamorphic rock fragments and minor constituents of igneous rock fragments.

Northeastern Powder River Basin—Little Powder River Area

Figure 13 shows locations of measured sections and the subsurface transect for the Tullock Member in the northeastern Powder River Basin in Montana. General geologic studies in the area include Robinson and others (1964), Love and compilers (1978), Stoner and Lewis (1980), and Belt and others (1984). Studies detailing Tertiary stratigraphy include Davis (1912), Dobbin and Barnett (1927), Olive (1957), Warren (1959), Bryson and Bass (1973), Kent and Berlage (1980), and Vuke-Foster and others (1986). The Tullock ranges in thickness from 125 m (410 ft) to 274 m (900 ft) in this area (appendix 1).

The conformable contact of the Tullock Member with the underlying Hell Creek Formation is placed at the base of the lowest coal bed overlying a yellowish-gray, crossbedded sandstone greater than 8.0 m (25 ft) in thickness (Robinson and others, 1964; Kent and Berlage, 1980). In this area the Tullock Member is distinguished from the Hell Creek Formation by its light-buff color, even bedding, and thin coal beds. The upper transitional contact of the Tullock Member with the overlying Lebo Member is generally placed at the base of a zone of multiple coal beds, some as much as 1.2 m (4 ft) thick (Kent and Berlage, 1980).

Subsurface data from the Little Powder River transect (pl. 2), shows that fine-grained overbank sediments comprise greater than 70 percent of the section as determined from lithologic interpretation of the electric logs. Thickest sandstone bodies are no more than 30 m (98 ft) and most are about 15 m (50 ft) thick. Some electric logs show almost 98 percent coal or carbonaceous shale and siltstone (#10), whereas adjacent logs (#14) show almost 50 percent sand in multiple sandstone bodies, indicating large lateral variability. The log signatures of the sandstones show they have sharp bases, are isolated, and fine upward.

Five partial sections (fig. 14*A–E*) were measured at outcrops in the northeastern Powder River Basin and paleocurrent trends determined (Brown, 1987): *A*, Pine Creek; *B*, Whitetail; *C*, Badger Creek; *D*, Buckskin Butte; and *E*, Red Ant.

Measured sections Pine Creek and Buckskin Butte represent the lower part of the Tullock Member; Whitetail and Red Ant represent the middle part of the Tullock; and Badger Creek represents the upper part of the Tullock Member. Paleocurrent measurements (fig. 14) from the lower Tullock (Pine Creek and Buckskin Butte) indicate sediment transport to the north and are consistent with the paleocurrent directions of Seeland (1988) determined from three other locations in the same area. By middle (Red Ant and White Tail

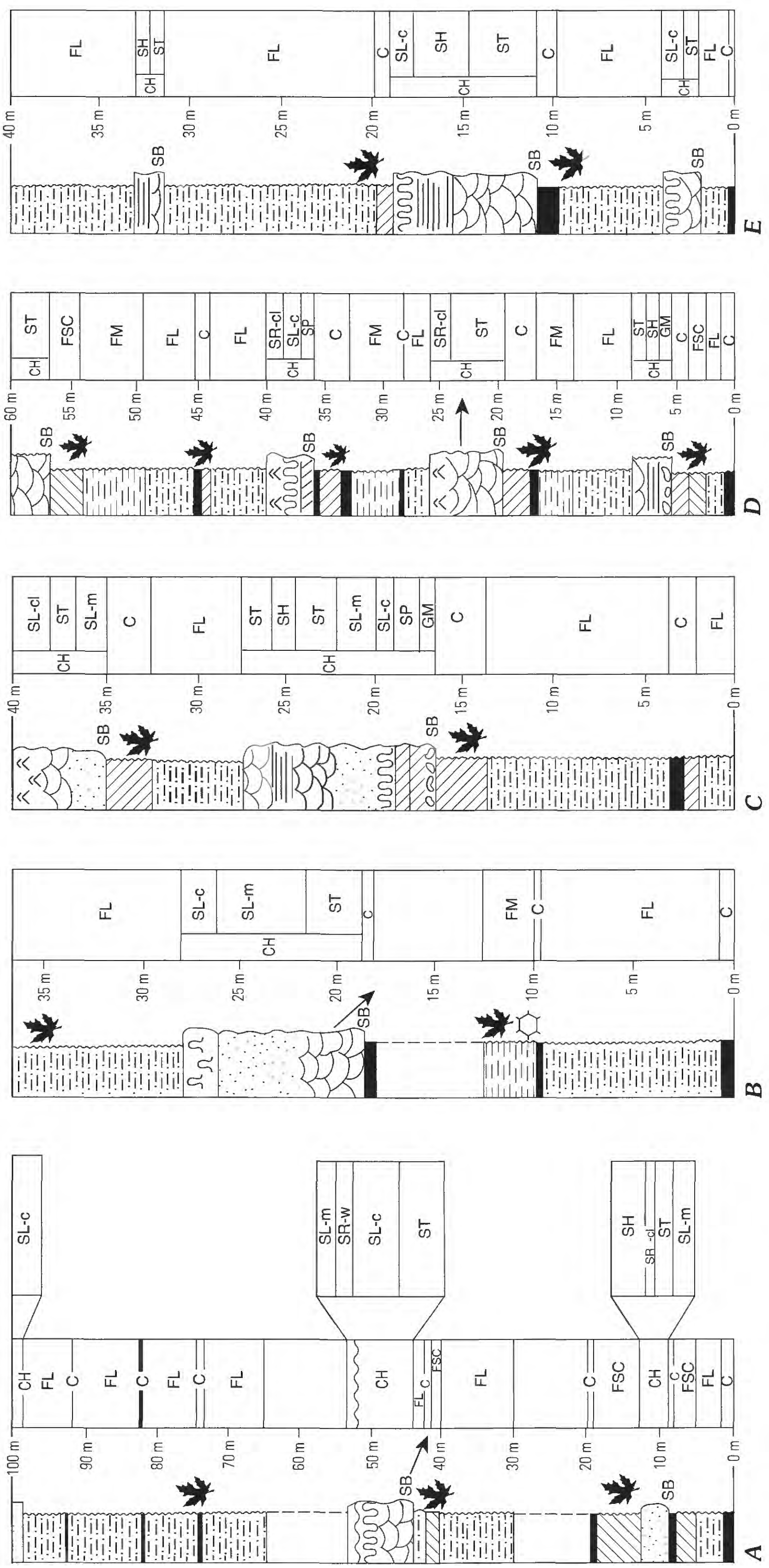


Figure 11. Diagrammatic outcrop profiles showing rock types, lithofacies code, and sketches of sedimentary structures within Tullock Member in Tullock Creek area, northwestern Powder River Basin. Azimuth directions of paleocurrent trends measured from large-scale trough crossbeds are shown by arrows. Note that vertical scales between sections are different owing to wide variance in vertical outcrop exposure. All sections begin with lowermost coal bed "A" of Rogers and Lee (1923). Lithologic symbols and lithofacies codes explained in figure 7; vertical dashed line in lithologic column indicates covered interval; SB, scoured base. *A*, Burnt Creek # 1 (lower). *B*, Burnt Creek # 2 (lower). *C*, Minnehaha Creek North # 1 (lower). *D*, Minnehaha Creek North # 2 (lower). *E*, Reno Creek (lower).

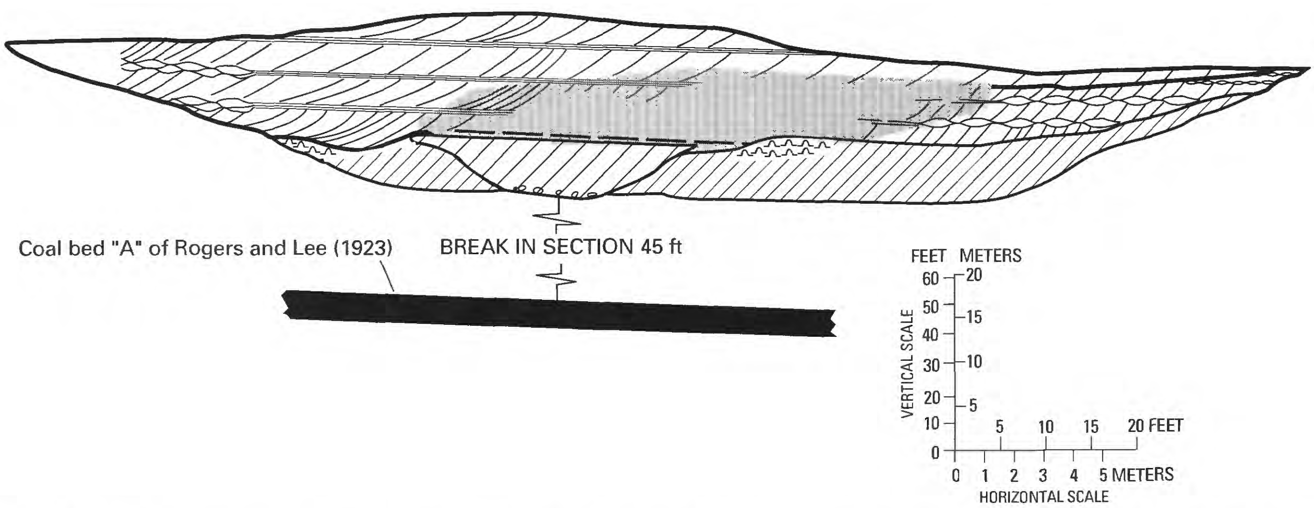


Figure 12. Diagrammatic representation of lowermost sandstone body in measured section at Minnehaha Creek North #1, showing possible lateral accretion surfaces (paleoflow direction away from viewer). Lithologic symbols explained in figure 7.

Sections) and late (Badger Creek Section) Tullock time sediment transport directions had changed to nearly due east. Samples for age determinations and palynological zonation were collected adjacent to the Buckskin Butte measured section at Dry Creek (appendix 3, this report; Nichols and Brown, 1992), but no distinctive K-T boundary was found. No samples were collected for petrologic analysis. Tullock outcrops form low, grassy, rounded hills; thin sandstone bodies form small rimrocks and ledges (fig. 15).

About 75 percent of the exposed Pine Creek section (48 m, or 160 ft) consists of interbedded siltstone, coal, and organic-rich shale containing layers of plant fragments. Capping the Pine Creek section is a thick (8.0 m, or 26 ft) channel-form sandstone containing multiple medium-scale sets (30–100 cm) of trough crossbeds that fine upward within each set. In contrast, the Buckskin Butte section (54 m, or 180 ft) consists of about 85 percent fine-grained sediments comprising siltstone, shale, and mudstone interbedded with minor coal and carbonaceous shale. Four thin tabular sandstone bodies 1.0–1.75 m (3.3–5.7 ft) thick are exposed, and three are composed entirely of climbing-ripple laminations.

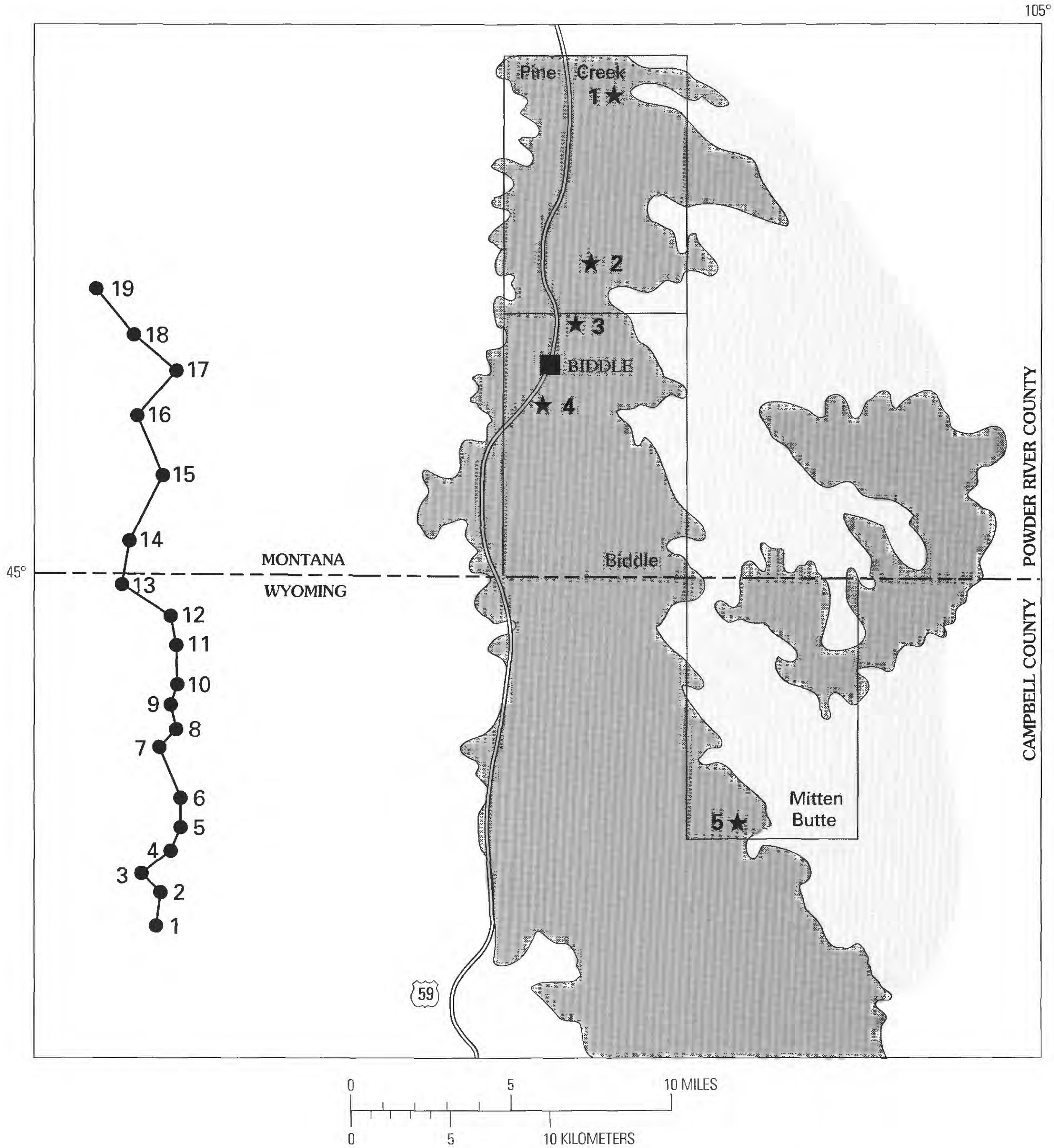
The Red Ant (61 m, or 200 ft) and Whitetail (47 m, or 160 ft) sections in the middle part of the Tullock contain less than 40 percent of fine-grained overbank sediments. The Red Ant section contains three isolated channel-form sandstone bodies 1.0–5.8 m (3.3–19.0 ft) in thickness. The lowermost sandstone of the Red Ant section has an erosional base and is laterally traceable for 46 m (150 ft), where it thickens to 9.0 m (30 ft); the margins of the sandstone body are not exposed. Capping the sandstone body are medium-scale trough crossbeds. The lower part of the middle sandstone body is massive, and the upper part is composed entirely of current ripples, which are rarely seen in the Tullock Member. The lowermost sandstone body (12.0 m, or 39.1 ft) of the Whitetail section shows the nature of the contact of the active channel facies with an underlying coaly zone (fig. 16). The contact plane is broadly undulatory and can be traced laterally for about 300 m (984 ft).

