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Geology of the Sand Arroyo and Bug Creek Quadrangles, McCone County, Montana

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ABSTRACT

Badlands along the eastern shore of Fort Peck Reservoir in northeastern Montana expose beds from Late Cretaceous to mid-Paleocene, including the Bearpaw Shale, Fox Hills Sandstone, Hell Creek Formation, Tullock Formation, and the lower part of the Lebo Formation, in the gently southeastward-dipping homocline of the western margin of the Williston Basin. Within the Bug Creek and Sand Arroyo Quadrangles the 15–20-m-thick marginal marine to littoral Fox Hills Sandstone crops out in anticlinal cores with structural relief of tens of meters in reservoir shore exposures. Immediately northwest of the Sand Arroyo area, upper Bearpaw Shale is exposed in reservoir-shore exposures. The somber Hell Creek Formation overlies the Fox Hills Sandstone and consists of fine-grained floodplain mudstone and siltstone units that are cut by commonly fossiliferous channel-filling sandstone lenses. Thin, splay sandstones, local coal beds, and paleosols allow subdivision of the 80–85-m-thick formation into upper and lower members.

A carbonaceous clay contains a weak iridium anomaly at the Cretaceous-Tertiary boundary within the quadrangles, 1–6 m below the upper Z-coal, that has been mapped as the Hell Creek–Tullock Formation boundary. Brighter colored lacustrine-deltaic Tullock beds are cyclic—a complete cycle consisting of a basal sandstone and an overlying "zebra-striped" siderite-bearing mudstone that grades to a massive bentonitic mudstone and finally to a carbonaceous shale, paleosol, or thin subbituminous coal. Such cycles are most complete and evident in the lower half of the 40–50-m-thick formation, here named the Nelson Ranch Member. That member contains the W-, X-, Y-, and upper Z-coals. The upper half, here named the Collins Ranch Member, contains proportionally more sandstone and extends from above the W-coal up to the U-coal, which is the somewhat arbitrary marker of the Tullock-Lebo contact. Only the lowermost 15–20 m of sandy Lebo beds are preserved within the quadrangles.

The fifty major fossil localities (known as of 1989) scattered through the Hell Creek, Tullock, and lower Lebo Formations provide a remarkable record of vertebrate history in the region. One to five tons of sediment have been washed and screened from each locality to recover fossils, but in some areas as much as 70 tons of sediments have been processed. Systematic descriptions and evaluations of the fossils will be presented in separate papers dealing with each group.

INTRODUCTION

Cretaceous and Tertiary outcrops in McCone and Garfield Counties in northeastern Montana have been, paleontologically, one of the most intensely studied Late Cretaceous–Early Tertiary sequences in North America. The rocks appear to record the final years of dinosaur history. Most intensely studied exposures occur in bluffs of the eastern side of the Big Dry Arm of Fort Peck Reservoir (fig. 1), where the sequence appears to be most nearly complete. Numerous localities record the decline and final extinction of dinosaurs; at the same time they record early expansion of mammalian faunas. Most work, to date, has been paleontologic, however, and considerably less effort has been expended in documentation of stratigraphic and geologic relationships of the many productive localities. The principal purpose of the present study is to provide geologic maps (plates 1 and 2, in pocket) and stratigraphic and structural data as background information for paleontologic studies, and to provide subsequent workers better geologic control.

The geologic section in eastern Montana (fig. 2) provides a record of marine transgressions and regressions during the Late Cretaceous and Early Tertiary (Butler

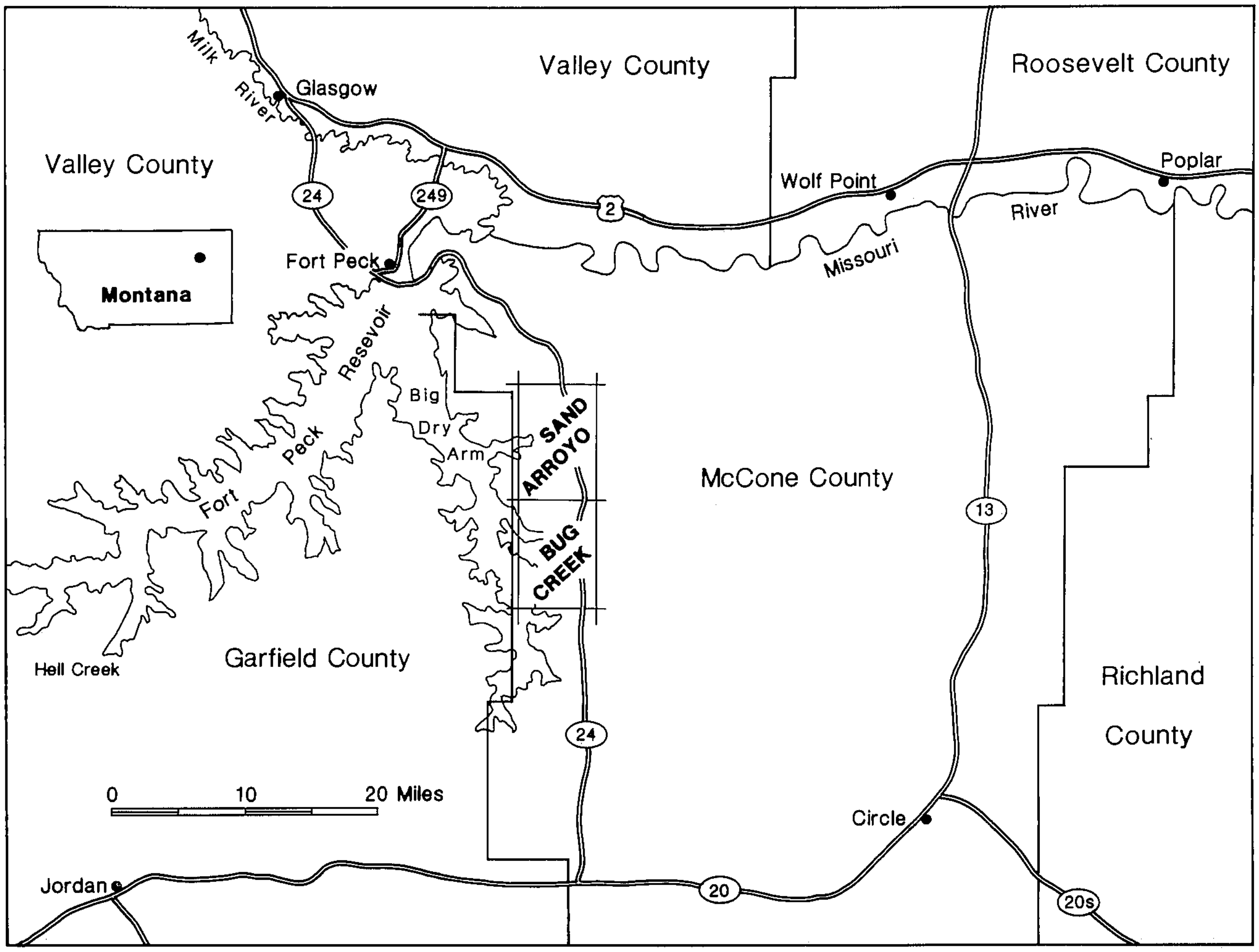

FIGURE 1.—*Index map of the Bug Creek and Sand Arroyo Quadrangles in McCone County, eastern Montana.*

1980, Frye 1969, Gill and Cobban 1973, Waage 1961). Most relevant research in the region has centered on the stratigraphic interval a short distance above and below the Cretaceous-Tertiary boundary from the Bearpaw Shale up through the Fox Hills Sandstone, Hell Creek, Tullock, and Lebo Formations (fig. 2). There are at least 11 major regionally recorded geologic events shown in table 1 that are concentrated at or near the Cretaceous-Tertiary boundary, including events associated with continental Cretaceous-Tertiary boundary extinctions. Interrelationships of most of these phenomena are not well documented or understood. Baseline data provided here aid in evaluation of relationships between these events and suggest cause-and-effect relationships. Early geologic research in the area surrounding the Fort Peck Reservoir has focused on two areas of interest: (1) stratigraphy, distribution, and nature of coal deposits (Bell 1965; Brown 1938, 1939, 1952, 1962; Calvert 1912; Collier and Knechtel 1939; Jensen and Varnes 1964); and (2) fossil vertebrates, primarily dinosaurs and mammals (Brown 1907).

Renewed interest in vertebrate paleontology of the area followed discovery of the magnificent Bug Creek Anthills locality by Sloan (Estes and Berberian 1970; Estes, Berberian, and Mesozoely 1969; Sloan 1987; Sloan and Van Valen 1965; Van Valen 1978; Van Valen and Sloan 1977a, 1977b) and subsequent studies by Russell (1982), for whom Russell Basin was named, and continuing studies by faculty and students from the University of California at Berkeley under the direction of W. A. Clemens (Archibald 1982, 1984; Bryant 1985; Dingus 1984) in Garfield County. These latter studies have centered in and around the type Hell Creek exposures along the southern margin of Fort Peck Reservoir, 65–100 km southwest of the Bug Creek area. The Dig-A-Dinosaur project of the Milwaukee Public Museum (Lupton, Gabriel, and West 1980; Sheehan, West, and Gabriel personal communications 1984–1987) has documented

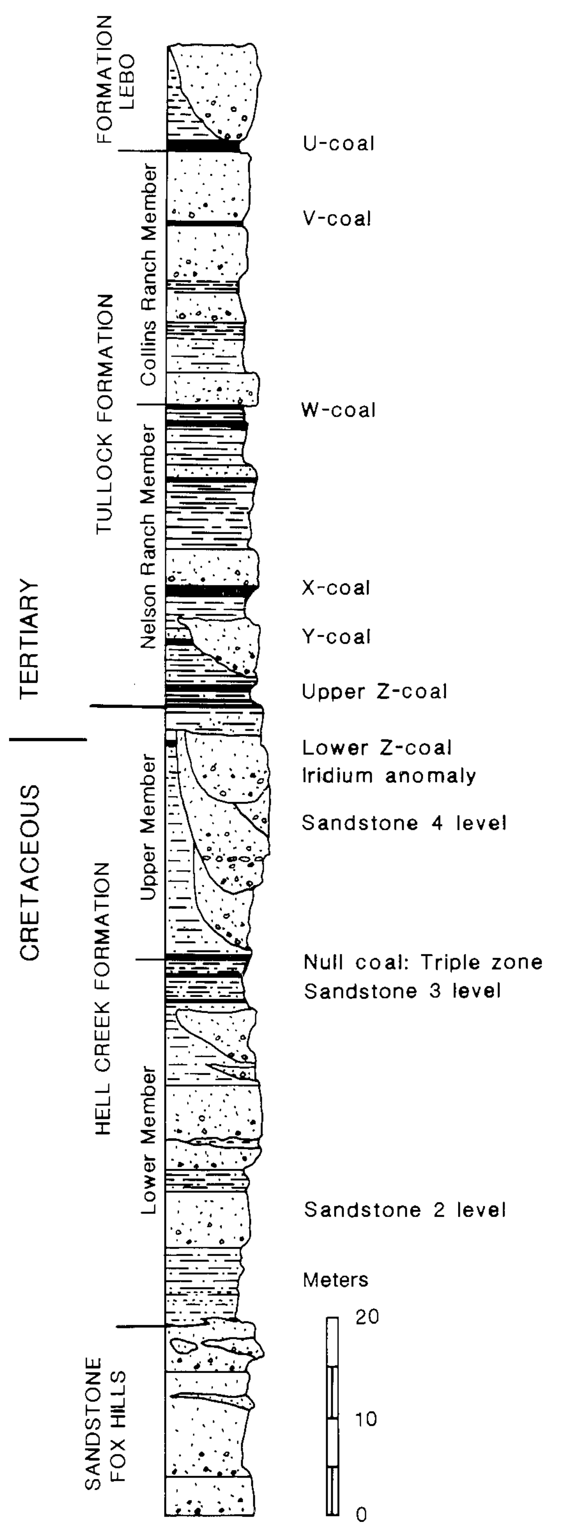

FIGURE 2.—*Generalized stratigraphic column for Cretaceous and Tertiary rocks exposed in the Bug Creek and Sand Arroyo Quadrangles, Montana.*

numerous dinosaur occurrences within the Hell Creek Formation in McCone and Garfield Counties along the east and southeastern margins of the Fort Peck Reservoir. The first modern geologic mapping in the Fort Peck fossil field was done by Bell (1965), who had to construct the base map from township plats and aerial photographs because no topographic quadrangle maps were available. The research reported here has been centered in McCone County (fig. 1) and involved study of stratigraphic and structural relationships, principally of the Hell Creek and Tullock Formations (Rigby and Rigby 1987; Rigby 1987).

Increased investigation of fossils and rocks near the Cretaceous-Tertiary boundary has been spurred by discovery of shocked mineral grains in several locations in North America (Bohor and others 1984, Bohor and Izett 1986, Bohor and others 1987, Izett and Pillmore 1985), the reassessment of some spherical grains as authigenic (Izett 1987), and an iridium anomaly associated with the K-T boundary event (Alvarez and others 1980, Alvarez and others 1984, Alvarez 1986 and references therein). The discovery and recognition of the iridium anomaly in eastern Montana and the fossil pollen break associated with that anomaly allow correlation of widely scattered outcrops and provide a reference datum for discussion of geologic events listed in table 1. Few studies of these sedimentologic and stratigraphic relationships of the Hell Creek, Tullock, and overlying Lebo Formations have been completed to date in northeastern Montana. The detailed but geographically limited studies of sedimentary facies of the Hell Creek and Tullock transition by Fastovsky (1986) and Fastovsky and Dott (1986a and 1986b) are the exceptions (see also discussion by Archibald 1986).

Palynological studies from selected spot localities and stratigraphic sections to define the pollen break traditionally associated with the Cretaceous-Tertiary boundary event include Jerzykiewicz and Sweet (1986); Johnson, Orth, and Nichols (1987); Nichols and others (1986); Norton and Hall (1969); Oltz (1969, 1971); Sweet 1986; Tschudy (1970); Tschudy and others (1984); and Tschudy and Tschudy (1986). Smit and van der Kaars (1984) and Smit, van der Kaars, and Rigby (1987) have published the most systematic study of spores and pollen completed in the Bug Creek area. Palynomorph spectra are available, at least on a reconnaissance basis, through the exposed Hell Creek–Tullock stratigraphic section (Newman 1988). Carol Hotton (1984) reported on a palynological study, part of which included samples from the Bug Creek area. Lofgren and Hotton (1988) recently reported that an upper Hell Creek Formation channel of Bug Creek facies in the McGuire Creek drainage contains a typical Cretaceous pollen flora. Leahy, Spoon, and Retallack (1985) also discussed plant extinctions linked to possi-

Table 1. Major Geologic Events or Relationships near the Hell Creek–Tullock Boundary in Montana, North and South Dakota, and Wyoming.

1. A pollen break and change from angiosperm to conifer-dominated palynofloras and leaf floras.
2. A change in sediment regime from the fluvial-dominated Hell Creek Formation to the more lacustrine and paludal Tullock Formation.
3. An unconformity at the boundary of the Hell Creek–Tullock Formations.
4. An iridium and shocked mineral grains "event" at the Cretaceous-Tertiary boundary.
5. Development and distribution of the Z-coal, bleached zone, and paleosols as mappable horizons in the Hell Creek and Tullock Formations.
6. Terminal Cretaceous and basal Tertiary eustatic sea level changes.
7. Transgression of the Cannonball Sea and its effects upon sediment regime and coal deposition west of the shoreline.
8. Mammal immigration from Asia? (*Protungulatum, Procerberus,* and the multituberculates *Catopsalis* and *Stygimys*) and apparent rapid early Paleocene mammalian evolution.
9. Dinosaur extinction—gradual rather than catastrophic, and sequencing of extinction events.
10. Numerous airfall tuffs in the Hell Creek and Tullock Formations.
11. Regional tectonic movement and sediment accumulation in relationship to the developing Laramide Rocky Mountain highlands to the west, and continued development of Powder River and Williston Basins to the south and east.
12. Paleosols change from mildly calcareous to less calcareous and from thin coaly surface horizons and thick clayey subsurface horizons to thicker, coaly, surface horizons, from subhumid- to humid-produced deposits.

ble impacts. Shoemaker (1966) documented leaf floras of the Hell Creek and Tullock Formations in eastern Montana, and Wolfe (1987) and Wolfe and Upchurch (1986, 1987) discussed floral changes at the Cretaceous-Tertiary boundary regionally and in the Raton Basin of New Mexico and Colorado.

A paleomagnetic composite section has been measured in the Hell Creek–Bug Creek area through the stratigraphic sequence from the upper Fox Hills Formation through the Hell Creek Formation and up through the W coal of the Tullock Formation (Archibald and others 1982). This section indicates that the middle of the sequence (upper Hell Creek to middle Tullock Formations) appears to be in magnetochron 29R. The Hell Creek–Tullock contact (K-T iridium event) occurs in magnetochron 29R (B– of fig. 5, Archibald and others 1982). A somewhat earlier and parallel analysis on equivalent beds in Alberta was completed by Lerbekmo, Evans, and Baadsgaard (1979). We have not done additional magnetic stratigraphy because mammalian faunal zonation provides higher resolution of stratigraphic events (Archibald 1982, p. 15; Rigby, and others 1987; Sloan 1987).

A weak iridium anomaly (~5 ppb), associated with the Cretaceous-Tertiary boundary, has been identified by Orth (see Fastovsky and Dott 1986a, 1986b; Sloan and others 1986; Smit and van der Kaars 1984) in the excellent exposures along the north side of Russell Basin in section 10, T. 22 N, R. 43 E, in the Bug Creek Quadrangle (plate 2). The anomaly occurs in part of a carbonaceous, turbated clay, possibly a paleosol, below the bleached soil profile, which is below the base of the formational boundary (upper Z-coal of authors). The event horizon is parallel to the more regionally obvious upper Z-coal and is generally from 2 to 6 m below the formation contact in outcrops mapped here.

The event horizon was mapped as part of the Z-coal zone during fieldwork in 1982–1987 and has been recorded in several stratigraphic sections measured in various parts of the quadrangles. For example, it has been recognized in sections near Harbicht Hill, at Wounded Toe, and at Andrews Hill in the Sand Arroyo Quadrangle, where it is associated with fossil vertebrates and where it occurs at a distinct pollen break (Rigby and others 1987). The event or lower Z-horizon was also documented in eight additional stratigraphic sections measured in the Sand Arroyo and Bug Creek Quadrangles during the 1986 field season and at three additional sections measured during the 1987 field season. The iridium anomaly at Brownie Butte in Garfield County, approximately 65 km to the southwest (Bohor and others 1984), is of considerably greater magnitude (~40 ppb) than the minor one recorded in the Russell Basin–Bug Creek section. The anomaly has also been recently documented in Wyoming (Bohor and others 1987). More recently, K-Ar, Rb-Sr, and U-Pb ages have been determined for the anomaly zone from Alberta, Saskatchewan, and the Hell Creek area in Montana by Baadsgaard, Lerbekmo, and McDougall (1988). They reported a weighted mean age of 64.3 + 1.2 Ma for the K-T boundary.

The Cretaceous-Tertiary boundary is also indicated by a marked change in palynomorphs below and above the carbonaceous iridium-bearing streak. Carl Orth, as noted above, found the relative weak iridium anomaly to occur at the Cretaceous-Tertiary boundary indicated by shifts in palynomorphs. More effort is needed to evaluate the weak anomaly in the northern part of the Fort Peck fossil field.

Paleosols have been identified in the Hell Creek Formation in studies by Fastovsky and McSweeney (1987); Fastovsky, McSweeney, and Norton (1988); Retallack and Leahy (1986); and Retallack, Leahy, and Spoon (1987). Retallack, Leahy, and Spoon, in general, interpreted the thick massive mudstones and claystones of the contact zone of the upper Hell Creek and lower Tullock beds as deeply leached layers capped by carbonaceous shales (? paleosols). Fastovsky and McSweeney (1987) have interpreted the same carbonaceous zones and mudstones as somewhat less mature soils.

Retallack, Leahy, and Spoon (1987) discussed changes in ecology across the Cretaceous-Tertiary boundary recorded in sediments and paleosols, in particular, in the Bug Creek–Russell Basin area. They concluded that evidence from paleosols in the Cretaceous Hell Creek Formation and Tertiary Tullock Formation support paleobotanic evidence for catastrophic shift in ecosystems at the boundary. They concluded that the area was subtropical, seasonably dry, subhumid, and forested mainly by angiosperms during the latest Cretaceous but shifted to more humid conditions in the Tertiary. They also concluded that the decline in diversity and abundance of preserved bones is a taphonomic effect because bones are not preserved in the noncalcareous paleosols of the boundary beds. For example, the highest occurring dinosaur bone in the overbank deposits is a marrow "ghost" of a vertebrae, from which all of the dense bone has been resorbed. The bone was recovered by Jan Smit 1 m below the lower Z or K-T boundary coal in the Russell Basin drainage. The bone was completely encapsulated in a paleo-root mass, which we consider as evidence of deep weathering associated with soil profile development. This is interpreted to substantiate conclusions about deep leaching of soils and the increased likelihood of total vertebrate fossil destruction within the leached zone. It is to be expected that preserved vertebrate fossils will be concentrated in channel sandstones where they were isolated from the attack of processes that occurred in overbank deposits and in soil formation.

Much work still remains to be done on paleosols of the area, not only in the Hell Creek Formation but also in the overlying Tullock Formation. These paleosols form some of the most continuous units in both formations. For example, paleosols and crosscutting channel relationships provide upper and lower limits on relative ages of the fossiliferous fluvial channels. These paleosols also provide stratigraphic limits for sources of fossil vertebrates concentrated in the channels. Paleosols and crosscutting channel relationships have been used to differentiate five distinct mammalian assemblages in the uppermost part of the Hell Creek beds alone (Sloan and others 1986).

The null coal, which separates upper and lower Hell Creek beds (Smit, van der Kaars, and Rigby 1987), is a paleosol that has been particularly useful stratigraphically. The null coal has proven to be one of the most widespread paleosols in the Bug Creek area, and essentially equivalent beds have been mapped in the Sand Arroyo Quadrangle to the north.

LOCATION

The Bug Creek and Sand Arroyo Quadrangles are located in northeastern Montana (fig. 1) and include part of the eastern shore of Fort Peck Reservoir. The quadrangles lie in western McCone County, but our study also included the small part of Garfield County along the east side of the reservoir in the Rock Creek State Recreation Area and outcrops near the mouth of Sand Arroyo Bay.

The central part of the quadrangles lies approximately 145 air kilometers north of Miles City, Montana, and 130 air kilometers northwest of Glendive, two major cities in the southeastern part of the state. The community of Fort Peck, near the dam of the reservoir on the Missouri River, is approximately 48 air kilometers north–northwest of the Bug Creek–Rock Creek area. Glasgow, the closest major source for supplies, groceries, gasoline, etc., is approximately 72 air kilometers to the north–northwest.

The mapped area is approximately 32 km long and 10 km wide along the east shore of the Big Dry Arm of the Fort Peck Reservoir. This part of the Missouri River Valley and Dry Creek drainage was drowned behind Fort Peck dam, completed in 1941.

The prairies on either side of the entrenched Missouri River rise in stair-step fashion away from the valley (figs. 3, 4). "Risers" are produced by the Cretaceous Fox Hills Sandstone and the Tertiary Tullock Formation, with broad upland "steps" produced by the Bearpaw, Hell Creek, and Lebo Formations (fig. 2). Badlands have been carved into each of the stratigraphic units along the river bluffs, and tributaries have formed moderately entrenched drainages, all combining to produce extensive exposures of the somber Hell Creek Formation and somewhat more brightly banded Tullock Formation.

Sand Arroyo and its tributaries in the north drain most of the Sand Arroyo Quadrangle (plate 1). The North and South Forks of Rock Creek and, somewhat more limited, Bug Creek, Black Spring Coulee, and tributaries of McGuire Creek drain the Bug Creek Quadrangle (plate 2). Lower parts of these tributaries to the Missouri River have been drowned along the east shore of the reservoir. Upper parts of their valleys are generally broad and flat-floored, margined by badland bluffs. Dryland grain farming takes place along the North and South Forks of Rock Creek (fig. 5), but other drainages are less intensely worked for agriculture, partly because they have been included within the Charles M. Russell National Wildlife Range. This preserve extends as a strip a few miles wide

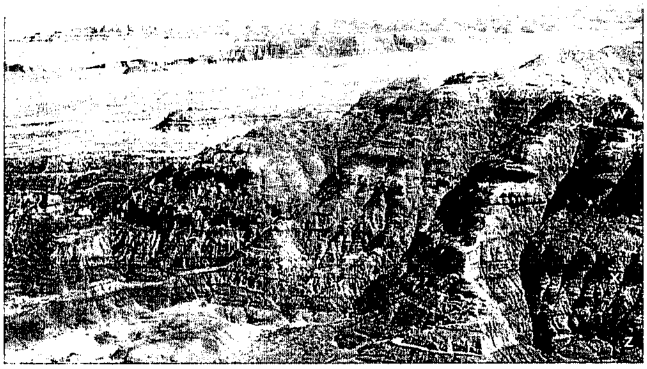

FIGURE 3.—*Low-angle oblique aerial view northward across the south central part of section 15, across Russell Basin, to the promontory in the southeastern part of section 10, T. 22 N, R. 43 E. The lower part of the Tullock Formation is exposed in the low hill in the foreground as well as in the lower part of the escarpment around Russell Basin, in the background. The formation Z-coal (Z) at the base of the Tullock Formation is the prominent, thin dark streak near the base of the escarpment in the background. It is exposed only in lowermost outcrops in badlands in the foreground. Low exposures near the left margin of the photograph, near cultivated fields, include rocks where the iridium anomaly of Russell Basin was sampled. The X-coal (X) is the double band in the foreground and the prominent double carbonaceous band in the lower part of the escarpment in the distance. The promontory is capped by sandstone of the basal part of the Collins Ranch Member.*

FIGURE 4.—*View southward across the valley of the South Fork of Rock Creek in the southwestern part of section 24, T. 23 N, R. 43 E. Exposures in the foreground are part of the type sequence of the Nelson Ranch Member of the Tullock Formation. The Walt Collins Ranch headquarters is in right center, along the South Fork of Rock Creek. Purgatory Hill is the small conical hill to the left of Montana 24, in the middle distance. Mesas are capped by the Collins Ranch Member of the Tullock Formation. Light-colored mudstones in the foreground immediately underlie the Y-coal (Y) and dark ironstone bands in the lower part of the Tullock Formation. The X-coal (X) is the dark gray reentrant beneath the massive sand, exposed on both sides of the gap in the ridge in the foreground. Hell Creek beds characteristically form broad steps, like along the South Fork of Rock Creek, and Tullock beds form the steep, clifflike "risers" up to the uppermost Tullock and basal Lebo beds that are exposed along the skyline in the far distance.*

along the eastern margin of the reservoir and characterizes effective multiple utilization of the resources.

Cabin-site clusters on some of the most accessible shores are utilized by both summer and winter campers and fishermen. Motorized vehicles, however, are restricted to established roads so that most of the Russell Refuge has remained in moderately primitive conditions. Major cabin clusters within the quadrangles, or immediately west of the quadrangles, are those in the Rock Creek State Recreation Area, south and north of the bays of North and South Rock Creek. Some limited cabin development has been allowed between the North and South Forks as well. Limited development has also been allowed on promontories between Black Spring Coulee Bay and Bug Creek Bay in the west central part of the Bug Creek Quadrangle, but other parts of the shore zone are generally roadless.

A few homes are occupied year-round in the compact cluster south of the Rock Creek State Recreational Area, in the southeastern part of the Spring Creek Bay, and in the northeasternmost part of the Ash Creek East Quadrangles (fig. 1).

Headquarters of five major ranches have been established in the eastern part of the mapped area, generally in headwaters of Rock Creek. The Nelson, Skyberg, Fergusson, and Clampitts ranches have headquarters along the North Fork of Rock Creek in the Sand Arroyo Quadrangle; the Collins ranch headquarters is along the South Fork of Rock Creek in the Bug Creek Quadrangle. These ranches generally have tilled the alluvium- and loess-filled broad upland valleys, and their principal crops are barley, wheat, and oats. Marginal badlands and less tillable prairies provide open pasturelands for cattle and sheep, the same areas shared by antelope and deer.

ACCESS

Montana 24, a paved and well-maintained road, traverses north–south across the eastern part of both quadrangles (fig. 1). That highway connects the generally east–west major highways to the north and south. U.S. 2 generally parallels the Missouri River by Glasgow and Wolf Point. South of the reservoir, Montana 24 joins Montana 200, which connects Jordan, Circle, and other

FIGURE 5.—*View northeastward from the west central part of section 2, T. 22 N, R. 43 E, showing the characteristic topographic expression of the Tullock Formation in the escarpment along the south side of the South Fork of Rock Creek. The Z-coal (Z), at the base of the Tullock Formation and top of the Hell Creek Formation, is the dark line near the base of the escarpment through the central and left part of the photograph. The flat uplands above the X-coal zone (X) are held up by sandstones (S) of the middle part of the Tullock Formation. Striped beds in the escarpment are in the Nelson Ranch Member of the Tullock Formation. Tilled fields in the foreground are on loess soils that bury the upper part of the Hell Creek Formation.*

small communities with the major highway system of east central Montana.

A graveled county road extends westward from the state highway into the Rock Creek Recreational Area in the southern part of the Sand Arroyo Quadrangle. A similar well-maintained road leads into the cabin area along the South Fork of Rock Creek and into the Bug Creek area through the northern part of the Bug Creek Quadrangle. A new gravel haulage road has been developed immediately south of the southern boundary of the Bug Creek Quadrangle along the north side of McGuire Creek. It leads westward to quarries near the reservoir that are currently being operated by McCone County. Numerous ranch and cabin access roads extend into most of both quadrangles from these roads, so that few areas are more than two miles from usable access roads. Much of the prairie country also would be readily accessible overland between roads, but such off-road vehicle traffic is prohibited within the Russell Wildlife Refuge.

The shore zone of Fort Peck Reservoir is readily accessible by small boats, and a marina with supplies of fuel and limited groceries has been established along the southwestern shore of the bay of the South Fork of Rock Creek. The marina is generally open from May until late September, but closes for the winter. Boat transportation, in fact, is one of the most effective ways to study some of the shore zone in regions removed from roads, particularly where collection of large fossils is concerned.

Although the community of Fort Peck is somewhat closer to the Bug Creek–Rock Creek area, more varied supplies and assured availability of materials prompted us to use Glasgow as our principal shopping area. Until late in 1986, the community of Fort Peck was under the jurisdiction of the U.S. Army Corps of Engineers and was basically a "company town," but now houses and other facilities may be owned by individuals or private firms.

Glasgow, the county seat of Valley County, is the largest community in the region with a population of approximately 6,000 people and is situated on U.S. 2 and the main line of the Great Northern Railroad. Consequently it is the marketing and shopping center for the area. However, supplies are also available in the small communities of Jordan and Circle, approximately 80 air kilometers to the south and southeast, respectively, but variety is limited.

Electric power is now provided to most ranches and recreational cabins in the area, particularly in the Rock Creek region. Most of the ranches and some of the more continuously occupied cabins also have telephones.

FIELDWORK

Preliminary stratigraphic sections and some limited mapping in the Bug Creek area were done during late July and early August of 1985 as part of continuing paleontologic studies underway by faculty and students of the University of Notre Dame, University of Minnesota, and University of California at Los Angeles. Most of the geologic mapping outside the Bug Creek area and the stratigraphic analyses, however, were accomplished during the summers of 1986 and 1987. Geologic contacts and key units were plotted on the same 1:20,000 aerial photographs used by Bell (1965). These contacts were visually transferred, in a preliminary compilation, onto the 1:24,000 topographic maps of the Bug Creek and Sand Arroyo Quadrangles during mapping. Final compilation on green-line mylar photocopies of the topographic base was done utilizing a Salzman projector and a Bausch and Lomb Stereo Zoom Transfer Scope.

Formation contacts and key beds were generally traced by "walking" in the field, but in some remote areas contacts were plotted utilizing distinctive topographic expression and isolated control points in the field. A few contacts, shown as short dashed lines on the geologic map, are essentially a combination of photogeology and rapid reconnaissance. The latter method was used particularly in areas of poor exposures in valley fill in headwaters of the North and the South Forks of Rock Creek and also in one small remote area north of the north shore of the "estuary" of Sand Arroyo. We did not have photographic coverage of Ash Creek East and Spring Creek Bay Quadrangles. Consequently, small areas on these quadrangles near the mouth of Rock Creek Bay were mapped on the topographic base.

Stratigraphic sections were measured with a Jacob's staff, generally to 0.1 m accuracy. Colors were determined by comparison with the standard Geological Society of America color chart. Grain shapes and sizes of clastic units were determined by comparison with prepared standard sand-gauge cards from W. F. McCollough, Beltsville, MD. Grain-size analyses were made at the fieldwork base at Rock Creek utilizing standard screens and techniques. These analyses were done by Tom McSweeney and Anne Benjamin as part of the field operation. Low-angle oblique aerial photographs taken during summer field seasons enabled further documentation of parts of the areal geology.

ACKNOWLEDGMENTS

We appreciate the active support of members of the field crew and our home institutions. Facilities, equipment, and some financial support has been given the study by the Department of Geology, Brigham Young University; by the Department of Earth Sciences, University of Notre Dame; and, through Dr. Robert Sloan, by the Department of Geology at the University of Minnesota. U.S. Fish and Wildlife Service administrators of the Charles M. Russell Wildlife Range and the U.S. Bureau of Land Management, who supervise some areas outside the range, allowed access to lands administered by their agencies.

We are especially thankful to local ranchers Bruce Fergusson, Walter Collins, Chris Skyberg, and Ray Clampitts for access to their ranches and continued interest in our research.

We are particularly appreciative of the constant assistance of Lyle Nelson and Darlyne Dascher, both of the Nelson ranch, who allowed us to use their ranch as a source for culinary water, telephone messages, mail delivery, laundry facilities, etc. They ideally exemplify the hospitality of western ranchers. In addition, they made extensive airplane flights in their two planes and allowed us to photographically document the geology, paleontological localities, and geomorphology of the quadrangles. For this we are indeed grateful. The Kountz and Sutton families of Circle, Montana, allowed us to use their very comfortable cabin for our base of operations.