The Badger Creek section (39 m, or 130 ft) represents the upper part of the Tullock. The trough crossbed sets at the base of the lowermost sandstone body (20 m, or 66 ft, thick) are about 1.1 m (3.6 ft) thick but decrease in thickness to 0.5 m (1.6 ft) upsection. Multiple sets of planar tabular beds in fine sand, the sets decreasing in thickness upward from 1.3 m (4.3 ft) to 0.25 m (0.82 ft) are also present in the sandstone body at this locality. About 40 percent of the exposed section is composed of siltstone and a few thin coal beds containing zones of plant fragments.

Southeastern Powder River Basin—Lance Creek Area

The first geologic investigation in the southern part of the basin in the Lance Creek area was a reconnaissance survey by Darton (1905). This area is now considered to be the type area of the Lance Formation (Stone and Calvert, 1910). Figure 17 shows locations of the measured sections and the subsurface transect for the southeastern Powder River Basin.

Five partial sections of the Tullock Member (fig. 18*A–C*) were measured and sampled for palynological and petrologic analysis: *A*, South Snyder Creek #1, #2, and #3; *B*; Leverett Butte, and *C*, Cow Creek. In general, the area consists of



EXPLANATION

- Wasatch Formation and Tongue River and Lebo Members of Fort Union Formation, undivided
- Tullock Member of Fort Union Formation
- Lance and Hell Creek Formations, undivided
- ★2 Location of measured sections—1, Pine Creek; 2, Whitetail 3, Red Ant; 4, Badger Creek; 5, Buckskin Butte
- ●10 Location and number of selected geophysical logs shown on plates 1–3

Figure 13. Detailed index map of northeastern Powder River Basin (Little Powder River area) showing locations of measured sections and well-log transect. Solid line shows boundary of 7.5-minute quadrangles.

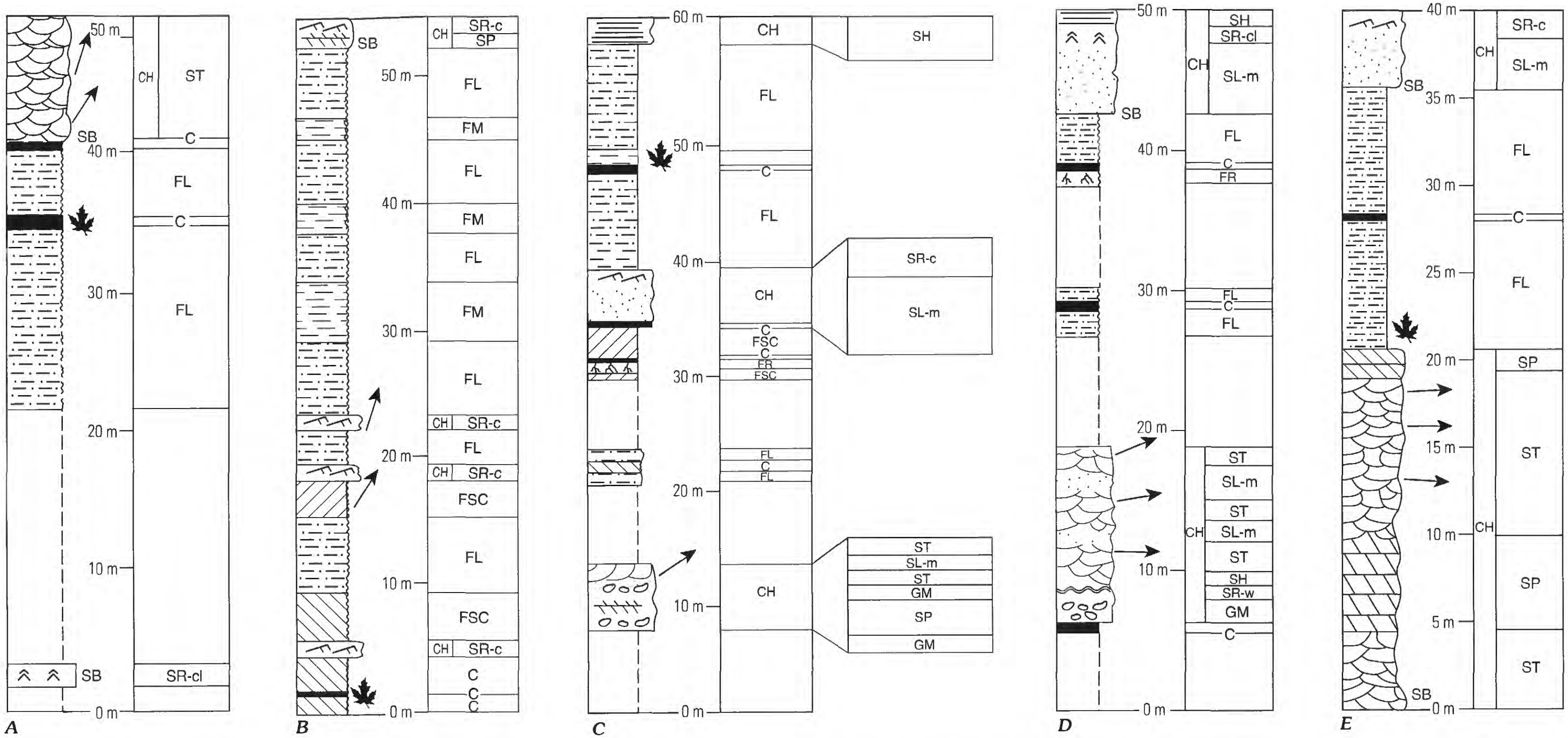


Figure 14. Diagrammatic outcrop profiles showing rock types, lithofacies code, and sketches of sedimentary structures within Tullock Member in Little Powder River area, northeastern Powder River Basin. Azimuth directions of paleocurrent trends measured from large-scale trough crossbeds are shown by arrows. Note that vertical scales between sections are different owing to wide variance in verticle outcrop exposure. All sections begin with equivalent of lowermost coal bed "A" of Rogers and Lee (1923). Lithologic symbols and lithofacies codes explained in figure 7; vertical dashed line in lithologic column indicates covered interval; SB, scoured base. *A*, Pine Creek (lower). *B*, Buckskin Butte (lower). *C*, Red Ant (middle). *D*, Whitetail (middle). *E*, Badger Creek (upper).

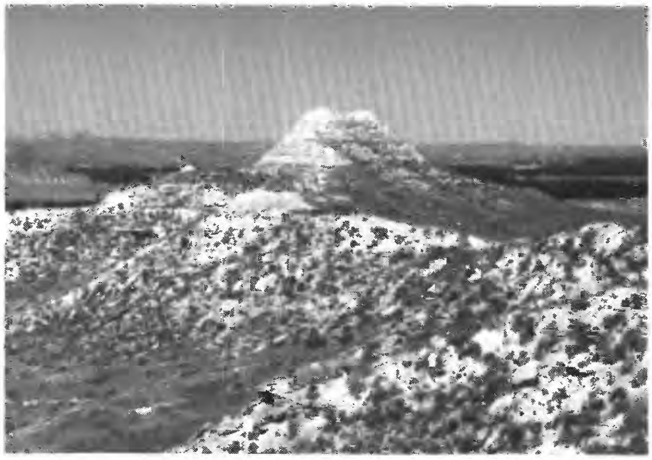


Figure 15. Bell Tower Butte, near Broadus, Mont., showing rolling badlands topography of Tullock Member. Thin sandstone ledges and carbonaceous and coaly zones impart a striped aspect to landscape. Outcropping part of Tullock Member is about 24.4 m (80 ft) thick.

Figure 16. Erosional contact of the active channel-sandstone facies overlying a coal bed in northeastern Powder River Basin, Whitetail section. Ice ax is 1 m (3.3 ft) long.

gently rolling grassy hills, small areas of badlands, and rare, isolated buttes such as Leverett Butte, which exposes a part of the middle Tullock (fig. 19).

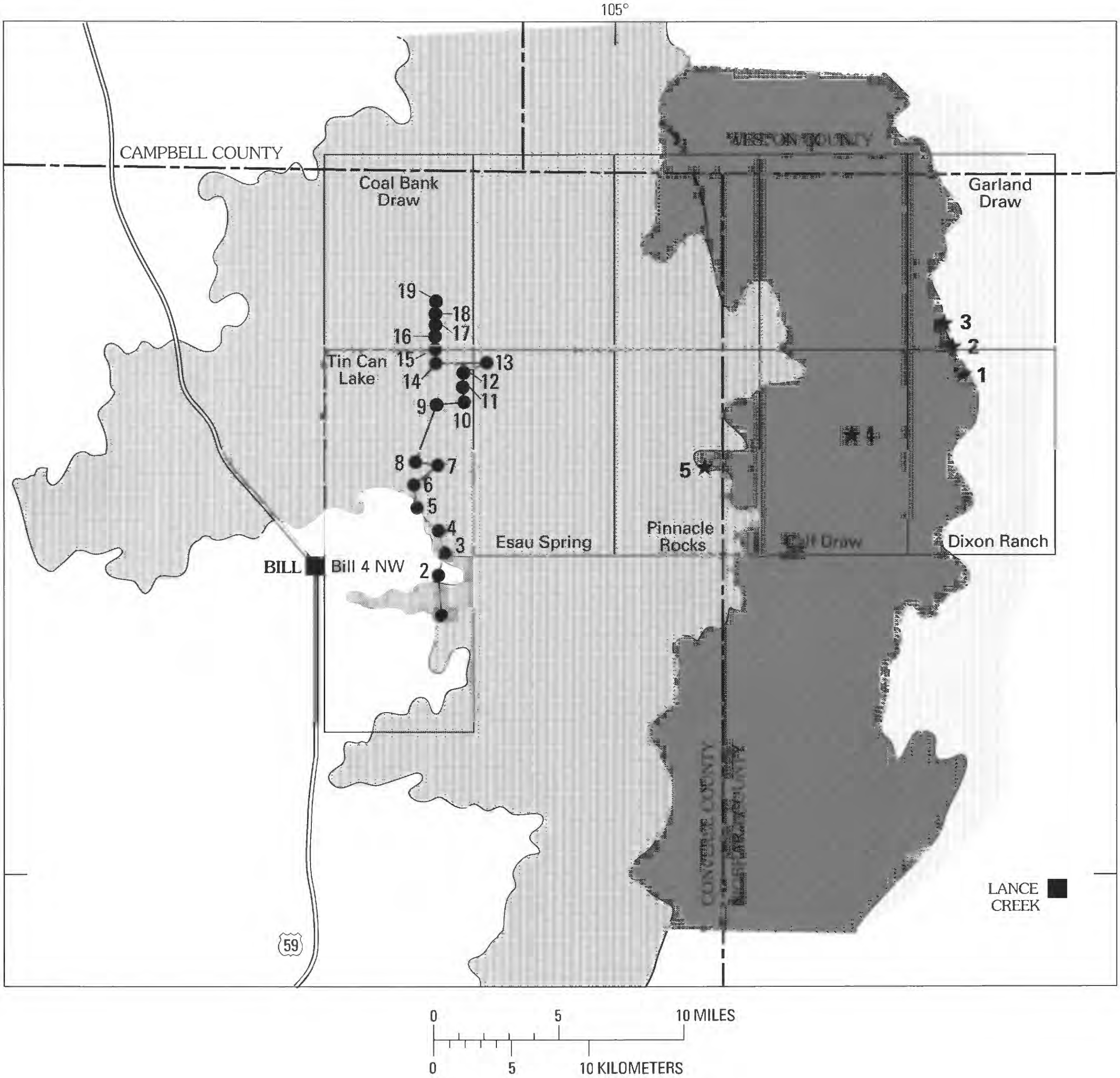
The gradational contact of the Tullock with the underlying Lance Formation is characterized by brown to gray, crossbedded sandstone interbedded with numerous dark carbonaceous shale beds and thin coal seams. The upper contact of the Tullock Member with the Lebo Member is transitional and characterized by a dark-gray carbonaceous shale containing many coal beds, some almost 0.5 m (1.7 ft) thick. Sandstone of the Lebo is drab to gray, thin bedded, and finely conglomeratic in contrast to the yellow-buff, nonconglomeratic sandstone of the Tullock Member (Denson and Horn, 1975; Love and others, 1980). The Lebo Member contains economic coal, unlike the Tullock Member, and in some places the coal beds have been metamorphosed to form a distinctive resistant red clinker zone that is responsible for the only relief in the area; the Cow Creek Buttes, Miller Hills, and Pinnacle Rocks. At Cow Creek (fig. 18*E*) new palynological data (Nichols and Brown, 1992) show that the strata exposed in the Cow Creek section contain the palynomorph assemblage characteristic of zone P3 (lower middle Paleocene) and that the contact between the Tullock and Lebo Members is below the coal zones of Dobbin and others (1957).

Subsurface data show that the Tullock in the Lance Creek area ranges in thickness from 344 m to 439 m (1,130 ft to 1,440 ft). In this area, it consists primarily of shale and mudstone, and minor amounts of siltstone. Thin beds of coal and (or) carbonaceous shale are common. Analysis of well-log signatures reveals isolated sandstone bodies having sharp bases, and the bell-shaped curve of the log signature indicates fining upward of grain size. Other sandstone bodies have a cylindrical log signature, sharp contacts at the base and top, and a uniform grain-size distribution (pl. 2). In outcrop, the Tullock consists of greater than 75 percent siltstone and mudstone containing minor zones of coal and carbonaceous shale, interbedded with thin, lenticular sandstone beds. Paleocurrent measurements from sets of medium-scale trough crossbedding indicates transport to the northeast for the lower part of the Tullock Member and to the northeast and east for the middle part.

South Snyder Creek partial sections #1 and #2 (fig. 18*A*, *B*), both 12 m (39.6 ft) thick, and #3 (fig. 18*C*) (7.5 m, or 24.7 ft) thick, are predominantly fine-grained, organic-rich floodplain sediments. Sections #1 and #2 expose the same part of the section but are separated by a covered interval 91.0 m (300 ft) wide. In that distance, a 2.5-m- (8.3-ft-) thick channel-form sandstone body pinches out.

The Leverett Butte section (44 m, or 140 ft) (fig. 18*D*) representing the middle part of the Tullock Member, contains predominantly organic-rich, fine-grained sediments. The sandstone facies is represented by three lenticular sandstone bodies ranging in thickness from 5.2 to 8.3 m (17 to 27 ft) that are trough crossbedded and decrease in scale upward. Evidence of bankside slumping is indicated by a 30-cm-thick, intact block of laminated bankside material incorporated in convolute bedding near the top of the middle sandstone body.

The Cow Creek section (26 m, or 85.8 ft) (fig. 18*E*) contains six coal beds interbedded with thick sequences of carbonaceous shale and dark-gray siltstone and includes a lenticular, internally massive sandstone that is 3.0 m (9.8 ft) thick. The sandstone body is laterally traceable for about 61 m (200 ft), but the precise orientation to paleoslope is unknown.



EXPLANATION

Wasatch Formation and Tongue River Member of Fort Union Formation, undivided

Fort Union Formation

Lebo Member

Tullock Member

Lance Formation

★4 Location of measured section—1, South Snyder Creek #1; 2, South Snyder Creek #2; 3, South Snyder Creek #3; 4, Leverette Butte; 5, Cow Creek

●4 Location and number of selected geophysical logs shown on plates 1–3

Figure 17. Detailed index map of southeastern Powder River Basin (Lance Creek area) showing locations of measured sections and well-log transect. Solid line shows boundary of 7.5-minute quadrangle.

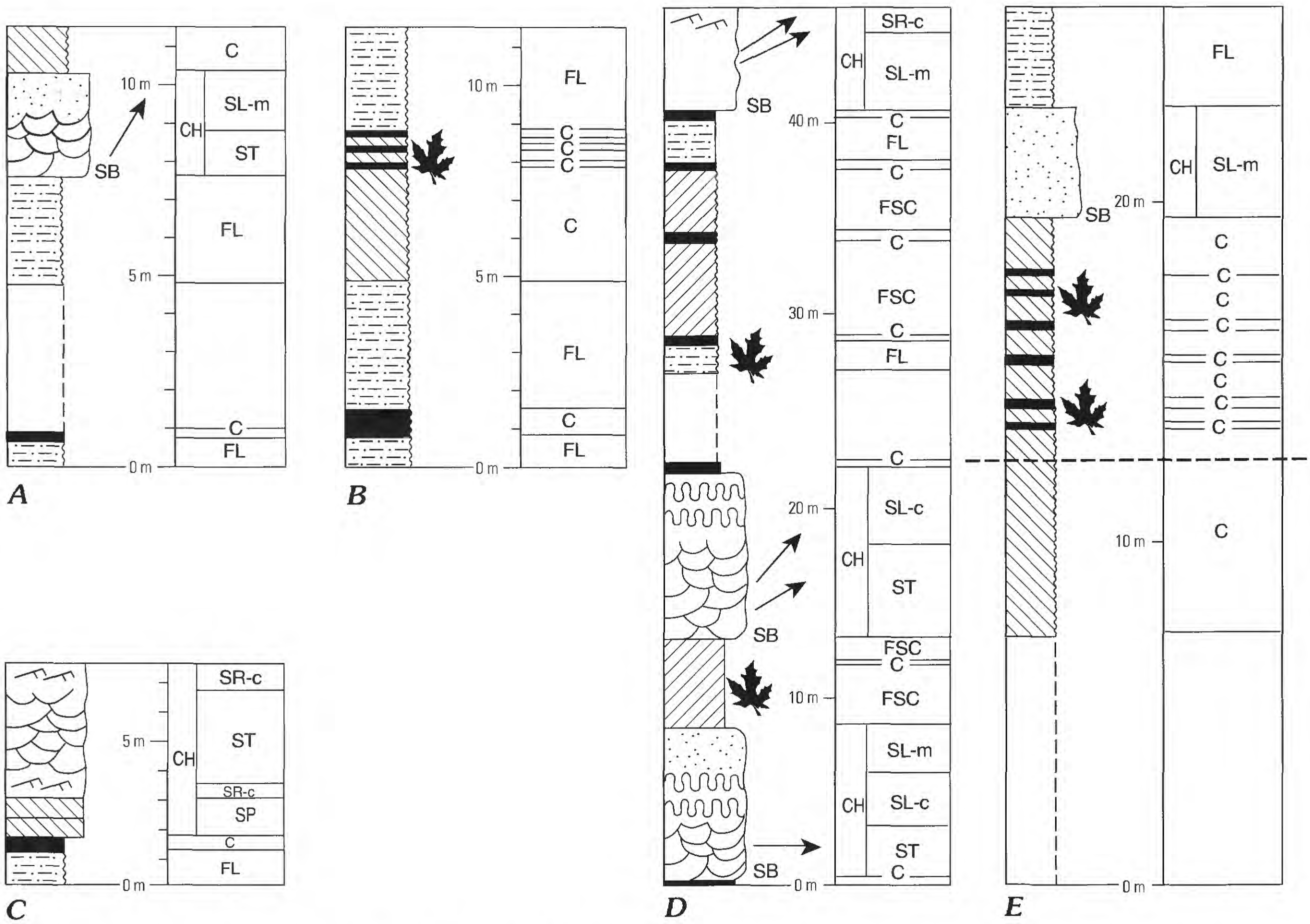


Figure 18. Diagrammatic outcrop profiles showing rock types, lithofacies code, and sketches of sedimentary structures within Tullock Member in Lance Creek area, southeastern Powder River Basin. Directions of paleocurrent trends measured from large-scale trough crossbeds are shown by arrows. Note that vertical scales between sections are different owing to wide variance in vertical outcrop exposure. All sections begin with the equivalent of lowermost coal bed "A" of Rogers and Lee (1923). Lithologic symbols and lithofacies codes explained in figure 7; vertical dashed line in lithologic column indicates covered interval; SB, scoured base. Horizontal dashed line shown in *E* represents the contact between the Tullock Member below and the Lebo Member above (transitional Tullock-Lebo boundary of Dobbin and others, 1957). *A*, South Snyder Creek # 1 (lower). *B*, South Snyder Creek # 2 (lower). *C*, South Snyder Creek # 3 (lower). *D*, Leverette Butte (middle). *E*, Cow Creek (upper).

A summary of the proportions of major rock fragments in these rocks determined from thin-section analyses is shown here in figure 8 and discussed more fully by Hansley and Brown (in press). Petrographic analysis reveals greater than 10 percent of large, angular carbonate clasts derived from a nearby source in early Tullock time. Other constituents include metamorphic rock fragments and minor constituents of igneous rock fragments.

Southwestern Powder River Basin—Teapot Dome Area

In the southwestern part of the basin, the Fort Union Formation is subdivided lithologically into the Tullock Member and the Lebo Member; the Tongue River Member is not recognized in this area (Love and others, 1978). Local thicknesses of the Tullock Member range from 332 m (1,090 ft) to 335 m (1,100 ft) (appendix 1, this report; Horn, 1955). Stratigraphy and structure in the area was described by Weitz and others (1954), Horn (1955, 1958), and Richardson (1957, 1961). Tertiary strata in this area also were evaluated for uranium favorability (Sharp and Gibbons, 1964; Davis, 1969; Childers, 1970, 1974) and coal resources (Wegemann, 1912; Wegemann and others, 1928; Hose, 1954; Denson and Horn, 1975). Unlike the other study areas in the Powder River Basin, local deformation caused by normal faulting has produced vertical offsets and structural dips of 14°–36° to the east and northeast in the exposed sequence (Horn, 1955; Blackstone, 1981). Figure 21 shows the locations of measured sections and the subsurface transect for the southwestern part of the basin. The

Figure 19. Leverett Butte, Wyo., showing interbedded siltstone, coal and carbonaceous shale, and thin, lenticular sandstone bodies characteristic of Tullock Member in southeastern Powder River Basin. Outcropping sequence is about 12.2 m (40 ft) thick.

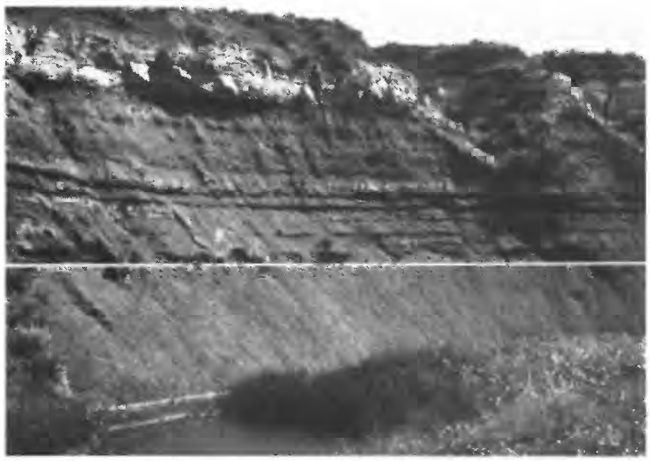


Figure 20. Upper contact of Tullock Member with Lebo Member in Cow Creek section (fig. 18) in southeastern Powder River Basin. Mappable contact (Dobbin and others, 1957) is characterized by a zone of coal beds, some more than 1 m (3 ft) thick, and shown here by a white line. Outcropping sequence is about 25 m (82 ft) thick.

Tullock Member is composed mainly of poorly consolidated to semi-consolidated, buff-colored sandy siltstone; shale; minor thin coal and carbonaceous shale; and isolated, thin lenticular sandstones. Because of poor induration, outcrops of the Tullock in the southwestern Powder River Basin consist of low brushy rounded hills (fig. 22).

Two partial sections of the Tullock Member were measured and paleocurrent trends determined in the southwestern Powder River Basin. Paleocurrent measurements from medium-scale trough crossbeds in sandstone in the lower part of the Tullock showed sediment transport to the northeast. The sections were sampled for petrologic (Hansley and Brown, in press) and palynological analysis (appendixes 2 and 3, this report) (Nichols and Brown, 1992; Nichols and others, 1992). Figure 23 shows two partial measured sections: *A*, Teapot Dome; and *B*, Sussex.

The Tullock Member conformably overlies the Lance Formation, and the transitional contact is marked by discontinuous coal beds as much as 0.4 m (1.3 ft) thick and by olive-gray to dark-gray, massive claystone. Just beneath the basal Tullock coal in this area is a newly discovered K-T boundary claystone layer (about 2 cm thick) containing shocked quartz and a very high concentration of iridium (Brown and Nichols, 1989; Nichols and Brown, 1989b; Nichols and others, 1992). The transitional contact of the Tullock Member with the overlying Lebo Member is distinguished by a thick sandstone complex 153–280 m (502–919 ft) thick at the base of the Lebo (Coss, 1985). The sandstone complex is composed of reddish to pinkish-red mudstone and sandy siltstone. The indurated, reddish, sandy intervals that make up part of the overlying Lebo Member form the prominent Great Pine Ridge structural escarpment.

Lithologic interpretation of the logs in the Teapot Dome subsurface transect (pl. 3) shows greater than 75 percent fine-grained overbank material and less than 25 percent sandstone. Interpretation of logs 1 and 3 show that sections are predominantly sandstone and indicates large lateral variability in the sequence. In the subsurface, the isolated sandstone bodies range in thickness from 7 to 35 m (20 to 116 ft). Many have sharp basal contacts and overlie coal and carbonaceous shale layers. The thickest sandstone bodies observed in outcrop, however, are not anywhere greater than 15 m (49 ft).

The Sussex section exposes 91 m (300 ft) of section (about one-third of the total) and represents the lower and middle parts of the Tullock Member. The partial section includes greater than 50 percent channel sandstone facies comprising six sandstone bodies that decrease in thickness upward. The lower three sandstone bodies have a lenticular cross section and an erosional base, and they all pinch out in less than 305 m (1,000 ft). The upper three sandstone bodies are thin and tabular and contain sets of small-scale tabular planar beds, convolute bedding, and climbing ripple lamination. The overbank fine-grained facies consists of gray-buff to yellow-buff siltstone, thin coal beds, carbonaceous shale, and minor dark-brown mudstone beds. Included in the fine-grained facies are zones of leaf and stem fragments.