Student assistants involved in the project included Michael Ferrari, Caroline Singler, Tom Hendrick, and Teressa Marzolf during the 1983 field season; Peter Edson during the 1984 field season; Tom McSweeney, Ray Ernst, and Robert Fowler during the 1985 field season; and Tom McSweeney, Anne Benjamin, Vince Sablan, and Fred Bosworth during the 1986 extensive fieldwork. Fred Bosworth also helped during the 1987 field season. Tom McSweeney and Ann Benjamin measured some of the stratigraphic sections cited here. The companionship of Fred Bosworth through most of the geologic mapping and stratigraphic studies of the 1986 and 1987 field seasons is particularly appreciated.

Information provided by Robert Sloan, Jan Smit, Karl Newman, Sander van der Kaars, and Carl Orth is much appreciated and has helped move the geological documentation and analysis more quickly. Newman provided most of the palynologic data used here. W. A. Cobban identified ammonites collected by us from the Bearpaw Shale. Maurice Smith helped with logistical arrangements. John Bowman, Dale Claflin, Becky Hammond, and Richard Brandley drafted some of the illustrations. Transcription of field notes and manuscript preparation were done at various times by Ann Bracken, Linda Isaacson, Camilla Mack, and Joyce Pritchard, all of the Department of Geology of Brigham Young University. Additional facilities and material for the research were provided through the Department of Geology at Brigham Young University by Wade Miller, the chairman, and Grant Mason, the dean of the College of Physical and Mathematical Sciences.

The manuscript has received critical review by Lehi Hintze, James Baer, and Wade Miller of the Department of Geology at Brigham Young University and by Robert Sloan of the University of Minnesota Department of Geology.

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We are particularly grateful for the continued support of Ruth and Susan Rigby. Free use has been made of the unpublished master's thesis by Robert Bell, done at the University of Minnesota under the direction of Robert Sloan.

REGIONAL AND LOCAL STRUCTURAL RELATIONSHIPS

The generally homoclinal southeastward dip of rocks in the Bug Creek and Sand Arroyo Quadrangles is characteristic of the broad, simple, southeastern margin of Bowdoin Dome (fig. 6). The Blood Creek syncline lies south of the dome, and the Bug Creek area and the Sheep Mountain syncline lie to the southeast. The latter is a mildly negative structure west of the prominent Cedar Creek anticline, a bounding structure on the southwestern margin of the Williston Basin. The Blood Creek syncline–Sheep Mountain syncline might be considered as a western extension of the Williston Basin, out of North Dakota and into Montana, south of Bowdoin Dome.

The gentle southeastward regional dip of only a few meters per kilometer off Bowdoin Dome is represented within the quadrangles by dips of generally less than one degree (figs. 7, 8). This results in broad cuestas that face toward the northwest (figs. 3, 4) up onto the flanks of the dome, with dip slopes that face toward the southeast into the broad synclines. Such relationships result in the older part of the Cretaceous section being exposed most extensively in the northwestern part of the quadrangles, and in the nearly complete, uninterrupted Tullock Formation and basal Lebo Formation in the southeastern part of the map area.

The gentle, simple, homoclinal structure is interrupted only locally in the Bug Creek–Sand Arroyo area by small-displacement faults and by minor folds (fig. 9) that have two orientations (figs. 7, 8). One trend is generally parallel to the northeast–southwest regional structural contours and the Weldon monocline and fault (Collier and Knechtel 1939, pp. 17–18, plate 9), and the other trend is more or less at right angles to that, regionally parallel to the Cedar Creek anticline but of considerably smaller scale (fig. 6).

Geologic structure of the Sand Arroyo and Bug Creek Quadrangles is dominated by broad southeastward plunging noses on the flank of the Bowdoin Dome and a prominent, though shallow, south–southeast-trending syncline that cuts across the plunging structure. Structural contours (figs. 7, 8) document the mildly irregular low dip.

The prominent Sand Arroyo Bay nose, named here, is well developed in southwestern Sand Arroyo Quadrangle and southeastward across the Bug Creek Quadrangle. It is a major structure through the Harms Flat area in section 5, T. 23 N, R. 43 E, and southeastward across the South Fork of Rock Creek into the region northeast of Robinson Coulee in sections 12, 13, T. 22 N, R. 43 E. It has a lateral relief of 70–75 m and plunges approximately one-half degree S 60°–70° E. Flank dips are of the same order.

A broad culmination occurs near Harms Flat in section 5, T. 23 N, R. 43 E, with closure of a few meters on the crest of the nose. Another culmination was mapped in the area of headwaters of Robinson Coulee, along Montana 24, in the northeastern part of T. 22 N, R. 43 E, in sections 1, 2, 11, and 12. A shallow, broad syncline interrupts the general plunge of the nose immediately northwest of that culmination, generally near where the crest of the nose crosses the drainage of the South Fork of Rock Creek in section 35, T. 23 N, R. 43 E.

Smaller structures parallel the major Sand Arroyo nose 3–5 miles to the northeast and southwest (figs. 7, 8). For example, one smaller nose plunges southeastward from the northwestern corner of Sand Arroyo Quadrangle in section 31, T. 25 N, R. 43 E, then trends immediately south of Goat Mountain into the headwaters of the North Fork of North Rock Creek, where it terminates in sections 24, 25, T. 24 N, R. 43 E. A similar, though somewhat less defined second-order nose on the southwestern part of the Sand Arroyo Bay structure is parallel to the trend of the large crest and is mappable from North Rock Creek Bay in section 19, T. 23 N, R. 43 E, southeastward diagonally across the quadrangle to the vicinity of McGuire Buttes in section 25, T. 22 N, R. 43 E. Broad, irregular synclinal troughs separate the noses as reentrants on the structural contour map (figs. 7, 8). A broad synclinal trough, northeast of the Sand Arroyo Bay nose, is generally identifiable near the northwestern corner of the Sand Arroyo Quadrangle, in sections 5, 6, T. 24 N, R. 43 E, southeastward to the vicinity of the headwaters of North Fork of Rock Creek in the northeastern part of the quadrangle, in sections 18, 19, T. 24 N, R. 44 E.

Similar broadly defined reentrants occur southwest of the Sand Arroyo Bay nose and extend as gentle depressions from the northwestern corner of the Bug Creek Quadrangle, in section 7, T. 23 N, R. 43 E, southeastward across the central part of the quadrangle into the Robinson Coulee area, north of McGuire Buttes, in section 24, T. 22 N, R. 43 E. Another such structure is a well-defined, broad depression that separates the smaller second-order Rock Creek Bay nose from the Sand Arroyo nose in the Bug Creek Quadrangle in sections 7, 17, and 21, T. 23 N, R. 43 E.

A smaller broad synclinal trough was mapped from the southern part of the Bug Creek Bay area, in sections 17, 18, T. 22 N, R. 43 E, southeastward across Black Spring Coulee (fig. 8). The general synclinal area is most clearly defined near the southern margin of the map in sections 34, 35, T. 22 N, R. 43 E, and loses its identity when traced to the northwest.

A well-defined broad syncline, here named the North Rock Creek syncline, extends south–southwestward from the east central part of Sand Arroyo Bay Quadrangle, generally along the trend of the valley of North Fork of North Rock Creek, in sections 24, 25, T. 24 N, R. 43 E, and continues to the south through a broad saddle, in section 14, T. 23 N, R. 43 E, into the Bug Creek Quadrangle, and farther as a series of shallow saddles across the Sand Arroyo nose in the Russell Basin region, in section 10, T. 22 N, R. 43 E, in the headwaters of Bug Creek, into the Black Spring Coulee region, section 21, T. 22 N, R. 43 E. Southeastward plunging structures in the central and northern part of the Sand Arroyo Quadrangle appear to truncate at the Rock Creek syncline. Those in the Bug

Creek Quadrangle, however, appear to cross the trend of the syncline as saddles and depressions, as the structure is presently interpreted.

Structural contours in figures 7 and 8 are drawn on the upper formation or boundary Z-coal or its projected position in areas west of the exposure belt where Hell Creek and Fox Hill Formations are exposed. The Z-coal is exposed at elevations of approximately 2300 feet in the structurally lowest part of the quadrangles in the Rough Prong of McGuire Creek region, in section 35, T. 22 N, R. 43 E, near the south edge of the Bug Creek Quadrangle and rises to the north and northwest to projected elevations of approximately 2700 feet in the northwestern part of the Sand Arroyo Bay Quadrangle. The Z-coal is well exposed at elevations of approximately 2620 feet in the Westland Hill area, in section 3, T. 24 N, R. 43 E, in the north central part of the Sand Arroyo Quadrangle.

Outliers of the Z-coal through the central parts of both quadrangles allow moderate control on the geologic structure. However, definition of structure in areas of Hell Creek and Fox Hill exposures becomes less certain because of stratigraphic complexity and lensing within the Hell Creek Formation, both regionally and in detail.

Thickness of the Hell Creek Formation increases toward the north as demonstrated by divergence of the Fox Hills and Z-coal projected positions (figs. 7, 8; plates 1 and 2). For example, the Z-coal crops out at elevations of approximately 2400 feet near the mouth of Black Spring Coulee, section 21, T. 22 N, R. 43 E, in the southwestern part of the Bug Creek Quadrangle where the top of the Fox Hills Sandstone is near reservoir level. The top of the Fox Hills Formation is essentially at reservoir level in the North Rock Creek Bay area, sections 19, 20, T. 23 N, R. 43 E, in the northwestern corner of the Bug Creek Quadrangle, where the projected elevation of the Z-coal is approximately 2520–2540 feet. The projected Z-coal is at an approximate elevation of 2600 feet in the North Arm of Sand Arroyo Bay, sections 20, 29, T. 24 N, R. 43 E, although the top of the Fox Hills Sandstone is again exposed essentially at reservoir level.

A small, sharply bounded syncline has been mapped in the vicinity of Snuff Gap, in section 14, T. 24 N, R. 43 E, in the northeastern part of the Sand Arroyo Quadrangle (fig. 7). Outcrops of moderately sharply folded Z-coal clearly define the generally east–west structure immediately west of Montana 24. The syncline is a bounding structure onto the northwest, north of Goat Mountain, as a second-order feature parallel to the Goat Mountain nose in the Westland Hill area.

A distinct small fold was mapped in the northeastern part of the Bug Creek Quadrangle (fig. 8) in section 24, T. 23 N, R. 43 E. Tullock and uppermost Hell Creek beds are sharply flexed in the small northeast-trending syncline. Trough of the sharp depression is generally parallel to the Rock Creek syncline, and it may be a short branch of that structure that extends into the Bonin Divide region and on into the southeasternmost part of the Sand Arroyo Quadrangle as a small negative area. Although the fold appears as a distinctly defined structure, flank dips are only approximately 1°, or locally slightly more. The fold appears more prominently on the contour map than in the field.

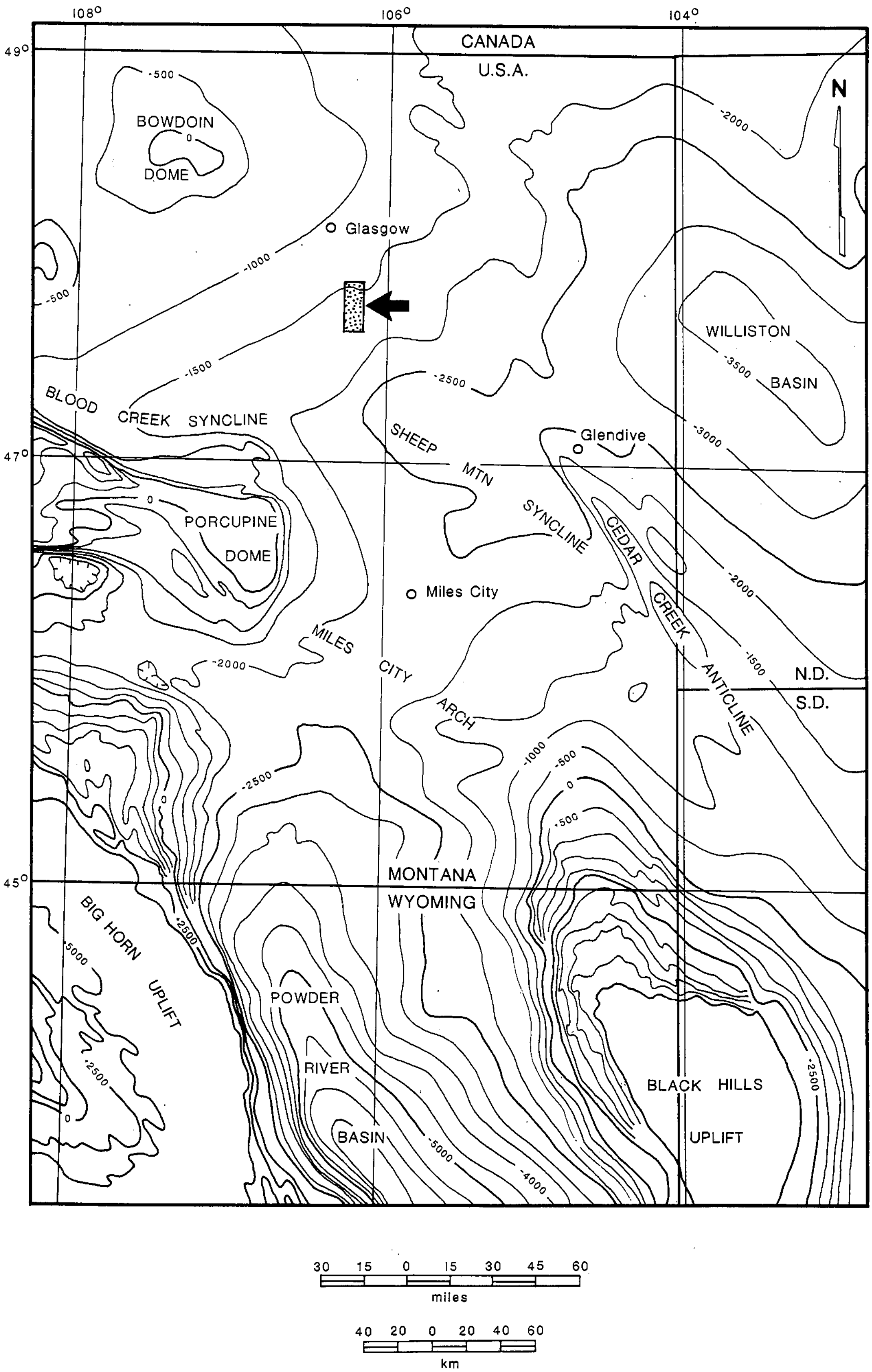
Several small faults, with displacements of only a few meters, are mapped in the Bug Creek and Sand Arroyo Quadrangles, but virtually every outcrop is interrupted, in detail, by small faults with displacements of a meter or less when individual beds are traced laterally. These small faults are not shown on the geologic maps (plates 1 and 2).

The southernmost fault mapped within the quadrangles affects the upper part of Hell Creek and lowermost part of the Tullock Formations, generally in the northeastern part of section 28, T. 22 N, R. 43 E, in the western part of what we have termed the Berkeley Face.

In the western part of the northeast quarter of the section, movement along this fault has dropped uppermost Hell Creek and lowermost Tullock beds, on the north, down against the relatively massive-appearing, cross-bedded sandstone of the upper part of the Hell Creek Formation, on the south. Displacement along the fault is a total of approximately 10 m where the Z-coal, the basal marker of the Tullock Formation, is approximately at grass level along both east and west margins of the southward projecting ridge on the north but is not preserved on the ridge on the upthrown block south of the block. The fault has a general strike of approximately N 70° E in the short segment that is exposed. Toward the west approximately 300 m, the fault is not evident in more or less continuous outcrops of Z-coal. A down-flexed broad saddle does occur, however, essentially where the fault trace would project through the ridge.

What is interpreted to be the same fault toward the southeast is exposed on a somewhat larger promontory in the southeastern part of the NE 1/4 of section 28, where

FIGURE 6.—*Regional structure contour map of eastern Montana showing relationships of the Blood Creek and Sheep Mountain downwarps to the broad Miles City Arch and to Bowdoin Dome, the Cedar Creek anticline, and the southwestern margin of the Williston Basin (generalized from Structural Contour Map of the United States).*


108°
106°
104°
49°
47°
45°
CANADA
U.S.A.
N
BOWDOIN
DOME
Glasgow
WILLISTON
BASIN
BLOOD
CREEK SYNCLINE
SHEEP
MTN
SYNCLINE
Glendive
PORCUPINE
DOME
CEDAR
CREEK
ANTICLINE
Miles City
MILES
CITY
ARCH
N.D.
S.D.
MONTANA
WYOMING
BIG HORN
UPLIFT
POWDER
RIVER
BASIN
BLACK HILLS
UPLIFT
-500
0
-1000
-1500
-2000
-2500
-3000
-3500
-4000
-5000
+500
+2500
+5000
30 15 0 15 30 45 60
miles
40 20 0 20 40 60
km

the fault trace has a strike of approximately N 65° to 70° W, and here has also offset uppermost Hell Creek and lowermost Tullock beds. Displacement of the Z-coal from essentially the base of the ridge at grass level to moderately high on the flank of the promontory suggests that displacement along the fault is 10 to 12 m. The fault is a normal fault with the surface dipping steeply northward. The fault surface, however, is exposed only along the small ridges. Extent of the fault to the southeast is unknown because of poor exposures and lack of adequate key horizons within the upper Hell Creek beds in section 27.

A minor subparallel structure is exposed on the north side of the broad ridge southwest of Wild Horse Pass, in the northwesternmost part of section 27, T. 22 N, R. 43 E. There a small lobe of lower Tullock beds dips up to 30 degrees northward into a deep, sharp gully at the edge of a grassy flat. The small fold involves an area approximately 200 m square where the X-coal, in the middle part of the lower Tullock Formation, is draped down and possibly faulted against the basal Z-coal of the formation. Unlike landslides within the formation in other areas, lower Tullock stratigraphic units here maintain fair continuity. The stratigraphic sequence within the fold or lobe is generally not internally disturbed.

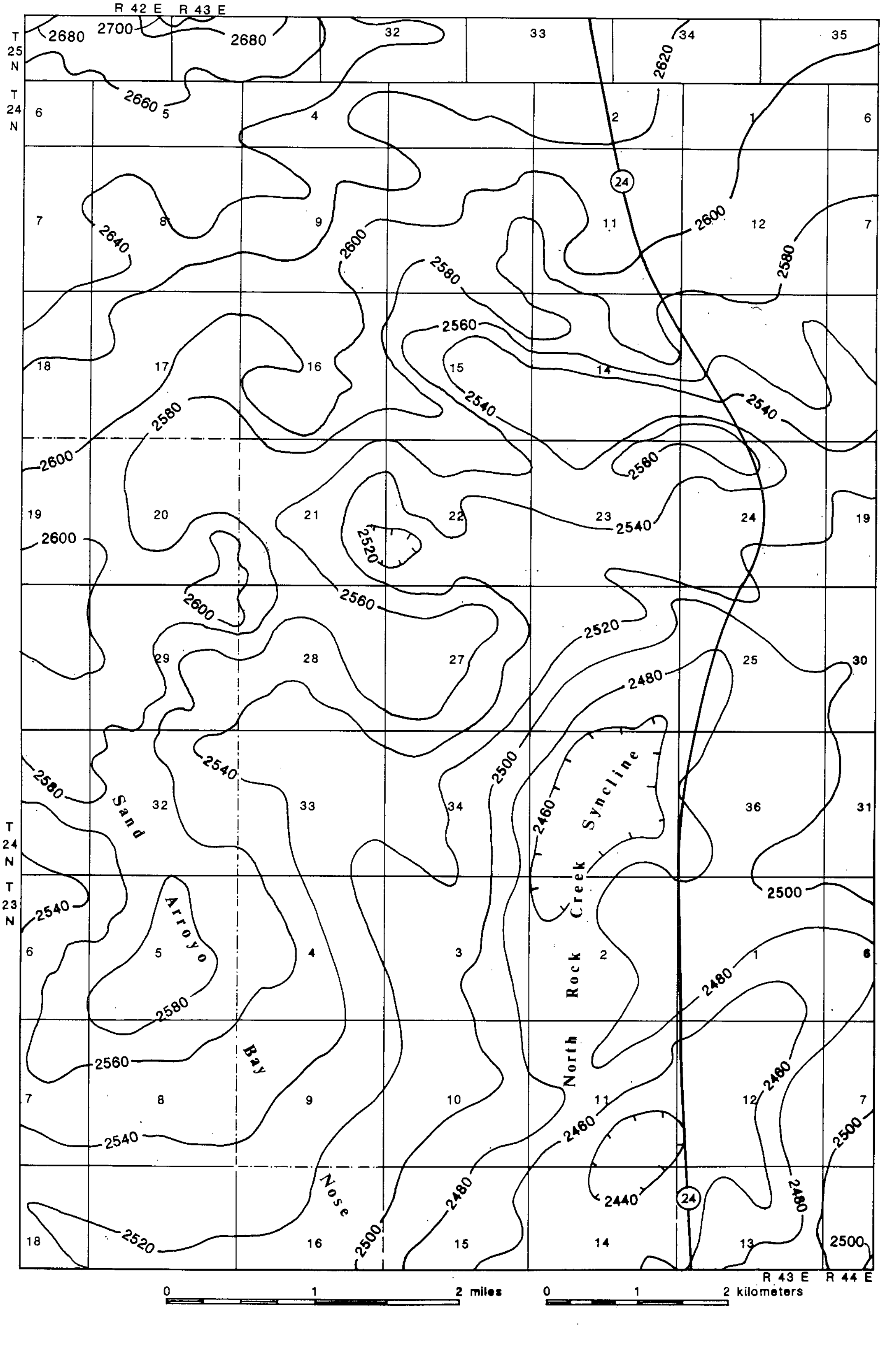
The front of the lobate structure and its moderate continuation to the southeast is shown on the geologic map as a fault. Displacement decreases abruptly toward the southeast, and the projected northwestern continuation is buried beneath the grassy prairies and is lost in the relatively massive upper part of the Hell Creek Formation. Total displacement across the disturbed zone amounts to approximately 20 m, at maximum, at the front of the lobe. The structure is very localized and of minimum displacement, but the trend of approximately N 60° W is subparallel to the small fault exposed in section 28 to the south.

A third small fault is exposed in the Berkeley Face, in the southeastern part of the NW 1/4 of section 27, where the Z-coal, on the eastern upthrown block, is juxtaposed approximately with the X-coal horizon on the western block. The Z-coal and overlying beds sweep up, eastward, toward the fault surface within a few meters of the fault. Most of the apparent displacement is expressed as drag in the system. This small fault is characteristic of numerous faults throughout the quadrangle with trends of approximately N 45° to 60° E. It is unusual, however, for displacements on most of the parallel small structures amount to a meter or less. Most of these structures have not been mapped because they occur in virtually every outcrop that is studied in detail. Displacements on many of these northeast–southwest trending faults are locally irregular, with approximately one-half down toward the northwest and one-half down toward the southeast.

A minor reverse fault is well exposed in the southeastern part of section 26, T. 22 N, R. 43 E. It is particularly evident in the low pass between a minor tributary of Lone Tree Coulee and Montana 24 in about the center of the SE 1/4 of section 26, T. 22 N, R. 43 E. Here the reverse fault strikes about N 50° W and dips approximately 60° SW. Uppermost Hell Creek and lowermost Tullock beds in the upthrown block, on the southeast side, are juxtaposed against Tullock beds, at approximately the X-coal horizon, in the middle part of the formation with a displacement of 20 to 30 m. The fault surface is well exposed both northwest and southeast of the pass (fig. 10) but is obscure in the prairie lands on the back side of the cuesta northwest and southeast of the pass. Uppermost Hell Creek and lower Tullock beds are nearly flat or dip very gently toward the southeast in exposures approximately 100 m away from the fault surface, but beds dip up to approximately 20 degrees into the fault on the southwest and away from the fault on the northeast. The fault does not extend far toward the northwest because the trace of the X-coal is virtually continuous around the small reentrant in the north central part of section 26. The extent of the fault toward the southeast, toward Rough Prong of McGuire Creek, is uncertain because of poor exposures in the vicinity of the highway and because it is buried by the deep valley fill along Rough Prong.

A subparallel, small normal fault is exposed 200 to 300 meters northeast of the reverse fault. The normal fault has a trend of approximately N 60° W and, in surface exposures, affects principally only Tullock beds near the X-coal in the lower part of the formation. Displacement of 6 to 7 m, down on the south, is most evident in the south central part of the NE 1/4 of section 26. There the X-coal is offset and a fault-line escarpment is developed along the trace. Lateral extent of this fault is also uncertain because of poor exposures, but it is probably only a local feature.

FIGURE 7.—*Generalized structural contour map of the Sand Arroyo Quadrangle. Structural contours are on the Z-coal, or its projected positions where removed by erosion from the western part of both quadrangles. The prominent first-order southeastward-plunging Sand Arroyo Bay nose is mapped in the west central part of the Sand Arroyo Quadrangle and southeastward. The diagonally crosscutting North Rock Creek syncline is mappable from the east central part of the Sand Arroyo Quadrangle to the southwestern part of the Bug Creek Quadrangle. Smaller second-order features parallel the major nose.*


R 42 E
R 43 E
T 25 N
T 24 N
T 23 N
R 43 E
R 44 E
Sand Arroyo Bay Nose
North Rock Creek Syncline
24
2700
2680
2660
2640
2620
2600
2580
2560
2540
2520
2500
2480
2460
2440
0 1 2 miles
0 1 2 kilometers

Small northeast-trending faults may be exemplified by the very local and small-displacement faults that offset the uppermost Hell Creek and lower Tullock Formations in the small outlier of the Tullock beds in the northwestern part of section 25, T. 23 N, R. 43 E. The small fault is readily apparent from Montana 24 (fig. 11) in the small hill south of Cactus Point, which is the sharp promontory immediately west of the highway, on the section line between sections 24 and 25. Offset of the Z-coal zone and uppermost beds of the bleached top of the Hell Creek Formation in the most prominent fault amounts to 2 to 3 m. A somewhat smaller displacement fault is visible in the eastern part of the same outlier. It has a displacement of approximately 1 m. The two combine to produce a small horst in the eastern part of the outlier. These small faults trend approximately N 40° to 50° E.

Similar minor faults are exposed in the Hell Creek Formation in the small outlier south of the South Fork Rock Creek access road in the northwestern part of section 28, T. 23 N, R. 43 E. Minor offsets in the carbonaceous shales and mudstones show particularly well in the lower part of the formation. Such small faults have not been mapped because they do not disrupt the overall pattern of formations and appear to be of relatively minor regional significance, other than perhaps indicating small-scale adjustment to the regional stress field as outlined and summarized by Stauffer and Gendzwill (1987).

Significant stratigraphic offset is exposed in the southeastern quarter of section 12, T. 23 N, R. 43 E, and in the northwestern part of section 18, T. 23 N, R. 44 E, in the southeastern corner of the Sand Arroyo Quadrangle along the south margin of a series of Tullock exposures locally termed Nelson Butte. Whether the offset lower Tullock beds along the south margin of the ridge have been faulted or only slumped is difficult to tell. There is minimal displacement at the base of the Tullock Formation, at the southwest base of Nelson Butte, but displacement increases toward the southeast along the "fault" trace so that 300–400 m to the southeast there is 10 to 15 m of displacement of the middle part of the Tullock. Apparent displacement increases to approximately 20 m between the two small hills approximately 300–400 m northwest of the southeast corner of section 12. Displacement diminishes farther toward the southeast into section 18 to only 10 to 15 m, 200 to 300 m southeast of the northwest corner of section 18, and decreases to essentially zero, approximately one-half mile beyond the section corner, near the edge of the quadrangle.

A large slumped mass of beds associated with the X-coal occurs on the north side of Nelson Butte, and if the same beds had slumped on the south side of the ridge they could produce some of the structural effects seen here and lower the middle Tullock beds along a detachment zone. The lower part of the slumped mass, however, is poorly exposed in the prairies at the base of the escarpment and hills. The fault trace, if the detached surface is a fault, is essentially parallel to other faults exposed farther to the south in the Bug Creek Quadrangle and also parallel to the major alignment of the region and prominent regional drainage patterns in southeastern McCone, Dawson, and Prairie Counties, in particular.

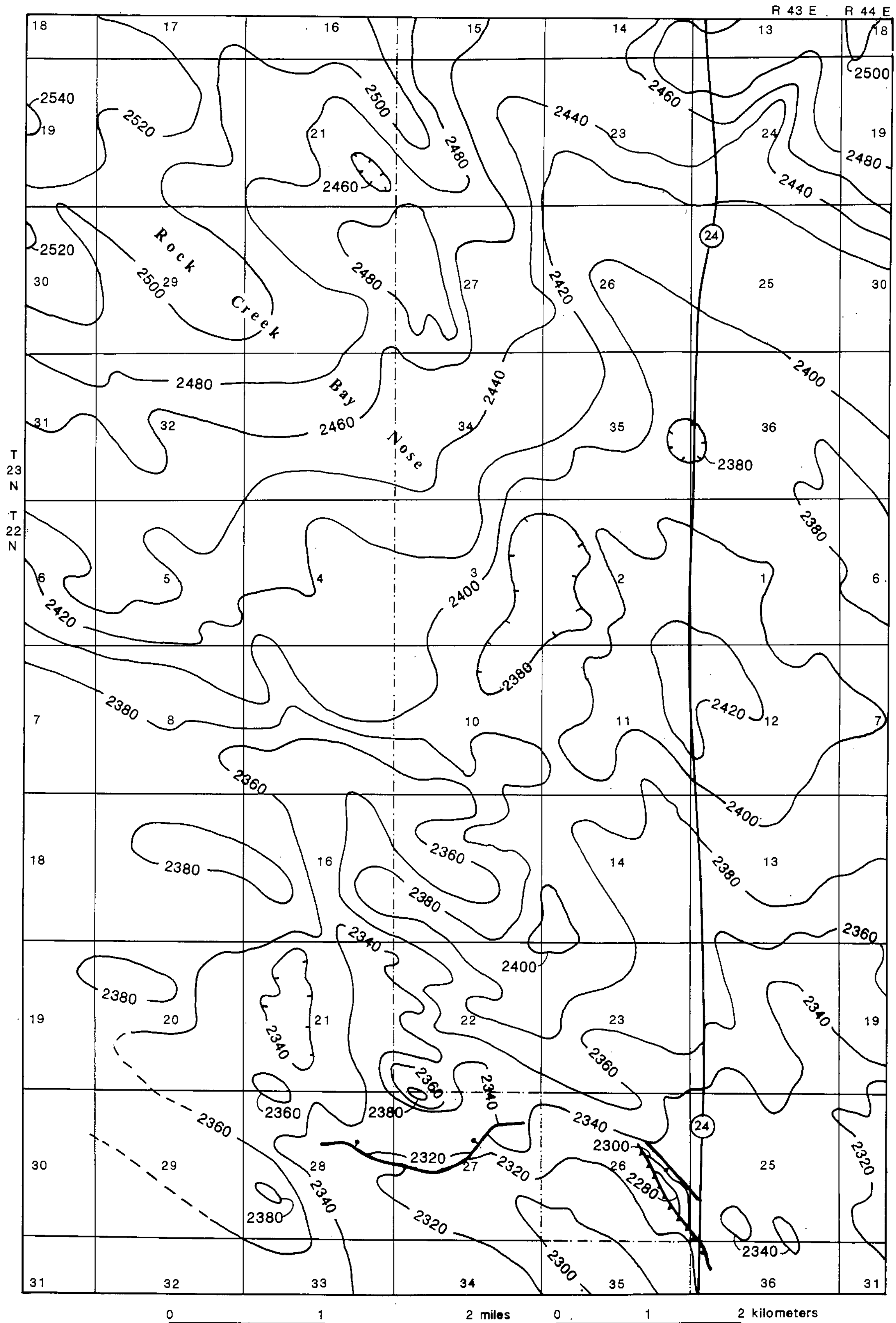
Numerous small-scale folds, with amplitudes of 2 to 3 m, have been observed throughout the quadrangles. Perhaps the best exposed of such folds occurs in the north central part of section 14, T. 23 N, R. 43 E, in the pass areas between outliers of the lower Tullock Formation, north of the older Nelson Ranch access road from Montana 24. Here a small fold, 100 to 150 m across, has flank dips of 2° or 3°. The fold has a northwesterly trend, as defined by the moderately convoluted trace of the Z-coal near the low divide of the pass. The small fold may have a local amplitude of 3 or 4 m, but the sharp structure is in marked contrast to the general homoclinal southeastward dip so typical of the entire region.

Similar small folds occur widely scattered throughout the quadrangle—for example, a minor fold exposed in a tributary of the South Fork of Sand Arroyo in the south central part of the SW 1/4 of section 32, T. 23 N, R. 43 E.

FIGURE 8.—*Generalized structural contour map of the Bug Creek Quadrangle. Structural contours on the Z-coal or its projected position. Contour interval is 20 feet. Small faults interrupt the generally smooth contours in southern Bug Creek Quadrangle. The normal fault in the south central part is shown as a more-or-less continuous fault on this map but as unconnected segments on the geologic map (plate 2). A fault mapped in the southeastern part of the Sand Arroyo Quadrangle apparently does not affect the Z-coal and is more probably a slump.*

The general rise in elevations of the Z-coal from approximately 2300 feet in the southern Bug Creek Quadrangle to approximately 2700 feet in the northwestern Sand Arroyo Quadrangle indicates the general rise up the flank of Bowdoin Dome, with smaller structures superimposed on larger features. Contour interval is 20 feet.

Structure is fairly well defined by outcrops and outliers of the Z-coal in eastern sections of both quadrangles. Structure in the western part of the map, from which the Z-coal has been largely removed, is less certain because of complex stratigraphy in the Hell Creek Formation.