About 75 percent of the Teapot Dome section is fine-grained, organic-rich sediment that includes interbedded yellow-buff siltstone, gray shale, dark-gray mudstone, thin coal beds, and carbonaceous shale. Poorly preserved leaf and stem fragments, mottling, and faint root impressions

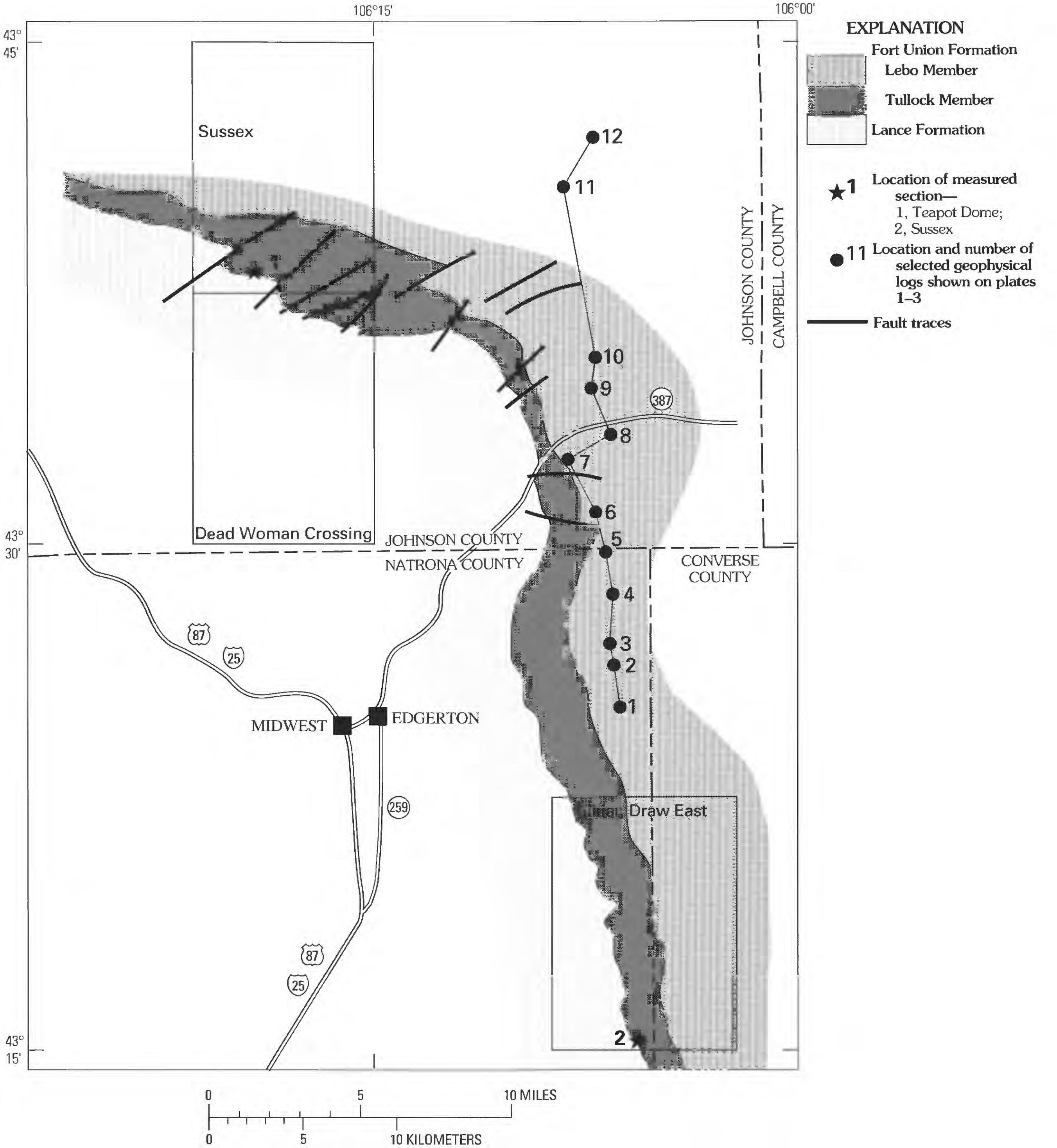


Figure 21. Detailed index map of southwestern Powder River Basin (Teapot Dome area) showing locations of measured sections and well-log transect. Solid line shows boundary of 7.5-minute quadrangle.

are associated with the floodplain sediments. The channel sandstone facies is represented by a tabular sandstone unit about 10 m (33 ft) thick that has an erosional base and pinches out in 138 m (453 ft), perpendicular to the inferred paleoslope. Sedimentary structures consist of tabular planar crossbeds, convolute bedding, and rare flame structures.

Figure 22. Tullock Member outcrop in southwestern Powder River Basin showing badlands topography.

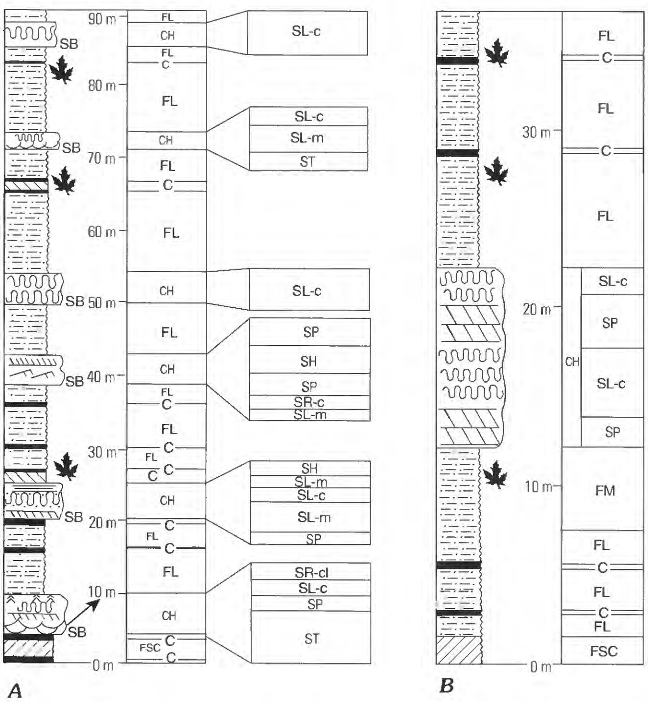


Figure 23. Diagrammatic outcrop profiles showing rock types, lithofacies code, and sketches of sedimentary structures within Tullock Member in Teapot Dome area, southwestern Powder River Basin. Azimuth directions of paleocurrent trends measured from large-scale trough crossbeds are shown by arrows. Note that vertical scales between sections are different owing to wide variance in vertical outcrop exposure. Measured sections begin with Cretaceous-Tertiary boundary clay near equivalent of lowermost coal bed "A" of Rogers and Lee (1923). Lithologic symbols and lithofacies codes explained in figure 7; SB, scoured base. *A*, Sussex (lower and middle). *B*, Teapot Dome (upper).

Some of the foresets of the tabular planar beds are oversteepened and deformed.

Sandstone of the lower, middle, and upper parts of the Tullock Member was sampled for petrologic analyses (fig. 8, this report; Hansley and Brown, in press). Petrographic analysis reveals greater than 10 percent igneous rock fragments for the whole member, minor amounts of metamorphic rock fragments, and an almost complete lack of carbonate fragments.

PALEONTOLOGY

Fossils are not abundant in the Tullock Member, and leaves are the most common megascopic fossils. The Tullock flora is known partly from the early work of Brown (1962), and more recently from Nichols and others (1988). Fossil plant species found in the Lance and Hell Creek Formations are distinct from the flora of the Fort Union Formation. Leaf megafossils typical of the Tullock flora (Dorf, 1942; Brown, 1962) and collected by the author are illustrated in figure 24. The fossil leaf specimens were identified by J.A. Wolfe, U.S. Geological Survey.

The Tullock flora comprises conifers (*Metasequoia*); fern allies (*Equisetum*, or horsetail rush); palms and lilies (monocotyledons); dicotyledons such as *Cissus* (Sycamore), *Eucommia* (living relatives in central China), and *Platanus* (sycamore); and an extinct early successional pond lily (*Paranymphaea*). The Tullock flora generally is of low diversity and is dominated by deciduous plants (*Cissus*, *Eucommia*, *Platanus*) and a few evergreens such as *Metasequoia* and palm. Wolfe and Upchurch (1986) regarded the low diversity of the Tullock flora as representing an early successional response to a change in environmental conditions represented by the K-T boundary horizon that marks the base of the Tullock Member. *Metasequoia*, a common Tullock plant, is related to the living dawn redwood of central China, and modern *Metasequoia* occurs in areas not subjected to flooding, preferring well-drained lowland sites, usually terraces in river valleys. *Equisetum*, which arose in Carboniferous time, inhabits swamps and has a rhizome that enables it to withstand seasonal peroids of climatic stress. A sandstone body in the Red Ant section, northeastern Powder River Basin, preserved a large (39 cm, or 15 in.) intact segment of *Equisetum* stem as illustrated in figure 24*A*. Living relatives of *Cissus*, *Eucommia*, and *Platanus* (fig. 24 *B–D*) are deciduous trees that inhabit drained, interfluve upland areas. This group has evolved and diversified through the subtropical climate of Paleocene time to the temperate climate of the present. An incomplete leaf of *Cissus* collected in the Lance Creek area (South Synder Creek section) measured 19 cm (7.5 in.) in width.

Research on the palynology of the Tullock Member has established temporal control and provided a basis for

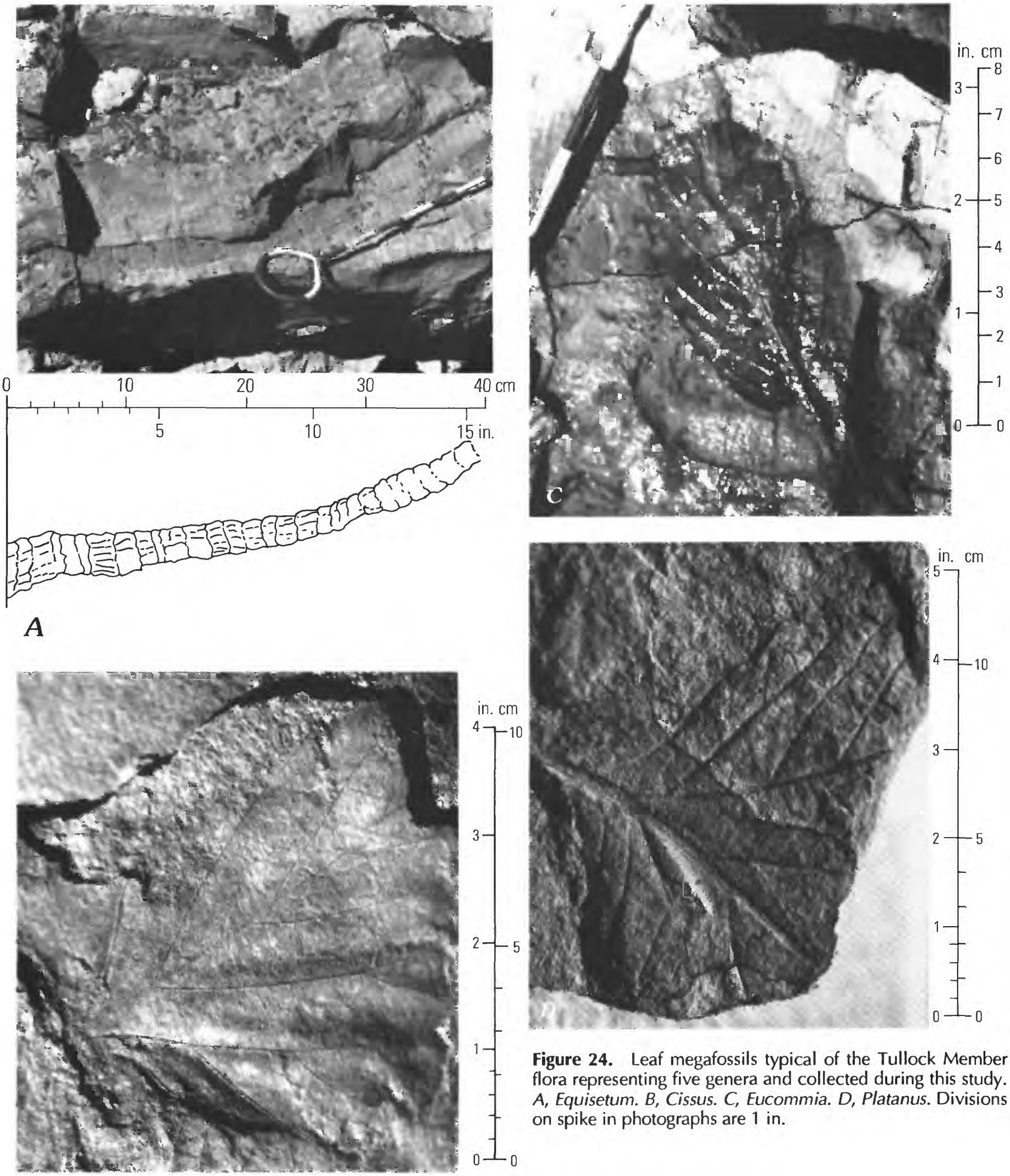


Figure 24. Leaf megafossils typical of the Tullock Member flora representing five genera and collected during this study. *A*, *Equisetum*. *B*, *Cissus*. *C*, *Eucommia*. *D*, *Platanus*. Divisions on spike in photographs are 1 in.

modeling the timing of depositional events during evolution of the Powder River Basin (Nichols and Brown, 1989b; Nichols and Brown, 1992). The palynoflora of the Tullock Member includes 75 or more taxa, the most common being palm, relatives of the sycamore and elm, conifers, and ferns. Tullock plant communities as interpreted from pollen and spores are composed of species that lived in wetlands and mires associated with lowland forests of warm temperate to subtropical aspect. Major conclusions on the palynostratigraphy, climate, and concentration of parent plants in certain depositional environments are given in Nichols and Brown (1992).

Rogers and Lee (1923) reported three genera of fresh-water gastropods: *Unio*, *Sphaerium*, and *Physa*. Modern representatives of these genera prefer perennial streams and lakes, slow currents, warm water temperatures, and a sandy (*Sphaerium*) or muddy (*Physa*, *Unio*) substrate.

A rare complete specimen of probable *Lepisosteus* sp, a fresh-water gar pike present in upper Cretaceous and lower Tertiary strata, was excavated from the upper part of the Lance Formation along Burnt Creek during early ranching days at Hope Ranch, below the Burnt Creek #1 section (Alice Hope, personal commun., 1987). The specimen, about 0.75 m (2 ft) in length, displayed the large diamond-shaped ganoid scales, heavy deep body form, and homocercal tail characteristic of this genus (Romer, 1966; Grande, 1980). Specimens of similar large ganoid gar scales were found by the author littering the surface of exposures in fluvial sandstone of the middle Tullock Member in the northeastern Powder River Basin. Modern gar prefer shallow, swampy areas in association with streams and rivers. Fossil mammals appear to be rare in the Tullock Member in the Powder River Basin (Archibald and others, 1987), but small unidentifiable podials weathered from the sandstone were recovered by the author near the site of the gar pike scutes.

SEDIMENTOLOGY

Architectural elements in the Tullock Member consist of channel-fill sequences (CH) and fine-grained overbank sequences (OF) (usage of Miall, 1985; see fig. 7, this report). The proportion of channel (CH) deposits to floodplain deposits (OF) varies, but the latter are usually of greater cumulative thickness than the former. Characterization of Tullock depositional style is based on the proportion of sandstone and fine-grained lithologies, the geometry and distribution of archictectural elements, and the vertical and lateral distribution of lithofacies. Lithofacies are listed below.