R 43 E
R 44 E
T 23 N
T 22 N
Rock Creek
Bay Nose
2540
2520
2500
2480
2460
2440
2420
2400
2380
2360
2340
2320
2300
2280
24
0 1 2 miles
0 1 2 kilometers

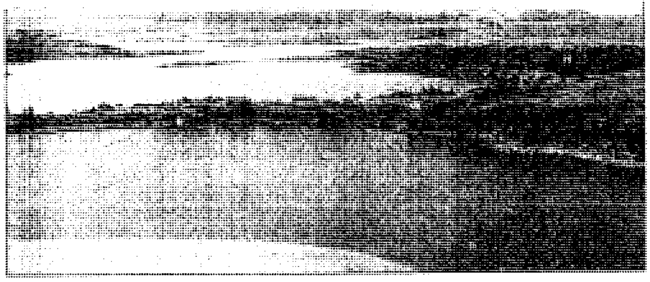


FIGURE 9.—*View southward across Rock Creek Bay to the marina in the middle distance. Exposures beyond the marina, on the right, are basal light-colored Hell Creek sandstone (H) above the somewhat darker cliff-forming upper Fox Hills beds (F), in the foreground. Badlands beyond are carved in the middle part of the Hell Creek Formation. The marina is in the southwesternmost part of section 19, T. 23 N, R. 42 E, on the Ash Creek East Quadrangle.*

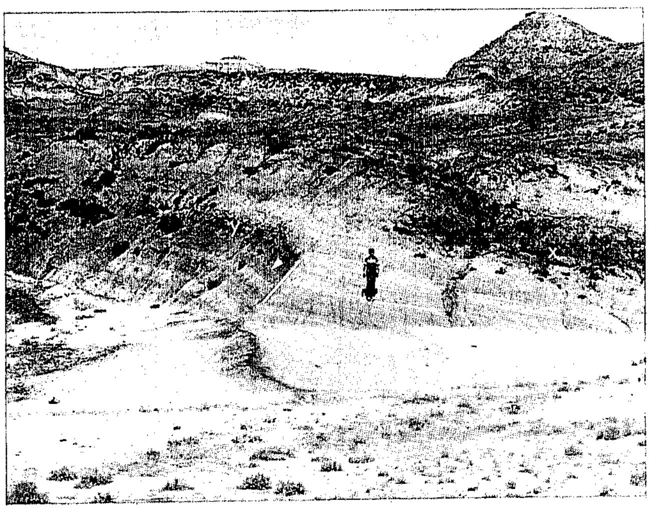


FIGURE 10.—*Small reverse fault in the east central part of section 26, T. 22 N, R. 43 E, at the extreme left, and the Y-coal, in the middle to the left of the figure and the fault, had been juxtaposed against beds directly beneath the X-coal, which is the prominent dark band toward the right. Such a steep dip is anomalous in the region and appears to be drag on the small reverse fault. Striped "zebra beds" are characteristic of the Tullock Formation.*

Rocks within the Hell Creek Formation there have dips of a few degrees to the south. Other small folds are exposed in the center of the SW 1/4 of section 15, T. 22 N, R. 43 E, on the divide at the south side of the headwaters of Bug Creek. There rocks have dips of a few degrees and outline small folds in uppermost Hell Creek and lowermost Tullock beds. None of the small folds appear to have more than local significance.

Regional influence of the Cedar Creek anticline (fig. 6) and parallel structures shows in erosional patterns and fracture patterns in the region (Shurr 1982; Stauffer and Gendzwill 1987, pp. 1090, 1093; Thomas 1974) and is emphasized by the striking northwest–southeast trend of many tributaries to the Yellowstone, Redwater, and Missouri Rivers across McCone, Dawson, Prairie, and parts of Garfield Counties. In general, this strong lineation of drainage occurs south of the possible interruption by glacial features in northern McCone and Garfield Counties. The strongly aligned drainage pattern shows particularly well on the state geologic map of Montana (Ross, Andrews, and Witkind 1955), which also shows the approximate southern limit of major glacial features of the Pleistocene.

STRATIGRAPHY

CRETACEOUS SYSTEM
MONTANA GROUP
BEARPAW SHALE

Introduction

The Cretaceous Bearpaw Shale is part of a broad sequence of dark gray shales that document the last major marine transgression into the interior of North America. Except for transition beds at the base of the Fox Hills Sandstone, the Bearpaw Shale is not exposed during normal water levels of Fort Peck Reservoir within the Bug Creek and Sand Arroyo Quadrangles, but it is well exposed along the shore zone to the west in the Sand Arroyo Bay area in the Spring Creek Bay Quadrangle. The formation underlies the Fox Hills Sandstone across the quadrangles (fig. 2).

Hatcher and Stanton (1903, pp. 211–212) originally defined the Bearpaw Shale as the concretion-bearing, dark clay shale of marine origin that conformably overlies the Judith River beds and underlies the Fox Hills Sandstone and its equivalent in northern and eastern Montana. The type locality of the formation is around the Bearpaw Mountains of central Montana, and the formation has been recognized in northern, eastern, and southern Montana in the Elk Basin region of central northern Montana and in southern Alberta. Hatcher and Stanton (1905) later republished their description of the Bearpaw type sequence.

Collier and Knechtel (1939, p. 9) noted that the contact of the Bearpaw Shale with the overlying Fox Hills Sandstone is gradational, with a general increase in sand upward within the transition zone, and that the formation is approximately 300 m thick in eastern Montana. Jensen and Varnes (1964, p. F5) noted that the Bearpaw Shale is about 348 m thick in the Fort Peck area, where the formation is one of the most extensively exposed units in the region. Lovering and others (1932, p. 702–703) defined the top of the Bearpaw Shale and base of the Fox Hills Sandstone at the base of the dominant buff and brown sandstones and the top of the gray, marine, clay shale and sandy shales. In our stratigraphic studies on the Spring Creek Quadrangle we have followed that definition.

Outcrop Area and Topographic Expression

In the limited area along the north shore of the mouth of Sand Arroyo Bay, Bearpaw Shale forms low, relatively barren hills capped by the resistant Fox Hills Sandstone. The formation is generally covered, except in areas of recent steep erosion or landslides, in areas away from the shore line of Fort Peck Reservoir. However, along the reservoir shore line the formation is magnificently exposed locally in the sea cliff (fig. 12). The transition beds are locally exposed below the Fox Hill Sandstone—for example, on the promontory west of the Rock Creek Marina and in the Annabelle Beach area, on the north and south shores of Rock Creek Bay, and on the promontory between the North and the South Arms of Sand Arroyo Bay. However, these beds are only visible at low-water stages, like that of the 1988 and 1989 field seasons, following dry years in the northern Rocky Mountain area.

The exposure belt of the formation broadens widely in quadrangles toward the north so that in the vicinity of the Fort Peck Dam, the Bearpaw Shale is the principal surface bedrock formation and is locally well exposed in the vicinity of the dam and in the badlands along either side of the reservoir. Because the shale is more easily eroded than the overlying beds, however, it tends to form smooth slopes and small hills, except where carved into badlands.

We investigated the Bearpaw beds only in the central part of the Spring Creek Bay Quadrangle, where the formation is exposed in sections 21, 22, 27, and 28, on the tip of the peninsula between Sand Arroyo Bay, on the south, and Spring Creek Bay, on the north. Excellent exposures occur in the northeasternmost corner of section 28, T. 24 N, R. 42 E, and, in general, around the small bay that appears in the southeastern quarter of section 21. A general dip toward the east and southeast puts the Bearpaw Shale below water level of the Fort Peck Reservoir to the south and east of Sand Arroyo Bay, but exposures to the west do help define the total thickness of the Fox Hills Sandstone, which was the principal reason for our study in that area. The uppermost 1–5 m of the transition zone are exposed below the Fox Hills Sandstone at reservoir level (1989) on both sides of the mouth of Rock Creek Bay in sections 24 and 25, T. 23 N, R. 42 E,

FIGURE 11.—*View toward the southwest from Montana 24 to small faults in the lower Tullock and uppermost Hell Creek beds in a small hill in the northwestern part of section 25, T. 23 N, R. 43 E. The Z-coal is the lowermost dark band exposed in the sequence and overlies light-colored Hell Creek beds. The subparallel, moderately thin, dark unit below the prominent Z-coal is the approximate position of the iridium layer and the Cretaceous-Tertiary contact zone. The Y-coal is the upper dark band also cut by the faults.*

where fossiliferous concretions occur in the shaly beds. Similar rocks are exposed in the shore zone of the North Arm of Sand Arroyo Bay in sections 19, 30, and 31, T. 24 N, R. 43 E.

Lithology

The Bearpaw Shale is principally a dark gray to medium gray clay shale that locally contains moderately common, large, calcareous concretions where the formation is exposed along the shore zone of Sand Arroyo Bay. Light gray bentonitic beds form thin marker horizons within the outcrop and allow lateral correlation, particularly when combined with horizons of more abundant concretions. The dark gray clay shale of the formation is best exposed at the shore zone in the exposures in the northeastern corner of section 28, T. 24 N, R. 42 E, and around the promontory toward the northwest.

Many of the large concretions have produced abundant ammonites (*Baculites grandis*). These concretions are up to 0.8 m in diameter, locally, and are commonly septarian appearing. They stand as resistent spheroidal masses on beaches and in the weathered outcrops.

In section 28, T. 24 N, R. 42 E, about 23 m of the upper Bearpaw Shale are exposed (fig. 12). The lower 6 m are dark gray to dark gray brown, weather light gray brown, and contain concretion horizons every 2 to 3 m. These shales are also gypsiferous with scattered small selenite crystals in virtually every fresh exposure.

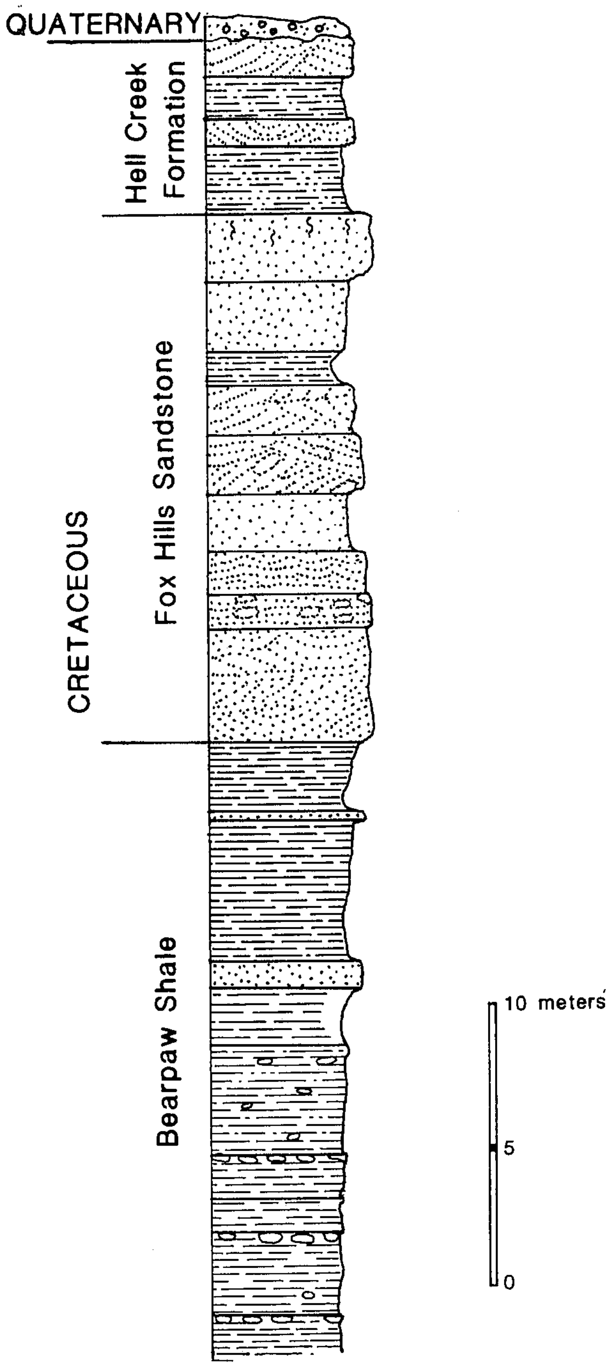


FIGURE 12.—*Generalized stratigraphic section of upper Bearpaw Shale, Fox Hills Sandstone, and lower Hell Creek Formation exposed in section 28, T. 24 N, R. 42 E, in the Spring Creek Bay Quadrangle. Only the upper few meters of the Bearpaw Shale are exposed in the Sand Arroyo and Bug Creek Quadrangles.*

The upper 15 m of Bearpaw Shale tend to be lighter gray brown to medium gray brown to light gray brown and become increasingly yellowish gray in the upper part. The beds become silty in the transition zone to the overlying Fox Hills Sandstone. A thin, yellowish gray, soft argillaceous sandstone occurs approximately 8 m below the contact, and another thin, platy, calcareous, medium gray brown sandstone, only 0.3 m thick, occurs 2 m below the contact. These sandstones are laterally persistent and are part of the shelf-forming zone of light yellow-gray-weathering uppermost Bearpaw Shale visible along the shore and in bluffs north of the mouth of the Sand Arroyo Bay. Uppermost silty shale in the formation becomes light or medium greenish gray to medium gray brown and lacks the concretions characteristic of the lower dark gray part of the formation. These upper shale beds are also locally gypsiferous, with abundant tan to light gray selenite crystals up to 3 or 4 cm across.

Fossils and Age

Marine fossils are moderately common in the lowest Bearpaw Shale exposures in section 28, T. 24 N, R. 42 E, and around the shore zone to the south into the estuary of Sand Arroyo Creek. Fossils occur in two beds, one approximately 15 to 16 m below the contact sandstone and another approximately 10 to 12 m below the sandstone. All of the ammonites recovered by us appear to be *Baculites grandis* (W. A. Cobban personal communication 1987). *B. eliasi* was reported by Bell (1965, p. 17) to be common in The Pines recreation area on the west side of the Fort Peck Reservoir and in the Bear Creek Camp area in the northern part of the Spring Creek Quadrangle.

Cobban, in Jensen and Varnes (1964, pp. F8–F10), reported a large fauna from the Bearpaw Shale, including many pelecypods, gastropods, and ammonites. The most useful faunal elements appear to be the cephalopods *Baculites*, which indicate that the upper Bearpaw beds are upper Campanian to lower Maestrichtian. Thus, the Late Cretaceous Bearpaw Shale is probably continuous with the upper part of the Pierre Shale of the Dakotas (Cobban and Reeside 1952). Sloan and others (1986) indicated that the Fox Hills Sandstone in eastern Montana is of middle Maestrichtian age (*Baculites grandis* zone) or younger, which would suggest that upper beds of Bearpaw Shale exposed near Sand Arroyo Bay may be of lower Maestrichtian and earlier ages.

Thickness

The full thickness of Bearpaw Shale is not exposed in the quadrangles of immediate concern but, as noted earlier, may range up to 370 m thick or slightly more. Only the upper 23 m of Bearpaw Shale is exposed on the north shore of Sand Arroyo Bay.

FOX HILLS SANDSTONE

Introduction

The Upper Cretaceous Fox Hills Sandstone was first differentiated by Meek and Hayden (1862, pp. 419, 427) for the gray and yellowish gray sandstone and sandy clays that occur below the coal-bearing "Fort Union Formation" and above shales that are now known as the Pierre Shale in the Dakotas, or the Bearpaw Shale locally in eastern Montana. The formation was named for exposures on Fox Ridge in Armstrong and Davey Counties in northwestern South Dakota, 515–560 miles southeast of the Fort Peck and the Rock Creek areas. The name has been widely used throughout the northern Rocky Mountains and the northern plains of Colorado, Wyoming, Montana, and North and South Dakota as the generally late regressive littoral sandstone facies of the gray shales of the Cretaceous Interior Seaway.

Stratigraphic boundaries of the formation were defined by Lovering and others (1932, pp. 702–703), who placed the base of the formation at the base of the dominant buff and brown sandstone above the gray marine clays, clay shales, and sandy shales of the Pierre Formation. They noted that the Fox Hills Sandstone contains numerous, large, gray, calcareous sandstone concretions. Rocks of the formation may grade locally upward into somewhat lighter gray brown sandstones and sandy shales. They concluded the top of the Fox Hills Formation should be placed where the sandstones grade upward into predominantly fresh- or brackish-water deposits, accompanied by coal or lignitic shale.

Brown (1914, p. 357) included the upper very light gray sandstone exposed at Hell Creek as the basal sandstone of the Hell Creek Member of the Lance Formation. Thom and Dobbin (1924, p. 490) assigned those light colored beds to the Colgate Sandstone Member of the Fox Hills Formation; that stratigraphic usage was followed by Collier and Knechtel (1939, pp. 9–10). Brown (1914, p. 357) recognized the Colgate Member of the Fox Hills Sandstone and an underlying marine Fox Hills sandstone, the latter as an unnamed member.

Collier and Knechtel (1939, p. 10) made no attempt to separate members of the Fox Hills Formation within their map area, which included the Bug Creek and Sand Arroyo Quadrangles. We have not differentiated the Colgate and underlying sandstone members of the Fox Hills Formation, if such persist into the Bug Creek and Sand Arroyo areas, but have mapped the formation as a single unit, for only the uppermost few meters of beds are extensively exposed. The lower beds of the formation are generally covered beneath water of Fort Peck Reservoir within the quadrangles, but a full section is exposed 4.5–6.5 km west of the boundary in the center of the adjacent Spring Creek Bay Quadrangle.

Outcrop Area and Topographic Expression

Upper beds of the Fox Hills Sandstone are extensively exposed in excellent outcrops in the sea cliff along the shores of Fort Peck Reservoir. Complete sections are exposed along the North and South Arms of Sand Arroyo Bay in the west central part of the Sand Arroyo Quadrangle in sections 19, 20, 29–31, T. 24 N, R. 43 E. Here the formation extends from reservoir level upward for 12–15 m in irregular outcrops at the shore zone. Similar outcrops occur in the vicinity of Rock Creek State Recreation area (figs. 13, 14) in the northwesternmost part of T. 23 N, R. 42 and 43 E, on the Spring Creek Bay Quadrangle. Exposures continue in the shore zone southward around the Rock Creek Recreation Area into the drowned "estuaries" of the North Fork and the South Fork of Rock Creek in the northwesternmost part of the Bug Creek Quadrangle in sections 19, 20, and 30 of T. 23 N, R. 43 E.

Some of the most spectacular exposures of the formation are those in the northeastern part of the Ash Creek East Quadrangle, in sections 25 and 36 of T. 23 N, R. 42 E, in the general vicinity of the Rock Creek Marina and the hills to the west (fig. 15). However, only uppermost parts of the Fox Hills Formation are exposed in low outcrops in Black Spring Coulee Bay in the west central part of the Bug Creek Quadrangle. The Fox Hills Sandstone generally is exposed along the east shore of Fort Peck Reservoir in the crests of broad, open anticlines that coincide with some of the deeply indented bays of the shore zone.

The formation is considerably more widely exposed in areas toward the north, near Fort Peck, where a full sequence of the formation is exposed in bluffs along either side of the Missouri River, east and west of the dam site, and in tributaries of the river south of the community of Fort Peck. These outcrops have been described by Jensen and Varnes (1964, pp. F11–F16). They noted (1964, p. F16) that Collier and Knechtel (1939, pp. 9–10, pl. 3) suggested that the Colgate Member of the Fox Hills Formation is present in McCone County. Further investigation by Jensen indicated that the light gray sandstone, characteristic of the Colgate Sandstone of southeastern Montana, is not developed in McCone County and is not distinguishable as a lithologic unit northeast of Hell Creek, some distance to the southwest of the Bug Creek area. Brown (1907, 1914), for example, did not note the occurrence of light gray sandstones in the McCone County area.

The Fox Hills Sandstone is magnificently exposed in nearly vertical undercut banks along the shore of Fort Peck Reservoir and in some of the deeply entrenched gullies that empty into the reservoir. Away from the reservoir margin, however, the formation is poorly exposed and produces a hilly rounded upland, locally

FIGURE 13.—*Prominent in situ* Ophiomorpha *trace fossils in upper massive Fox Hills Sandstone in the eastern part of Rock Creek State Park, east of the boat launch area near the southeast corner of section 11, T. 23 N, R. 42 E, on the Spring Creek Bay Quadrangle. Outcrops show the characteristic grape-cluster-like external sculpture of the pellet-lined burrows and their downward bifurcation. The scale is in centimeters.*

armored by the large concretions characteristic of the formation.

Contacts

The basal contact of the Fox Hills Sandstone on the Bearpaw Shale is exposed only along the North Arm of Sand Arroyo Bay within the Bug Creek and Sand Arroyo Quadrangles. To the southeast those beds have been largely flooded over by Fort Peck Reservoir, but the complete Fox Hills Sandstone and uppermost Bearpaw Shale are exposed along the north shore of the mouth of Sand Arroyo Bay in sections 21, 22, 27, 28, T. 24 N, R. 42 E, in the Spring Creek Bay Quadrangle. Bell (1965, p. 19) noted that the Fox Hills Sandstone conformably overlies the Bearpaw Shale and, as we have done, placed the contact where the yellow gray sandstone of the Fox Hills predominates over the fine clastic rocks of the Bearpaw Shale. In a few exposures in the northwestern part of section 29, T. 24 N, R. 43 E, thin interbedded shale units of the contact transition zone were exposed at reservoir level during the low-water stages of the reservoir during the summers of 1988 and 1989. These fine clastic units contain fossiliferous concretions in the upper Bearpaw beds.

The upper contact of the Fox Hills Sandstone with the overlying Hell Creek Formation has been drawn at the top of the buff and yellow gray sandstones and the base of the first, laterally persistent, thick mudstone (figs. 13, 15).

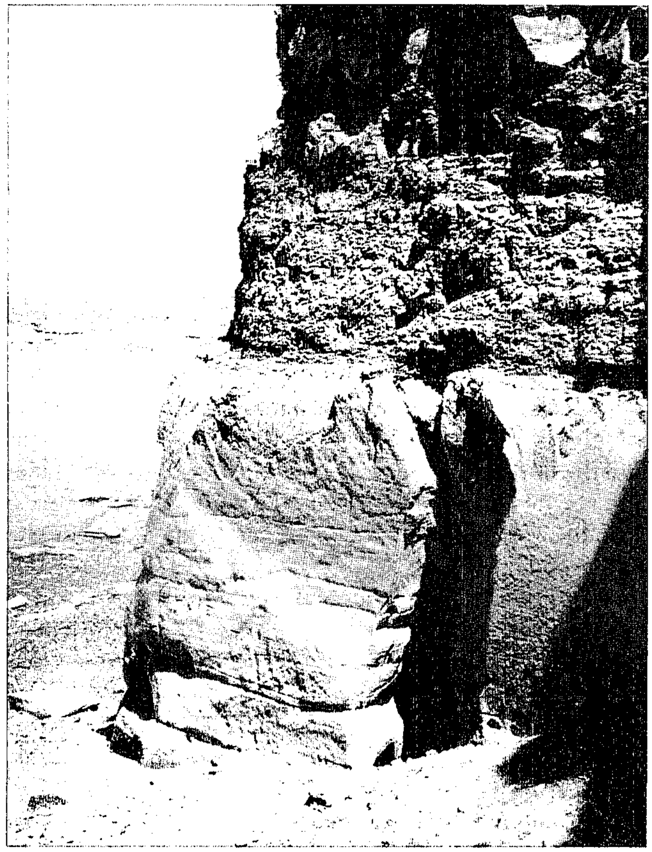


FIGURE 14.—*Contact zone of the top of the Fox Hills Sandstone, in the foreground, and the overlying lower part of the Hell Creek Formation, above the prominent shaly break in the southeastern corner of section 11, T. 23 N, R. 42 E. The shale break has been mapped to separate dominantly fluvial and lacustrian Hell Creek beds, above, from the marine shore-zone sandstones of the Fox Hills below. The shale break is probably equivalent to the interbedded unit in figure 15.*

The uppermost few meters of the sandstone are commonly well cemented and locally produce extensive overhanging ledges of brown concretionary, commonly platy sandstone that function as key units. They allow ready separation of the more easily eroded overlying basal Hell Creek Formation from the tan, concretionary sandstones of the Fox Hills Formation.

Such a topographic expression is magnificently developed in Pretty Place, in exposures along the south fork of Sand Arroyo, in northeastern section 31 and northwestern section 32, T. 24 N, R. 43 E. (fig. 16). Here the platy to concretionary sandstones have produced overhangs that had been utilized as shelter areas by game animals and cattle, and by local ranch personnel as camp areas. Elsewhere, however, uppermost Fox Hills beds form a gentle ledge with only modest overhangs, but a ledge that, nonetheless, enables consistent recognition of the top of the sandstone and base of the overlying Hell Creek Formation.

The contact is also moderately well exposed along the north side of the estuary of North Rock Creek and in the hills southwest of the Rock Creek Marina (fig. 15), in sections 24 and 25, T. 23 N, R. 42 E, on the west side of Rock Creek Bay.

Outcrops on the north shore of the North Arm of Sand Arroyo Bay in southwestern section 20 and southeastern section 19, T. 24 N, R. 43 E, show an interdigitating contact of Hell Creek and Fox Hills Formations. A moderately thick tongue of gray mudstone separates two ledge-forming sandstones in the contact zone in southeastern section 19. That mudstone is overlain and underlain by prominent platy resistant sandstones. The overlying sandstone thins toward the western boundary of the quadrangle but persists as a thin, platy, ledge-forming unit to the edge of the quadrangle. The gray mudstone tongue, on the other hand, thins eastward and disappears in the southern part of section 20, about at the small bay of the West Fork of Sand Arroyo. East of section 20, the Fox Hills Sandstone appears to be a continuous sequence of tan sandstones from the shore of Fort Peck Reservoir up to the contact with the Hell Creek Formation.

The mudstone tongue, visible on the north shore of the North Arm, was not recognized on the south shore, nor is it developed in the section exposed in the South Arm of Sand Arroyo Bay. There the Fox Hills is a more or less continuous cross-bedded, tan or buff sandstone capped by a resistant concretionary ledge. The interdigitation, however, does document that the contact between the Fox Hills and Hell Creek Formations is transitional and time transgressive and marks the gradation from a marginal-marine littoral section into a nonmarine fluvial-dominated sequence. The mudstone is clearly exposed in shore exposures in and near Rock Creek State Recreation area (fig. 13) in sections 11–14, T. 23 N, R. 42 E, on the Spring Creek Bay Quadrangle. It is particularly evident in cliffs of the shore zone in section 14, near the tip of the peninsula south of the recreation area bay.

Dobbin and Reeside (1929, p. 25) concluded, as have we, that the contact between the Fox Hills Sandstone and Hell Creek Formation is transitional, with only minor and local erosion, as the sheetlike regressive Fox Hills Sandstone gives way upward to the fluvial Hell Creek Formation. In a transition from a marginal marine to fluvial sequence, it is not surprising that the contact may be interpreted as locally unconformable. Barnum Brown (1907, p. 84) reported an unconformity at the Fox Hills–Hell Creek contact to be of regional significance. However, later, Brown (1914, p. 357) concluded that the earlier observed break was evidently of local nature. Badgley (1953), in an unpublished thesis on Tertiary sediments in eastern Montana, done at the University of Wyoming, reported a basal Hell Creek conglomerate that contains pebbles of granite, gneiss, limestone, and quartzite. Brown (1961, p. 9) reported that he and fellow workers were able to trace the granite- and gneiss-bearing conglomerate "north and south of the Missouri River, east and west, and south of the Fort Peck Dam, and southward as far as Forsyth on the Yellowstone River" over hundreds of square miles, including the Sand Arroyo and Bug Creek Quadrangles. Bell (1965, p. 20) was unable to find evidence of the conglomerate at the contact zone in his study of the Fort Peck fossil field, which included the quadrangles under consideration here. Neither have we been able to find such a conglomerate, although we did observe a well-exposed lakeshore sequence in section 14 of T. 23 N, R. 42 E. on the Spring Creek Bay Quadrangle.

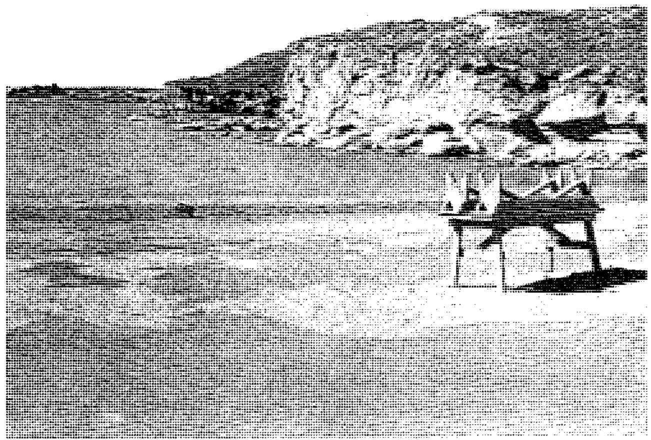


FIGURE 15.—*Cliff along Fort Peck Reservoir on the south side of Rock Creek Bay in the southeast quarter of section 24, T. 23 N, R. 42 E, on the Ash Creek East Quadrangle. Lower massive beds are Fox Hills Sandstone, overlain by sandy mudstone transition beds. Uppermost rocks are basal sandy units in the Hell Creek Formation. The basal sandstone cliff is approximately 3 m high. The lower massive sandstone may be equivalent to Waage's (1961) Timber Lake Member, and the overlying interbedded sandy shale and fine-grained sandstone may be the Bull Head Member of Waage, as interpreted by Bell (1965).*

Members

Waage (1961), in studies of the type Fox Hills Formation, subdivided the formation into several members. These appear to be major time-transgressive facies divisions rather than regionally mappable time-stratigraphic units. Consequently, we have not utilized member subdivisions, although Bell (1965) concluded that the Bull Head Member of Waage (1961) is represented by upper interbedded, gray sandy shale and fine-grained sandstones, a unit that ranges from 2 to as much as 10 m thick. Bell (1965) reported that the maximum thickness of the member in this area is exposed in Sand Arroyo. What Bell interpreted to be the Bull Head Member may be the approximately 6 m of intertonguing marginal mudstones and upper sandstones exposed on the north side of the North Bay of Sand Arroyo and in the recreation area to the southwest.

Bell (1965, p. 23) noted that the middle and major part of the Fox Hills Sandstone can be referred to Waage's Timber Lake Member and that the lower few meters of the Fox Hills Sandstone may be referred to the Trail City Member, which he considered to represent a transition from the marine Bearpaw Shale up to the shore-zone deposits of the Fox Hills Sandstone. Possible Trail City Member facies is the lower 4 or 5 m of the formation exposed in bluffs along the north shore of Sand Arroyo Bay and in small bays to the northwest. Most of the formation, as mapped in the Bug Creek and Sand Arroyo Quadrangles, is a facies equivalent to Waage's Timber Lake Member of the type area. However, we consider the members to represent only time transgressive units, roughly equivalent to the upper and lower shore face, like sandstones II and III in Cretaceous shore zones of central Utah (Balsley 1982; Rigby, Russon, and Carroll 1987).

Lithology

Most exposed Fox Hills Sandstone in the Sand Arroyo to Bug Creek area is a moderately uniform, consistently cross-bedded, very fine-grained sandstone that varies in its resistance to erosion depending upon the degree of limonite or silica cementation. The formation shows little variation over most of the region. Generally, the sandstone is not well cemented and erodes readily to rounded hillsides, except in the shore zone of Fort Peck Reservoir, where the rocks have been undercut and hold up sheer walls.

The sandstones are generally yellowish gray to dusky yellow, and weather yellowish gray, except in concretionary bands where they are dusky yellow to grayish orange or dark yellowish orange. Most exposures are of massive, irregularly cross-bedded, very fine-grained and moderately well-sorted sandstone. Locally, small lenses of rip-up clasts of siltstone, or clay-pebble clasts, up to 3 or 4 mm in diameter, occur as bounding units between cross-bed sets (fig. 17). The small rip-up pebble lenses appear as lag gravels between cross-bed sets that are less than 1 m high, where well exposed in the Pretty Place, along the South Arm of South Fork of Sand Arroyo, and near the Rock Creek Recreation area. Cross-bed sets within the sandstone, however, may range up to 2 or 3 m high, but most sets are approximately 1 m or less.

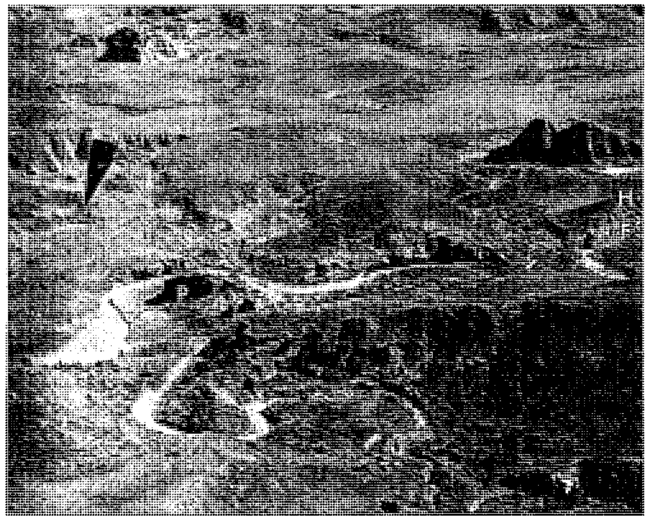


FIGURE 16.—*View toward the north across Pretty Place (P) in the center of the photograph. Uppermost Fox Hills Sandstone (F) is well exposed along the South Fork of Sand Arroyo in the northwest quarter of section 31, T. 24 N, R. 43 E. Badlands, above, are carved on soft gray claystone and mudstone of the lower part of the Hell Creek Formation (H). The contact of the Hell Creek Formation on the Fox Hills Sandstone was mapped at the concretionary resistant layer in the lower right around the promontory near Pretty Place.*

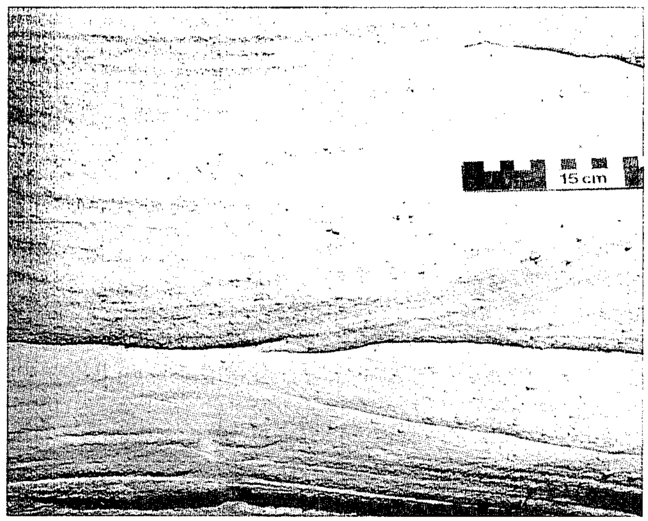


FIGURE 17.—*Cross-bedded sandstones of the upper part of the Fox Hills Sandstone exposed in Rock Creek State Park area, in the southeasternmost part of section 11, T. 23 N, R. 42 E. Pebbles are clasts of calcareous mudstone and generally form a lag at the base of the trough cross-bed sets.*

Spectacular loglike concretionary bands demonstrate the cross-bedded character in most shore-zone exposures, and the consistency of cross-bed direction is striking, particularly when compared with the considerably more irregular cross-bed directions of the overlying Hell

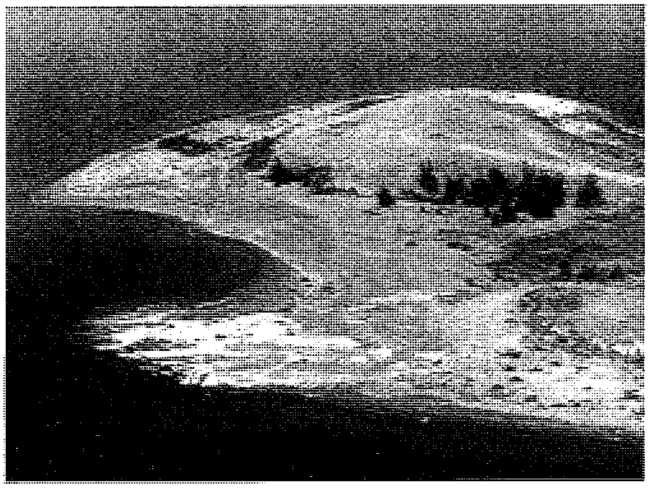
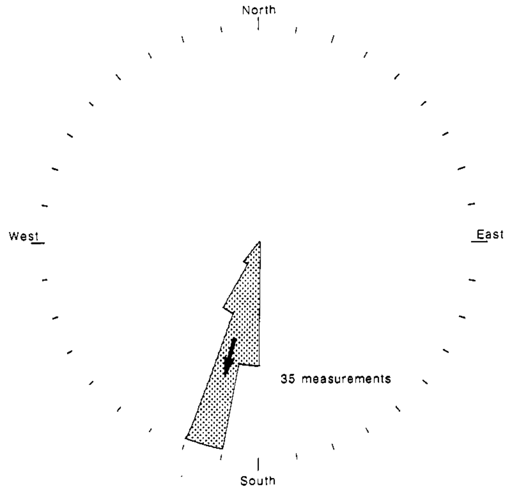


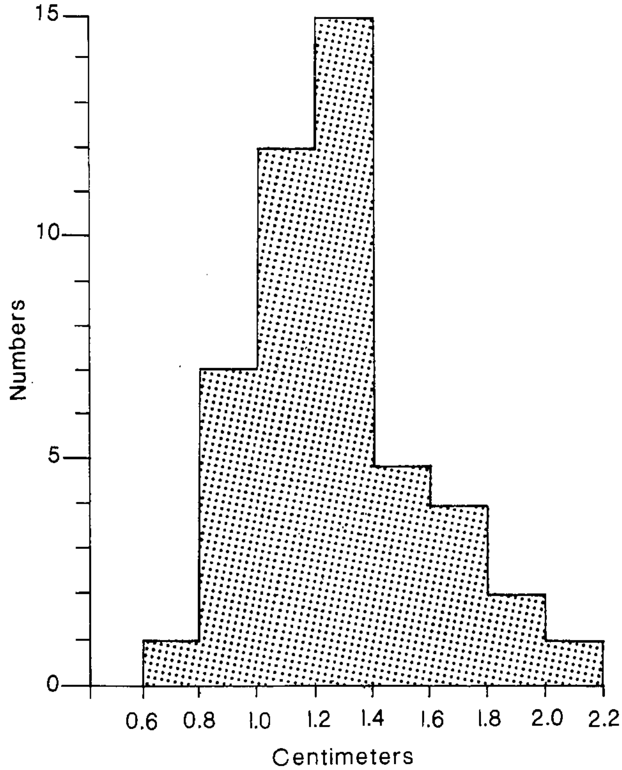
FIGURE 18.—*Aerial view of Annabelle Beach toward the west; the vertebrate fossil screening site along the north part of Rock Creek Bay in the southwest part of SE 1/4 of section 13, T. 23 N, R. 42 E, on the Ash Creek East Quadrangle. Linear exposures of cross-bedded sandstone are generally accumulations of migration of single, large, barchanoid sand deposits, with the current flowing from right to left.*

Creek Formation. Some of the best exposures of the loglike development of trains of cross-bed sets are those on Annabelle Beach, here named for the project screening area in the NW 1/4 NE 1/4 of section 24, of T. 23 N, R. 42 E. (figs. 18–21). Here massive-weathering, rhythmically bedded cross-beds form barchanoid trains up to 2 or 3 m wide and 1–1.5 m high. Individual trains are tens of meters long in the exposure. Similar, systematically oriented cross-bed sets of the fine- to medium-grained sandstone characterize shore-zone exposures at virtually every outcrop along the margin of Fort Peck Reservoir. Small cross-bed sets appear like deposits of braided stream systems with a uniform direction, but the larger cross-bed sets apparently accumulated as migrating tidal bars of barchanoid sheets of sand and show remarkable tidal bundle uniformity. That uniformity is well demonstrated by exposures on Annabelle Beach where several concretionary "logs" are made of U-shaped sets composed of remarkably similar tidal bundles. Laminae dip 27°–28° at their steepest, at the top, but curve to become horizontal where they wedge out at their bases. The limited variations in flow directions are shown in fig. 19A, which indicates a nearly constant southward motion. This is what one would expect from regional patterns (Gill and Cobban 1973, fig. 19; Parish, Gaynor, and Swift 1984).

The bundled sandstone shows remarkable uniformity in pulses of sedimentation like that described in tidal bundles and mud couplets from the McMurray Formation of Alberta (Smith 1988). For example, measurements taken on one cross-bed set are shown in fig. 19B. The total range of thickness of approximately 50 laminae, measured



A



B

FIGURE 19.—*Orientation rose (A) and histogram (B) of cross-bed orientations and thicknesses of individual cross-set laminae in one set of upper Fox Hills beds on Annabelle Beach.*

at the same height on the cross-bed set, is from 0.8 to 2.0 cm. In 40 adjacent superposed laminae, in a single set, the range is from 1.0 to 1.8 cm, but nearly all of them are from 1.0 to 1.3 cm thick. Some of the irregularity is related to weak rippling on the cross-bed sets. The laminae are

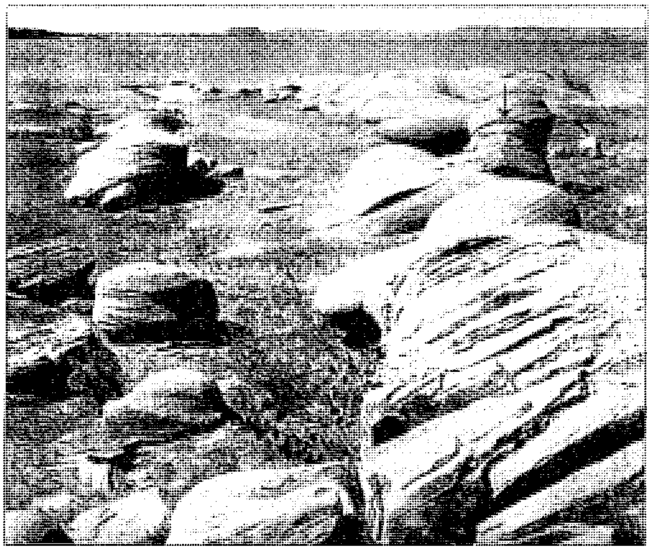


FIGURE 20.—*View southward along a trough cross-bed set shows uniform cross-lamination in the Annabelle Beach area and the limited concretionary development in the top of the Fox Hill Sandstone.*

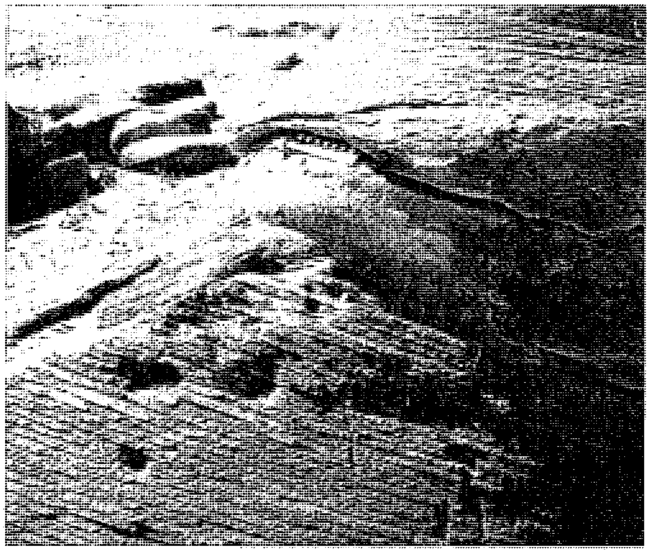


FIGURE 21.—*Prominent cross-bedding shows in the northern end of a barchanoid loglike accumulation of trough cross-bedded sandstone on Annabelle Beach. Remarkably uniform cross-laminae are 1.5 to 2 cm thick. The locality is shown with an arrow on figure 20.*

clearly defined, here, by slightly finer-grained sandstones. Each lamina begins with coarsest medium-grained sand at the base of principally fine sand individual lamina and grades up to very fine sand at the parting at the top. There is also a general shift in calcareous nature, with the upper finer-grained material being slightly more calcareous.

Bundle sets show remarkable uniformity, laterally, with exceedingly regular cyclicity in the events. At the crest of a characteristic trough cross-bed set, the total range in thickness is from 0.8 to 2 cm, with most 1.2 to 1.5 cm thick.

Sand in an individual lamina is generally fine grained with a minor admixture of very fine-grained sand, principally of dark ferromagnesian minerals and green and black chert. Sandstones are moderately well sorted and grain supported. Clear quartz grains are subrounded to rounded, but most of the chert grains, which make up 10%–15% of the total fragments, are subangular.

Single trains of U-shaped cross-beds are traceable for 60 to 70 m and are 10 to 12 m across. In general, laminae within individual cross-bed sets thin from the axis of the U trough toward the horns of the dunelike set. They average 1.2–1.8 cm thick in axes, but thin to 0.8–1.0 cm thick in the vicinity of the cross-bed set intersections.

Truncation surfaces and tops of many of the tidal bundle sets are marked by small-scale, trough-shaped ripples, 1–2 cm high. These generally indicate a direction of current motion like that of the major set and a significant lessening of the current velocity and reduction in local relief. Smaller ripple sets still show remarkable regularity of current motion and rhythmic deposition with laminae 5 to 8 mm thick in the steep upper parts of individual sets. These sets, like the thicker ones, show pulses of deposition that end with increased matrix and somewhat increased calcareous cement.

Differential cementation of laminar fine partings, 1 to 2 mm thick, clearly mark individual sets. These partings weather into slight relief, in part because of relatively increased matrix. There are only minor shifts in total grain sizes, however, between the bulk of the laminae and partings between laminae.

The consistency of current direction and magnitude of individual laminae within sets indicate these were probably deposited by tidal currents. However, nowhere in the Annabelle Beach outcrop have we seen evidence of reversed direction of flow, even in the small ripple marks that appear to form at the crest of virtually every dune set. Minor cross-bed sets and prominent rippled bedding do show currents in two directions, 180° apart, at the westernmost tip of the promontory in the center of section 13, T. 23 N, R. 42 E, and document that tidal currents deposited some of the uppermost beds of the Fox Hills Formation (fig. 22). These ripple marks have 15 to 20 cm wavelengths and 4 to 5 cm amplitudes, with sharp crests. Internally, the ripples show alternating series of cross-beds inclined in both directions away from the sharp crests. The sharp ripple crests trend N. 40°–45° E. and indicate tidal current motion at right angles to that, to the northwest and to the southeast.

A variety of large and small concretions also characterizes the Fox Hills Sandstone. Most large concretions represent well-cemented, single cross-bed sets or parts of such sets. Smaller concretions are generally rusty brown remnants of marcasite or pyrite. The large concretionary units characteristically form ledges or cap undercut exposures. They are dark brown or dark yellowish brown to moderate brown and weather to the same colors or to moderate reddish brown where exposed by slower natural processes. In general, newly exposed concretions along the shore zone, however, are the same yellowish gray to dusky yellow as the principal part of the formation.

Small limonite concretions, 1 to 2 cm across, occur scattered throughout the sandstones. Rare scaphopod and razor clam fragments occur as obviously transported debris in some of the concretions. Some of the larger concretions range from 0.2 m up to over 1 m in diameter. Small concretions generally form subspherical masses but may also be joined in grapelike clusters or as "elbows" or leglike concretions. Concretionary units show structure of cross-bed sets particularly well. Some cross-bed sets are marked by linear sequences of concretions, but in others, the concretions merely stand as subspherical masses from sides of large lenticular cross-bedded loglike masses.

In shore-zone exposures in the central part of the promontory in the northeasternmost part of section 24, T. 23 N, R. 42 E, some of the individual laminae in some concretions contain common fossil wood, and possibly oyster fragments. These are breccias with fragments up to 4 or 5 cm across. The wood debris is now limonite, altered from pyritized material. The fossil plant debris is unidentifiable. The same kinds of fossil material are also preserved in shore-line exposures in the center of section 13, T. 23 N, R. 42 E. Fossil debris is particularly prominent in some of the more limonite-cemented concretions.

The concretions are moderately calcareous, although most of their resistance to weathering is apparently related to limonite cement. The large concretions are elongate parallel to the cross-bed direction, the direction of paleoflow, and appear to be a result of differential cementation in zones of better initial porosity. Large concretions range up to 2 or 3 m across and may be 5 or 6 m long in the cross-bed transport direction.

Concretions of intermediate size, ranging from a few centimeters to 1 or 2 m long or in diameter, appear similar to the large forms, but are considerably more irregular and leglike or armlike in shape. Some are subspherical, but most are irregularly lenticular and weather into strong relief, even in wave-cut exposures. These are distinctly more calcareous than the larger concretionary units.

Smaller subspherical to irregularly nested or grape-cluster-like limonite and marcasite concretions are common throughout the exposed part of the Fox Hills Sandstone. They are generally light brown to moderate brown,

FIGURE 22.—*Long, straight-crested ripple marks show accumulations in two directions and are of probable tidal origin. Exposure is in uppermost beds of the Fox Hill Sandstone, on the shore zone in the cabin area in the center of the SW 1/4 of section 13, T. 23 N, R. 42 E, on the Spring Creek Bay Quadrangle. Ripples are sharp-crested and trend N 60° E. They show motion of water in two directions at right angles to the ripples.*

and weather dark yellowish orange to orange brown because of their higher iron content. Some of the concretions have gray marcasite bands as centers, particularly ones associated with *Ophiomorpha.* These common small concretions range from isolated masses only a few millimeters in diameter to ones that are 3 or 4 cm in diameter, or they may be joined in dumbbell-like, chainlike, or grapelike clusters. These small concretions commonly have liesegang-like banding, at least as seen in weathered examples. Jensen and Varnes (1964, p. 15) noted these concretions "form the intricately eroded rimrock that is a conspicuous feature of the Fox Hills Sandstone in this area."

Fossils and Age

Fossils are relatively rare in the Fox Hills in this area. Concretions do contain fragments of *Pteria* and *Baculites,* where exposed on the promontory in the NW corner, NE 1/4 of section 24, T. 23 N, R. 42 E. Elsewhere, however, the principal fossils are trace burrows, generally *Ophiomorpha. Ophiomorpha* traces are locally numerous (fig. 13) but are particularly common near the base of exposures at Rock Creek State Park in the southwestern part of section 12, T. 23 N, R. 42 E, on the Spring Creek Bay 7 1/2′ Quadrangle. Branching *Ophiomorpha* impressions with exterior grapelike sculpture have been preserved in the limonite- or marcasite-cemented sandstones where the burrows are most common.

An as yet unstudied leaf and compression flora was discovered during the summer of 1988 in upper slabby sandstones of the Fox Hills Sandstone on the promontory in NE 1/4 of section 14, T. 23 N, R 42 E, across the bay south of the Rock Creek recreation area in the Spring Creek Quadrangle.

The Fox Hills Sandstone is of probable lower Maestrichtian age in central Montana (Gill and Cobbin 1973), but is of Middle Maestrichtian age (*Baculites grandis* zone or younger) in this part of Montana (Sloan and others 1986). Numerous specimens of *Baculites grandis* (Hall and Meek 1856) were collected during our study from upper Bearpaw Shale a few meters below its contact with the Fox Hills Sandstone.

Thickness

The full thickness of the Fox Hills Sandstone is exposed only along the North Arm of Sand Arroyo Bay within the Sand Arroyo or Bug Creek Quadrangles. The complete section of the formation is broadly exposed 4–5 km to the west in Spring Creek Bay Quadrangle, where it is 19.4 m thick on the north side of Sand Arroyo Bay. A section of the upper 9.5 m of the formation was measured along the South Fork of Sand Arroyo in the northeastern part of section 31 and the northwestern part of section 32, T. 24 N, R. 43 E. Complete thicknesses of the formation were reported by Jensen and Varnes (1964, p. F12) as up to 37 m (120 feet) in the Fort Peck area. Bell (1965, p. 159) reported a measured section of that part of the upper Fox Hills, exposed above reservoir level, in section 21, T. 24 N, R. 43 E, in Sand Arroyo as approximately 25 m (82.0 feet) thick, but he may have included some tan, interbedded siltstone and sandstone that we included as upper units of the Bearpaw Shale, or upper sandstone and mudstone here mapped as basal Hell Creek beds within the formation.

Collier and Knechtel (1939, p. 9) noted that the lower or basal member of the Fox Hills Sandstone ranges from 24–60 m (80–200 feet) thick, and the upper member is about 24 m (80 feet) thick in exposures along the Missouri River and in Big Dry and Prairie Elk Creeks in the general vicinity of Sand Arroyo and Bug Creek Quadrangles and to the north. Their usage of the Fox Hills Formation, however, certainly included part of the Bearpaw Shale as the basal member. Modern usage of the Fox Hills Sandstone would be limited essentially to what they showed (Collier and Knechtel 1939, pl. 3) as the Colgate Sandstone Member. Such a restricted Fox Hills Sandstone is 24–25 m thick. This would suggest that nearly the full thickness of the formation is exposed near Rock Creek State Park as measured by Bell (1965, p. 159). However, the full formation is exposed within the Spring Creek Quadrangle to the north.

POST-MONTANA GROUP FORMATIONS

HELL CREEK FORMATION

Introduction

The Hell Creek beds were differentiated from rocks above and below by Barnum Brown (1907, p. 829–35) as the fossiliferous freshwater deposits that occur above the Fox Hills Sandstone and that are approximately 170 m thick in the western part of then Dawson County, now in part Garfield County, Montana. The formation was named for exposures at Hell Creek, in Garfield County, and on nearby tributaries of the Missouri River. These exposures are a few miles southwest of the Bug Creek area, along the south flank of the Missouri River Valley, north of the community of Jordan.

The early, somewhat convoluted nomenclature of Hell Creek beds has been summarized by Frye (1969, p. 3–16). In the McCone County report, Collier and Knechtel (1939, p. 10–11) discussed the Hell Creek Member of the Lance Formation as exposed along Big Dry Creek. They noted that the lower, more somber unit, the Hell Creek Formation of subsequent authors and the present report, is differentiated from an upper member, the Tullock Formation of this paper, in a broad strip of exposures across the northern part of McCone County.

Brown (1907, p. 823–45) reported that fragments of the dinosaur *Triceratops* occur throughout the formation. Thom and Dobbin (1924) further discussed Hell Creek beds, within the Lance Formation, as occurring above the Fox Hills Sandstone and below the yellowish Tullock Member of the Lance Formation. They utilized the A-coal of Brown to mark the base of the Tullock Formation. In December of 1935, the Hell Creek and Tullock beds, which previously had been classified as members of the Lance Formation, were raised to formation rank by the U.S. Geological Survey (Collier and Knechtel 1939, p. 11). The Hell Creek Formation was then considered to be of Late Cretaceous age and the Tullock Formation of Late Cretaceous to Tertiary (?) or Eocene age.

Brown (1938) concluded that the Mesozoic-Cenozoic boundary should be placed between the Hell Creek and Fort Union or Tullock beds at the approximate position where it is placed today. He raised the Hell Creek unit to formation status in North Dakota, and suggested that the Fort Union beds should be considered as Paleocene. R. W. Brown (1938) noted that the Fort Union Formation overlies the Cretaceous Hell Creek Formation and, later (1952, p. 91), again reviewed criteria for differentiating Cretaceous and Tertiary rocks of the region.

In the 1960s, the boundary became stabilized and the Cretaceous-Tertiary division was more clearly recognized, with beds mapped in the present study as Tullock Formation included in the Paleocene series and the Hell Creek Formation placed totally within the Upper Cretaceous. Much recent effort has concentrated on more detailed documentation of the exact position of the Cretaceous-Tertiary boundary, and much effort has been expended, particularly in the Bug Creek area along the east edge of Big Dry Arm of the Fort Peck Reservoir. Debate concerning the exact time of extinction of dinosaurs (Bryant and others 1986, Retallack and Leahy 1986, Rigby 1987, Sloan and Rigby 1986, Sloan and others 1986) has added impetus to the paleontologic and stratigraphic study of the rocks considered here. That debate has been fueled, perhaps, by description of a possible catastrophic cause of extinction related to a comet shower or one or more meteorite impacts. An extensive literature of this topic was summarized by W. Alvarez (1986) and L. W. Alvarez (1987). A thin carbonaceous sandstone and clay near the Cretaceous-Tertiary boundary, as traditionally mapped, shows enrichment of iridium at the level of pollen change (Nichols and others 1986; Orth and others 1981; Orth in Sloan and others 1986; Smit, van der Kaars, and Rigby, Jr., 1987; Tschudy and others 1984).

Outcrop Area and Topographic Expression

Virtually unbroken exposures of the Hell Creek Formation extend southward across Sand Arroyo between the limited outcrops of the Fox Hills Sandstone, near the shoreline of Fort Peck Reservoir, and ledges of Tullock beds in eastern parts of the quadrangles (fig. 23). The upper contact and occurrences are further defined by isolated outliers of the overlying Tullock Formation in the central and eastern part of Sand Arroyo Quadrangle. The band of exposures narrows somewhat when traced southward in the Bug Creek Quadrangle.

The Hell Creek Formation is the most widespread stratigraphic unit in the quadrangles and is magnificently exposed in badlands and bluffs. Excellent exposures of nearly complete sections can be seen in headwaters of Black Spring Coulee and Bug Creek, in the Russell Basin area, and in the Sand Arroyo badlands eastward from reservoir bays of the North and South Arms of Sand Arroyo.

Hell Creek beds consist of several major interbedded mudstone and sandstone units. In general, the mudstones form steep badlands, where protected by overlying resistant sandstones, or rounded rolling uplands on divides between the drainages west of the skyline rim escarpment held up by Tullock beds.

Sandstone units characteristically form flat-topped mesas or buttes or shoulders in badlands and provide key stratigraphic units within the interbedded sequence that allow subdivision of the formation. Such subdivisions vary from area to area, however, and are probably not precisely correlative for more than a few miles. Prominent flat-topped Lonnies Bench (fig. 24), in section 5 of T. 22 N, R. 43 E, and flat-topped buttes in sections 22 and 27 of T. 23 N, R. 43 E, in the Bug Creek Quadrangle, along with Harms Flat in sections 5, 6, and 8 of T. 23 N, R. 43 E, characterize mesa topography held up by resistant, sheet-like sandstones. Rolling uplands around the flank of Goat Mountain (fig. 25), in the north central part of the Sand Arroyo Quadrangle, and the high buttes in the northwesternmost part of the quadrangle also exemplify topographic features held up by resistant sandstones. These uplands rise above steep-margined badlands carved on mudstones of the lower and middle parts of the formation.

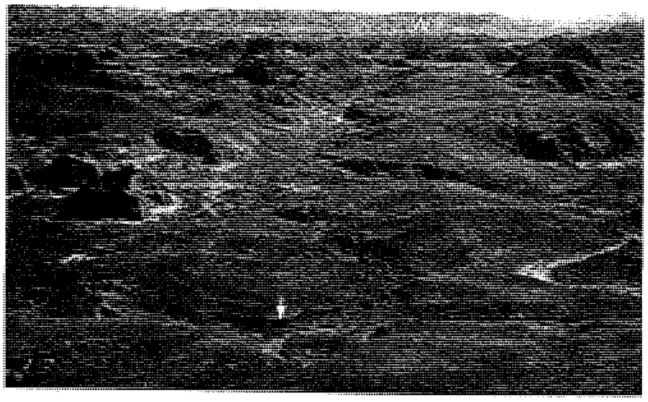


FIGURE 23.—*Low-angle aerial view eastward from near Pretty Place to "The Wall" (W) showing characteristic exposures of the Hell Creek Formation above the uppermost Fox Hill Sandstone. The latter forms a low shelf along the South Fork of Sand Arroyo Creek, in the foreground (arrow). The escarpment on the skyline is held up by the lowermost Tullock beds. Steep-walled, castellate buttes in the foreground and intermediate distance are of lower, very argillaceous sandstones and mudstones of the lower Hell Creek Formation. The road to Pretty Place shows as the dark line in the lower part of the photograph. Prominent bluffs in the distance are in the NE 1/4 of section 32 and in the south part of section 39, T. 24 N, R. 43 E, on the Sand Arroyo Quadrangle. Fox Hill beds hold up the prominent ledge in the foreground, in the NW 1/4 of section 32.*

The formation is dissected into badlands along both sides of Sand Arroyo drainage and in lower parts of the North and South Forks of Rock Creek drainage. However, the formation erodes to open rolling uplands, often loess-covered, in headwaters of Rock Creek in a distinctively different topographic expression. Steep, intricate badlands with fluted slopes are characteristic of some of the more bentonitic mudstones and sandstones. Isolated domical hills and round-topped ridges stand as remnants whose protective sandstone covers have been removed recently by erosion.

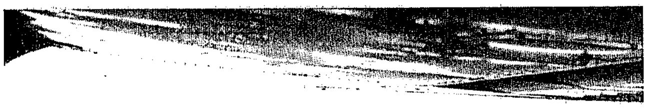


FIGURE 24.—*Hell Creek beds in characteristic badlands along the north side of Lonnies Bench, as seen southward over the southern part of section 32, T. 23 N, R. 43 E. Lonnies Bench is the flat upland in the middle distance. Much of the Hell Creek Formation is made of massive mudstones or very argillaceous sandstones. Prominent dark bands ringing some of the conical hills in the foreground are paleosols and dark carbonaceous shales of the lower part of the formation. Light-colored exposures along the north flank of Lonnies Bench, in the middle distance, are the Toadstool Park sandstone (T), which is at the approximate position of the null coal. The latter has been used to separate the Hell Creek Formation into upper and lower members in the Bug Creek Quadrangle. Resistant sandstones and an armor of terrace gravels cap Lonnies Bench and help to produce the flat, mesalike topography above the badlands.*

FIGURE 25.—*View eastward from the west fork of Sand Arroyo, past Goat Mountain and across the east fork, into "The Wall" area (W) in the eastern part of the Sand Arroyo Quadrangle. Rolling uplands in the foreground and around the base of Goat Mountain are held up by middle (3) and upper sandstones within the Hell Creek Formation. The Z-coal is exposed at the shoulder on Goat Mountain. The peak of the mountain is capped by a coarse conglomerate made, in large part, by bank failure breccia blocks of the middle part of the Tullock Formation. The small reservoir near the left margin, in the middle distance, is along the section line between sections 11 and 15, T. 24 N, R. 43 E.*

Contacts

The basal contact of the Hell Creek Formation on the underlying Fox Hills Sandstone has been mapped at the base of the prominent bedded mudstones and muddy sandstones that overlie the ledge-forming, relatively clean, tan sandstones of the Fox Hills Formation. The contact has been drawn where the overlying mudstones dominate over interbedded sandstones.

In the area mapped, the contact occurs immediately above a moderately resistant ledge-forming sandstone that marks the top of the Fox Hills sequence (figs. 16, 23). The relationships of the contact zone have been treated more extensively in discussion of the Fox Hills beds.

Collier and Knechtel (1939) named the major coals within the Tullock Formation, from the top down, as the U- through the Z-coals. The Z-coal was mapped by them as the base of the Tullock Formation because it is the lowest prominent coal in the contact zone. Utilization of the Z stratigraphic level as a single coal works for regional analysis, but two or three separate coals have been recognized within a few meters of each other in the Z-coal zone within the quadrangles, and up to seven distinct coal beds occur near the K-T boundary in Russell Basin. These multiple coals have resulted in some confusion in stratigraphic studies where the assumption of a single Z-coal was made.

The uppermost coal within the general Z-coal zone is the most prominent one and has been mapped in our study as the boundary between the predominantly Cretaceous Hell Creek and overlying Paleocene Tullock Formations. This results in a few meters of probably basal Paleocene beds and incised channels of Paleocene age being included in the Hell Creek Formation because the formational or upper Z-coal lies 2–6 m above the lower carbonaceous shale and coal beds that characterize the iridium K-T boundary event or the lower Z-coal in the Bug Creek–Sand Arroyo area. The upper, or what we term the formational Z-coal, however, is the more easily mapped unit on a quadrangle scale. Both the formational (upper Z-coal) and the lower (or iridium or event) Z-coal have been differentiated throughout the Bug Creek and Sand Arroyo Quadrangles. We have elected to follow tradition and have used the lithologically more distinctive upper Z-coal as the formational boundary.

Confusion of the upper and lower Z-coals has led to uncertainty about which represents the iridium event within the stratigraphic section and, consequently, the exact boundary between Cretaceous and Paleocene beds (Retallack, Leahy, and Spoon 1987). Throughout our text the upper or formational Z-coal is separated in discussion from the lower or K-T boundary event Z-coal. Confusion has arisen in earlier works because of common use of the term boundary Z-coal, which has been interpreted variously as the boundary between the Hell Creek and Tullock Formations or the boundary between Cretaceous and Tertiary rocks. The two boundaries are not the same.

The upper formation contact is discussed more extensively in treatment of the Tullock Formation.

Members

The Hell Creek Formation has been subdivided into upper and lower informal divisions, separated by the moderately persistent null coal in the Bug Creek Quadrangle (plate 2) and a nearly equivalent splay sheet-sandstone in the Sand Arroyo Quadrangle (plate 1).

Subdivision of the formation into these divisions or members is arbitrary because the same general patterns of interbedded sandstone and mudstone occurs both below and above the null coal and equivalent beds in both quadrangles. Even this informal separation, however, allows greater structural and stratigraphic control within the formation.

Subdivisions of the Hell Creek Formation are shown in a generalized stratigraphic column for the western McCone County area (fig. 2).

Lithology

The Hell Creek Formation consists of a complex, lenticularly interbedded sequence of sandstones of various origins, siltstones, mudstones, carbonaceous shales, and coal. Fastovsky and Dott (1986a, p. 279–82) differentiated five major sedimentary facies within the formation at Bug Creek. These include a cross-stratified sandstone, a green and purple siltstone, a lateral accretionary sandstone, coal, and a variegated siderite-bearing siltstone. Such rocks, in general, are the major lithologies of the Hell Creek Formation throughout both the Bug Creek and Sand Arroyo Quadrangles.

The Hell Creek Formation was commonly referred to as the "somber beds" in early literature because of the contrast of the gray and brown mudstones of the formation with the distinctly yellowish gray, tan, and buff underlying Fox Hills Sandstone and the considerably lighter, more banded, yellowish gray beds of the overlying Tullock Formation.

Clay-pebble conglomerates are an integral part of many channel fills within the formation and constitute a distinctive lithology that has considerable significance in terms of distribution of fossil small-vertebrate localities (Rigby 1987). Clasts of these pebble- to cobble-conglomerates are generally of local derivation, but elsewhere some of the fluvial sandstone lenses may also have incorporated exotic clasts of quartzite, apparently derived from exposures far to the west. Such clasts in Hell Creek beds have been reported by Badgley (1953) and Brown (1961, p. 9). We have seen quartzite pebbles and rare cobbles in the channel-lag sediments of the number 2 sandstone in exposures in the western part of section 33, T. 24 N, R. 43 E, in the southern Sand Arroyo badlands. Elsewhere, similar quartzite fragments appear to have been derived from Quaternary terrace gravels and not from the Hell Creek Formation, but may be confused with Cretaceous deposits locally.

Sandstones in the Hell Creek Formation occur in either elongate channel-fill lenses, in wide braided-appearing sheets, or in extensive relatively thin sheets that cover several square miles. Sandstones in each of these deposits within the formation are remarkably similar. They are generally very fine to fine grained, although a few sandstone lenses range up to medium grained, particularly in some of the coarser, deeper channel fills. Almost all of the sandstones are cross-bedded or ripple marked at various scales.

In general, they are medium- to well-sorted sandstones, but most have high clay content and generally little cement. Consequently, they weather to rounded hills or, where protected by thin, more well-cemented layers, form steep bluffs that may slump where oversteepened and little cemented. Most sandstone lenses and beds range from light olive drab to light yellow gray, and weather medium olive gray to dark yellow brown, depending upon how much iron is present.

Sandstones of the formation appear like salt-and-pepper sandstones because of a moderate admixture of dark chert and some ferromagnesium minerals. In general, however, dark mineral grains constitute less than 2% of the grain composition. Bell (1965, p. 82–88) reported heavy-mineral determinations from ten samples of Hell Creek sandstone. Opaque grains of magnetite, ilmenite, and limonite were the most common grains in all of his samples, followed by biotite, chlorite, muscovite, zircon, apatite, epidote, and tourmaline, although composition varied somewhat from sample to sample. They were apparently derived from volcanic terrains to the west or northwest.