Lithofacies in Channel-Form Sandstone Bodies (Channel Architectural Elements)

Sandstone is associated with all other lithologies, but is concentrated in the middle of the Tullock interval (figs. 10, 15, 19, and 23). Grain sizes in sandstone of the Tullock Member range from very fine to coarse, and the grains are well to moderately sorted. Most sandstone bodies fine upward in grain size. The colors (Munsell system) range from yellowish gray (5Y 7/2) to grayish yellow (5Y 8/4), but weathering and cement composition commonly alter the coloration to dark reddish brown (10R 3/4) or grayish brown (5YR3/2).

Figure 25. Outcrop of facies GM, conglomerate, in northeastern part of Powder River Basin (Little Powder River area). Divisions on spike are 1 in. Bankside slumps, a common conglomerate in Tullock Member, consist of large, very poorly sorted, angular to subangular clasts of undercut and slumped bankside material.

Conglomerate (GM)

The facies GM conglomerate is represented by clast- and matrix-supported, massive or crudely stratified zones commonly present at the base of channel-form sandstone bodies. Matrix grain size ranges from fine to coarse sand. Clasts are composed of clay-chips (less than 1 cm) scoured from the channel floor and intact blocks of mudstone that average 8 cm (3 in.) in the longest dimension and are interpreted as bankside slumps (fig. 25). Depositional units may be as much as 1.0 m (3.3 ft) in thickness.

One large siltstone clast incorporated in massive fine-grained sandstone was 32 cm (13 in.) long. Both types of clasts showed little evidence of transport: they are either intact or only slightly deformed. The lower bounding surface of depositional units is nearly everywhere the sharp base of channel-form sandstone bodies overlying fine-grained

Figure 26. Outcrop of facies SH, horizontally stratified sandstone, in northeastern part of Powder River Basin (Little Powder River area). Divisions on spike in photograph are 1 in. In center is a small, migrating sand bar showing tangential slip faces developed by increasing flow velocity. Paleoflow was from right to left in photograph.

overbank material. The upper bounding surface is commonly associated with facies SP, planar crossbedding, although in one example, facies SR-w, wavy bedding is first and is succeeded by facies SP.

In the Tullock Member, facies GM is rare and where present makes up less than 10 percent of channel sandstone bodies as determined from measured sections (fig. 11*C*, *D*; fig.14*C*, *D*). The GM facies occurs rarely because the source of sediment is dominated by fine-grained, easily eroded material.

Horizontally Stratified Sandstone (SH)

In the Tullock Member, facies SH comprises mainly fine-grained (rarely medium- to coarse-grained), horizontally bedded or laminated sandstone. Depositional units range in thickness from 3.0 to 5.0 m (9.8 to 16 ft). The basal bounding surface of depositional unit facies SH is commonly facies ST, trough crossbedding. The upper bounding surface is more variable, consisting of either facies SP (planar crossbedding) or facies SL–c (convolute bedding). In one example, facies SH is the sole sedimentary structure in a thin (1 m, or 3 ft), tabular sandstone body interbedded with fine-grained overbank deposits. Bedding planes are commonly accentuated by laminae of plant fragments and coal chips (fig. 26).

Facies SH is relatively uncommon in the Tullock, comprising only about 15 percent of channel sandstone bodies as determined from measured sections (figs. 11, 14, 18, and 23). The SH facies typically occurs in the upper part of these sandstone bodies. Comparison with flume studies of bed

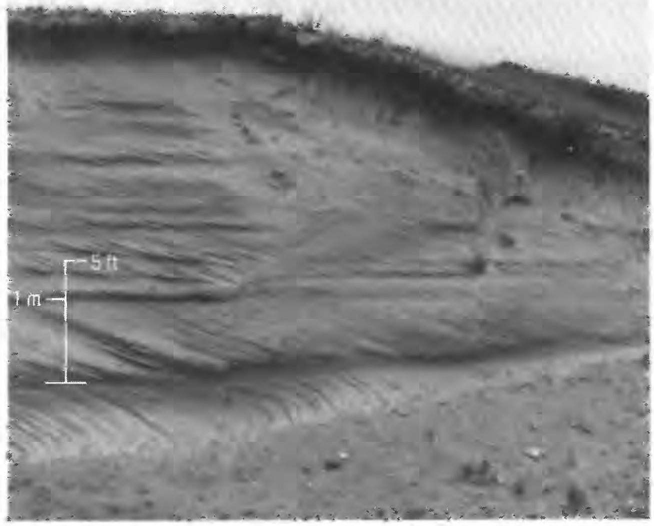


Figure 27. Outcrop of facies SP, planar crossbedded sandstone, in northeastern part of Powder River Basin (Little Powder River area). Bar scale on photograph shows that bottom set is 1.0 m (3.3 ft) thick and sets decrease in thickness upward. SP facies constitutes entire tabular sandstone body in this exposure.

forms in sediment of similar grain size (Middleton and Southard, 1977) suggests upper-flow-regime, plane-bed deposition.

Planar Crossbedded Sandstone (SP)

Facies SP comprises mainly fine-grained (rarely medium- to coarse-grained), planar crossbedded sandstone. Depositional units range in thickness from 10 cm (4 in.) to 2.0 m (6.6 ft), but sets less than 1 m (3 ft) thick are most common. The basal bounding surface of SP is almost everywhere the sharp base of channel-form sandstone bodies, but in some places it is above the GM facies. Rarely, the SP facies overlies facies SH, horizontally stratified sandstone. The upper bounding surface of facies SP is commonly facies SL–c, convolute bedding; rarely, facies SL–m (massive) and SR–c (current ripples) were noted. Foreset laminae are generally planar although some are tangential, and foresets dip as much as 30°. In some places, thin lenses of clay-chip clasts are incorporated in the foreset laminae at the bases of sandstone bodies. Bounding surfaces between sets and other lithofacies are planar to undulatory. Facies SP is relatively common, comprising about 30 percent of channel sandstone bodies as determined from measured sections (figs. 11*A*, *D*; 14*B*, *C*; 18*C*; and 23*A*, *B*). The facies typically occurs in the lower parts of lenticular sandstone bodies and in the upper, fine-grained parts in some places. Facies SP also occurs in tabular sandstone bodies, where it constitutes the only sedimentary structure, and sets are separated by reactivation surfaces (fig. 27). Tabular planar crossbedding is generated by

Figure 28. Outcrop of facies ST, trough crossbedded sandstone, in northeastern part of Powder River Basin (Little Powder River area). Ice ax is 1.0 m (3.3 ft) long. This set of trough cross-strata is 2.5 m (8 ft) wide, 1.0 m (3.3 ft) thick, and 14 m (46 ft) long.

the downstream migration of straight-crested sandwaves (Harms and others, 1975), and flume studies of bedforms in sediment of similar grain size (Middleton and Southard, 1977) suggests lower-flow-regime deposition.

Trough Crossbedded Sandstone (ST)

Facies ST comprises mainly medium-grained (rarely coarse- and fine-grained) trough crossbedded sandstone. Depositional units range in thickness from 30 cm to 1.5 m (12 in. to 4.9 ft), and in width to as much as 2.5 m (8.2 ft) (fig. 28).

The basal bounding surface is almost always at the sharp basal contact of lenticular sandstone bodies with fine-grained overbank sediments. Less common occurrences are in the upper part of lenticular sandstone bodies in fine-grained sandstone. The upper bounding surface of facies ST is commonly facies SL–c (convolute bedding) or SL–m (massive bedding), and less commonly facies SH (horizontally stratified sandstone) or SR–cl (climbing- ripple lamination). Rarely, the upper boundary of facies ST is facies SP (planar crossbedding) or SR–c (current-ripple lamination). Concentrations of clay rip-up clasts are found in some places at the bases of large sets, and grain size within the sets decreases upward from coarse to fine. In some cases, plant fragments and coal chips accentuate the foresets, which have dips that average 12°–15°. Facies ST is common, comprising about 40 percent of channel sandstone bodies as determined from measured sections (figs. 11, 14, 18, and 23), and occurring in all of the measured sections. Where sets are well defined, they are useful structures for paleocurrent measurements. Trough crossbedding is generated by the migration of dunes (Harms and others, 1975), and comparisons with flume studies of bedforms in sediment with similar grain size (Middleton and Southard, 1977), suggests lower-flow-regime deposition. In the center of figure 26 is a transverse section of a migrating bar form showing tangential slip faces (movement from right to left), which have a process of formation similar to trough crossbedding.

Massive or Disturbed Sandstone (SL)

Facies SL comprises mainly fine-grained sandstone that is either structureless or contains soft-sediment-deformation structures. Depositional units within sandstone bodies are as thick as 2.5 m (8.2 ft). Some SL facies occur as the only bedform in tabular sandstone bodies from 3.0 to 5.0 m (9.8 to 16 ft) thick. Within sandstone bodies the SL–c facies can be as much as 2.5 m (8.2 ft) thick and commonly overlies sets of ST facies. The basal bounding surfaces of depositional units are commonly either at the sharp basal contact of lenticular sandstone bodies or in association (top and bottom) with facies ST. In some places, inferred liquefaction zones completely obliterate the ST facies at the upper bounding surface. The upper bounding surface is commonly in fine-grained sediment at the top of sandstone bodies, and, rarely, the upper surface comprises climbing-ripple or current-ripple lamination. Sedimentary structures included in the SL facies are convolute bedding, massive or structureless bedding, load casts (fig. 29), and zones of inferred liquefaction (fig. 30).

Facies SL is common, making up as much as 60 percent of some sandstone bodies as determined from measured sections (figs. 11, 14, 18, 23). Individual tabular sandstone bodies containing only facies SL may be the result of a single depositional event, and as such have been interpreted as crevasse splays on floodplains (Coleman, 1969). SL–m facies are important components of the channel-form sandstones and may actually show bedding or crossbedding but not vary in grain size, color, composition, or cementation sufficiently to accentuate or preserve the bedding. SL facies that include massive or structureless sandstone are commonly confined to single bedding sets, the structureless zone being truncated by the upper and lower bounding surfaces. SL–m facies may represent zones where processes of rapid fluid escape shortly after deposition may have destroyed original structures. Development of these zones can be triggered by seismic shaking or dewatering and compaction of underlying sediment, mechanisms that would probably be favored in rapidly accumulating river-channel deposits. Other interpretations of massive beds include very

Figure 29. Outcrop of facies SL, massive sandstone, in southwestern part of Powder River Basin (Teapot Dome area). Hammer at base is approximately 28 cm (1 ft) long. Load casts are developed where fine-grained sandstone overlies a zone of very fine grained, massive, silty sandstone. Load casts are believed to form by unequal loading of water-saturated hydroplastic sediments that founder into unstable sediments below. Overlying the load casts are foresets of planar crossbeds deformed and oversteepened by rapid sediment loading from above.

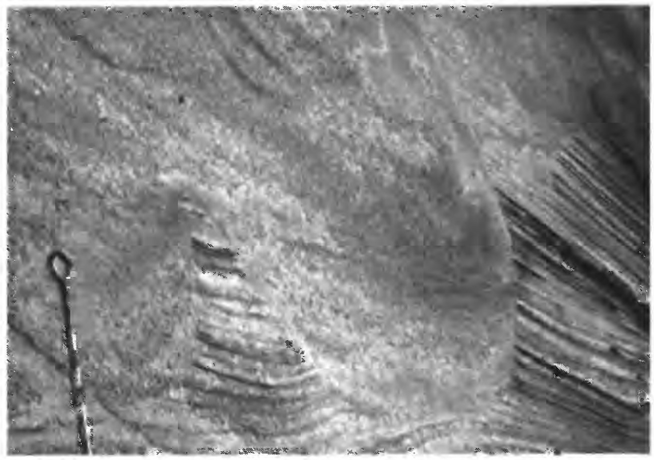


Figure 30. Outcrop of facies SL, massive sandstone, in northeastern part of Powder River Basin (Little Powder River area). Divisions on spike in photograph are 1 in. A liquefaction zone obliterates primary stratification in fine-grained sandstone. Deformation of fine-grained sand is sometimes caused by waters rising through loosely compacted sediment and carrying entrained grains that destroy primary structure and resettle, forming massive structure (Lowe, 1976). The exposed homogenization zone, about 3.0 m (9.8 ft) thick and 5.0 m (16.5 ft) wide, has completely obliterated primary sedimentary structures along the sharp scalloped contacts.

rapid deposition from suspension of highly concentrated sediment dispersions (Blatt and others, 1980).

Small-Scale Cross-Laminated Sandstone (SR)

Facies SR comprises mainly very fine grained to fine-grained sandstone having climbing-ripple lamination SR–cl) as the predominant sedimentary structure (fig. 31). Wavy lamination (SR–w) and current-ripple lamination (SR–c) are uncommon. Within sandstone bodies, depositional units range in thickness from 0.3 to 6.0 m (1 to 20 ft). Some SR–cl facies occur as the only bed form in tabular sandstone bodies 1.0 m (3.3ft) thick interbedded with fine-grained overbank sediment (fig. 14*A*).

Figure 31. Outcrop of facies SR, small-scale cross-laminated sandstone, in southeastern Powder River Basin (Lance Creek area). Divisions on spike in photograph are 1 in. Sedimentary structures at base are climbing ripple lamination that is overlain by wavy beds.

The lower bounding surface of facies Sr–cl is characteristically facies ST, and SR–cl represents the last sedimentary structure in a fining-upward sequence. The angle of climb of ripples in facies SR–cl ranges from 3° to 5°. They are developed in homogeneous fine sand and commonly occur in discrete sets that show no change in the angle of climb. Facies SR–c, current-ripple lamination, most commonly occurs as

Figure 32. Outcrop showing sedimentary structures in facies FM, mudstone and siltstone, in northwestern Powder River Basin (Tullock Creek and Lodgegrass areas). Shale and sand-filled mudcracks overlie a coal zone in Burnt Creek section. Divisions on spike in photograph are 1 in.

the only sedimentary structure in flat-based, thin, tabular sandstone bodies interbedded with fine-grained overbank deposits (fig. 13 *B*). Facies SR–w is rare, in one instance occurring near the base of a lenticular sandstone body above facies GM and in another instance in a zone 0.5 m (1.6 ft) thick near the top of a fining-upward sequence in a 9.0-m-(30-ft) thick channel-form sandstone above facies Sl–c, convolute bedding. The wavy beds are characterized by alternating, symmetric, in-phase, ripple-bedded sand layers having an amplitude of about 1 cm and a wavelength of about 4 cm, which are interbedded with thin, wavy mud drapes. Facies SR is relatively uncommon, comprising about 15 percent of channel sandstone bodies as determined from measured sections (figs. 11, 14, 18, and 23). Where SR–cl and SR–c occur as tabular sandstone bodies they are interpreted as crevasse splays (Coleman, 1969; O'Brien and Wells, 1986). Within channel-form sandstone bodies, SR–cl is interpreted as resulting from a low-flow regime coupled with abundant sediment supply, causing aggradation in floodplain channels (Jopling and Walker, 1968). Wavy beds within sandstone bodies are interpreted as products of a low-flow regime, a high aggradation rate, and episodic deposition (Collinson and Thompson, 1989).

Lithofacies in Tabular Fine-Grained Rocks (Overbank Architectural Elements)

Massive Mudstone (FSC and FM)

The FSC facies consists of mudstone composed entirely of clay and is dark gray to very dark grayish brown (5YR3/2). FSC everywhere underlies coal beds and ranges in thickness from 10 to 35 cm (4 to 18 in.). Facies FM is composed of mudstone and siltstone, and ranges in thickness from 1.0 to 5.0 m (3.0 to 16 ft). It is medium gray (N–5) to pale brown (5YR 5/2). The facies is typically massive, but there are sand-filled desiccation cracks on bedding planes (fig. 32).

The darker colors indicate greater organic content of the sediments. Facies FM is commonly associated with facies FSC; both contain color mottling and plant, wood, and coal fragments dispersed throughout the sequence. Although both facies are obscurely bedded or have no apparent internal structure, they differ in that facies FSC is indurated and thin bedded, has a higher organic content, and is everywhere associated with coal beds. Facies FSC and FM are gradational with facies FL, and together these three facies make up about 70 percent of the measured sections. McLean and Jerzykiewicz (1978) reported similar associations of these facies (FSC, FM, and FL) and suggested peat accumulation on an alluvial plain, probably in areally restricted back-levee swamps that parallel fluvial channels.

Rippled and Horizontally Laminated, Very Fine Grained Sandstone, Siltstone, and Mudstone (FL)

Facies FL is the most common fine-grained overbank facies. It is characterized by very fine grained sandstone, siltstone, and mudstone that have small-scale ripple lamination and parallel lamination as the predominant sedimentary structures. Colors range from grayish yellow (5Y8/4) to yellowish gray (5Y7/2). Depositional units are generally less than 2 cm thick, and facies Fl sequences range from 0.5 to 20.0 m (1.6 to 65.6 ft). Upper and lower bounding surfaces with associated facies FSC, FM, and C are gradational and may be laterally traceable for tens of meters. The lower and upper bounding surfaces of facies FL with channel-form sandstone bodies is abrupt almost everywhere, but some upper bounding surfaces are gradational. Facies FL is interpreted as overbank or waning flood deposits in fluvial systems, but of minor importance in braided river systems (Miall, 1985).

Coal and Carbonaceous Shale (C)

The C facies consists of coal and carbonaceous shale characterized by discontinous intervals that are either massive or contain indistinct thin laminae. Tullock coal beds range in thickness from 0.25 to 2.0 m (0.82 to 6.6 ft). Carbonaceous shale sequences range in thickness from 0.5 to 5.0 m (1.6 to 16.5 ft). Interbedded with coal and carbonaceous shale and the other fine-grained facies are layers that are almost wholly leaf fossil impressions, indicated by the leaf symbol on the lithofacies diagrams for each measured section. Leaf fossil layers are at most about 1 cm thick and associated mainly with coal beds. Upper and lower bounding surfaces with other lithfacies elements are commonly gradational, but are sharp in contact with the bases of channel-form sandstone bodies. Facies C forms a minor part of the fine-grained facies and is interpreted as having derived from poorly drained swamp deposits in a basin subsiding at a moderate rate (McLean and Jerzykiewicz, 1978).

Mudstones Containing Root Casts and Impressions (FR)

The FR facies represents root mats in association with possible soil horizons (Bown and Kraus, 1981; Retallack, 1988). The FR facies commonly underlies coal beds, but distinct zones of facies FR are uncommon. The rootlets and root tracings are vertically oriented and presumably in life position. Where distinguishable, FR horizons are as much as 2 m (7 ft) thick, and it is probable that FR horizons may be more prevalent than observable in outcrop.

Depositional Environments

Geometry and Internal Structure of Elements CH and OF

Two architectural elements, channel-fill sequences (CH) and fine-grained overbank sequences (OF) (Miall, 1985), are present in the Tullock Member. Fine-grained overbank sediment constitutes a far greater proportion of the sequence than channel-fill sandstone. The fine-grained overbank element accounts for as much as 50 m (170 ft) in thickness of siltstone, mudstone, and minor coal beds as determined from outcrop and subsurface analyses. Tullock channel-form sandstone bodies, which are as wide as 600 m (1,970 ft), are composed of angular to subangular, fine- to medium grained, chert-rich litharenite. Two types of sandstone body geometry are distinguishable in the Tullock Member. The first type is the most common and consists of isolated, lenticular sandstone bodies that have low width-to-depth ratios and inferred ribbon geometry. In outcrop, these sandstone bodies range in thickness from 3.0 to 11.0 m (9.8 to 36.1 ft), but most are less than 5.0 m (16 ft) thick. In the subsurface, thicknesses range from 5 to 20 m (20 to 66 ft) thick. The second type consists of thin (as much as 3.0 m, or 9.8 ft, thick), sheetlike, tabular sandstone bodies that can be traced laterally for tens of meters. Generally, both types have sharp lower contacts and show an upwardly decreasing grain size as determined from outcrop and in subsurface analysis.

Internal components of the sandstone bodies are the predominant lithofacies, vertical sequence, and internal bounding surfaces. The predominant lithofacies within the sandstone bodies is trough-crossbedded sandstone (ST) followed by massive or disturbed sandstone (SL), planar-crossbedded sandstone (SP), horizontally stratified sandstone (SH), conglomerate (GM), and small-scale, cross-laminated sandstone (SR). The vertical sequence of sedimentary structures in the channel-form sandstones is typically GM, ST, SL or SP, SH, and SR, but not all these lithofacies are present everywhere. In the thin, tabular sandstone bodies lithofacies SR–cl, SR–c, and SH are the predominant sedimentary structures, and in some sandstone bodies only one lithfacies type is present. Two types of internal bounding surfaces were noted: probable lateral-accretion surfaces and reactivation surfaces within tabular planar crossbeds. The internal structure of the overbank mudstone units is characterized by the predominance of facies FL, which is interbedded with lesser thicknesses of FSC, FM, C, and FR.

Dominant Processes of Channel and Floodplain Deposition

Principle stratification types in the Tullock Member are trough and tabular cross-stratification, horizontal stratification, and climbing-ripple lamination. Trough cross-stratification is formed by downstream migration of dunes and suggests a low-flow regime and unidirectional flow (Harms and Fahnestock, 1965). Tabular planar crossbedding is formed by unidirectional migration of sand waves in a lower flow regime than is required for migration of dunes. Reactivation surfaces within planar tabular sets suggest that the steady advance of the bed form was interrupted and indicates either changes in sedimentation process or in flow direction during low river stages (Collinson, 1970). Size, type, and distribution of sedimentary structures indicate downstream migration of small transverse bars (Smith, 1971) composed of fine- to medium-grained sediments. The transverse bars build by aggradation to equilibrium and then grow downstream by down-current extension of slip faces (Jopling, 1966; Smith, 1971). These bars form by the migration of straight-crested megaripples and sandwaves, and some of them consist entirely of sets of tabular crossbedding, which in the Tullock attain a thickness per set of as much as 1.3 m (4.2 ft) and appear to extend completely across the paleochannel. Predominant internal sedimentary structures in the channel bar-forms are planar and trough crossbeds. Some crossbeds contain basal clay rip-up clasts and bankside slump blocks, which indicate erosion of the stream floor and undercutting of the cohesive banks. In some Tullock outcrops, successive sediment pulses appear to have overriden, compressed, and thereby dewatered the underlying sediments and created zones of convolute bedding, load casts, and obliteration of primary structures.

Horizontal stratification suggests an upper-flow regime in which velocities were higher than those required for the formation of dunes, sandwaves, and ripples and which is associated with high sedimentation rates and changing flow conditions (Harms and others, 1975). Ripple-drift cross-lamination (Jopling and Walker, 1968) forms if the rate of aggradation exceeds the rate of migration of the bed form and is associated with fluvial flood deposits characterized by rapid deposition of sediment from suspension.

The geometry of the sandstone bodies provides evidence for channel migration. Friend (1983) reported that fixed channels cause formation of laterally restricted and highly elongated sand ribbons that are usually isolated in finer grained sediment. The fact that Tullock channels are filled with fine to medium sand but are surrounded by mudstone, siltstone, and very fine grained sand deposits suggests a mixed load system carrying a high suspended load. Additionally, Tullock channel-form sandstone bodies have steep sides, concave-upwards bases, flat tops (lacking alluvial ridges), and cross sections that are probably close to that of the original channel. Some Tullock sandstone bodies are thin, solitary, flat-based tabular bodies of fine to medium sand containing only planar crossbeds, current ripples or climbing-ripple lamination, features that are commonly attributed to crevasse splay deposition in meandering rivers. These units are interpreted to be small-scale crevasse splays (O'Brien and Wells, 1986) that overflowed the sides of the channel and spread over floodplain wetlands composed of silt, mud, and vegetation. In outcrop, the splay sediments are small thin wedges that pinch out within tens of meters and are less than 2 m (7 ft) thick. Avulsion and resultant crevasse splay deposits provide important clues to the character of a fluvial system (Coleman, 1969). Channel migration and development of anastomosed streams seem to be dominated by erosion of cohesive, vegetated banks, and by aggradation by bar construction within channels (Smith, 1976). Lack of prominent alluvial ridges is due to the predominance of clay, silt, and fine sand in the overbank fraction and presence of bank vegetation that prevents coarse-grained bedload sediment from washing onto the floodplain surface. Lateral accretion surfaces suggesting point bar forms and a greater sinuosity (McGowan and Garner, 1970) are rare in the Tullock, but this may be an artifact of preservation, inadequate exposure, and a system that is dominated by silt and mudstone.

Types of Fluvial Systems

Leopold and Wolman (1957) first distinguished fluvial channel morphologies as braided, meandering, and straight. The vertical succession of sedimentary structures in the Tullock shows classic fining-upward sequences characterizing meandering systems (Allen, 1970). Sandstone body geometry and basal erosion surfaces, type and distribution of sedimentary structures, upward decrease in scale of sedimentary structures, consistently unidirectional paleoflows, terrestrial vegetation assemblages, and presence of coal beds indicate that the Tullock Member was deposited in a continental fluvial environment. Crowley (1983) modeled processes of downstream movement of large sediment pulses as bar forms having diagnostic vertical sequences of sedimentary structures, and he documented the influence of sinuosity and nonerodible banks on bed form size and geometry. Conclusions based on sinuosity and processes of sediment movement applied to Tullock geometry and bed forms suggest bankfull depths equal to paleochannel thickness, low fluvial gradient, low sinuosity, highly stable vegetated banks and lenticular channel form. Haszeldine (1983) studied a large elongate fluvial bar that was part of a system of low-sinuosity, fine-grained sandstone bodies that traversed a coalfield. Facies in this bar were dominated by tabular planar crossbed sets. Similar (but poorly exposed) sequences of tabular planar crossbed sets in the Tullock Member show a similar vertical hierarchy of bed forms, grain-size distribution, and decreasing thickness of cosets. Bernard and others (1970) studied a meandering alluvial system dominated by silt and fine sand in the Brazos River, southeastern Texas. They noted that natural levee sediments are difficult to distinguish from the uppermost point-bar sediments and that abandoned channel fills consisted principally of laminated clay and silt. The deposits ranged from a few feet to approximately 40 ft thick and usually occupied positions within the upper two-thirds of point-bar sequences. Stewart (1983) reported an example of claystone and siltstone point bars from ancient channel systems carrying predominantly suspended loads on mature, low-gradient flood plains. They are characterized by sequences that generally fine upward, have small-scale crossbedding, and range in thickness from 2 to 10 m (7 to 33 ft) thick. Similar sedimentary features in the Tullock suggest similar suspended-load point-bar systems.

Sedimentary features and geometry of Tullock sediments suggest anastomosed river systems (Schumm, 1968; Smith, 1976; Smith and Putnam, 1980; Smith and Smith, 1980; Rust, 1981; Smith, 1983). Anastomosed channel systems occur in temperate as well as in arid climates (Rust, 1981), and they result mainly from a local reduction in gradient, promoting river aggradation (Smith and Smith, 1980). Sedimentary structures and facies relationships in the Tullock contain features found in both intermontane and plains settings (Smith, 1983).

Smith and Smith (1980) and Smith and Putnam (1980) proposed models for anastomosing fluvial facies that include some features applicable to braided and meandering systems. Principal features of anastomosing systems are stable, laterally confined channels, rapid aggradation, and associated wetland and overbank complexes. Based on the association between surface morphology and subsurface analyses, stable, laterally confined channels, rapid aggradation, and associated wetland complexes are also predominant in Tullock sedimentation. Smith (1983) found that anastomosing river systems are associated with deposition in foreland basin tectonic regimes provided that uplift and basin subsidence were nearly synchronous in time. Johnson (1984) reported that in a rapidly subsiding basin there is a decrease in grain size and stream-flow capacity, an increase in the fine-grained component toward a mud-dominated system, and an increase in channel bank stability. A comparison of features of these systems with Tullock sedimentation patterns suggests initiation of alluvial disequilibrium as Laramide tectonics began.