Although Bell showed some variation in heavy mineral concentration from the lower to the upper part of the Hell Creek Formation, he concluded (1965, p. 87–88) that the heavy mineral differences would not clearly differentiate subdivisions of the Hell Creek Formation without considerable effort. Stow (1946) reportedly was able to subdivide the Hell Creek Formation into two subunits that reflected minor uplift and separation within the major sedimentary basin. Badgley (1953) studied heavy minerals of the Hell Creek and overlying Tullock Formation and concluded that the heavy mineral suites from the two formations were very similar, with only local exceptions. We have not made additional heavy mineral studies, but instead have relied on local key units to subdivide the formation.

Individual sand grains are subangular to subrounded, with moderate sphericity. In general, the rocks are immature sandstones with high clay content. Fastovsky (1986) reported that although the sandstones within the lens-shaped deposits contain up to 15% clay, nonetheless, the sandstones are grain-supported deposits.

Most of the sandstones are poorly consolidated with only limited cement—mainly calcite, gypsum, or limonite. Sandstone beds consequently weather away to form grassy slopes, except where protected by overlying limonitic or calcareous, commonly nodular beds. Almost every coarse sandy unit shows distinct cross-bedding in sets ranging from only a few centimeters up to approximately 1 m high. Most pronounced are barchanoid trains of dunelike forms that are now preserved and exposed as concretionary "logs" of moderate to well-cemented sandstone. These concretions are more calcareous or limonitic than sandstone between them and are parallel to paleocurrent directions within individual channels.

Many cross-bed sets have macerated plant debris on cross-beds. Resulting alternating laminae are light brown to light olive gray, dependent upon the organic material present. Only rarely, however, have identifiable leaves been preserved in cross-bed sets, and most organic material is fine "coffee grounds–textured" debris. Other sets are defined by clay-pebble rip-up clasts. Such coarse materials are most common in bedload or lower parts of channel fills or in lower parts of sections of multistory fills. Cross-bedding is also defined by silt and clay partings that may occur with the macerated debris. Shortly after summer thunder showers, when the organic material appears darker and the clay laminae are swollen from absorbed water, cross-bedding becomes particularly evident.

Large concretions within the cross-bedded sandstone commonly involve one or two trains of cross-bed sets. Individual concretions may be up to 2 m across and 1 m high. Some up to 25 m long have been observed in sandstones in the middle and lower parts of the formation. These concretions generally weather dark yellow brown and form protective layers, "toadstools," or long subparallel drumlinlike ridges. Such common alignment parallel to flow allows determination of that direction even from a distance or, within limits, on aerial photographs.

In general, cross-bedded lenses within the formation have concave-upward bases and are obvious channel fills. Many of the channel cross sections are asymmetric, with one gentle and one steep side. One good example was mapped along the margin of a pronounced meander of the Big Bugger channel in the SW 1/4 of section 10, T. 22 N, R. 43 E, where nearly vertical walls of two intersecting necked meanders show well. Smit and van der Kaars (1984) coined the term "Big Bugger" for what they interpreted as a major point-bar complex, which they considered to cover virtually all of the headwaters of Bug Creek drainage. With more detailed investigation, that complex is now interpreted to have formed from at least five different point-bar systems that have merged at essentially the same stratigraphic level. At least five distinct point-bar systems are recognizable because of crosscutting relationships and differences in faunal contents. These are particularly well exposed in the margin of Russell Basin, through the east central part of section 9 and the southwestern part of section 10, as well as into the northwestern part of section 15, of T. 22 N, R. 43 E, generally in the northeastern headwaters of Bug Creek.

Channel fills within the Hell Creek Formation are rarely single events, but most show multistoried occupation and deposition. Others show discrete lateral accretion, with strong epsilon cross-bedding, as that term was defined by Allen (1965). Perhaps the best example of large-scale lateral accretion in point-bar accumulations is that of the Big Bugger sandstone, well exposed along the cliffs below the Tullock outlier in the east central part of section 9, T. 22 N, R. 43 E. Here, epsilon cross-bed sets up to 15 m high dip toward the south and southeast, in the obvious direction of accretion of the point bar. Internally, however, current ripples show prominent sweep of the depositing current toward the west in classic form. Big Bugger sandstone lenses are generally a silty sand with a moderate admixture of clay. It is cleanest and coarsest toward the bottom of a single epsilon cross-bed and siltiest at the top, in classic fashion. Although the lower part of each epsilon cross-bed set is relatively clean, the Big Bugger deposit is distinctly gypsiferous and weathers to puffy, punky-appearing sand because of fine disseminated gypsum and silt in some of the units. These easily weathered punky beds make driving cross country over the Big Bugger channel fills difficult because of their powdery weathering habit.

Dimensions of individual major channels are difficult to determine, even where best exposed in the upper part of the Hell Creek Formation. The Big Bugger channel, however, must have been approximately one-quarter mile wide and with a broad curve of meanders that must be on the order of one-half to one mile in diameter. Most of the other channels within the Hell Creek beds are considerably smaller, although the braided Toadstool Park sandstone channel (fig. 26) did spread up to approximately one-half mile wide. It is well-exposed in the upper part of the lower Hell Creek beds around the western margin of Lonnies Bench in sections 5 and 6, and southward across Bug Creek Bay into central and western section 17, T. 22 N, R. 43 E. It cuts out the null coal throughout much of sections 5, 8, and 17. Depth of entrenchment of various

FIGURE 26.—*View southward to the middle part of Lonnies Bench, in the center of section 5, T. 22 N, R. 43 E. The irregular ragged outcrop in the middle part of the escarpment is held up by the Toadstool Park sandstone (T). The equivalent horizon of the null coal is near the base of the sandstone. Lonnies Bench is capped by a younger sandstone in the upper part of the Hell Creek Formation and is locally veneered with terrace gravels and glacial outwash. The flooded Dry Arm of Fort Peck Reservoir is in the background.*

channels varies from only a few meters up to approximately 20 m. Channels in the lower part of the Hell Creek Formation tend to be relatively shallow and broad and distinctly meandering—for example, in a channel fill so well exposed as a single meander in the west central part of section 9 and east central part of section 8, T. 22 N, R. 43 E, in headwaters of Bug Creek Bay. Those channel fills in the upper part of the formation tend to be rather deeply entrenched.

Broad, sheetlike sandstone deposits, usually only a few meters thick, are also characteristic of the Hell Creek Formation, but are somewhat less continuous than the light-colored sandstones of the overlying Tullock Formation. One such sandstone, for example (the one mapped as the number 2 sandstone in the middle part of the lower Hell Creek Formation in the Black Spring Coulee–Bug Creek Bay areas), was traced over much of 10 square kilometers. A sandstone equated with the number 2 sandstone has also been mapped in the South Fork–North Fork areas of Rock Creek where it forms a distinctive thin key horizon that separates lower and upper mudstones of the lower part of the formation. The Lonnies Bench sandstone, in the lower part of the upper Hell Creek Formation, is also a pronounced sheetlike sandstone and is well exposed in the northern part of T. 22 and southern part of T. 23 N, R. 43 E, along the valley of the South Fork of Rock Creek.

In the Sand Arroyo area to the north, a prominent and relatively thick sheetlike sandstone, at approximately the stratigraphic position of the null coal to the south, has been mapped as a key unit to separate the formation into upper and lower divisions. This particular sandstone occurs widely throughout the Sand Arroyo drainage over approximately 75 square kilometers, where it has been differentiated and documented.

Sheetlike sandstones thin in uniform fashion away from their source areas. Almost all of sandstone sheets mapped in the Bug Creek–Sand Arroyo area have distinct, flat, depositional, not erosional, bases. They have complex cross-bedding, reminiscent of sediment-charged, braided stream deposits. Many of these sandstones show climbing ripples, and all have relatively low, irregular, U-shaped trough cross-bed sets, generally well below a meter high.

These sandstones tend to be well-sorted and are composed of subangular to subrounded grains that show moderate sphericity and tend to have less clay than the lenticular channel-fill sandstones. Their mineral compositions appear to be essentially the same as the channel-fill sandstones.

They also tend to be consistently moderately well cemented, and commonly hold up thin caps on mesas and buttes or resistent shoulders around the bold bluffs. All of them are light yellow gray to a light olive gray and weather medium olive gray to dark yellow brown again, depending upon the amount of calcite and limonite cement.

Concretions in the sheetlike sandstones tend to be more irregular and less distinctly aligned than those in the lenticular-channel sandstones, presumably because the zones of optimum porosity were less regular, more discontinuous, and smaller. Most of these sandstones are capped by a resistent, moderately well-cemented sandstone, and many appear to be stacked multiple sheets.

Silicified conifer wood is locally common in several sandstones, particularly in lower units of the formation in the southwestern part of the Sand Arroyo Quadrangle. One particularly productive sequence of sandstones is exposed in the southeast part of section 32, T. 24 N, R. 43 E, along both branches of the South Fork of Sand Arroyo. Wood fragments there are associated with waxy-appearing siderite ironstones.

Much of the Hell Creek Formation is made of siltstone-mudstone (figs. 24, 27). These, too, are widespread laterally persistent units and are interbedded with the sandstones. Most siltstones in the formation are pale olive or light olive gray to olive gray green, but some are light to medium yellow gray. Siltstones may occur as moderately thick, massive-appearing beds in the middle and upper part of the formation, or they may occur in thin interbeds within the sheetlike sandstones or as parting laminae within the cross-bedded sandstones. They are commonly clay-rich bentonitic beds that grade imperceptibly at contacts into sandstones or claystones. They are characterized on weathered surfaces by a soft spongy "dirty pop-

FIGURE 27.—*View southeastward, over flat uplands at the west end of Lonnies Bench, into the Bug Creek drainage area. The upper end of Bug Creek Bay shows as a light, water-filled depression at the right margin. The ragged concretionary sandstone in the foreground is the Toadstool Park sandstone (T). Most of the fossil localities in the Bug Creek Embayment occur in the rounded hills in the intermediate distance—(1) Bug Creek Anthills, (2) Bug Creek West, (3) Kens Saddle, (4) Doverzee.*

corn" appearance. These siltstone-mudstone units are routinely fine grained and darken upward. The darker shales commonly contain fossil leaves and were a major source of the floras described by Shoemaker (1966).

Siltstone-mudstone beds appear to be composed of quartz silt and smectite and illite, although the clays appear to be of mixed layer montmorillonite-illite—some have a moderate admixture of illite and of kaolinite-chlorite (Bell 1965). We have done no additional work on the clays, but noted that Fastovsky (1986) reached the same conclusion, with clays showing extreme variability and with the siltstone-mudstone somber beds composed principally of mixed-layer smectites and illites.

Bedding ranges from well developed, in slightly silty beds, to poor in some of the massive thicker beds. The latter appear to have undergone early diagenesis or to have been bioturbated by roots of plants. Such disturbed beds tend to be mottled with introduced organic materials or by the complex intermix of silt and clay materials. Occasionally, organic debris produces distinct laminae in some fine beds, and sandstone layers produce some laminae in the thick units. The thick, light gray green mudstone that underlies the formational Z-coal and the K-T boundary bed appears to have been deeply leached. This layer contains some of the most waxy-appearing massive bentonitic clay and mudstones in the sequence, although some mudstones up to 10 or 12 m thick occur in the formation.

Some thin interbedded siltstone and bentonitic claystone beds occur as the lower mudstone of the formation. This slope-forming unit is well-exposed along the north shore of the bay of the North Fork of Rock Creek. These beds are pinkish and purple gray where well-exposed in the southern part of sections 17 and 18 of T. 23 N, R. 43 E. Similar purplish and light brown gray, massive, mudstones also occur in the middle of the formation, in both the Bug Creek and Sand Arroyo Quadrangles. A triplet of three thin, reddish and purple mudstones interbedded in light olive mudstones and sandstone form a key unit with considerable lateral continuity in the middle of the Hell Creek Formation in the Rock Creek and Sand Arroyo region. The purplish mudstones commonly grade laterally into distinct brown carbonaceous shales that are some of the most persistent thin key units in the formation.

Carbonaceous shales of the formation are commonly brown to dark gray and coaly with thin siltstone streaks and thin vitrain horizons. They generally range from a few centimeters to a few 0.1 meters thick and contain considerable flattened macerated plant debris. They are moderately clay-free and usually weather to distinct shoulders or reentrants in steep bluffs or gully walls. They generally gradationally overlie mudstones and record sediment-dead areas where plant debris was not diluted by influx of terrigenous sediments.

Charcoal chips are common in virtually every one of the carbonaceous shales, and resin lumps occur scattered irregularly throughout. Such charcoal suggests large wild fires as common in the history of the region, for at least four charcoal layers, one up to 10 cm thick, have been recognized in upper Hell Creek beds (Rigby 1987, p. 121). These are as well developed as charcoal-bearing clays at the K-T boundary that were considered by Wolbach, Lewis, and Anders (1985) as evidence of global wildfires. Jarosite, a yellow hydrous iron sulfate, is common in irregular veins and partings within the coaly organic layers. Gypsum is also present, usually as fine coconutlike vein fillings, but occasionally it also occurs as discrete crystals of selenite 1 to 2 cm long.

Where the brownish shale layers are most coaly, they weather to a dull black powdery residue. Where the plant debris is somewhat restricted, they commonly weather to a purple or reddish brown zone. These appear to represent paleosol or marshy horizons that are more or less time-line markers through the quadrangles. One of the most continuous of these coaly beds, the null coal, and two associated carbonaceous streaks have been mapped to separate the lower from the upper Hell Creek Formation in the Bug Creek area (fig. 2). This same triplet has been recognized widely in the Sand Arroyo Quadrangle, although the division into lower and upper Hell Creek there has been mapped above the triplet of carbonaceous shales at the base of one of the prominent key sheet sandstones.

Locally, kaolinitic ash beds (tonsteins) occur within the carbonaceous beds. It was suggested by Smit and others (1987) that the associated charcoal-bearing carbonaceous beds may have resulted from wildfires initiated by volcanic activity, or as a result of impacts, as suggested by Wolbach, Lewis, and Anders (1985). Such tonsteins are generally only a few centimeters thick and tend to be relatively pure clays, although some contain volcanic-derived phenocrysts of the ashfall.

These carbonaceous layers rarely reach 1 m thick, but they are the laterally most persistent identifiable horizons within the formation. They are not distinct bedded coals, however, such as characterize the overlying Tullock Formation, but they tend to be carbonaceous shales or siltstones with thin vitrain partings and blebs.

The siltstone-mudstone sequences appear to be sheetwash interfluve deposits, and some may represent lacustrine, perhaps playa, accumulations because of the common gypsum crystals that occur throughout some of the beds. The carbonaceous shales represent ephemeral marshes, but probably not forests, because fossil wood, evidence of stumps, or other evidences of large trees are largely wanting in most of the organic layers in the formation.

The organic shale, coal, and siltstone-mudstone of the formation represent floodplain deposits, in contrast to the sandstones that appear to be deposits of meandering and braided channels and splay systems. Nodular to bedded ironstones, principally siderite, in mudstones occur throughout the formation but do not produce the thick zebra-striped beds so characteristic of the overlying Tullock Formation.

Rigby (1987) concluded that the Hell Creek beds accumulated in an environment similar to that now seen along the Fitzroy River of western Australia. There, dense tropical vegetation, in a riparian zone, borders the river in a belt only a few hundred meters wide at its widest, but with an open canopy black soil interriver area. Like the Fitzroy River, those rivers that carved channels in the Hell Creek beds appear to have dried up during part of the year, except for isolated pools where forms like turtles, fish, and crocodiles survived the dry season. The channels were subject to flash flooding. Such floods produced the distinctive flat-pebble conglomerate and fossil vertebrate concentrations so extensively developed in channel fills in the Bug Creek–Russell Basin area.

Fossils and Age

The Hell Creek Formation includes youngest Cretaceous and basalmost Paleocene rocks in western McCone County. Contact with the underlying Fox Hills Sandstone is time transgressive, with that regional contact rising in time eastward. In this general area, the Hell Creek Formation is of late Maestrichtian age (Sloan and others 1986) but also includes 2–6 m of beds slightly younger than the boundary of the Paleocene and Cretaceous. Earliest Paleocene rocks are included in the uppermost part of the formation represented by that thin interval between the iridium-bearing lower Z-coal that marks the top of a Cretaceous and base of the Paleocene, and the overlying formational or upper Z-coal. A mild unconformity is developed at the contact zone (Rigby, Rigby, and Sloan 1986), and some major channel fills of basal Paleocene rocks occupy deep entrenched cuts excavated in uppermost Cretaceous rocks. The various fossil assemblages within these channels and their ages will be treated in subsequent papers.

For some time, the Cretaceous-Tertiary boundary had been recognized as immediately overlying the uppermost beds that contain extensive ceratopsian skeletal material, generally fragments of the skull, limb bones, or vertebral sections. Youngest ceratopsians, however, are not recorded by such bony elements, but by teeth from some of the younger channel fills. More detailed treatment of distribution of those dinosaur fossils and their stratigraphic relationships will be covered in subsequent papers.

Baadsgaard, Lerbekmo, and McDougall (1988) determined an age of 64.3 + 1.2 Ma for the K-T boundary using K-Ar, Rb-Sr, and U-Pb ages on bentonites associated with the iridium anomaly in Alberta, Saskatchewan, and Montana.

Thickness

Bell (1965) noted that the Hell Creek Formation is approximately 114 m thick in Hell Creek State Park and that it thickens up remarkably toward the west and south. The roughly equivalent Livingston Formation is approximately 1050 m thick in areas to the west (McMannis 1955), but the formation thins to as little as 30 m thick on the Souris River of north central North Dakota (Lemke 1960). In the Bug Creek and Sand Arroyo Quadrangles, the formation ranges from approximately 51 m thick in the Black Springs Coulee area, in the southern part of the Bug Creek Quadrangle, up to approximately 70 m thick in the central and northeastern part of the Sand Arroyo Quadrangle near Goat Mountain and Andrews Hill in eastern drainages of Sand Arroyo Creek.

The upper part of the formation, above the null coal and equivalent beds, ranges from approximately 28 to 30 m thick across the two quadrangles. Greatest variation in thickness is expressed by differences in the lower member where it is only approximately 19 or 20 m thick in the southern part of the Bug Creek Quadrangle but ranges up to 36 m thick in the central part of the Sand Arroyo Quadrangle. Some of that variation may be a result of

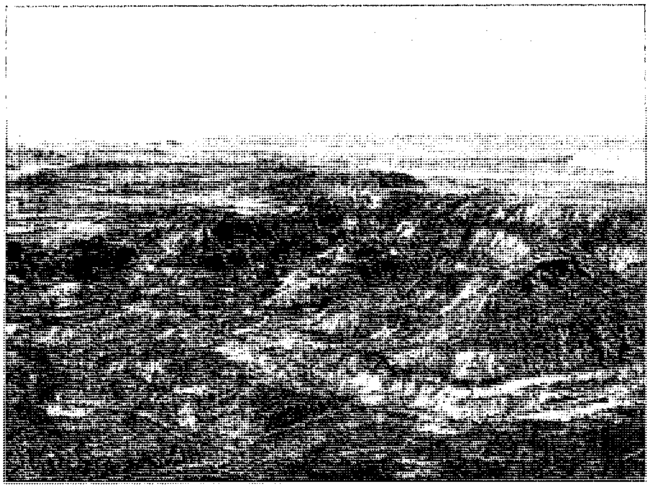


FIGURE 28.—*View southward from headwaters of Black Spring Coulee into the drainage of McGuire Creek and to McGuire Creek Bay. The flat-topped mesa in the left center is in section 28, T. 22 N, R. 43 E. The Z-coal (Z), at the base of the Tullock Formation, is the prominent dark band near the base of the escarpment. The promontory is capped by massive sandstone of the upper part of the Nelson Ranch Member of the Tullock Formation. The sandstone overlies the somber gray boundary X-horizon beds (X). The Y-coal (Y) is the dark band in the middle of the Nelson Ranch Member, the lower part of the Tullock Formation.*

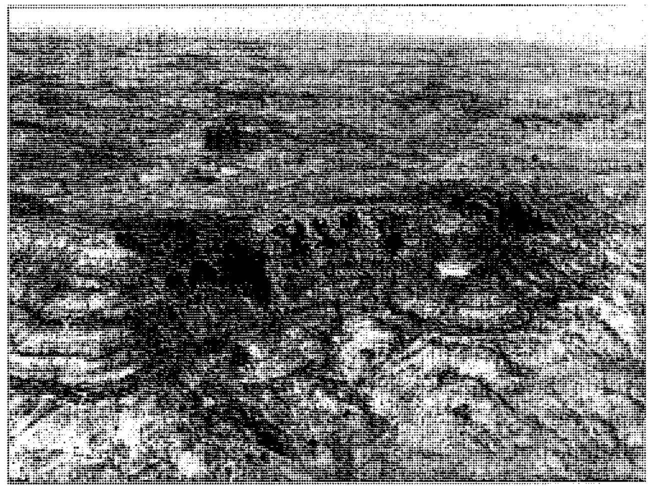


FIGURE 29.—*View southwestward across part of the ridge of "The Wall" into the main drainage of Sand Arroyo Creek. Covered slopes on the promontory are in the NW 1/4 of section 14, T. 24 N, R. 43 E, and, in general, occur below the basal sandstone of the Collins Ranch Member of the Tullock Formation. Striped beds below, down to the prominent Z-coal (Z), are included in the Nelson Ranch Member of the formation. The Z-coal is a distinctive pair of coals or carbonaceous streaks, in the lower left of the photograph, that become a single coal zone along the ridge toward the right. The Y-coal is the next overlying, thin carbonaceous streak, and the X-coal (X) is the prominent dark band in the middle part of the escarpment. Exposures beyond the ridge are of the Hell Creek Formation in the badlands along the east and west forks of Sand Arroyo.*

slight shifts in the mapped boundary between the upper and lower Hell Creek Members, from south to the north within the quadrangles. Slight difference in structure between broadly folded Hell Creek and older beds and the less broadly folded Tullock beds may also account for some variation. Hell Creek beds appear slightly thicker in synclinal areas, as for example in the McGuire area, than in anticlinal areas, such as in the Black Springs Coulee and Sand Arroyo Bay areas. More detailed stratigraphic sections must be measured to determine the real extent of these apparent patterns.

TERTIARY SYSTEM
PALEOCENE SERIES
TULLOCK FORMATION

Introduction

The Tullock Formation (figs. 3, 5, 28–30) disconformably overlies the Hell Creek Formation in the Bug Creek and Sand Arroyo areas and is the basal Tertiary formation of the section. The Tullock Formation was named by Rogers and Lee (1923, p. 29) for the yellowish sandstones and shales, with interbedded lenticular coal beds, that are the upper part of what was then termed the Lance Formation in the Tullock Creek coal field in Treasure County, Montana. The complex history of nomenclature of these and associated beds has been summarized by Frye (1969) in a paper on stratigraphy of the Hell Creek Formation in North Dakota. He also discussed development of stratigraphic nomenclature of Cretaceous and Tertiary units in nearby parts of Montana, Wyoming, and North Dakota.

Collier and Knechtel (1939, p. 11) discussed Tullock beds as a member of the Lance Formation of questionable Eocene age, but in a footnote reported that the Hell Creek beds had been reassigned to the Cretaceous and Tullock beds to the Cretaceous or Eocene by the U.S. Geological Survey after they had prepared their manuscript. Brown (1938) discussed evidence related to the Cretaceous-Eocene boundary in Montana and placed the Cretaceous-Tertiary boundary where it is currently mapped, between the Hell Creek and Fort Union, or Tullock beds, the first time that the boundary was so delineated.

R. W. Brown (1952, 1962) discussed criteria for differentiating Cretaceous from Tertiary deposits and for mapping the boundary in his discussion of the Fort Union Formation in eastern Montana and western North Dakota and South Dakota. He divided the Fort Union Formation into six members and included the Tullock and Lebo units as the lower two members.

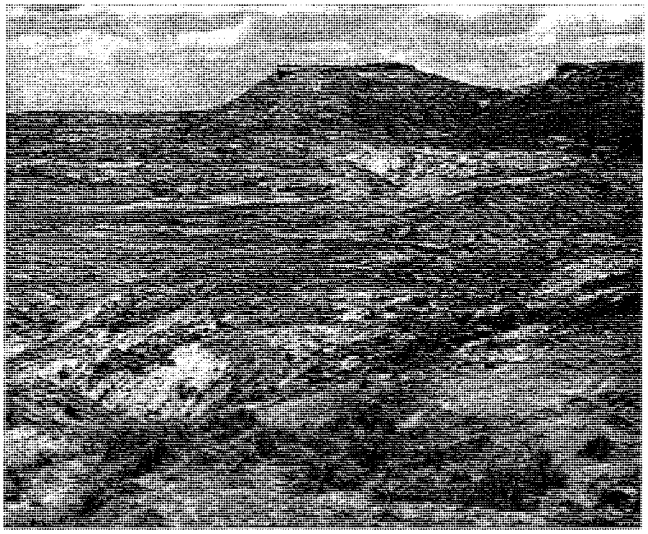


FIGURE 30.—*View northward across the basin carved in Tullock beds in the NW 1/4 of section 36, T. 22 N, R. 43 E. The total thickness of the Tullock Formation is exposed here. The Z-coal (Z) is the thin dark unit in the middle distance around the small outlier; to the left, the X-coal and the massive overlying sandstone form prominent banded exposures in the central part of the photograph. A large channel fill (C) forms light-colored exposures at the right middle distance, where the channel has cut down to the X-coal through the upper part of the Nelson Ranch Member of the Tullock Formation. The banded beds, above, and those that form the grassy slope on the right, are in the Collins Ranch Member of the Tullock. That member extends upward to the base of the dark U-coal (U) beneath the prominent, overlying massive channel-fill sandstones of the Lebo Formation that hold up McGuire Buttes. The McGuire Buttes fossil locality is at the base of the channel-fill sandstone on the east side of the pass between the two high buttes (arrow).*

Confusion still persisted, however, because Denson, Bachman, and Zeller (1959, p. 16, 17) concluded there were no distinct lithologic reasons for differentiating the upper lignitic beds from the lower Hell Creek Formation and assigned the rocks, equivalent to the ones here mapped as Tullock Formation, as the upper part of the Hell Creek Formation, although, as earlier pointed out by Brown (1952), the top of the Hell Creek Formation is essentially defined as the uppermost limit of common *Triceratops* fossils and is also clearly differentiated by floral contrast with overlying units. Some of the confusion arose because earlier collections of floras and faunas from different stratigraphic horizons were combined and obscured paleontologic differences (Knowlton 1911, p. 358; 1914, p. 325; 1921, p. 307–8). Stanton (1909, p. 286) correctly recognized that the early-collected floras were mixed and that the dinosaur-bearing beds ought to be considered separately from the overlying Tullock rocks, much as in modern nomenclature.

Dorf (1942, p. 95–97) concluded that deposits above the Lance, or the Hell Creek Formation as used here, have generally been referred to the Fort Union Formation on the basis of stratigraphic position, lithology, and paleontology, including both vertebrate and plant fossils. His work in the northern part of Wyoming substantiated that the Tullock Formation contains plants of typical Paleocene aspect, and not of the uppermost Cretaceous.

Outcrop Area and Topographic Expression

The Tullock Formation is exposed as scattered discontinuous outliers of the lower and middle part of the formation across the eastern one-third of the Sand Arroyo Quadrangle. Most extensive and thickest preserved sections occur in the northeastern part of the quadrangle, in sections 11 and 12 of T. 24 N, R. 43 E, and in the southeasternmost part of the quadrangle, where the general cliff zone of the Tullock cuesta swings westward along the east side of Anderson Creek, in northeastern T. 23 N, R. 43 E, and northwesternmost T. 23 N, R. 44 E.

The Tullock Formation is more extensively preserved in the southeastern part of the Bug Creek Quadrangle (figs. 30, 31). Complete or nearly complete sections are exposed in the easternmost part of T. 22 N, R. 43 E, and westernmost T. 22 N, R. 44 W. The outcrop band of the formation swings far to the west on the divide between the South Fork of Rock Creek and northern McGuire Creek. Tullock beds are particularly well exposed in bold west-facing escarpments around the headwaters of Bug Creek, in Russell Basin (fig. 3), and around the headwaters of Black Spring Coulee, in the Wild Horse Pass area, in the central part of T. 22 N, R. 43 E. Similar bold exposures occur along both the northern and southern margins of the valley of the South Fork of Rock Creek (fig. 4) and in the drainage divide between the headwaters of Sand Arroyo and the North Fork of Rock Creek, in the vicinity of Westland Flats in "The Wall," west of Montana 24 (fig. 22). Tullock beds are also well exposed on the drainage divide between the North Prong of Shade Creek and the North Fork of Rock Creek, east of the highway.

Contacts

Considerable effort has been spent in defining the precise Cretaceous-Tertiary contact in Montana and defining relationships of the lignite beds above the Z-coal (figs. 30, 31) and the relationships of the Z-coal to the "iridium event." We have mapped the boundary between the Tullock and Hell Creek beds at the base of the upper or formational Z-coal (fig. 2), although the pollen break and the carbonaceous clay of the iridium anomaly of the precise Cretaceous-Tertiary boundary occur 1 to 6 (commonly 2 to 3) m below that coal. The carbonaceous shale that marks the iridium layers is less easily mapped, and

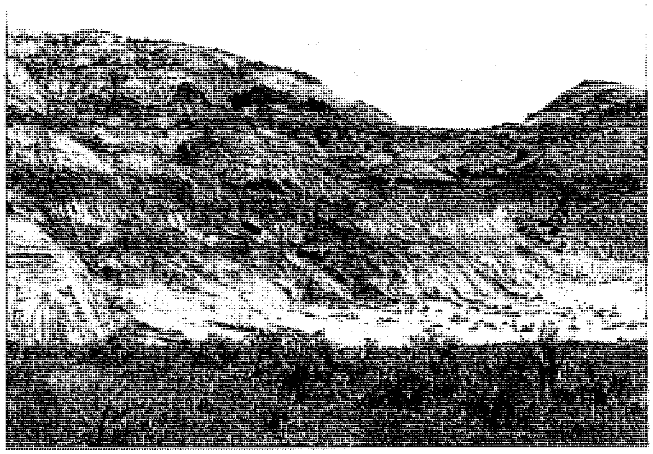


FIGURE 31.—*View northeastward into badlands carved in the lower Tullock Formation and uppermost Hell Creek Formation. The prominent dark band in the middle part of the escarpment is the Z-coal. The X-coal (X) occurs beneath the massive sandstones, essentially at the level of the pass between the two hills on the skyline. Cross-bedding shows well in the sandstones of the upper Hell Creek Formation, below the Z-coal (Z). The thin gray stripe (A) below the Z-coal marks the approximate position of the iridium anomaly layer at the Cretaceous-Tertiary boundary. These exposures are in the NW 1/4 of section 26, T. 22 N, R. 43 E, on the Bug Creek Quadrangle.*

the formation contact on the geologic map has been drawn at the base of the upper Z-coal, well above the iridium-anomaly carbonaceous shale. As earlier workers had observed, the upper Z-coal is a remarkably continuous zone of coal or coaly shale that occurs consistently at the contact of the Hell Creek and Tullock Formations throughout the two quadrangles.

The Tullock Formation apparently rests unconformably across the Hell Creek Formation throughout the Bug Creek and Sand Arroyo Quadrangles (Rigby, Rigby, and Sloan 1986). The unconformity between the two formations is evidenced by the numerous Paleocene channels that cut down into Cretaceous beds of the upper part of the Hell Creek Formation, by variation in thicknesses of the Hell Creek Formation, by development of deep soil profiles, and by the abrupt differences in depositional patterns below and above the contact. The channel fills contain different mammalian faunas and are truncated at their upper surfaces by the upper or formational Z-coal. Fastovsky, McSweeney, and Norton (1988) recognized a major soil zone and unconformity slightly lower than the formation boundary near the K-T boundary.

The upper Z-coal is persistent over much of the mapped area (figs. 3, 11, 28–31), although it may consist of up to seven distinct coals, as locally in Russell Basin, and up to three splits over broader areas where the thin coals drape over interfluvial areas and down into channels in parts of the region. Bell, in his unpublished thesis, noted that the Z-coal zone persists throughout the Fort Peck fossil field and has been traced along the margin of Fort Peck Reservoir to Seven Black Foot Coulee in Garfield County, a distance of about 50 miles westward, and as far north as Opheim, Montana, about 80 miles to the north of the Bug Creek area.

The upper Z-coal marks a prominent shift in environments of deposition from the fluvial-dominated sequence, below, to the lacustrian-fluvial sequence, above. The upper or formational Z-coal commonly rests across light gray green clays of the upper Hell Creek Formation and below the distinctly banded to striped beds of the Tullock Formation. The marked contrast of the lower somber gray and uppermost light gray green Hell Creek beds with the overlying tan and striped beds of the Tullock Formation allows differentiation of the two units, even from some distance. Presence of the upper Z-coal and the color contrast permit ready identification of many outliers of the Tullock Formation on top of Hell Creek beds throughout the quadrangles. The contact is one of the most consistent and unambiguous key relationships within the quadrangles.

The upper Z-coal occurs a few meters above the abundant *Triceratops*-bearing mudstones of the upper part of the Hell Creek Formation and has been utilized in other reports as marking the final extinction of the dinosaurs. This in general is true. However, dinosaur remains occur in beds of unquestioned Paleocene age (Rigby 1985, 1987; Rigby and others 1987). Arguments against reworking as a general cause for these late occurrences have been summarized in the same papers.

The contact of the Tullock Formation and overlying Lebo Shale was defined by Collier and Knechtel (1939). They designated coal beds within the Tullock Formation as U to Z, from the top down, and utilized the "Big Dirty" or U-coal as the base of the Lebo Shale Member of the Fort Union Formation. They concluded, however, that the U-coal could have been included appropriately in the Tullock Formation as one of the numerous coal beds characteristic of that Paleocene unit, but selected it as a somewhat arbitrary key horizon for mapping. We have continued their usage and have placed the U-coal and overlying sandstones into the lower Lebo Formation. The contact appears to represent a local change from fluvial-paludal to lacustrine dominated deposition.

Differences between the boundary selected by Sloan and Van Valen (1965) and some subsequent workers, and that of Collier and Knechtel (1939), who did the original mapping of McCone County, amount to shifting only a few meters. That shift, however, has significant effect on areal distribution of the formations, particulary of the basal part of the Lebo Shale.