TECTONICS AND PALEOGEOGRAPHY

The Cretaceous Sevier orogeny in the Western United States was characterized by folding and thrusting of older strata eastward over their foreland (Armstrong, 1968). The loading of the crust triggered subsidence and the formation of a foreland basin to the east that accomodated the Western Interior Seaway (Burchfiel and Davis, 1975; Dickinson and Snyder,1978; Jordan, 1981). Initiation of the Washakie uplift and Beartooth Mountains and the arching of the Granite Mountain, Laramie, and Hartville highs (Merewether and Cobban, 1985) began in the Late Cretaceous. This Laramide deformation commenced in western and southwestern Wyoming before marine deposition had ended in northeastern Wyoming and affected timing and migration of local sedimentation patterns in the Powder River Basin (Blackstone, 1981; Gries, 1983; Merewether and Cobban, 1985; Brown, 1985, 1987; Brown and Nichols, 1989). Structural basins such as the Powder River Basin formed concurrently with the uplifts through Eocene time but at different times in different places (Tweto, 1975, 1980; Dickinson and others, 1988). Previous studies have suggested that the structural development of the Powder River Basin and bounding Bighorn uplift began in early middle Paleocene time and continued through late Eocene time (Coney, 1972; Blackstone, 1975, 1986; Gries, 1983). The present study suggests an earlier initiation of the Bighorn uplift.

The present-day Bighorn Mountains consist of a large doubly plunging anticline that has a topographically high core of exposed Precambrian crystalline basement rocks. They are part of a major Laramide foreland uplift and were deformed by compression into a broad arc convex to the east. Vertical deformation of the Bighorn Mountains commenced with initial uplift on the north end of the block, then doming to form an anticlinal structure, and consequent unroofing from north to south of Paleozoic and Mesozoic strata in early middle Paleocene time (Blackstone, 1981; Gries, 1983). West-to-east lateral tectonic stress was concentrated in the central Bighorn anticline, which consequently failed and began to override the Powder River Basin along west-dipping reverse faults. The Powder River foreland basin axis deepened and lengthened north to south. As the uplift of the Bighorn Mountains progressed, long east-west faults developed along regional lineaments that mark zones of major discontinuity in the basement. The central Bighorn block began to overthrust eastward, forming the incipient Piney salient and deforming the Sussex and Teapot Dome areas. The final tectonic configuration of the Bighorn uplift and the adjacent foreland basin was not achieved until early Eocene time (Gries, 1983).

Integrating previous structural studies with preliminary studies of petrology and paleocurrent directions (Brown and Hansley, 1989; Hansley and Brown, in press; fig. 8, this report) provided additional details on the uplift sequence of the Bighorn Mountains and formation of the adjacent Powder River foreland basin. The structural evolution is depicted in a series of paleogeographic maps that suggest possible source areas for Tullock sediments and probable basinal paleocurrent directions (fig. 33).

Tullock sandstone varies in composition from lithic arkose, to feldspathic litharenite, to sublitharenite (Hansley and Brown, in press). Analyses of petrologic data gathered from sandstone from the lowermost part of the Tullock in the northwestern Powder River Basin just above the K-T boundary show a predominance of unstable, large carbonate clasts derived from the unroofing and stripping of Paleozoic and Mesozoic strata from the rising Bighorn Mountains (figs. 8 and 33). Many carbonate clasts, in fact, contained silicified crinoid stems. Sediment that contained greater than 10 percent carbonate grains was dispersed by paleostreams to the east and southeast in the northern Powder River Basin. In contrast, sediment in the lowermost part of theTullock in the southern part of the basin contains less than 1 percent carbonate grains. Within the Tullock Member sandstone bodies, the proportion of unstable grains (feldspar, rock fragments, glauconite, and carbonate) decreases to the east with increased lateral distance from the influence of the rising Bighorn Mountains. Vertical compositional changes reflect the unroofing of successively older rocks from the Bighorn uplift. Where igneous rock fragments predominate, they were probably transported from uplifts to the south (Laramie Mountains, Granite Mountains, and Hartville uplift) along the east margin of the basin toward the north and northeast.

Sandstone from the middle part of the Tullock shows abundant igneous rock fragments and minerals suggesting derivation of materials from the unroofing of plutons of quartz diorite and quartz monzonite in the central Bighorns (figs. 8 and 33). Additionally, hornblende and actinolite-tremolite in sandstone in the southwestern part of the basin may have been derived from amphibolite in the Laramie-Medicinebow uplifts south of the Powder River Basin. Paleostreams flowed predominantly to the east and northeast basinwide.

Sandstone from the upper part of the Tullock contains abundant igneous rock fragments and metamorphic minerals suggesting continued unroofing and erosion of gneiss and other metamorphic rocks from the Bighorn Mountains (figs. 8 and 33). The Powder River Basin downwarping along the

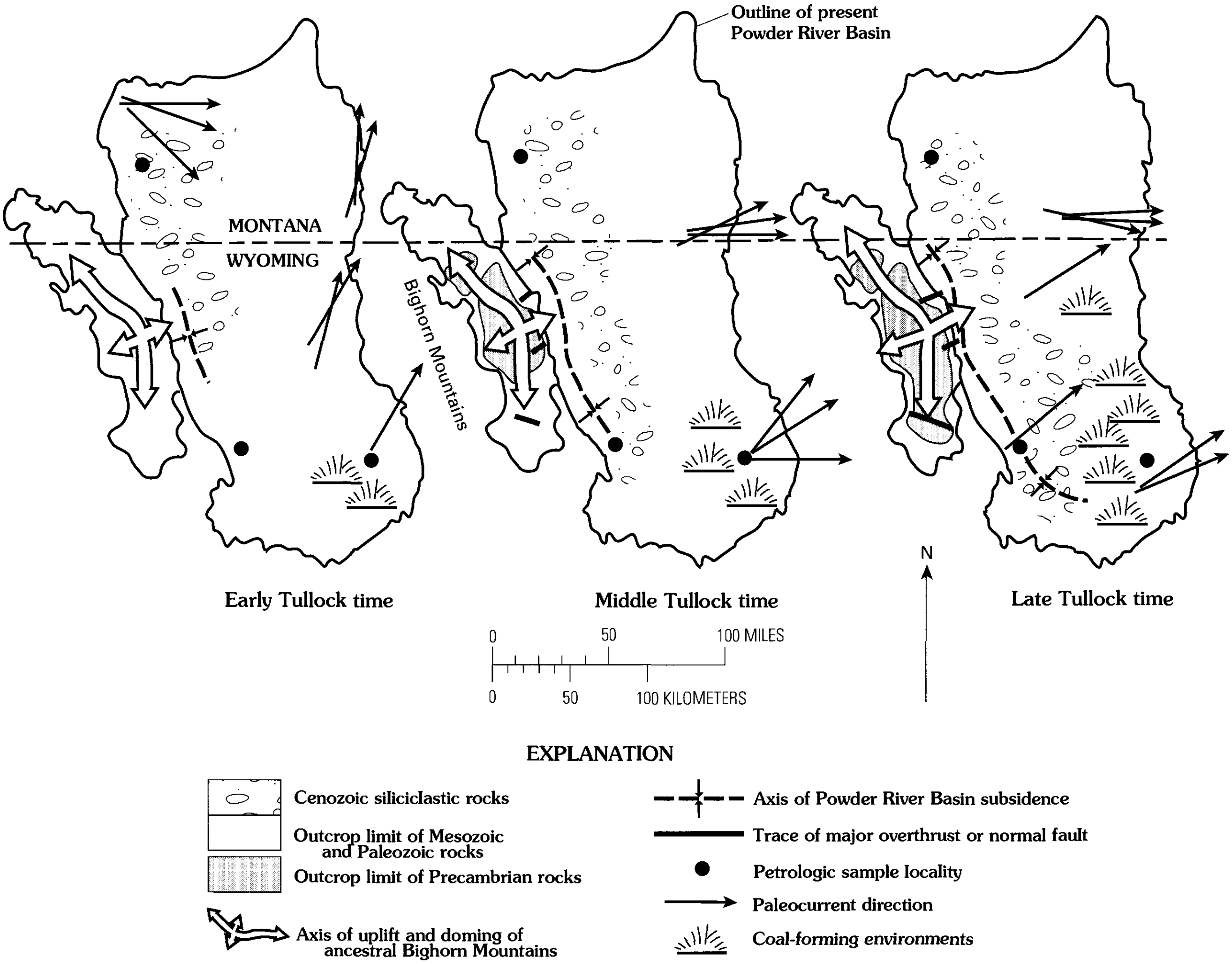


Figure 33. Paleogeographic maps depicting rise of Big Horn Mountains, unroofing of source rocks, and paleocurrent directions as derived from structural, petrologic, and sedimentologic data.

axis continued to widen and deepen, and paleostreams continued to flow predominantly to the east and northeast basinwide.

Palynology provides insights for the sedimentary history of the Tullock Member. Carbonaceous zones and coal beds are present in the lower, but not the lowermost, Paleocene in the northwestern part of the basin. Tullock-style deposition did not begin until sometime after earliest Paleocene in that area. In contrast, coal beds are present in the Lance Formation in the southeastern part of the basin, and the Lance-Tullock contact is transitional in that area (Clemens, 1963; Leffingwell, 1970). This evidence suggests that swampy depositional environments expanded from the southeast to the northwest across the basin in Tullock time (Nichols and Brown, 1992). The palynologically defined K-T boundary, which is a time line, shows that the formation contact is time-transgressive from southeast to northwest across the basin. A likely control on early Paleocene paleoenvironments is a temporary readvance of the Cannonball sea (Nichols and Brown, 1990). The readvance gradually raised base level and tended to pond the slowly flowing streams in the region of the Powder River Basin (Nichols and Brown, 1989b; 1990), promoting peat accumulation. The inferred anastomosing style of fluvial systems in the Tullock Member is evidence for a rise in base level.

CONCLUSIONS

Sediments of the Tullock Member indicate infilling of a Laramide intracratonic foreland basin, and the K-T time line provides temporal control for the timing and distribution of these sedimentation events. Improved temporal control derived from palynological analysis has allowed interpretation of the mode and rate of development of early Paleocene sedimentation patterns in the Powder River Basin. Earliest Paleocene doming in the area of the future

Bighorns generated subsidence in the adjacent north-south-trending foreland depression. Sedimentation and subsidence continued until the end of Eocene time, the future axis of greatest subsidence being parallel and proximal to the Bighorn uplift. Associated Paleocene-Eocene basin-fill clastic rocks have a maximum thickness of about 6,560 ft (2,000 m) in the west and south. The infilling Tullock clastic sediments merged eastward with distant delta-plain systems containing aggrading distributary channels that flowed into the Cannonball epicontinental sea (Cherven and Jacob, 1985).

The geometry of sandstone bodies and basal erosion surfaces, type and distribution of sedimentary structures, upward decrease in scale of sedimentary structures, consistent unidirectional stream flows, terrestrial vegetation assemblages, and presence of coal beds indicate that the Tullock Member was deposited in a continental fluvial environment. Channel deposits (making about one-third of the sequence) contain mainly trough and tabular planar cross-bedded, and climbing-ripple-laminated sandstone; reactivation surfaces, liquefaction fronts, and structures resulting from soft-sediment deformation are also common, suggesting episodic rapid deposition, saturation of sediments, and high watertable. Fine-grained overbank rocks (making up about two-thirds of the sequence) show color mottling and contain plant, wood, and coal fragments, obscure bedding or no apparent internal structure, and thin coal beds.

In the Tullock, geometry, sediment movement, and bed forms suggest bankfull depths equal to paleochannel thickness, low fluvial gradient, low sinuosity, highly stable vegetated banks, and lenticular channel form. Natural leevee sediments are difficult to distinguish from the uppermost point-bar sediments in the Tullock, and abandoned channel fills consist principally of laminated clay and silt. Tullock claystone and siltstone point bars are characterized by sequences that generally fine upward and small-scale cross-bedding, and they range in thickness from 2 to 10 m (7 to 33 ft). They result from channel systems carrying predominantly suspended loads on mature low-gradient flood plains. Movement of mud-dominated sediment through Tullock fluvial channels was principally by downstream aggradation resulting in construction of bars, and by build up of the floodplain through overbank flooding, which deposits mainly suspended-load material. The bar forms are dominated by tabular planar crossbed sets in which grain size fines upward and cosets decrease in thickness.

Sedimentary features and geometry of the Tullock sediments suggest deposition in anastomosed river systems. Presence of unstable carbonate clasts in the lowermost part of the Tullock in the northwestern basin suggests the beginning of doming and stripping of Paleozoic and Mesozoic strata from the area of the future Bighorn Mountains. Contemporaneously, coal-forming environments indicated by carbonaceous zones and coal beds spread from the southeast to the northwest across the basin in early Paleocene time. A likely control of peat accumulation was a temporary readvance of the Cannonball sea (a part of the Western Interior Seaway), which raised base level and locally reduced the gradient in the southeastern part of the basin. The reduced gradient promoted river aggradation, ponding, and swamp formation, and created anastomosing river systems having low sinuosity.