In their generalized stratigraphic section, Collier and Knechtel (1939, pl. 3) show the U-coal beneath a distinctly sandy section. If one were to map the zone of most persistent sandstones in the Bug Creek and Sand Arroyo Quadrangles, the isolated outcrops mapped as U-coal by Collier and Knechtel (1939, pl. 1) would occur significantly above the most prominent sandstones, and the U-coal, as identified by Sloan and Van Valen (1965), would occur below that prominent continuous sandstone sequence well down into what is considered here as upper Tullock Formation.

For the present report, we have concluded that the prominent, thick, double shaly band, mapped provisionally as the U-coal by Sloan, his students, and others, represents the W-coal as interpreted by Collier and Knechtel (1939). Consequently, the contact between Tullock and Lebo beds is preserved in only a few small outliers in the southeastern and northeastern parts of the Bug Creek Quadrangle. The full thickness of the Tullock Formation is not preserved in the Sand Arroyo Quadrangle.

Members

Two relatively distinctive subdivisions of the Tullock Formation can be recognized in northern McCone County. The lower part of the formation, included here in the new Nelson Ranch Member, is characterized by cyclic-appearing, yellow gray to light gray sandstones, shales, and mudstones. These rocks are described in more detail on the following pages. Concretionary and laminated ironstone and claystone units occur as parts of the cyclic sequences. The base of the member is placed at the formational or upper Z-coal, and it includes the cyclic beds associated with the Y- and X- coals and up to and including the distinctive, somber gray, gypsiferous boundary sequence interpreted as the W-coal. We have utilized this uniform and widespread, distinctive horizon at the uppermost bed of the Nelson Ranch Member.

The member is named after the Nelson Ranch, in the Sand Arroyo Quadrangle, and the type section (appendix A) is at Cactus Point, a narrow ridge west of Montana 24 in the southwesternmost corner of section 24, T. 23 N, R. 43 E. In the type section the Z-coal is well exposed above light colored and bleached uppermost Hell Creek beds along the fence line immediately west of Montana 24 and at the south edge of the ridge.

The moderately prominent Y-coal and the distinctly thick and widespread X-coal are exposed in the ridge crest outliers and on to the north. The upper part of the section, which continues basically along the section line between sections 23 and 24, includes the gypsiferous dark claystones of the W-coal zone that form the top unit of the member. The member is approximately 43 m thick in the type area. Such a thickness appears to be an average thickness for the member across the Bug Creek and Sand Arroyo Quadrangles.

Most outcrops of Tullock Formation within the Sand Arroyo Quadrangle are of the Nelson Ranch Member of the formation. Description of the type section is included in appendix A.

The upper member, here named the Collins Ranch Member, is characterized by the distinctive sandy and coal-bearing part of the formation, in contrast to the mudstone-dominated lower part of the unit. The upper member extends from the top of the somber boundary claystones of the W-coal zone up to the top of the formation at the U-coal below the very light gray sandstones and somber gray shales of the Lebo beds. The Collins Ranch Member is composed of moderately resistent tan sandstones that cap many of the mesas and features of moderately high topography throughout the southeastern part of the Bug Creek Quadrangle.

The member is named for the Collins Ranch that covers much of the Bug Creek Quadrangle and has headquarters along South Rock Creek. The type section of the member (appendix B) is in the headwaters of a tributary of South Rock Creek, generally in the northeastern part of section 12, T. 22 N, R. 43 E, and the westernmost part of section 7, T. 22 N, R. 44 E. The measured section lies essentially along the section line and leads up through the abandoned strip mine (fig. 32) in the U-coal, which was utilized by Collier and Knechtel (1939) as the arbitrary boundary bed at the top of the Tullock Formation and base of the Lebo

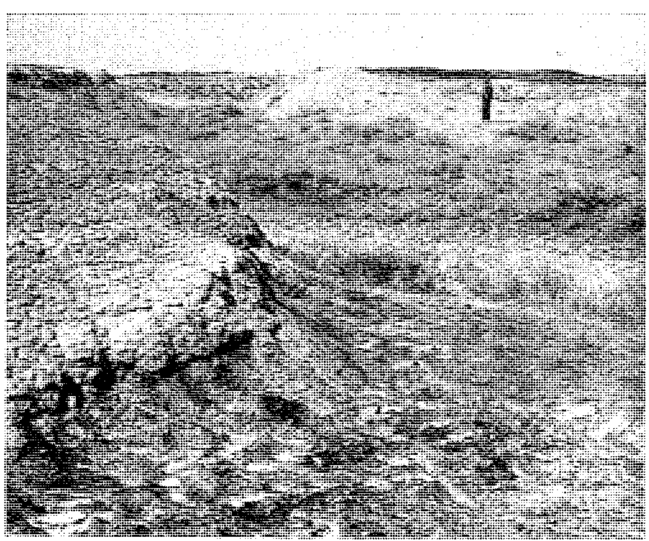


FIGURE 32.—*View southwestward along the long-abandoned strip mine pit in the U-coal at the base of the Lebo Formation in section 7, T. 22 N, R. 44 E, toward section 12, T. 22 N, R. 43 E. This is locality five of Collier and Knechtel (1939, p. 55). They noted that in the strip pit the coal is approximately 2 m thick. The spoil pile is toward the right.*

shale. The Collins Ranch Member is approximately 20 m thick in the type section.

Lithology

The Tullock Formation consists of interbedded, commonly cyclic-appearing, tan to light gray sandstones, light yellow gray to gray shales or mudstones, which locally contain interlaminated or concretionary ironstone units, and carbonaceous shale or minor coal (figs. 3, 4, 31). The formation is 50–60 m thick and, generally, appears in badland exposures as a distinctive yellowish band above the somber gray Hell Creek Formation.

Thin, laterally continuous coal beds are distinctive of the formation. Major coals have been termed the U-, V-, W-, X-, Y-, and Z-coals, from the top down, following a nomenclature earlier established by Collier and Knechtel (1939). None of the coals in the formation are of major economic significance, for most are far less than 0.5 m thick over most of their areal extent. The Z-, X-, W-, and U-coals have proven to be the most readily identifiable and have been mapped regionally. The Y- and V-coals have been differentiated locally. The coal beds are generally deeply weathered and appear as powdery residues, although in some areas they range to moderately vitreous-appearing subbituminous coals. All of them vary considerably in thickness when traced laterally, and many grade locally to thin carbonaceous shales.

Coal beds appear to be upper elements of moderately clearly defined cycles (fig. 33), particularly in the lower part of the formation, included here in the newly named Nelson Ranch Member. Cycles generally begin at their bases with very light gray channel-fill, massive to cross-bedded sandstones, or with tan, striped, muddy sandstones (fig. 34). The latter apparently originated as splay deposits spread across the coal swamps, which had low relief. These sandstone units grade upward, commonly moderately abruptly, into interlaminated siltstones and siderite-bearing mudstones as second units in the cycles. In many areas, the siderite bands weather into prominent relief and hold up thin, paperlike shelves in eroded slopes of the interbedded sequence. Elsewhere, however, the mudstones and claystones may contain bands of siderite nodules or concretions of ironstone siltstones. These beds are generally tan to light gray, and record the waning phases of vigorous introduction of clastic sediments into the local basins.

Third units in most complete cycles are generally interbedded light gray to light yellow gray mudstone or claystone, with prominent banded siderite beds making the "zebra beds" that produce much of the yellowish color evident in the Tullock Formation (fig. 34).

Fourth units in complete cycles are characteristic bentonitic claystones or mudstones that contain only minor

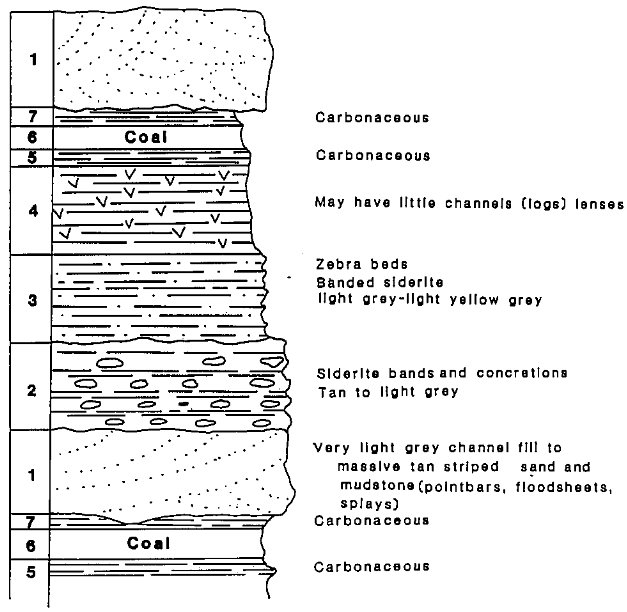


FIGURE 33.—*Generalized diagram of an idealized stratigraphic cycle within the lower Tullock Formation. Cycles may range from 5 to 10 m thick. Many cycles are incomplete, but all show a general gradation from deposits of very active, prograding fluvial systems at the base through a lacustrian sequence into marshy and paludal coal swamp deposits at the top.*

ironstones. Locally they may contain thin, concretionary-appearing sandstone beds that may represent small channels, or channel fills, in nearly filled lacustrine or marshy environments.

Fifth units of complete cycles are generally brown-weathering, carbonaceous shales that may contain irregular, thin paleosol horizons (fig. 34). Commonly these shales contain much macerated plant debris and thin coaly streaks or lenses. These are the units that produce most of the moderately complete plant fossils of the formation. They tend to be thin and grade abruptly into sixth units of the cycles, which are usually lignite or subbituminous coals. These coals may contain thin, cross-bedded, sandstone splits, or, more commonly, fairly thick splits of carbonaceous shale. They record sediment-dead areas; that is, areas where no additional terrigenous fluvial-derived material was being swept into the basin.

Seventh elements of the cycles may occur as a repeat of carbonaceous shales, like fifth units; but these upper carbonaceous shales tend to be distinctly sandy as precursors to the flood of sediment that marks the beginning of the next cycle.

Nearly complete cycles may range from only 2 or 3 m thick up to 10 m thick in various parts of the formation. In general, cycles in the lower half of the formation are dominated by mudstone and siltstone parts of a cycle,

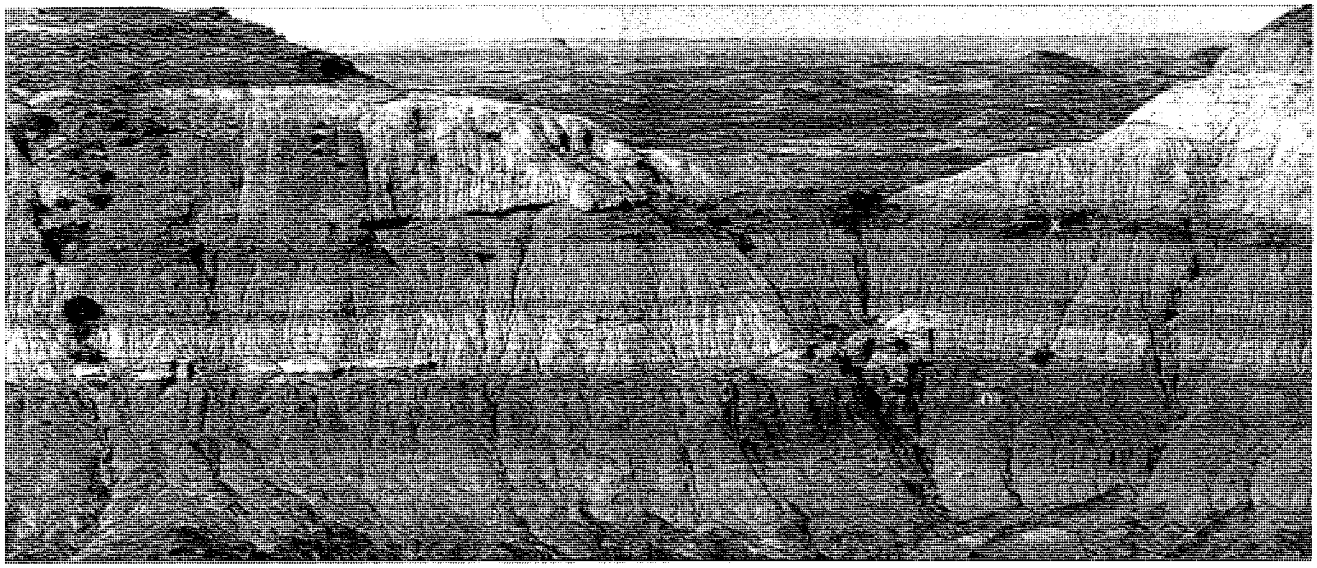


FIGURE 34.—*View toward the south of exposures along the Cactus Point ridge in southwesternmost section 24, T. 23 N, R. 43 E. The prominent, light-colored sandstone, at the top in the pass area, overlies the dark shoulder of the X-coal (x) and shows some epsilon cross-bedding left of the pass. The "zebra-striped" beds (z) at the base overlie the Y-coal. They are banded siderite-bearing mudstones (m) that grade up to a prominent gray mudstone with a carbonaceous streak at the top, in part of one cycle. A second cycle begins with the prominent, thin sandstones (s) in the middle part of the escarpment and grades up through the "zebra-striped" zone and into relatively massive mudstones below the prominent dark, carbonaceous X-coal horizon. Lateral wedging of sandstone in the middle of the sequence shows distinctly by thinning of the section toward the right. The Y-coal underlies the sequence. The view through the pass is into the South Fork of Rock Creek. The massive muddy sandstone above the X-coal is approximately 7 m thick.*

those in the uppermost part of the formation by a proportional increase in sandstones.

Channel-fill sandstones occur throughout the formation. Some channel fills contain coarse cobbles to blocks of bank-failure debris. The coarsest such Tullock-age material is preserved in a small outlier of an upper sandstone in the Nelson Ranch Member on Goat Mountain. Blocks over 1 m in diameter are locally replaced or cemented with limonite. Some platy blocks of ironstone also occur floating or jumbled in the sandy matrix.

Ranges in thickness, outcrop patterns, and lithology of channel-fill deposits of the formation might be exemplified by three separate large channel sandstones that are particularly well exposed. The lower of these is a broadly exposed massive sandstone in the northeastern part of section 23, T. 24 N, R. 43 E, south of Snuff Gap between the upper Z- and the X-coals. It is the channel-fill deposit of a southeastward-flowing stream. The sandstones are medium grained, cross-bedded, and relatively thick. They accumulated in a wide channel eroded through the Y-coal and the mudstone above the upper Z-coal. The sandstone rests disconformably on the black to dark gray bentonitic shales and mudstones associated with the upper Z-coal zone.

A few flat-pebble rip-up clasts are incorporated as a lag in the basal part of the sandstone throughout its exposure, but are particularly evident near the eastern end of the bluff in the center of the northeast quarter of section 23. The basal coarse lag deposits of the channel fill are locally fossiliferous. Toward the southeast, coarse gravel occurs at the base of the channel fill, preserved in the small outliers of the sandstone in the east central part of section 23. Lateral relationships are not as well preserved there as in the broader outcrop toward the north. The sandstone does not show marked epsilon-type cross-bedding of a point-bar environment, but appears to be more linearly trough cross-bedded, as along the axis of a moderately straight segment of the paleochannel.

The channel fill is 450–500 m wide and up to 15 m thick. It has a relatively flat base, as exposed in cross section both north and south of the drainage divide. The sandstone is moderately clean, with some resistant calcareous and limonite concretions in the very sandy and silty parts of the channel fill. This particular sandstone lens segment accumulated in a stream flowing approximately S 60°–70° E.

A somewhat younger channel-fill sandstone is exposed near the southern part of the Bug Creek Quadrangle, above the X-coal, in the northeastern part of section 36, T. 22 N, R. 43 E. Here the sandstone is magnificently exposed in bold bluffs about mid-distance from the valley floor of Rough Prong, up to the massive basal Lebo sandstone that caps McGuire Buttes. This sandstone is a prominent, massive ledge-former that holds up vertical gully walls (fig. 30). Concretionary, loglike, cross-bed "trains" are scattered throughout. These indicate an eastward flow to the stream. These rocks suggest a considerably lower energy environment than indicated by the clay-pebble conglomerate of the channel to the north. In addition, well-developed epsilon-type cross-bedding indicates some lateral channel migration, and interbedded mudstone units grade upward into a more massive sandstone with thin clay partings.

Most of the channel-fill sandstone is a very pale orange to pale yellowish gray, with some grayish orange to dark yellowish orange bands. The latter are thin concretionary sideritic layers that produce some striping. Some cross-bedded elements include interlaminated mudstone and sandstone, particularly in the middle part of the thick sandstone. These mudstone-sandstone interbeds form striped, moderately light yellowish brown to light olive brown layers a few cm thick. From a distance the sandstone appears massive, but it evidently accumulated in 10–15 cm thick depositional units separated by somewhat thinner carbonaceous or bentonitic mudstones.

Loglike concretionary, cross-bedded, rippled dune "trains" occur in the upper part of the unit. These concretions are well cemented with calcium carbonate and form massive blocks several meters across and up to 2 m thick. Where cleanest, the sandstones are yellowish gray to pale olive and locally have cross-bed sets up to 1 m high.

The overall unit coarsens upward. The upper 1–2 m grades upward from very fine-grained sandstone near the base to fine-grained and locally medium-grained sandstone at the top. With coarsening, the sands show an increase in maturity. Lower parts of the unit include more clay or silt, and uppermost parts are moderately clean quartz sand.

The coarsening upward sequence appears to represent initial relatively low-energy accumulations, which were then trenched into by the higher-energy advancing channel system, in which the upper relatively mature sandstone accumulated. This channel-fill sandstone grades laterally into the massive, tan, claylike sandstone that blankets the X-coal over much of the Bug Creek and Sand Arroyo Quadrangles to the north and northwest.

A third type of sandstone complex is composed of markedly laterally migrating but distinct channel-fill sandstones. One such complex, here named the Nelson Pass Channel, is well exposed in the southeastern part of section 13 and northeastern part of section 24, T. 23 N, R. 43 E, east of Montana 24 on the divide between the North and South Forks of Rock Creek (fig. 35). These relatively narrow channel fills accumulated in arcuate to nearly straight east-flowing streams. The channels were cut down through the somber gray beds above the X-coal in the upper part of the Nelson Ranch Member of the Tullock Formation. Another channel of the complex in southernmost section 13 is more similar to the large channel near Snuff Pass than it is to the somewhat thicker, broader sandstone accumulations south of McGuire Buttes. Sandstones in all the channels of the complex are concretionary, medium to fine grained, and distinctly cross-bedded. Locally, as in exposures in the southwesternmost part of section 13, west of the highway, and the east central parts of section 24, east of the highway and Nomland Dam, clay pebbles and freshwater *Unio* bivalves occur as a basal lag deposit in the fossiliferous lower part of the channel fills.

In the section 13 locality, sandstone that contains freshwater bivalves can be traced laterally for at least 10 m in an accumulation up to 0.4 m thick. The lowermost part of the lag is of intensely macerated, broken *Unio* valves, and contains an upper layer where the shells are less intensely broken. In the upper part of the deposit, bivalve fragments, 6 to 7 cm long, show marked imbrication and transport directions toward the east. In both upper and lower parts of the lag there appears to be only a single species present, although it is difficult to be certain because of the fragmental nature of the shells. Similar accumulations occur at the bottom of the channel fill that extends eastward across the southern part of section 13, T. 23 N, R. 43 E.

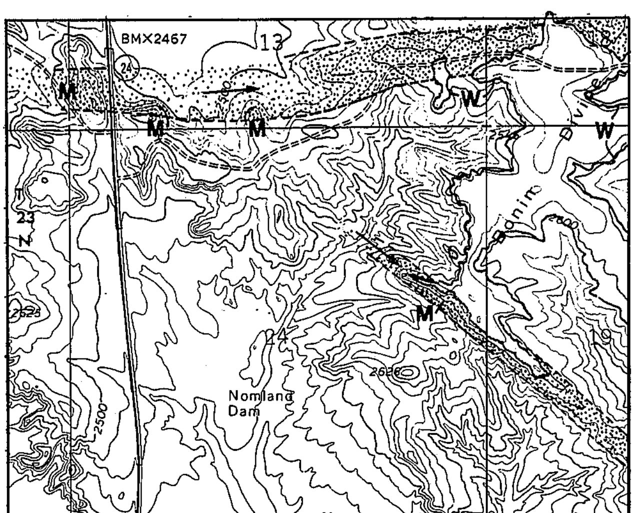


FIGURE 35.—*Map of generalized channel fills of Bonin Divide complex and relationships of the two major channel sequences, shown in stippled pattern, to the W-coal mudstone (W). The complexes are well developed in sections 13 and 24 of T. 23 N, R. 43 E, in the northeastern part of the Bug Creek Quadrangle. Freshwater bivalves (M) occur in the channel lags of both channels. Arrows show flow directions.*

A somewhat younger series of channel fills is exposed in the general area of Bonin Divide in the northeastern part of section 24, T. 23 N, R. 44 E, and in the western part of section 18, T. 23 N, R. 44 E. Axes of these channels swing from nearly east–west in section 19 to approximately N 45° W in the north central part of section 24 (fig. 35). These are also composed of basically the same type of sandstone as that seen in the Bonin Divide–Nelson Pass channels. These channel fills are also underlain by coarse lags of *Unio* bivalve fragments. Perhaps the best-preserved bivalves and coarsest lag observed in the district is that in one of the younger channels in the southeast part of the NE 1/4 of section 24 where large shells of *Unio stantoni* White occur with both valves together, and as unabraided valves, which indicates that accumulation was essentially in place. Some of these valves show freshwater sponge borings, particularly evident in the nacreous layer that is well preserved around many of the steinkerns. Relationships of the southern Bonin Divide channels to the somewhat earlier northern channels are shown in fig. 35.

Upper parts of the sandstone are generally cross-bedded, with dunelike sets approximately 1 m thick that locally produce loglike concretions. Cross-beds in the concretions indicate the paleostreams flowed almost due eastward to southeastward in a sweeping migrating meander complex.

One of the most spectacular series of nested meander channel fills occurs in the east central part of the Bug Creek Quadrangle in hills marginal to the south side of South Rock Creek valley in the Purgatory Hill area (fig. 36). The arcuate channel fills occur in sections adjacent to the common junction of T. 22 and 23 N, R. 43 and 44 E. This sequence of subparallel meanders is particularly important because it allows the Purgatory Hill fossil locality (fig. 37) to be moderately well dated as part of the basal sandstone sequence of the Collins Ranch Member of the Tullock Formation.

Figure 36 shows the relationships of the various channel fills that are part of the complex. More or less certain relationships are shown as dashed lines, and uncertain relationships are shown by dotted lines that correlate exposures in the western part of the Tullock belt immediately east of Montana 24, with those in the eastern hills near the border of the quadrangle.

Individual channel fills are from 150 to 300 m across and are part of a nested group that compose a migrating meander sequence that presumably migrated southward. There is no internal evidence that we observed to sequence the channels relative to one another. They are separated from one another and are not part of a continuously migrating point-bar series, but appear to represent separate events of avulsion and occupation of a new channel site, with individual channels spaced from 200 up to 500 m apart.

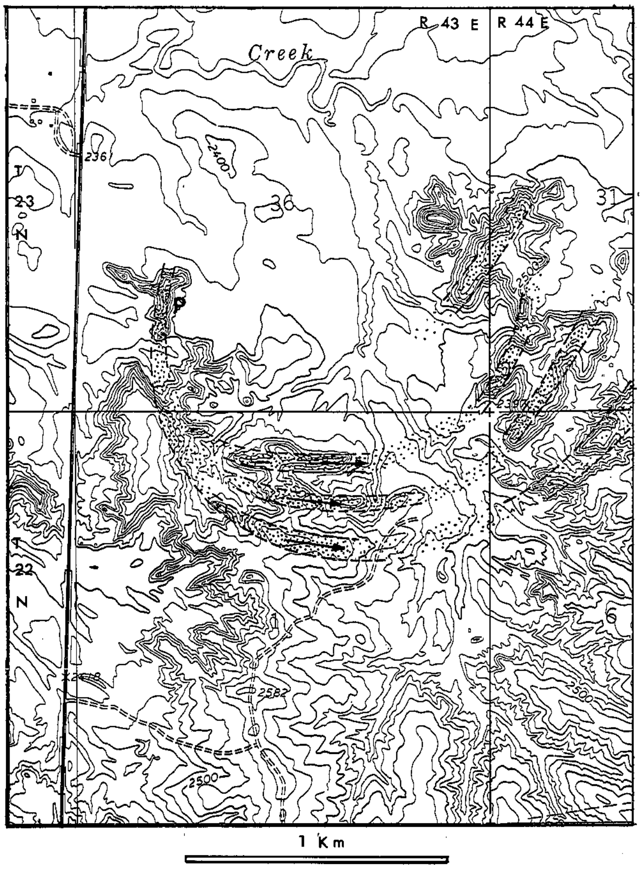


FIGURE 36.—*Generalized map of the Purgatory Hill (P) complex of nested meander channel fills in the general junction area between T. 22 and 23 N, R. 43 and 44 E, south of the South Fork of Rock Creek and east of Montana 24. Channels are indicated by stippled areas outlined by dashed lines where moderately certain, but as dots only across the tributary where erosion has removed the beds and obscured the relationships. Arrows show flow directions.*

The entire complex is part of a massive, widespread sandstone sheet that marks the basal part of the Collins Ranch Member over much of eastern Bug Creek and Sand Arroyo Quadrangles, and also extends into the Crow Springs and Willis Buttes Quadrangles to the east. Much of the basal sandstone of the member appears to be sheetwash splay sands from the major migrating fluvial system.

The nested channels south of Rock Creek are essentially the same age as the large major channel of the north Bonin Divide complex. Both are apparently overlain by the boundary-marking dark bentonitic gypsiferous mudstones and coal of the W-coal horizon that separates the lower and upper parts of the Tullock Formation. The Purgatory Hill localities, thus, are certainly of middle Tullock age rather than toward the top of the formation.

FIGURE 37.—*Purgatory Hill from the southwest, over Montana 24. The Z-coal (z) is well exposed, at the base, as a prominent dark band, although the Y-coal (y) above is somewhat thicker. The upper of the two dark bands is the X-coal (x). The Purgatory Hill fossil locality (p) is in the massive channel fill that caps the hill. That channel is part of the nested series of meanders that occur in upper beds of the Nelson Ranch Member of the Tullock Formation in the middle of the Tullock Formation. Purgatory Hill is in the southwest corner of section 36, T. 23 N, R. 43 E.*

Generally, Tullock sandstone channels fills are confined, have coarse lag gravel deposits at their base, and show uniform cross-bedded "trains" that may persist for tens of meters along the flow direction. These channelized deposits contrast markedly with ones that appear to be of splay origin and that spread sheetlike across many of the coals or striped lacustrine "zebra" beds. Sandstone sheetlike splay deposits in the Tullock Formation generally have flat, uneroded bases and are composed of blanketing, complexly cross-bedded, fine-grained sandstone sheets. Cross-bedding in many of these sandstones appears to have resulted from almost braided flow. The splay sandstones are less mature than the principal channel fills and have a high admixture of disseminated silt and clays. They also contain distinct interlaminated, cross-bedded silt and clay. In general, these rocks are not well cemented, but nonetheless form fairly resistant units because of the binding of clay and siltstone. Because they are not well cemented, they commonly slump where exposed in steep slopes and produce small terracelike interruptions in outcrop patterns. This is particularly evident in the clay-rich sandstone above the X-coal in the northern part of the Bug Creek Quadrangle and the eastern part of the Sand Arroyo Quadrangle. The splay sandstones commonly appear as thick prominent massive sandstones, with occasional concretionary lenses of somewhat more cemented, cleaner, sandstone within the massive outcrop.

A massive splay sandstone is also well exposed above the W-coal in the northeastern part of section 22, T. 22 N, R. 43 E, in headwaters of Black Spring Coulee, north of Wild Horse Pass. Here the prominent, massive, light gray-weathering sandstone has a flat depositional base and an upward-convex upper surface. It rests directly on the W-coal and carbonaceous shale and forms a prominent bold bluff. The sandstone is not particularly calcareous, but owes its resistance to a high admixture of clay and silt. This particular sandstone thins toward the northeast and the south along the outcrop band. The massive sand is 4–5 m thick in the southeastern part of section 15, and the north central part of section 22, but thins to less than half that thickness approximately one-half mile to the south. It is only 1 m thick near Wild Horse Pass, at the south edge of section 22.

Sandstones in the Collins Ranch Member of the Tullock Formation form several broad sheets of splay sandstones that generally weather light yellow gray to grayish yellow. Some of these sandstones are not well cemented and erode away readily to form slopes and terraces, but others above and below are prominent, resistant, moderately well-cemented, thin, mesa-capping sandstones (fig. 38). These upper Tullock sandstones tend to be somewhat more mature than lower ones, but are still mainly very fine to fine grained, and only locally medium-grained sandstone. They are only slightly more calcareous than the massive clay-rich sandstones of the lower part of the formation. Locally they have some limonite, gypsum, and calcite cement.

As in sandstones lower in the Tullock Formation, the concretionary resistant layers tend to be moderately coarse, ripple-marked sandstones. The splay sandstones may grade laterally into "zebra" beds, or locally may be overlapped by "zebra" beds at the outer edges of splay sandstone development (fig. 34). Such relationships are particularly evident in the lower part of the formation. Splay sandstones of the upper part of the formation are so laterally persistent that individual thin units in the Collins Ranch Member can be carried for several miles as distinct yellowish gray and light yellow gray paired sandstones.

"Zebra-striped" mudstone and siltstone beds are distinctive of the Tullock Formation in the Bug Creek and Sand Arroyo Quadrangles and are particularly characteristic of the Nelson Ranch Member (figs. 34, 38). "Zebra" beds are transitional rocks that grade laterally from outer edges of splay sandstones into the moderately massive claystones and mudstones. The "zebra" beds generally are complexly interbedded claystone and siltstone, with interlayered sideritic claystone or yellowish orange, concretionary siderite bands. Thin carbonaceous shale partings or thin sandstones are occasionally interbedded, particularly where "zebra" beds interdigitate or grade laterally into splay sandstones.

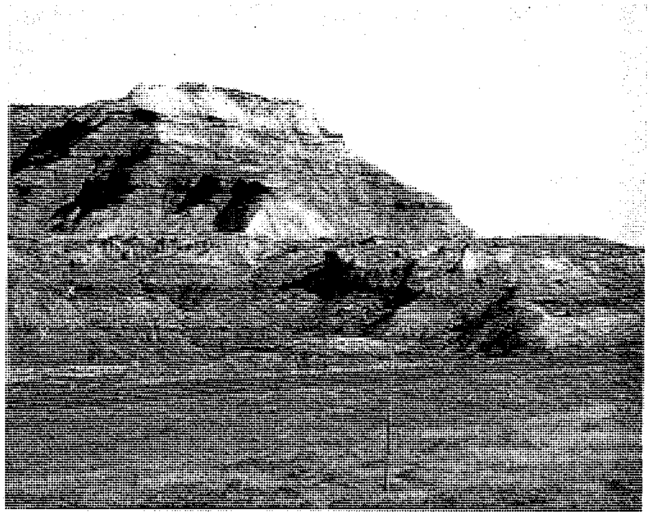


FIGURE 38.—*Nelson Ranch Member of the Tullock Formation viewed northwestward from Montana 24 in the northeasternmost part of section 2, T. 22 N, R. 43 E. The Y-coal (y) is the lowest dark band, above the "zebra-striped" beds, exposed left (west) of the road. The prominent X-coal (x) is the major dark band beneath the massive channel-fill sandstone. That sandstone forms the concretionary band through the middle part of the escarpment. The somber slope zone, above the light-colored sandstone, is capped by a prominent sandstone (s) in the upper part of the Nelson Ranch Member.*

Generally speaking, claystones of "zebra" units are yellowish gray to dusky yellow, with some bands that may be light brown to light orange brown. Interbedded siltstones tend to be somewhat darker light brown to dark yellowish orange, and the concretionary siderite bands or laminae tend to be dark yellowish orange to yellow brown. Claystone and siltstone beds are generally 10–20 cm thick and may be separated by sideritic claystones 1–2 cm thick. Locally siderite occurs as moderately concretionary undulating bands up to 5 or 6 cm thick, but, in general, entire "zebra" units form distinctive, laminated, banded yellowish gray outcrops. Siderite layers and concretions form shoulders and, where laminated, may form distinct steplike outcrops, with steps from a few cm up to 0.5 m high. Where siderite is common, "zebra" beds form massive ledges to semislope zones that are generally more resistant than all but the calcareous concretionary beds in the thick sandstones.

Some massive claystones and siltstones that lack ironstones occur throughout the formation, particularly in areas apparently removed from rapid influx of terrigenous debris. These siltstones and mudstones tend to be light grayish green to yellowish gray and weather light gray to light yellow gray. The claystones may contain silt, but commonly are not sandy. Where silty, they are more distinctly bedded, and where bentonitic, they are consistently more massive. Bentonitic claystones weather with a characteristic "dirty popcorn" to irregularly mudcracked surface. Claystones appear to grade vertically, as well as laterally, into siltstones and carbonaceous shales.

Carbonaceous shales of the formation are brown to dark brown, and most are marked by coal streaks and sandy partings. Most form prominent slopes and are distinctly flaky, although where macerated plant debris is uncoalified and common, carbonaceous shales may form small shoulders in an otherwise smooth slope. Carbonaceous shales are commonly interbedded in each of the coal beds or, more commonly, occur as a basal transition from fine-grained terrigenous sedimentation into organic-rich coaly beds.

Many coal beds in the Tullock Formation contain thin veins and streaks of jarosite, and selenite gypsum crystals are locally abundant, particularly in the V- and W-coals. Coarse amber to light yellow gray selenite crystals up to 10 cm long occur as roses or as irregular twins and blades in exposures of the upper part of the formation in WC SW 1/4 of section 24, and the NE 1/4 SE 1/4 of section 23, T. 23 N, R. 43 E.

Thin, brown carbonaceous shales, generally less than 0.5 m thick, occur scattered throughout the formation. A pair of thicker, distinctive dark gray to medium gray (figs. 39, 40) carbonaceous shales and mudstones occur in the middle part of the formation. The top of this complex has been mapped to separate the lower Nelson Ranch Member from the upper Collins Ranch Member of the formation because the dark shales are mappable across both quadrangles, and even the most prominent associated sandstones are not. These dark, somber gray, abundantly gypsiferous units are bentonitic and characteristically weather with an expanded "dirty popcorn" surface. They erode to barren slopes or rounded shelves where exposed best in southeastern exposures in the Bug Creek Quadrangle in upland parts of the escarpment at the head of Bug Creek and Black Spring Coulee. These somber mudstones are particularly well exposed north and south of the access road from Montana 24 into the Bug Creek area in the central part of section 11 of T. 22 N, R. 43 E (figs. 39, 40). These same dark beds are also well exposed in roadcuts along Montana 24 in easternmost section 11 and westernmost section 12, T. 22 N, R. 43 E, where they form a double band of dark gray to medium gray, barren exposures.

Here and elsewhere, these somber gray beds are abundantly gypsiferous, so much so that crystals of selenite have been utilized as a key characteristic in tracing these particular beds throughout the quadrangles. These somber gray units contain minor interbedded coal in some exposures, but throughout their exposure they contain considerable intermixed macerated, coaly plant debris.

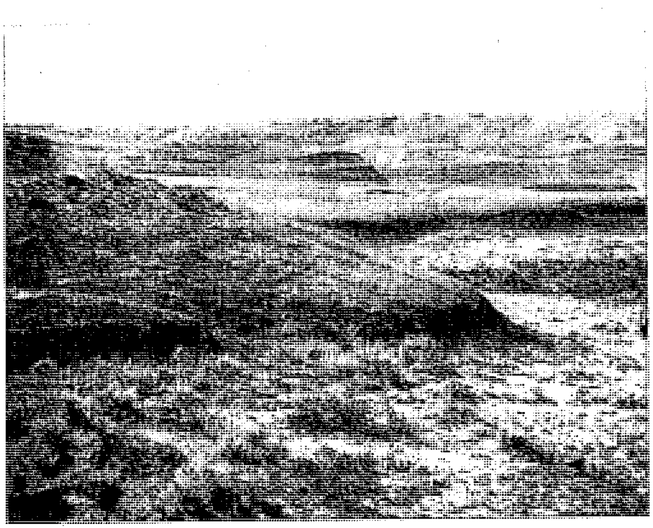


FIGURE 39.—*Somber dark mudstones of the W-coal zone are exposed along the Bug Creek access road in the southeastern part of the NW 1/4 of section 11, T. 22 N, R. 43 E, on the Bug Creek Quadrangle. These dark gray, gypsiferous beds are bentonitic and produce a slippery section along the Slick Hill road when they are wet. These beds have been utilized to separate the Nelson Ranch Member, below, from the Collins Ranch Member, above. Sandstones in the distance are characteristic of the Collins Ranch Member of the formation.*

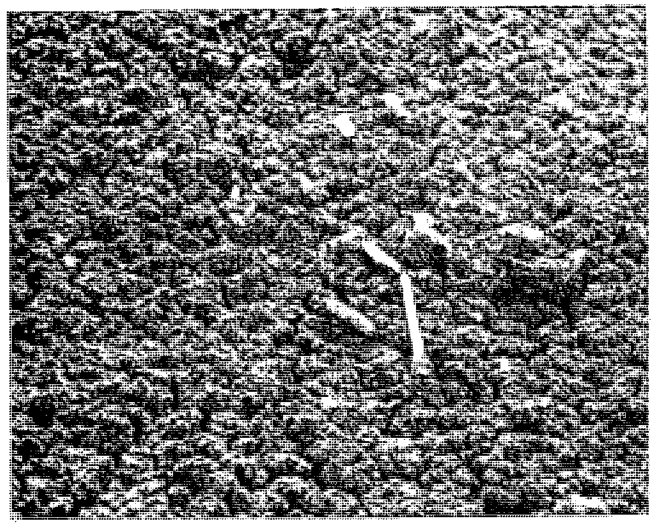


FIGURE 40.—*Typical selenite crystals in the popcornlike weathered surface of the W-coal boundary mudstones as exposed along the Slick Hill road in the central part of section 11, T. 22 N, R. 43 E.*

These somber gray shales (figs. 39, 40) probably accumulated in a slightly saline playa. The widespread occurrence of selenite suggests moderately elevated salinities in a carbonate-poor basin.

Coal beds in the Tullock Formation of the quadrangles are thin, noneconomic units, but they form remarkably persistent mappable key horizons throughout the quadrangles. These coals are generally subbituminous to lignitic, but only locally are unweathered outcrops available. Where freshly exposed, they contain considerable vitrain in an otherwise powdery, dark gray residue. Most coal outcrops contain veinlets of yellow iron sulfate and small gypsum crystals. Many also contain thin sandstone splits or interbeds of pinkish volcanic ash, paleosols, or siltstones. Almost all coal beds show complex interlamination and gradation with the brown to dark brown carbonaceous shales. Consequently, even where coal zones may be up to 1 m thick, coal beds within the zone are generally only 0.2–0.3 m thick and of high ash. They are of little commercial value, even where thickest. Most carbonaceous shale beds contain considerable charcoal, suggesting that these layers, like many similar units in the Hell Creek Formation, record wildfires and paleosols.

Bell (1965) did preliminary clay analysis of units within the Cretaceous and early Tertiary formations exposed in the McCone County area. He noted (1965, p. 69) that within the upper 13 m of the Tullock Formation "the relative percentages of montmorillonite decreases from about 70% to an average of 15% per sample, while the illite increases from about 15% to approximately 40%, and the kaolinite and/or chlorite content increases to about 45%." He concluded that the change in clay mineralogy may be related to changes in sources of the sediments from the lower to the upper part of the formation, to changes in depositional environment too subtle to be detected, or to a change in local weathering conditions. The change in clay composition takes place at about the stratigraphic level where the prominent "zebra" beds of the lower part of the Tullock Formation, the Nelson Ranch Member, give way to the consistently more sandy beds of the upper part of the formation, the Collins Ranch Member, or from the more lacustrine lower part of the formation into the more dominantly fluvial and swampy upper beds. Like Bell, however, we are uncertain what the change in mineralogy represents.

Fossils and Age

The Tullock Formation includes lower Paleocene rocks and extends upward from the upper Z-coal, which is a few meters above the iridium-anomaly lower Z-coal or K-T boundary coal. The Tullock Formation represents all of Puercan time and Mantuan time, as used by Van Valen (1978) and Sloan (1987, p. 169, 174–75), except for earliest Mantuan and/or Bug Creekian beds (as used by Sloan 1987, pp. 174–75), which are included in the uppermost 2 to 6 m of the Hell Creek Formation (fig. 2). A late Puercan fauna (early Paleocene) occurs in the middle Tullock Formation on Purgatory Hill, although some early Torrejonian beds may be represented in the uppermost sandy part of the sequence. A probable middle Torrejonian mammal fauna was collected during the present study from a Lebo channel fill that has cut uppermost Tullock beds in the southeastern part of the Bug Creek Quadrangle at McGuire Buttes. The Tullock beds, then, represent from earliest Paleocene Mantuan, through Puercan, to probably earliest Torrejonian ages in the Bug Creek and Sand Arroyo Quadrangles.

Several localities have now been discovered where dinosaur remains, largely teeth, occur in Paleocene deposits. They have been recovered from screen-washed concentrates from Paleocene channels entrenched into the upper part of the Hell Creek Formation, and also from several localities in channel fills in the lower part of the Paleocene Tullock Formation. Some of these localities are well above the Cretaceous-Tertiary boundary. Evidences of the Paleocene age of the dinosaur fossils have been treated by Rigby (1987). Reworking of Cretaceous deposits to produce these lazarous-type dinosaur assemblages, as suggested by Bryant, Clemens, and Hutchison (1986) and Argast and others (1987), was early considered but discarded as an origin for most of the fossils, based on evidence summarized by Rigby (1985, 1987), Rigby and others (1987), and Sloan and Rigby (1986). Additional faunal information will be presented in discussions of particular localities and of faunas in later papers.

Thickness

A complete section of the formation is approximately 55 m thick in the McGuire Buttes area in the southeastern part of the Bug Creek Quadrangle. The formation is approximately 66 m thick, however, in the Russell Basin area in the northern part of the quadrangle. It is also over 60 m thick over the southeastern part of the Sand Arroyo Quadrangle and the northeastern part of the Bug Creek Quadrangle, although the top of the formation there is not preserved and the overlying Lebo Shale has been stripped away so that even the most nearly complete Tullock sections lack a few meters of the Collins Ranch Member at the top of the formation.

LEBO FORMATION

Introduction

The Lebo Formation was first proposed by Stone and Calvert (1910) as the basal member of the Fort Union Formation in outcrops northeast of the Crazy Mountains in central Montana. There, the Lebo Member was considered as an andesitic sandstone, but to the east, in eastern Montana, equivalent beds become so shaly they are termed the Lebo Shale Member of the Fort Union Formation. Collier and Knechtel (1939, pp. 11–13, pl. 3) noted that in McCone County, including the Bug Creek and Sand Arroyo regions, and to the east, the Lebo Shale Member consists of approximately 122 m (400 feet) of interbedded thick units of dark shale, white sandy clay, and sandstone with minor coal beds.

Maple (1958, p. 218, fig. 1, pp. 220–21) used the Lebo Shale as the middle member of the Fort Union Formation that overlies the Tullock and underlies the Tongue River Members. Bell (1965) treated the Lebo beds as a formation that overlies the Tullock Formation and underlies the Tongue River Formation, and we have followed that usage.

Outcrop Area and Topographic Expression

The Lebo Formation is so limited in areal exposure within the Bug Creek and Sand Arroyo Quadrangles (plate 2) that we can contribute little additional to the understanding of its regional relationships. Only the lower few meters of the formation are preserved as rounded, often nearly barren outliers within the quadrangles, although major exposures have been recognized in uplands in headwaters of McGuire Creek and south of the South Fork of Rock Creek in the Crow Springs Quadrangle, east of the Bug Creek Quadrangle (figs. 40, 41).

As mapped by Collier and Knechtel (1939, pl. 1), the basal beds of the Lebo shale are preserved in the east central part of section 12, T. 22 N, R. 43 E, and in the

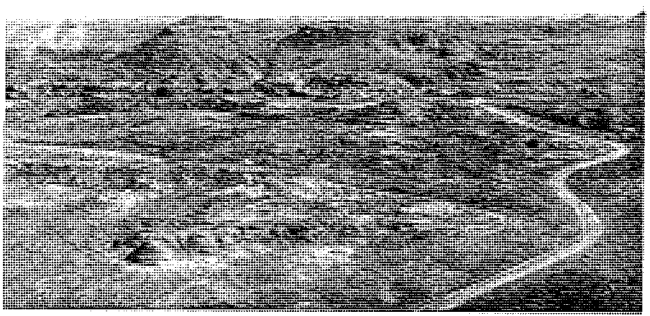


FIGURE 41.—*Low-angle aerial view across the eastern part of section 36 to the prominent McGuire Buttes that form the upland in the southeasternmost part of section 25, T. 22 N, R. 43 E. Tullock beds in the foreground and in badlands beyond the ridge crest in the middle distance below and immediately above the X-coal (x) are included in the Nelson Ranch Member of the formation. The slope zone, beyond, up to the U-coal (u) below the massive channel fills is included in the Collins Ranch Member of the formation. Lebo beds are exposed in hills along the skyline beyond the buttes and toward the right, in front of Tongue River beds, on the skyline in the distance.*

adjacent part of section 7, T. 22 N, R. 44 E, generally along the divide between McGuire Creek and the South Fork of Rock Creek, east of Montana 24. Additional outliers occur in west central section 12, T. 22 N, R. 43 E, east of Montana 24, and a newly recognized outlier occurs on this drainage crest, west of the highway on the line between sections 11 and 14 of T. 22 N, R. 43 E.

The high McGuire Buttes (figs. 30, 40), in sections 30 and 31, T. 22 N, R. 44 E, and in the northeasternmost part of section 25, T. 22 N, R. 43 E, are held up by a basal Lebo sandstone, included within the "crescent channel" by Bell (1965). Small outcrops of much more continuous exposures of Lebo Formation within the Crow Spring Quadrangle extend into sections 19 and 30, T. 22 N, R. 43 E, in the southeastern part of the Bug Creek Quadrangle. Two additional small outliers of U-coal occur in northwestern section 31, T. 22 N, R. 43 E, south of McGuire Buttes in the southeastern corner of the Bug Creek Quadrangle.

Contacts

The basal contact of the Lebo Formation is distinctly unconformable in areas where the entrenched channel-fill sandstones of the formation have cut down into the underlying upper beds of the Tullock Formation (fig. 42). However, over most of the region the contact appears to be conformable at the base of the U-coal. Sedimentation apparently continued more or less uninterrupted from Tullock time into that of the overlying Tongue River Formation. Collier and Knechtel (1939, p. 12) noted that the gradational boundary between the Lebo Shale and the overlying Tongue River Member was placed somewhat arbitrarily about 16 m (50 feet) below the S-coal, the most valuable coal bed in McCone County. That contact is not preserved within the Bug Creek and Sand Arroyo Quadrangles.

Lithology

Only the basal few meters of the Lebo Formation are exposed in the Bug Creek and Sand Arroyo Quadrangles, and these rocks consist principally of remnants of sandstone channel fills. These basal deposits of the formation either overlie or cut into the yellowish sandstone and carbonaceous shale above the U-coal, which marks the boundary between the Lebo and Tullock Formations.

The U-coal is the thickest coal bed in the mapped area. It ranges up to 5 m thick in the easternmost part of section 12, T. 23 N, R. 44 E, and in section 11 of T. 23 N, R. 44 E, at locality 4 (fig. 32) of Collier and Knechtel (1939, p. 59, 60). Collier and Knechtel (1939, pl. 1) show the U-coal as occurring in a series of small outliers along the crest of the divide in the northeastern part of T. 22 N, R. 43 E. Additional small outcrops of Lebo beds are preserved west of Montana 24 in the Bug Creek Quadrangle, but

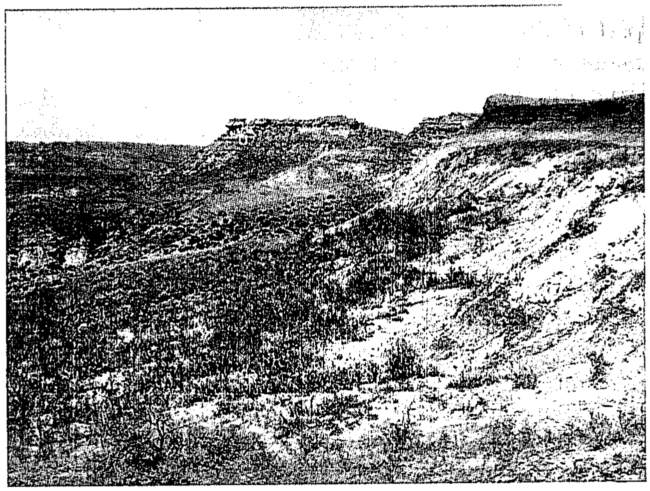


FIGURE 42.—*View northwestward from the northwest part of section 31, T. 22 N, R. 44 E, toward McGuire Buttes. The dark coal-bearing mudstone that caps the ridge, toward the right, is the same as the dark U-coal band below the massive sandstone of McGuire Butte. The entrenched channel of Lebo beds, beyond, cuts through uppermost Tullock and lowermost Lebo beds above the U-coal.*

none are known west of the highway in the Sand Arroyo Quadrangle.

The most extensive exposures are those in the southeastern part of the Bug Creek Quadrangle, where a massive sandstone caps the McGuire Buttes. This is the youngest sandstone in that part of the quadrangle, and it forms a prominent bluff above a sheer wall over the dark gray shales and coals of the U-coal zone (fig. 42). The lower part of the sandstone is weakly cemented, but the upper part is distinctly calcareous and forms a concretionary, massive, sandstone cap to the buttes. The upper massive ledge is particularly well cemented and is characteristic of the entire sand body, which is fine to very fine grained and homogeneous throughout. The entire unit is cross-bedded, but cross-bedding shows most distinctly in the upper concretionary part where strong linear sets of barchanoid cross-beds are well exposed (fig. 43). The entire unit is light yellow gray, both on fresh and weathered surfaces, although there is a moderate admixture of dark ferromagnesium minerals and dark chert that may account for 3–5% of the rock volume. In general, these sandstones are moderately clean, fairly mature deposits.

A lag concentrate of *Unio* bivalve shells occurs as one element in a clay-pebble conglomerate in the southeastern part of the high McGuire Butte. These freshwater fluvial bivalves have not moved far. Their preservation suggests that channeling and deposition were only moderate-energy fluvial events in a perennial stream. Within the deposit, most of the bivalves have both valves preserved in contact, and many appear as steinkerns, where the somewhat more calcareous fillings between the valves

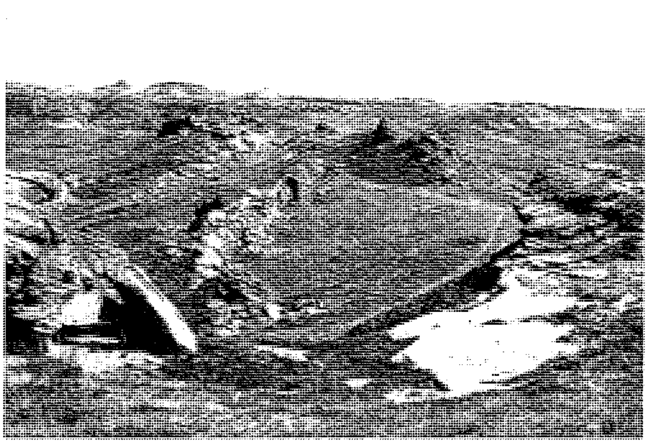


FIGURE 43.—*View eastward along the McGuire Butte channel from the southeast part of section 25, T. 22 N, R. 43 E, in the southeastern corner of Bug Creek Quadrangle. Massive cross-bedded sandstones form linear ridges along the channel axis. The paleostream flowed eastward into the distance. Lebo beds (L) are exposed in badlands and hills along the skyline, left of the channel fill.*

have been preserved. Although some of the bivalves appear horizontal, with the valves separated, 70% to 80% have opposed valves, and most of these appear in growth positions.

Lowest "clams" occur in an interbedded, clay-pebble sandstone, interlaminated unit. Most of the bivalves, however, occur in the overlying sandy section where they are associated with abundant charcoal fragments. This relatively soft, poorly cemented lower part of the bivalve-bearing sequence is about 0.5 m thick. The zone of concentration near the base is overlain by a somewhat better-cemented sand, approximately 0.5 m thick, in which the bivalves are scattered throughout the sand. Many of these fossils are oriented with the hinge down, and the valves gaping upward. These, in general, are 5 or 6 cm high, although some up to 10 cm high occur in the deposit. This middle layer in the sequence has common charcoal fragments, up to 2 cm in diameter, making up to 10% of the rock volume. It becomes less abundant upward into a third level of bivalve development where most of the bivalves appear transported, but only toppled and winnowed rather than having undergone some distance of transport.

Energy level of transport of the terrigenous debris must have been low to allow occupation of the stream bottoms by the bivalves. In addition, some of the separated valves are concave up, which is not a position of stability in even moderate-energy currents. A bivalve-bearing sequence is overlain by the calcareous, cross-bedded, light yellow gray sandstone that makes up most of the massive McQuire Buttes channel. The basal part of that sequence contains a thin, moderately coarse, flat-pebble conglomerate sequence with moderate charcoal. Clay pebbles and charcoal fragments grade out abruptly upward as the unit becomes the relatively clean sandstone that makes up most of the channel fill.

Rare Torrejonian-age mammalian teeth and a virtual conglomerate of datelike seeds are also associated with the *Unio*-bearing lag at the contact of the base of the formation.

Elsewhere, immediately east of the border of the Bug Creek Quadrangle, in the northwestern part of T. 22 N, R. 44 E, extensive outcrops of dark gray, clay shales form rounded buttes above slopes on prominent light gray to very light gray, sandy clays and dirty sandstones. The latter units are so light colored that they form the distinctive basal key unit of the Lebo Formation. They occur above the basal brownish, cross-bedded sandstones that are associated with lacustrine and fluvial fill immediately over the U-coal. Only the basal U-coal and overlying sandstones of the Lebo Formation are exposed within the Bug Creek and Sand Arroyo Quadrangles.

Fossils and Age

Bell (1965) noted that the Lebo Shale in the type area is of Torrejonian, or middle Paleocene, age (Simpson 1937). A middle to upper Torrejonian age is suggested for the member in McCone County (Sloan 1987, p. 181) because a late Puercan (early Paleocene) mammal fauna occurs in the middle Tullock Formation of Purgatory Hill, and an earliest Tiffanian (late Paleocene) fauna occurs in the basal Tongue River Formation near Circle, in southern McCone County, Montana. A small, probably Torrejonian mammal fauna was recovered from basal beds of the McGuire Buttes sandstone during our project.

Thickness

Collier and Knechtel (1939, pl. 3, p. 11–12) reported the Lebo Shale Member of the Fort Union Formation within McCone County as up to approximately 122 m thick. They concluded that no reliable estimate of thicknesses could be made because of the gentle dip, paucity of distinctive key horizons within the member, and the great map distances that separate outcrops of the base and top of the formation.

CENOZOIC DEPOSITS

The present study was primarily concerned with bedrock relationships within the Bug Creek and Sand Arroyo Quadrangles. The locally extensive loess and alluvial fill of the valleys and the patches of debris that blanket the low divides have not been differentiated on the geologic map. For example, loess cover is extensive along much of the upper drainage of the North Fork of Rock Creek and is commonly tilled in the valley. Such loess-based soils are generally less than 1 m thick, but they do form an effective local blanket over the Cretaceous and Tertiary bedrock.

High-level pediments are commonly veneered by unconsolidated pebble- and cobble-gravels. Along margins of the now-drowned Big Dry Creek drainage, such gravels occur, for example, on the pediment across Lonnies Bench and on high areas of the divide between McGuire Creek and the South Fork of Rock Creek.

A lobe of ice extended far up the Dry Creek drainage in western McCone County and eastern Garfield County. This valley apparently provided a low-relief area through which the ice could pour. Ice did not extend as far to the south through central McCone County or central Garfield county, however, because these areas were somewhat topographically higher.

Some divides in the quadrangles also preserve patchy remnants of what must have been a much more extensive blanket of ground moraine. These patches generally are composed of pebbles to coarse cobbles and somewhat less common large blocks of exotic igneous and metamorphic rocks mixed with quartzite in unsorted debris blankets. Such deposits occur, for example, on Goat Mountain and the high flat-topped uplands of the "The Wall" between Westland Hill and Snuff Gap, in the northeastern part of the Sand Arroyo Quadrangle, where they are only 1 or 2 m thick. Ground moraine patches also occur on the Bonin Divide, in the northeastern part of the Bug Creek Quadrangle, and on the McGuire Creek–Rock Creek divide area to the south. Patches of ground moraine now commonly cover areas only a few tens of meters across on many of the isolated high points and, as a consequence, are not realistically mappable at a scale of 1:24,000. The widespread occurrence of morainal debris throughout the two quadrangles, however, certainly documents the former presence of Pleistocene ice over even the highest peaks and ridges within the quadrangles. That distribution substantiates that a lobe of ice, a hundred or so meters thick, flowed southward along the Dry Arm drainage from the main glacier in the Missouri River drainage to the north and northwest.

Localized areas of sand dunes occur along the east shore of Fort Peck Reservoir, particularly on the promontory between the bays of the South Arm of Rock Creek and Bug Creek, in the region south and southwest of the Rock Creek Marina. Somewhat stabilized dunes, as well as very active ones, occur over much of section 36, T. 23 N, R. 42 E, and blanket outcrops of the upper part of the Fox Hills Sandstone and lowermost parts of the Hell Creek Formation in that area. Some recent landslides have been differentiated on the geologic map, particularly in the outcrop belt of the Tullock Formation where landslides have disrupted or buried outcrops of key coal units within the formation. Middle and upper parts of the interbedded sandstone and mudstone sequence of the Nelson Ranch Member have been particularly prone to landslides throughout the two quadrangles. Slide areas have been mapped where the deposits are large enough to materially affect the geologic mapping, as for example, in the southeastern part of "The Wall" in the eastern part of section 14, T. 24 N, R. 43 E, and in the southern part of section 12 and central part of section 14, T. 23 N, R. 43 E. Minor landslides also occur in the broad belt of Tullock exposures in the eastern part of the Bug Creek Quadrangle, but those areas are sufficiently small that they do not materially affect the outcrop pattern of key units within the Tullock Formation, the basal Lebo Shale, or the uppermost part of the Hell Creek Formation.

Recent sand and silt beds mark the shore zone of Fort Peck Reservoir. They locally have blanketed the bedrock in some critical areas within the estuaries along the major entrenched tributaries of the eastern part of the lakeshore. For example, silt and sand blanket much of the shore-zone part of the lower valley of the South Fork and North Fork of Rock Creek. Extensive sand and silt has blanketed the shore zone in the deeply indented coastline of Bug Creek Bay, where contact beds of the Fox Hills–Hell Creek Formations are buried moderately deeply.

Similar thick deposits of lake-controlled sand and silt occur in headwaters of Black Spring Coulee and the deep unnamed bay in the east part of section 20 of T. 22 N, R. 43 E, south of Black Spring Coulee.

Generally, the shore-zone deposits are of little consequence, but where they obscure the contact of the Fox Hills Sandstone and overlying Hell Creek beds, they take on some importance. They have not been differentiated on the geologic map, however, and the contact has been shown as a dashed line in areas where obscured by the reservoir-related deposits.

APPENDIX A

Type section of Nelson Ranch Member, Tullock Formation at Cactus Point, the promontory west of Montana 24 at mile 28.1. Section measured on the west side of the highway along the fence line and the ridge to the northwest; offset to north in upper part to basin headwaters. Section begins in the roadcut where Montana 24 crosses the line between section 24 and 25, T. 23 N, R. 43 E, and continues northwestward to 600 m north of the SW corner of section 24, Bug Creek Quadrangle.

Unit	*Description*	*Unit Thickness (meters)*	*Cumulative Thickness (meters)*
38	Sandstone, light gray, clay at the base, at top of the hill. Selenite crystals occur up into the sandstone.	1+	3.7+

W-Coal Zone, top of Nelson Ranch Member—base Collins Ranch Member

37	Claystone, upper carbonaceous unit, dark somber gray, with abundant selenite crystals, some of which are zoned brownish gray and distinctly platy. Unit forms a dark reentrant, although with no real coal, capped by more brown shale.	1.3	42.7
36	Claystone, light gray brown weathers light gray; flaky-weathering, grades to brown carbonaceous shale at the top; lower part like sandy zebra-striped sandstone.	0.4	41.4
35	Siderite zone, flaky sandy ironstone concretions form a discontinuous band.	0.3	41.0
34	Claystone, gray with interbedded carbonaceous shales, forms a shoulder above the lower W-coal and below the siderite band; upper part has streaks of coal in brownish flaky, silty shale.	2.1	40.7
33	Coal zone with three coal beds; the lower approximately 0.1 m, the middle approximately 0.3 m, and the upper approximately 0.1 m thick, all separated by carbonaceous brown shale. Unit forms a prominent shelf zone and contains abundant crystals of selenite.	1.0	38.6

W-Coal Zone, base

32	Sandstone, light yellowish gray to grayish brown, weathers light gray, forms prominent light band; capped by a siderite zone, approximately 0.3 m thick, which is somewhat less continuous than the one below the unit, with a thin carbonaceous shale streak below the upper siderite.	3.0	37.6
31	Siderite, prominent zone caps coal at the base of the cream-colored sandstone.	0.3	34.6
30	Shale, carbonaceous, brown with coaly streaks near the base and sandy partings near the middle; moderate brown, flaky, becomes somewhat darker brown in the vicinity of the coal partings at the base. Forms a prominent slope zone that is mappable over much of the Bug Creek Quadrangle. Sandy partings are moderately yellowish brown.	1.1	34.3
29	Coal, generally a powdery dirty coal, but with some bands of bright vitrain.	0.5	33.2
28	Sandstone or sandy shale, poor exposures form loess-covered zone and grassy shoulder.	4.3	32.7
27	Siderite forms prominent shoulder and caps the outlier to the south; resistant unit although with concretionary interruptions; concretions are 0.3–0.4 m thick in broad band.	~0.4	28.4
26	Claystone to silty clay, dark yellowish brown, semi-slope zone, only moderate exposures.	1.4	28.0
25	Coal, stray, thin carbonaceous streaks in carbonaceous shales below capped by a powdery thin coal.	0.2	26.6
24	Claystone, silty, dark yellowish brown, particularly in the upper part, somewhat lighter in the lower part; prominent band, holds up nearly vertical walls or semiledges, clayey. Weathered surface certainly mudcracked but not quite a "dirty popcorn" surface. Laterally equivalent to a cross-bedded sandstone 100 m to the east.	~1.0	26.4
23	Sandstone, light gray with brownish streaks marking some cross-bed sets; fine-grained, subangular grains; 10–20% black chert and other dark grains; weathers to a crumbly, semi-slope zone.	0.7	25.4
22	Shale, carbonaceous, with medial thin coal; shale dark yellowish browns with somewhat darker brown flecks where the plant material hasn't been coalified. Coal only 3 cm thick. Unit forms a prominent recess and shoulder.	0.4	24.7
21	Claystone, dark yellowish brown with iron streaks; weathers to moderate yellow brown zone, silty, puffy-weathering, semi-slope zone. Forms a low shoulder above the coal.	~1.0	24.3
20	Coal, with prominent dark yellowish brown, flaky, carbonaceous shale at top and bottom. Coal powdery with only moderate amounts of vitrain in the center. Coal contains a high admixture of thin shaly partings, forms a slope zone that weathers to moderate brown particularly in the upper part. Section offset from outlier to north wall of basin.	0.5	23.3
19	Sandstone, dusky yellow to light olive brown, some darker brown streaks mark prominent, high, cross beds of the thick set. Sandstone very fine-grained with considerable clay matrix; holds up a	1.8	22.8

	moderate ledge, particularly in the lower part, where concretions hold up prominent overhangs above the X-coal. Sand grains angular to subrounded, with a high admixture of ferromagnesian minerals and dark chert.		
18	X-coal, with 0.1–0.2 m carbonaceous shale at bottom and top. Coal is powdery, forms a prominent recess below the thick sandstone. Section offset northward from the crest of the southern outlier across the pass. In that distance, the massive sandstone of unit 16 grades into a striped zone with massive gray sandstone wedging out in low-angle fore-set lenses. Zebra-striped beds on the north side of the pass overlap onto and grade toward the south into the massive light sandstone.	0.6	21.0
17	Shale, carbonaceous, silty, becomes distinctly brown and increasingly silty toward the top in characteristic shallowing-upward sequence.	1.0	20.4
16	Sandstone, yellowish gray with a speckled salt-and-pepper appearance, fresh and weathered; sand, fine-grained subangular; massive but with thick calcareous concretions in the lower part. Concretions show excellent cross-bedding with current flow N 50° E, and some siderite banding. One prominent light gray band is moderately clean, fine sandstone, particularly in the lower part, but becomes somewhat more clayey in the upper part above the concretion zone. Salt-and-pepper appearance produced by about 40% dark elements that include chert and ferromagnesian minerals. Top of unit appears to be flat, and the bottom is controlled by underlying resistant siderite bands.	2.1	19.4
15	Mudstone, clayey and prominent siderite-banded zebra beds; siderite layers 1 cm thick form orange streaks and a few ironstone concretions; prominent ledge former. Claystone has siltstone partings and some thin, bentonitic clays, particularly in the upper part. Banded siderite is more common near the top and base than in the center, and near the top forms distinct, laminate steps. Lower in the section they are more concretionary. Unit is prominent, massive ledge former at the base but becomes a semi-slope former at the top, but with characteristic laminate general appearance.	6.3	17.3
14	Y-coal, powdery, dirty, with 0.1 m brown to very dusky red carbonaceous shale parting between upper and lower coals. The lower coal approximately 0.1 m thick. Unit forms a prominent recess beneath massive protective zebra beds, which overlie it abruptly.	0.8	11.0
13	Claystone, at the base, grades to siltstone at the top; medium gray at the bottom both fresh and weathered, with distinctly brownish carbonaceous and yellowish orange siderite streaks. Carbonaceous beds contain brown, not coalified, organic debris. This unit is a late pond-filling phase, in which coarser sediment flushed into the basin and converted it to a marsh.	1.4	10.2
12	Claystone grades upward to siltstone with thin sandstone at the top; zebra beds with distinct orange banding of siderite streaks but less distinct concretionary ironstones. Sandstone in the upper approximately 0.4 m shows excellent ripple marks and cone-in-cone structures. Current in the lower part of the rippled sandstone moved toward N 29° E. Upper 4 or 5 cm of sandstone shows long, sinuous ripples and is a very fine-grained, moderately dirty sandstone with subangular grains, contains approximately 20% dark chert and possibly ferromagnesian minerals. Unit weathers to a prominent tan slope zone and extends up to the brow of the hill by the fence on the west side of the highway.	1.5	8.8
11	Claystone, silty zebra beds with prominent, thin, 1–2 cm bands of ironstone nodules and laminated iron-rich bands approximately every 10–15 cm. Unit is a distinctly banded zone, capped by a 0.1 m thick bentonitic mudstone that weathers a popcorn surface. Claystone yellowish gray on fresh surfaces and weathers slightly lighter. Some ironstone concretions are moderate reddish brown, but most are yellowish orange, with considerable variation. Bentonitic mudstone is light olive to olive gray, with a distinctive "popcorn" surface; it holds up the bench.	1.5	7.3

10	Shale, carbonaceous, olive black; weathers essentially the same; flaky; lower part forms weak shoulder, upper recess.	0.5	5.8
9	Claystone, slightly silty at the base becoming distinctly silty toward the top. Light gray at the base becomes light olive gray with limonite streaks and isolated ironstone concretions up to approximately 0.1 m in diameter at about midunit; becomes more fissile as silt increases toward the top.	1.0	5.3
8	Shale, brownish gray where fresh, weathers somewhat lighter; flaky with some fissility produced by carbonaceous fragments that are particularly common toward the top. Upper part forms a small shoulder with ironstone fragments that drop out abruptly in the upper 0.1 m. Fragments are light yellow gray, typical of the zebra beds with alternating claystone and thin ironstone bands. Ironstone bands tend to be moderately continuous to isolated concretionary; moderate brown on fresh exposure but weathers slightly more orange brown and somewhat lighter. The siderite bands form prominent little steplike resistant units in the semi-slope zone.	0.9	4.3
7	Z-coal, upper or formation boundary coal; lower 0.1 m dark carbonaceous shale. Grades up to 0.1 m interbedded coaly streaks and carbonaceous shale and then to coal; top 0.2 m principally coal with carbonaceous streaks; coal has much shiny vitrain in 1-cm-thick lenses, particularly toward the top. Near the base brown streaks are moderately brown to grayish black. Upper shaly partings are moderate reddish brown to brown gray. A medial parting is more light olive gray and waxy-appearing bentonitic claystone.	0.6	3.4

Top of Hell Creek—base Tullock Formation, base of Nelson Ranch Member

6	Mudstone, fresh yellowish gray to pale yellowish brown, weathers a light olive gray to yellowish gray; has a powdery surface on the relatively massive slope former. Minor macerated plant material with limonite and jarosite in the middle part along some of the partings; the upper 0.1 m carbonaceous. Massiveness may be due to paleoroot development that broke up initial stratification.	~0.4	2.8
5	Siltstone like unit 4; basal carbonaceous zone has macerated plant debris and is somewhat less massive and more fissile, although plants appear to be reedlike or cattail fragments and record marsh environment. Weathers more to chips than to flakes.	0.2	2.4
4	Siltstone, carbonaceous streaked, grades up to a light gray at the top; lower part pale yellowish brown on the fresh surface, but weathers a light olive gray. Upper part, fresh and weathered, is light olive gray. Lower carbonaceous streak up to 0.1 m thick has disseminated carbonized and coalified reedlike plant fragments with some coffee-ground-like coal fragments. Lower part is fissile and shaly, upper part more flaky and powdery.	0.3	2.2
3	Mudstone, fresh color between light olive gray and yellowish gray; weathers yellowish gray; bedding massive; calcareous, slope former; contains disseminated plant debris.	0.9	1.9
2	Lower Z-coal, probable iridium-event claystone; with 0.1 m carbonaceous streaks at top and bottom; middle part is light olive gray, weathers about the same. Carbonaceous streaks top and bottom fresh are olive gray and weather the same, although carbonaceous streaks at the top somewhat lighter, form small low shoulders and middle slope zone; contain disseminated, coffee-ground-like plant debris; massive, without bedding or splitting.	0.3	1.0
1	Claystone; fresh dusky yellow weathers to a yellowish gray; slope former, bentonitic, massive. Base not exposed in borrow pit along the west side of the highway.	0.7	0.7

APPENDIX B

Type section of the Collins Ranch Member of the Tullock Formation and lower part of the Lebo Formation. Section begins 400 m south of the NE corner, continues southward essentially along the east line of section 12, T. 22 N, R. 43 E, and ends 600 m south and 60 m west of the same NE corner, passing through the coal mine cited by Collier and Knechtel (1939, p. 55), Bug Creek Quadrangle.