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APPENDIXES 1–3

APPENDIX 1. WELL LOGS USED IN CONSTRUCTION OF SUBSURFACE TRANSECTS OF THE POWDER RIVER BASIN, WYOMING AND MONTANA

Well-log No.	Location	Thickness of Tullock Member of Fort Union Formation
NORTHWESTERN POWDER RIVER BASIN—TULLOCK CREEK AND LODGEGRASS AREAS		
Sheridan County, Wyo.		
1	Sec. 35 (6), T. 58 N., R. 84 W.	236 m (775 ft)
2	Sec. 27 (13), T. 58 N., R. 84 W.	208 m (681 ft)
Bighorn County, Mont.		
3	Sec. 27 (4), T., 9 S., R. 39 E.	198 m (650 ft)
4	Sec. 16 (11), T. 9 S., R. 39 E.	206 m (675 ft)
5	Sec. 33 (7), T. 8 S., R. 39 E.	195 m (640 ft)
6	Sec. 35 (1), T. 7 S., R. 39 E.	165 m (540 ft)
7	Sec. 23 (16), T. 7 S., R. 39 E.	149 m (490 ft)
8	Sec. 2 (8), T. 7 S., R. 39 E.	128 m (420 ft)
9	Sec. 25 (16), T. 6 S., R. 39 E.	162 m (530 ft)
10	Sec. 36 (16), T. 5 S., R. 39 E.	113 m (370 ft)
11	Sec. 36 (16), T. 4 S., R. 39 E.	143 m (470 ft)
12	Sec. 19 (6), T. 2 S., R. 40 E.	122 m (400 ft)
NORTHEASTERN POWDER RIVER BASIN—LITTLE POWDER RIVER AREA		
Campbell County, Wyo.		
1	Sec. 25 (5), T. 56 N., R. 73 W.	158 m (518 ft)
2	Sec. 23 (2), T. 56 N., R. 73 W.	206 m (676 ft)
3	Sec. 11 (4), T. 56 N., R. 73 W.	168 m (550 ft)
4	Sec. 1 (12), T. 56 N., R. 73 W.	227 m (745 ft)
5	Sec. 36 (14), T. 57 N., R. 73 W.	210 m (690 ft)
6	Sec. 25 (14), T. 57 N. R. 73 W.	221 m (725 ft)
7	Sec. 23 (2), T. 57 N., R. 73 W.	232 m (760 ft)
8	Sec. 13 (12), T. 57 N., R. 73 W.	232 m (760 ft)
9	Sec. 11 (16), T. 57 N., R. 73 W.	274 m (900 ft)
10	Sec. 12 (4), T. 57 N., R. 73 W.	213 m (700 ft)
11	Sec. 36 (13), T. 58 N., R. 73 W.	152 m (500 ft)
12	Sec. 26 (16), T. 58 N., R. 73 W.	172 m (565 ft)
13	Sec. 22 (13), T. 58 N., R. 73 W.	186 m (610 ft)
Powder River County, Mont.		
14	Sec. 32 (4), T. 9 S., R. 50 E.	192 m (630 ft)
15	Sec. 16 (13), T. 9 S., R. 50 E.	125 m (410 ft)
16	Sec. 8 (9), T. 9 S., R. 50 E.	152 m (500 ft)
17	Sec. 5 (13), T. 9 S., R. 50 E.	152 m (500 ft)
18	Sec. 33 (7), T. 8 S., R. 50 E.	152 m (439 ft)
19	Sec. 29 (4), T. 8 S., R. 50 E.	171 m (560 ft)

Well-log No.	Location	Thickness of Tullock Member of Fort Union Formation
SOUTHEASTERN POWDER RIVER BASIN—LANCE CREEK AREA		
Converse County, Wyo.		
1	Sec. 4 (9), T. 37 N., R. 69 W.	372 m (1,220 ft)
2	Sec. 28 (1), T. 38 N., R. 69 W.	439 m (1,440 ft)
3	Sec. 21 (4), T. 38 N., R. 69 W.	408 m (1,340 ft)
4	Sec. 16 (3), T. 38 N., R. 69 W.	415 m (1,360 ft)
5	Sec. 8 (11), T. 38 N., R. 69 W.	424 m (1,390 ft)
6	Sec. 5 (7), T. 38 N., R. 69 W.	393 m (1,290 ft)
7	Sec. 33 (13), T. 39 N., R. 69 W.	399 m (1,310 ft)
8	Sec. 32 (3), T. 39 N., R. 69 W.	378 m (1,240 ft)
9	Sec. 16 (13), T. 39 N., R. 69 W.	405 m (1,330 ft)
10	Sec. 15 (6), T. 39 N., R. 69 W.	418 m (1,370 ft)
11	Sec. 15 (4), T. 39 N., R. 69 W.	350 m (1,150 ft)
12	Sec. 12 (4), T. 39 N., R. 69 W.	344 m (1,130 ft)
13	Sec. 10 (1), T. 39 N., R. 69 W.	366 m (1,200 ft)
14	Sec. 4 (15), T. 39 N., R. 69 W.	378 m (1,240 ft)
15	Sec. 4 (7), T. 39 N., R. 69 W.	338 m (1,110 ft)
16	Sec. 4 (3), T. 39 N., R. 69 W.	378 m (1,240 ft)
17	Sec. 33 (15), T. 40 N., R. 69 W.	372 m (1,220 ft)
18	Sec. 33 (1), T. 40 N., R. 69 W.	366 m (1,200 ft)
19	Sec. 28 (11), T. 40 N., R. 69 W.	360 m (1,180 ft)
SOUTHWESTERN POWDER RIVER BASIN—TEAPOT DOME AREA		
Natrona County, Wyo.		
1	Sec. 22 (9), T. 40 N., R. 77 W.	306 m (1,005 ft)
2	Sec. 15 (2), T. 40 N., R. 77 W.	299 m (980 ft)
3	Sec. 10 (11), T. 40 N., R. 77 W.	265 m (870 ft)
4	Sec. 34 (15), T. 41 N., R. 77 W.	251 m (825 ft)
Johnson County, Wyo.		
5	Sec. 27 (6), T. 41 N., R. 77 W.	284 m (930 ft)
6	Sec. 22 (4), T. 41 N., R. 77 W.	277 m (910 ft)
7	Sec. 9 (4), T. 41 N., R. 77 W.	302 m (990 ft)
8	Sec. 3 (7), T. 41 N., R. 77 W.	290 m (950 ft)
9	Sec. 28 (16), T. 42 N., R. 77 W.	241 m (790 ft)
10	Sec. 22 (13), T. 42 N., R. 77 W.	216 m (710 ft)
11	Sec. 28 (4), T. 43 N., R. 77 W.	283 m (930 ft)
12	Sec. 15 (5), T. 43 N., R. 77 W.	332 m (1,090 ft)

APPENDIX 2. SAMPLE LOCALITIES FOR THIN-SECTION STUDIES TO DETERMINE PROVENANCE OF SANDSTONE IN THE TULLOCK MEMBER OF THE FORT UNION FORMATION, POWDER RIVER BASIN, WYOMING AND MONTANA

[*, heavy-mineral separations]

Lowermost part of the Tullock Member:

T-1 SE1/4SW1/4SW1/4 sec. 36, T. 4 N., R. 35 E., Hope Ranch 7.5-minute quadrangle, Treasure County, Mont. (East Burnt Creek section); fine-grained, friable sandstone, about 45 m (148 ft) above the palynological K-T boundary, on East Burnt Creek, a tributary to Tullock Creek.

***88LC-1** NW1/4SE1/4 sec. 8, T. 39 N., R. 65 W. Dixon Ranch 7.5-minute quadrangle, Niobrara County, Wyo. (Lance Creek section); fine-grained, friable sandstone, about 7 m (23 ft) above the K-T basal coal on South Snyder Creek.

88LC-2 NW1/4NE1/4 sec. 8, T. 39 N., R. 65 W., Garland Draw 7.5-minute quadrangle, Niobrara County, Wyo. (Lance Creek section); fine-grained, friable sandstone, about 1.2 m (4 ft) above the K-T basal coal on South Snyder Creek.

88LC-3 NW1/4NE1/4 sec. 8, T. 39 N., R. 65 W., Garland Draw 7.5-minute quadrangle, Niobrara County, Wyo. (Lance Creek section); fine-grained, friable sandstone, about 0.6 m (2 ft) above the K-T basal coal in South Snyder Creek.

***88TEA-1** SE1/4NW1/4 sec. 23, T. 38 N., R. 77 W., Gillam Draw East 7.5-minute quadrangle, Converse County, Wyo., (Teapot Dome section); fine-grained, friable sandstone 12 m (40 ft) above the K-T boundary clay layer.

***88CRO-1** SW1/4 sec. 12, T. 4 S., R. 36 E., Thompson Creek NW 7.5-minute quadrangle, Big Horn County, Mont. (Crow Indian Reservation section); fine-grained, friable sandstone 9 m (30 ft) above the basal coal and K-T boundary clay layer.

Middle part of the Tullock Member:

***88LEV-1** SE1/4SW1/4 sec. 27, T. 39 N., R. 66 W., Calf Draw 7.5-minute quadrangle, Niobrara County, Wyo. (Lance Creek section); fine-grained, friable sandstone, from lowest exposed sandstone below road at Leverette Butte, at base of total section of 44.0 m (144.5 ft).

***88LEV-2** SE1/4SW1/4 sec. 27, T. 39 N., R. 66 W., Calf Draw 7.5-minute quadrangle, Niobrara County, Wyo. (Lance Creek section); fine-grained, friable sandstone, from sandstone exposed at top of Leverett Butte.

***88SUS-1** SW1/4SE1/4 sec. 3, T. 42 N., R. 79 W., Sussex 7.5-minute quadrangle, Johnson County, Wyo. (Sussex section); coarse-grained, friable sandstone, about 10 m (33 ft) up from saddle between B.M. Hill and hill just to the north.

Uppermost part of the Tullock Member:

***88LC-4** SW1/4NW1/4 sec. 3, T. 38 N., R. 67 W., Pinnacle Rocks 7.5-minute quadrangle, Niobrara County, Wyo. (Lance Creek section); fine-grained, friable sandstone in about middle of a 15.2-m (50-ft) thick transition zone with overlying Lebo Member Cow Creek.

***88LC-5** NW1/4SW1/4 sec. 35, T. 39 N., R. 67 W., Pinnacle Rocks 7.5-minute quadrangle, Niobrara County, Wyo. (Lance Creek section); fine-grained, friable sandstone at roadcut on Cow Creek Road just below transition zone between Tullock Member and Lebo Member on Cow Creek. Grab sample, no measured section here.

***88TEA-2** SE1/4SE1/4 sec. 24, T. 38 N., R. 77 W., Seven L Creek East 7.5-minute quadrangle, Converse County, Wyo. (Teapot Dome section); fine-grained, friable sandstone, about 6 m (20 ft) below transitional contact with Lebo Member marked by clinker.

APPENDIX 3. SAMPLE LOCALITIES FOR PALYNOLOGICAL ANALYSIS AND AGE DETERMINATIONS, POWDER RIVER BASIN, WYOMING AND MONTANA

[Analyses by D.J. Nichols. The samples, organic residues, and microscope slides are filed by their paleobotany locality (PL) number in the U.S. Geological Survey paleontology and stratigraphy laboratory in Denver, Colo.]

PL No.	Stratigraphic unit	Age
East Burnt Creek: SE1/4SW1/4SW1/4 Sec. 36, T. 4 N., R. 35 E., Treasure County, Mont., Hope Ranch 7.5-minute quadrangle, on East Burnt Creek, a tributary to Tullock Creek		
D6936–A through G	Hell Creek Formation	Late Cretaceous
D6936–H through K	Hell Creek Formation	Paleocene
D6936–L through N	Tullock Member	Paleocene
East Beaver Creek: Near center NE1/4NE1/4 sec. 34, T. 4 N., R. 37 E., Treasure County, Mont., Minnehaha Creek North 7.5-minute quadrangle, on East Beaver Creek road		
D6937–A through R	Tullock Member	Paleocene
Jacobs Coulee 1: NW1/4NW1/4NW1/4 sec. 15, T. 5 N., R. 35 E., Treasure County, Mont., Eldering Ranch 7.5-minute quadrangle; along abandoned road in Jacobs Coulee		
D6940–A through H	Tullock Member	Paleocene
D6940–AA through BB	Tullock Member	Paleocene
Jacobs Coulee 2: SW1/4NE1/4 sec. 2, T. 5 N., R. 35 E., Treasure County, Mont., Eldering Ranch 7.5-minute quadrangle; roadcut on abandoned road in Jacobs Coulee		
D6941–A and B	Hell Creek Formation	Late Cretaceous
Dry Creek: NW 1/4NW1/4NE1/4 sec. 6, T. 56 No., R. 69 W., Campbell County, Wyo., Bowman Hill 7.5-minute quadrangle, in bluff on cut bank of Dry Creek		
D7000–A through F	Tullock Member	Paleocene
Trail Creek 1: NE1/4NE14NW1/4 sec. 11. T. 57 N., R. 70 W., Campbell County, Wyo., Mitten Butte 7.5-minute quadrangle, in bluff on north side of road		
D7001–A and B	Tullock Member	Paleocene
Trail Creek 2: NE1/4NW1/4NW1/4 sec. 11, T. 57 N., R. 70 W., Campbell County, Wyo., Mitten Butte 7.5-minute quadrangle, in gully on south side of road		
D7002	Tullock Member	Paleocene
Lance Creek 1: SE1/4SW1/4SE1/4 sec. 5, T. 38 N., R. 65 W., Niobrara County, Wyo., Dixon Ranch 7.5-minute quadrangle		
D7100–A through C	Tullock Member	Paleocene
Lance Creek 2: SW1/4SW1/4SE1/4 sec. 5, T. 38 N., R. 65 W., Niobrara County, Wyo., Dixon Ranch 7.5-minute quadrangle		
D7137–A through D	Lance Formation	Late Cretaceous
D7137–E through J	Tullock Member	Paleocene

PL No.	Stratigraphic unit	Age
Sussex: SW1/4SE1/4 sec. 3, T. 42 N., R. 79 W., Johnson County, Wyo., Sussex 7.5-minute quadrangle		
D7299–A through G	Lance Formation	Late Cretaceous
D7299–J through R	Tullock Member	Paleocene
D7299–AA through PP	Lance Formation	Late Cretaceous
D7299–QQ	Tullock Member	Paleocene
D7299–PPP	Tullock Member	Paleocene
Teapot Dome: SE1/4NW1/4 sec. 23, T. 38 N., R. 77 W., Converse County, Wyo., Gillam Draw East 7.5-minute quadrangle, in gully SW of road		
D7300–A through H	Lance Formation	Late Cretaceous
D7300–I through R	Tullock Member	Paleocene
Reno Creek: SW1/4 sec. 12, T. 4 S., R. 36 E., Big Horn County, Mont., Thompson Creek NW 7.5-minute quadrangle, in bluffs north of Reno Creek on Crow Indian Reservation		
D7411–A through C	Hell Creek Formation	Paleocene
D7411–D through K	Tullock Member	Paleocene
Cow Creek 1: SW1/4NW1/4 sec. 3, T. 38 N., R. 67 W., Niobrara County, Wyo., Pinnacle Rocks 7.5-minute quadrangle, in cut bank of Cow Creek		
D7418–A and B	Lebo Member	Paleocene
Cow Creek 2: NW1/4SW1/4 sec. 35, T. 39 N., R. 67 W., Niobrara County, Wyo., Pinnacle Rocks 7.5-minute quadrangle, on northwest side of Cow Creek Road		
D7419	Tullock Member	Paleocene
Leverett Butte: Center of SW1/4SW1/4 sec. 27, T. 39 N., R. 66 W., Niobrara County, Wyo., Calf Draw 7.5-minute quadrangle		
D7421–A through H	Tullock Member	Paleocene
South Snyder Creek: SW1/4NW1/4NE1/4 sec. 8, T. 39 N., R. 65 W., Niobrara County, Wyo., Garland Draw 7.5-minute quadrangle, in gully on north side of road		
D7422–A and B	Lance Formation	Late Cretaceous
D7422–C	Lance Formation	Paleocene
D7422–D through F	Tullock Member	Paleocene

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