Unit	Description	Unit Thickness (meters)	Cumulative Thickness (meters)
	Lebo Formation, eroded surface		
19	Mudstone, medium brown, bentonitic, with abundant selenite crystals up to 4–5 cm long. Caps small brown hill 100 m west of the mine pit face. To the west, across a broad pass, this mudstone is overlain by a light gray to tan sandstone in a small hill. Top of exposed section.	0.8	24.2
18	Mudstone interbedded with dark carbonaceous shale, forms the basal unit of a prominent dark brown, gypsiferous mudstone band. Carbonaceous shale distinctly brown with selenite crystals up to 2–3 cm long. Platy, silty, and flaky-weathering in contrast to the unit below, which weathers to chips.	1.3	23.4
17	Sandstone, muddy, gypsiferous, forms a very light gray shoulder above the dark gray section of the mine.	0.9	22.1
16	Shale, carbonaceous black to dark brown.	0.1	21.2
15	Sandstone, very light gray, forms the upper rim of the south edge of the open-pit mine, now long abandoned.	1.2	21.1
14	Coal with thin basal and top carbonaceous shale.	0.1	19.9
13	Mudstone, gray green, sandy, with brownish gray gypsiferous streaks and some limonitic ironstone stains.	1.3	19.8
12	U-coal with interbedded carbonaceous shale. Unit poorly exposed even in the open-pit mine face except for the uppermost 1 m of coal moderately well exposed with carbonaceous streaks. Entire unit gypsiferous, with small 1–2-cm-long selenite crystals. The coal is better exposed in the west end of the mine where it consists of about three coal units separated by platy, carbonaceous shale and with platy, carbonaceous shale at the top and the bottom.	2.3	18.5
	Base Lebo Formation—top Tullock Formation, Collins Ranch Member		
11	Sandstone, muddy, very light gray, forms part of distinct light sandstone band when combined with the sandstone and coal below. Sandstone very fine grained, muddy ledge former. Exposed at base of spoil pile of mine in the U-coal.	1.5	16.2
10	Coal zone with basal and upper brown, carbonaceous shales; lower one 0.2 m thick and upper one 0.1 m thick. This coal forms a prominent bench above and below very light gray-weathering, shoulder-forming sandstones.	0.8	14.7
9	Sandstone, very light gray, weathers very light gray. Lower part contains local ironstone concretions. Upper two-tenths meter become mudstone, bentonitic, slightly gypsiferous, light greenish gray grading up to carbonaceous shale at the top.	1.4	13.9
8	Sandstone, medium to light medium gray brown with locally abundant ironstones. Entire unit forms a brownish slope and semi-ledge zone between the coal of unit 7 and the overlying light-colored sandstone. Ironstones about 20% of the total volume, dark brown to distinct orange brown.	1.8	12.5
7	Coal and interbedded carbonaceous shale; shale gray to brown forms a prominent shelf on the promontory. Coals approximately 0.2–0.3 m thick at bottom and top.	1.0	10.7
6	Sandstone, semi-ledge former, medium to light yellow gray at the base becoming light yellow gray to light gray yellow at the top, somewhat muddy appearing. Forms a prominent light band beneath the overlying coal.	1.4	9.7
5	Mudstone, light medium gray, sandy slope zone, slightly bentonitic.	1.1	8.3
4	Sandstone, prominent ledge former, grades up from muddy sandstone at the bottom to clean sandstone at the top; platy, limonitic brown to medium orange brown. An ironstone concretionary layer forms platy rubble on the upper part.	2.0	7.2
3	Sandstone, platy, levee or overbank type stratification, forms a small shoulder above the slope of unit 2. Includes interbedded mudstone up to a prominent ironstone band, basal sandstone and upper ironstone both approximately 0.1 m thick.	0.6	5.2
2	Mudstone, gray, variegated tan and light gray, becoming increasingly sandy upward.	3.6	4.6

Base Collins Ranch Member—top Nelson Ranch Member, Tullock Formation

1	Mudstone bentonitic, dark gray with coaly streaks, gypsiferous slumped upper surface. Upper of the double, gypsiferous W-coal bentonitic gypsiferous beds exposed in the gully.	1.0+	1.0+

APPENDIX C

Section of Upper Bearpaw Shale and Fox Hills Sandstone Section begins at reservoir level, 150 m W and 60 m S of the NE corner of section 28, T. 24 N, R. 42 E, and continues northward to plateau top and road, 60 m W and 60 m N of the SE corner of section 21, T. 24 N, R. 42 E, on north side of Sand Arroyo Bay, Spring Creek Bay Quadrangle.

Unit	*Description*	*Unit Thickness (meters)*	*Cumulative Thickness (meters)*
24	Mudstone and loess soil with Pleistocene gravel cap on top of section.	1.0	52.4

Hell Creek Formation, eroded

23	Sandstone, yellowish green gray to greenish gray, intensely cross-bedded in low sets 0.2–0.3 m high, with paleocurrent generally toward the south; contains a prominent tan band. Medium to coarse grained, locally, with minor clay rip-up clasts; generally homogeneous despite cross-bedding.	1.6	51.4
22	Mudstone, dark gray to dark gray brown at the base, becomes medium to light gray brown in the upper part, laminated; common limonitic septarian concretions up to 0.2 m in diameter; prominent slope former. Thickness varies considerably because of channelling in underlying sandstone.	1.0	49.8
21	Sandstone, cross-bedded, much like unit 19; some lateral discontinuity and lensing with thickness variation because of channel cut and fill above flat base.	0.7	48.8
20	Interbedded mudstones and sandstones prominently horizontally bedded in 0.1–0.2-m-thick intervals; forms a prominent slope zone above the ledge held up by the top Fox Hills Sandstone. Mudstones light medium gray with abundant limonite-stained variegated beds; sandstones essentially like unit 19 at top of Fox Hills Sandstone. Mudstone dominates in lower half of unit, but mudstone and sandstone nearly equal in upper half.	2.1	48.1

Top of Fox Hills Sandstone and base of Hell Creek Formation

19	Sandstone, as below although locally distinctly yellowish brown with abundant limonite-cemented *Ophiomorpha* traces well exposed on hill north of roadcut; massive, cross-bedded, relatively clean.	1.9	46
18	Sandstone, very fine grained, relatively massive appearing. Light yellow gray with some orange ironstone-stained bands with common thin mudstone bands. Mudstone 0.1–0.2 m thick. Most common in the lower part where it may make up to one-third of the sequence. Rocks poorly exposed. In the roadcuts to the north, mudstone bands pinch out and unit is totally sandstone there, well exposed.	3.0	44.1
17	Mudstone, variegated medium yellow gray to dark brown; shaly to platy, very sandy, slope former.	1.0	41.1
16	Sandstone.	2.0	40.1
15	Sandstone, bright orange brown to reddish brown, very fine grained, laminated, cross-bedded, distinct shelf former on the traverse, concretionary.	2.2	38.1
14	Sandstone, light greenish gray or yellowish greenish gray, very fine grained; prominent cross-bedding with current motion toward the south; sets 0.2–0.5 m high, relatively massive appearing; soft, poorly cemented semi-slope former, above ledges of concretionary unit 13.	3.1	35.9
13	Sandstone, light yellow gray, very fine grained, distinctly horizontally bedded with some prominent isolated ripple marks in the middle; weakly cross-bedded, but horizontal stratification is dominant; well sorted, relatively clean, soft, nonlithified except isolated ripple marks and limonite-bound units.	1.5	32.8
12	Sandstone concretionary, basalmost coarse concretionary unit; forms a prominent although discontinuous ledge; calcareous, fine grained, limonitic. Thickness varies significantly because of concretionary thin-bedded nature.	1.1	31.3
11	Sandstone, light yellow gray, weathers essentially the same;	4.5	30.2

	soft, poorly cemented, cross-bedded, interbedded with 3-cm- to 10-cm-thick gray mudstones make up about one-third of upper meter.		
10	Shale, silty and muddy, slope former, medium gray brown, weathers light gray brown; top of unit with limonite ironstone concretions.	2.2	25.7
9	Sandstone, medium gray brown, weathers light gray; slightly concretionary with limonite stains in part, fine grained, calcareous, platy; forms a prominent small shelf. First bed above unit 5 unquestioned in place.	0.3	23.5

Top of Bearpaw Shale and base of Fox Hills Sandstone

8	Shale, medium to light gray green, weathers a light greenish gray; sandy; prominent slope former; slightly gypsiferous, with small crystals up to 1 cm in diameter.	5.1	23.2
7	Sandstone, light, yellow gray, very argillaceous with some platy-weathering, concretionary, limonitic cross-bedded units, but poorly exposed. Concretions may be slumped from above.	1.0	18.1
6	Covered, but probably shale as below.	5.0	17.1
5	Shale, medium brown gray to light gray brown, weathers light gray brown; slope former; somewhat sandier toward the top with small concretions up to 0.3 m in diameter scattered throughout, but more rare than below. Unit is exposed on roadcut and in bluff below.	4.0	12.1
4	Shale as below, but weathers slightly more yellowish brown, with same types of concretions at the top.	1.6	8.1
3	Shale, same as below, with distinctive, concretionary band at the top, although some concretions occur throughout the unit. These are up to approximately 1 m in diameter. Shale dark gray brown weathers light gray, gypsiferous with brown selenite in upper part and light gray selenite in lower part.	2.1	6.5
2	Shale as below, but abundantly gypsiferous with selenite crystals up to 4–5 cm long, mainly needle-like crystals rather than rosettes; slope former, well exposed in the sea cliff. Top marked by a zone of limestone concretions up to 0.5 meter in diameter, septarian and oblong, with long dimensions parallel to stratification.	3.2	4.4
1	Shale, dark gray to dark gray brown, weathers light to medium gray, flaky. Top marked by a distinctive zone of concretions up to 0.5 m in diameter of fine-grained, muddy limestone. Concretions septarian, spaced 1–1.5 m apart in the sea cliff. Base not exposed.	1.2	1.2

APPENDIX D

Pretty Place Section. Section begins at Pretty Place on the South Fork of Sand Arroyo, 50 m west and 500 m south of the northwest corner of section 32, T. 24 N, R. 43 E, and continues up gully to east, to near center of east line of section 32, Sand Arroyo Quadrangle.

Unit	*Description*	*Unit Thickness (meters)*	*Cumulative Thickness (meters)*
	Hell Creek Formation, eroded top		
17	Sandstone as unit 16, but with large concretions, some subspherical and up to 2 m in diameter; most, however, only approximately 1 m in diameter; all are limonite cemented. Concretions present throughout the unit, which is a prominent shoulder former throughout the quadrangle, but become particularly pronounced toward the top. Locally the upper half appears light olive to light yellow gray rather than as tan as the rocks below. Upper part becomes distinctly flaggy bedded and forms a prominent shoulder crest. This is the same unit that forms the prominent "waterfall" north of the cattle pens along the Pretty Place road. Top of exposures and the section.	16.5	51.8
16	Sandstone, Sandstone 2, pale olive to light olive gray, weathers pale olive to yellowish gray, massive, poorly cemented, forms a distinctive mappable brush-covered slope zone traceable over much of this part of Sand Arroyo Quadrangle. Silicified wood fragments common at the base. Sandstone medium grained, salt-and-pepper appearing, argillaceous, poorly cemented with brownish siderite streaks that become more common toward the top. Locally,	4.2	51.8

	approximately 0.2–0.3 m of light gray mudstone occurs between the reddish mudstone, below, and the sandstone above.		
15	Mudstone, grayish red to blackish red, weathers moderate red to grayish red; siderite-bearing shoulder former, forms prominent dark band at the top of the lower mudstone as part of the mappable reddish band that characterizes the beds.	0.3	31.1
14	Mudstone, light yellow gray to light olive, weathers the same. Sandy at the base, becomes distinctly bentonitic and shoulder former above, contains a few siderite nodules, particularly in the upper part; unit has a pinkish hue at about the middle of the shoulder former.	1.3	30.8
13	Sandstone, muddy, and very sandy interbedded mudstone, dusky reddish gray to reddish brown, semi-slope zone, forms the basal part of reddish zone, distinctive of the top of the lower mudstone, somewhat lighter reddish gray, abundant macerated plant materials disseminated throughout; massive appearing although somewhat cross-bedded, locally, with paleocurrent directions toward the east.	1.4	29.5
12	Sandstone as below, with silicified wood fragments, forms upper massive part of vertical wall of the lower mudstone of the Hell Creek Formation.	7.2	28.1
11	Sandstone as unit 10 with common mudstone partings 0.3–0.4 m apart; partings form small bentonitic shoulders, with the prominent concretionary sandstones as somewhat cleaner units. Paleocurrents flowed S 70° W; unit forms a gray green mudstone and sandstone, erodes to a vertical face like unit below.	3.2	20.9
10	Sandstone, yellowish gray to pale olive, weathers the same or to dusky yellow; noncalcareous, clayey, cross-bedded but massive cliff former; protected by the upper 0.2–0.3 m of moderately well-cemented, limonite-bound sandstone that forms a small shelf. Brownish carbonaceous streaks in the cross-beds show transport direction toward the south but with some irregularity; more argillaceous bands produce mudstone zones spaced about 0.3 m apart.	2.8	17.7
	Section offset to the east along the north branch of South Fork of Sand Arroyo on the upper dark siderite bands exposed at the base of prominent "pyramid" one-quarter mile east of Pretty Place. Section resumes upward at the top of unit 10. Gully-bottom outcrops contain large silicified conifer (?) wood fragments up to 0.5 m long, from the prominent concretionary sandstone of unit 10. Transport direction is toward S 60°–70° E.		
9	Sandstone, light yellow gray to light gray green, weathers the same; argillaceous, soft, poorly cemented, cross-bedded, with speckled salt-and-pepper appearance because of a mixture of dark gray cherty fragments and lighter gray quartz. Uppermost exposures in the shear wall and basal exposures above the siderite band in the bluff pyramid to the north. Top of the unit 1.0 m of discontinuous dark brown to medium orange brown or moderate orange brown siderite nodules that form a small shoulder at the base of the pyramid. Siderite nodules generally fractured intensely, range up to 0.3 or 0.4 m across. Unit forms part of the vertical wall at the base of the pyramid. Lower sandy units contain selenite.	1.3	14.9
8	Mudstone, sandy, light yellowish gray to light gray green, slope zone. Upper 0.2–0.3 m rich in dark siderite, fine grained, noncalcareous; forms slumps over exposures except in the vertical wall to the west where it is a prominent gray vertical band capped by the dark siderite.	3.1	13.6
7	Mudstone, pale brown to dark yellowish brown, weathers moderate brown to pale brown with some light brown orange streaks, probably from bands of small siderite nodules that litter the surface; forms a brownish band above the gray sandstone in the vertical wall to the west.	1.0	10.5

Top of Fox Hills Sandstone and base of Hell Creek Formation

6	Sandstone, light greenish gray, massive, semi-slope former, lacks concretions and contrasts to the more yellowish beds below.	0.7	9.5
5	Sandstone, massive concretion cap, dark brown or dark yellowish	0.5	8.8

	brown to moderate brown, weathering the same or moderate reddish brown; ledge former; caps overhang of unit below, which caps the pedestal at the base of trail at Pretty Place. The section is offset approximately 200 m southeast from Pretty Place, up the main arroyo, to the shear wall on the north side.		
4	Sandstone as below but with abundant subspherical concretions up to 6 or 7 cm in diameter, forms a recess in the vertical cliff beneath the overhang of unit 5.	2.4	8.3
3	Sandstone, same as unit 1 and part of the same vertical cliff above the corral; contains small vertical burrows, some pebble rip-up clasts and concretions as thin lenses in the complex braided-appearing cross-bed sets. Small concretions relatively rare, but upper part includes large oblong concretions 3–4 m long up to 1.5 m high and wide. These are most common in the upper part.	2.5	5.9
2	Sandstone, same as unit 1, except moderately common flat-pebble rip-up clasts in cross-bed sets and separating sets as lag gravels. Pebbles are fine-grained claystones or mudstones that are moderately calcareous and well cemented to noncalcareous and limonite cemented; forms a pebble band at the base of the cross-bed set 2 or 3 cm thick. Additional sets of cross-beds with rip-up clasts occur irregularly in the lower part of the unit and are similarly 2–3 cm thick. One thin unit, 0.1 m above the base, contains fragments of belemnites evident principally as hollow cross sections, which have been largely kaolinized in the noncalcareous stratigraphic sequence. Large horizontal *Ophiomorpha* burrows evident particularly in the upper part. Upper 0.3 m brownish to concretionary bands forms a small shelf, laterally discontinuous. Concretions light brown to moderate brown, locally weathering dark yellowish orange. Some of these have gray marcasite cores, particularly where associated with *Ophiomorpha* and the secondary subspherical units.	1.9	3.4
1	Sandstone, yellowish gray to dusky yellow, weathers yellowish gray, except in concretionary bands where rocks are dusky yellow to grayish orange or dark yellowish orange and weather essentially the same; massive, irregular, cross-bedded, very fine grained, moderately well sorted. Moderate orange brown streaks, subhorizontal in the lower part, become more or less concretionary in the upper part. Upper part has ill-defined *Ophiomorpha* burrows that have been sand-filled and bound by limonite modifications. Occasional flat, rip-up pebble clasts to 3 or 4 mm and concretions up to 2 or 3 cm in diameter as isolated subspherical units. Top is at rip-up clasts conglomerate. Base not exposed at alluvial fill near small corral.	1.5	1.5

APPENDIX E

Cow Pens section of middle Hell Creek Formation, exposed along the Pretty Place road in NW 1/4, section 5, T. 23 N, R. 43 E. Section begins in gully near fence north of road crossing, 450 m east of the NW corner of section 5, and continues southward 500 m to top of mesa, Sand Arroyo Quadrangle.

Unit	*Description*	*Unit Thickness (meters)*	*Cumulative Thickness (meters)*
	Hell Creek Formation, eroded top		
20	Sandstone 3, sandstone as below but capped by prominent concretionary unit that forms the top of small mesa. Upper 3 m are concretionary units that appear to be the same age, or slightly older and lower in the sandstone section, as the sandstone that caps Harms Mesa to the south. Top of hill, end section.	7.5	30.9
19	Sandstone, light yellow gray, considerably lighter weathering than underlying concretionary unit; interbedded clay laminae soft, weather away to a semi-slope zone. Some carbonaceous streaks in the cross-bed sets of the obvious fluvial channel sandstone, grades up to about 0.3 m light olive mudstone at the top.	4.6	23.4
18	Sandstone like unit 17, but becomes increasingly cleaner toward the top; ledges of abundant concretions typical of upper part of Sandstone 3; medium-grained, abundant cross-beds with trans-	4.1	18.8

	port direction toward the southeast. Upper part becomes increasingly muddy; concretionary units are noncalcareous with limonite cement. Upper part of the unit, in particular, contains abundant siderite concretions, each approximately 1–2 cm in diameter, particularly where unit becomes slightly more muddy.		
17	Mudstone as unit 15.	0.4	14.7
16	Sandstone, base of Sandstone 3, light yellow gray to dusky yellow, weathers essentially the same; low ledge zone, basal part with concretions.	0.9	14.3
15	Mudstone, slightly carbonaceous, forms a somewhat darker streak near the base of the yellowish sandstone; grades to typical muddy, drab mudstone in the upper half.	0.3	13.4
14	Mudstone, sandy like unit 12.	3.8	13.1
13	Sandstone at the base becomes muddy sandstone toward the top; lower units locally concretionary, light yellow gray to light gray green, weathers essentially the same; contains isolated siderite concretions up to 5 or 6 cm in diameter.	0.7	9.3
12	Mudstone, olive gray green to light olive gray, slope former, somewhat sandy but still with "bentonitic" weathered surface; grades up to increasingly sandy units near the top.	1.3	8.6
11	Shale, carbonaceous, with a mudstone parting forming the middle third. Shale brown, weathers light brown, flaky, abundant macerated plant debris, forms a prominent low ledge, key zone.	0.4	7.3
10	Mudstone, sandy at the base above a 0.1 m carbonaceous zone parting; forms a slope and a low ledge, like unit below.	0.5	6.9
9	Mudstone same as unit 7.	2.2	6.4
8	Mudstone, dark gray to medium gray brown, bentonitic, slightly sandy.	0.2	4.2
7	Mudstone, bentonitic, medium olive gray, weathers the same; forms a slope and shoulder above the carbonaceous zone. In some exposures, the dark bentonitic shale has a brown carbonaceous upper 0.1 m; unit becomes light gray green toward the top.	1.5	4.0
6	Mudstone, dark gray brown, weathers dark brown, forms a prominent brown slope above the carbonaceous shale.	0.2	2.5
5	Shale, carbonaceous, forms pinkish brown slope and low ledge or shoulder between bentonitic beds; abundant macerated plant debris, some local coaly streaks; good key unit.	0.4	2.3
4	Mudstone, sandy, bentonitic as unit 2; sandy siderite bands in the top 0.1 m.	0.3	1.9
3	Mudstone, medium gray to gray brown, weathers olive brown, holds up a small shoulder, appears as a carbonaceous streak in otherwise gray green beds.	0.4	1.6
2	Mudstone, bentonitic, light olive gray, weathering medium olive gray; some yellow brown tinges; ledge and semi-slope former, forms a shoulder just north of the road crossing.	0.2	1.2
1	Sandstone, light olive drab, concretionary in the upper part, lower part somewhat bentonitic and slope forming. Unit is equivalent to top of unit 17 of Pretty Place section. Base not exposed in gully, but is to north; base of section.	1.0	1.0

APPENDIX F

South Sand Arroyo Badlands section of middle and upper Hell Creek Formation. The section begins 580 m east and 595 m south of the northwest corner of section 33, T. 24 N, R. 43 E, and ends 825 m east and 580 m south of the same corner in section 33, Sand Arroyo Quadrangle. The section begins at the top of Sandstone 2, equivalent to units 10–11 in the Pretty Place section.

Unit	*Description*	*Unit Thickness (meters)*	*Cumulative Thickness (meters)*
31	Loess and slope wash.	1.2	47.4
	Hell Creek Formation, eroded top		
30	Sandstone, light yellow gray brown, weathers the same; abundant ironstone concretions in the top limonite-stained layers. Top of formation not preserved.	1.6	46.2
29	Mudstone, yellowish gray, very sandy, grades into muddy sandstone in upper part.	1.1	44.6
28	Mudstone, basal part medium gray green, grades to brownish gray in upper part.	1.5	43.5
27	Mudstone, medium gray green to mottled gray and light greenish gray, weathers light greenish gray to light yellowish gray upward,	3.2	35.5

	bentonitic, "dirty popcorn" shoulder former. Basal part locally may be medium gray, weathering somewhat brownish gray with lenses of carbonaceous mudstone that are light gray brown to medium gray, but weather somewhat purplish. Massive, somewhat sandy in the middle part.		
26	Sandstone 3; sandstone, light gray green, argillaceous, cross-bedded with numerous sets of sandy mudstone, indicating a compound braided system for the depositing stream; large concretionary "logs" up to 2 meters across and many meters long form about the middle fifth of the unit. This middle concretionary band contains dark gray to dark gray brown ironstones generally 10–20 cm across but up to 0.5 m in diameter; many are platelike, but they weather out to produce dark debris, grade into overlying unit.	2.3	32.3
25	Sandstone 3, lower part, sandstone channel fill with extensive cross-bedding and local medium brown gray, muddy, cross-bedded lenses, particularly at the base; paleocurrent toward the east. Lower part forms a semi-slope zone, but upper 0.3–0.4 m concretionary unit is ledge former. Concretionary unit is fine grained, limonitic, and occurs at the transition from the muddy channel up to the gray green ledge-forming channel fill. This unit and unit 26 combined form the prominent Sandstone 3 ledgy zone, equivalent to the sandstone at the top of the Cow Pens section. In the Cow Pens section, the sandstone is considerably thicker, probably along the axis of the channel fill, whereas this section is on the flank of the sandstone channel-fill–levee sequence.	1.7	30.0
24	Mudstone, light grayish green, but weathers somewhat pinkish green, sandy, laterally discontinuous, cut out by a sandstone channel fill 20 m to the east, bentonitic and soft where exposed on crest of the hill.	0.4	28.3
23	Sandstone, forms a tan green band with some platy limonite-cemented, locally calcareous, concretionary layers; cross-bedded in the lower part, which is a ledge former; upper part becomes increasingly muddy and slope former.	1.2	27.9
22	Mudstone, light gray brown with greenish top and bottom, forms the mottled purplish and green slope.	0.4	26.7
21	Sandstone, tan to orange mottled with gray green, semi-ledge former, forms a brownish sideritic band.	1.7	26.3
20	Mudstone, sandy, particularly in the base, where it forms a tan shoulder, bentonitic, forms a lower tan and upper gray green band. Upper part has abundant, small, dark brown and orange brown ironstone concretions up to 0.2–0.3 m across, most of which are tabular and irregularly fractured.	2.7	24.6
19	Mudstone like unit 18, but with light to medium brown mudstones 0.2 m thick at the base and top. Basal unit grades up through dark gray green mudstone into the yellowish sandy mudstone; all capped by thin carbonaceous shale. Units sparingly gypsiferous with selenite crystals most common in carbonaceous shale.	1.3	21.9
18	Mudstone, medium gray green, with some purplish and gray streaks, becomes tan and very sandy in the upper half. Slope former, slightly bentonitic.	1.1	20.6
17	Sandstone, light yellow gray to light gray green, laterally continuous tan, locally ledge-forming band, contains some bright orange gray, limonite-stained concretions. Sandstone is argillaceous, but cleans up a bit where concretionary.	1.0	19.5
16	Shale, carbonaceous, weathers pinkish brown with thin coaly mudstone at the top, coal layers laterally discontinuous.	0.2	18.5
15	Mudstone, light greenish gray at the base, becomes yellowish green and gray at the top, bentonitic particularly in the upper part, sandy, slope former. This unit characteristically forms slumps in exposures to north.	2.0	18.3
14	Shale, carbonaceous, light to medium gray brown; forms a pinkish weathered zone, but not as dark as unit below. Top and bottom with dark brown ironstone concretions, all fractured to bits 2–3 cm across. Becomes somewhat darker to medium brown at the top.	0.5	16.3
13	Sandstone, light to medium gray green, well cemented, with locally abundant tan limonite-	1.5	15.8

	stained concretions, semi-ledge former with prominent dark, ironstone bands in the upper 0.1 m. Sand poorly sorted, argillaceous, approximately 20% dark ferromagnesian minerals.		
12	Mudstone, variegated light brownish gray and medium gray green with well-defined lower and upper pinkish-weathering thirds. Entire unit bentonitic and shows soft deformation apparently related to adjustment in channel below. Top of unit is a prominent 0.1-m-thick, black, carbonaceous shale with coal streaks.	2.1	14.3
11	Mudstone, light yellow gray, sandy, bentonitic, forms a distinctive tan band on the brow of the hill, low ledge former. Unit is a channel filling with mudstones and splay sandstone across unit 9 and is thicker to north and south.	1.4	12.2
10	Shale, carbonaceous with thin coal; forms a distinctive thin, dark band on the hill, with a medium brown lower and upper third, with coaly streaks throughout the middle third.	0.4	10.8
9	Mudstone, massive gray to medium gray at the base, grades up to through medium to light gray green and yellowish gray to light yellow gray at the top; slightly gypsiferous.	0.9	10.4
8	Shale, carbonaceous, forms distinctive dark, pinkish brown flaky surface with some coaly streaks, becomes less dark brown in the sandy upper half, although coaly streaks occur throughout.	0.4	9.5
7	Mudstone, bentonitic, light gray slope former.	1.6	9.1
6	Mudstone, light greenish gray to medium greenish gray at base in basal 0.1 m and middle fifth and upper fifth, the other two fifths are yellowish gray; entire unit forms a distinctive striped band between prominent carbonaceous shales.	0.6	7.5
5	Shale carbonaceous, grades up to a massive brown mudstone.	0.4	6.9
4	Mudstone, same as unit 2.	0.4	6.5
3	Sandstone, light yellow orange to light orange gray, forms a moderate shoulder at the top of the prominent sandstone ledge, gypsiferous.	0.3	6.1
2	Mudstone, light gray green, sandy, forms a slight recess at the top of the sandstone section.	0.8	5.8
1	Sandstone, muddy, cross-bedded with paleocurrent toward the east. Occasional mudstone cross-bed lenses and some carbonaceous shale indicating that the sequence is a moldy event succession. Unit is top of the thick cliff-forming Sandstone 2, equivalent to units 10–11 of Pretty Place section, appendix D.	5.0	5.0

APPENDIX G

Wounded Toe Section of Upper Hell Creek and Lower Tullock Formations. Section begins at the base of Sandstone 3 in gully 800 m east and 400 m south of NW corner of section 33, T. 24 N, R. 43 E, and continues northward to top of outlier of Tullock beds, 900 m east and 250 m south of same NW corner, Sand Arroyo Quadrangle.

Unit	*Description*	*Unit Thickness (meters)*	*Cumulative Thickness (meters)*
	Tullock Formation, top of outlier		
21	Sandstone, slope former at the base, but forms prominent resistent concretionary bed toward the top; weathers like the sandstone above the X-coal in areas to the east. The upper 1.5 m forms a distinct concretionary protective cap at the top of the outlier. Top of section and exposures.	~2+	24.1+
20	X-coal and carbonaceous shale, interbedded coal and argillaceous beds both approximately 0.1 m thick. Brown carbonaceous shales with abundant macerated plant debris.	0.6	22.1
19	Mudstone, gray green, bentonitic, with a basal carbonaceous shale approximately 0.2 m thick and a thin coaly streak at the top; gypsiferous, becomes somewhat carbonaceous in the upper part as well; forms a gray slope zone.	1.1	21.5
18	Sandstone, like unit 16 above the Z-coal.	3.2	20.4
17	Mudstone, greenish gray, very sandy, bentonitic, forms a slope zone between the yellowish sandstones that produce a gray green outcrop along the eastern margin of the hill.	0.7	17.2
16	Sandstone, fine grained, argillaceous, light yellow gray to dusky yellow, semi-slope zone, abundant limonite and orange siderite nodules up to 2 or 3 cm in diameter.	0.2	16.5
15	Z-coal zone, basal 0.1 m of coal and the upper part of carbona-	0.5	16.3

	ceous brown shale; forms a distinct shoulder around the outlier, although only locally exposed, particularly on the southeast margin of the small hill.		

Top of Hell Creek Formation and base of Tullock Forma-tion

14	Mudstone, bentonitic slope zone, light gray green with a light sandy streak at the base, becomes somewhat darker olive green in the upper part.	0.7	15.8
13	Sandstone, argillaceous and very muddy, light gray green becomes somewhat more orange and limonite stained at the top; forms a slope zone and a rounded shoulder above the reentrant or shoulder on the thin carbonaceous shale. Cross-bedded with current directions toward the southeast or east, with mudstone partings within the sandstone, particularly in the middle and lower part.	0.3	15.1
12	Shale, carbonaceous with coaly streaks toward the top; shale is medium reddish brown to light reddish brown, forms a small shoulder and recess around the slope; iridium layer (?).	0.1	14.8
11	Mudstone, sandy with brown carbonaceous partings in the middle, becomes more carbonaceous toward top.	1.6	14.7
10	Sandstone, argillaceous, soft, grades up to light yellow gray green slope and shoulder between mudstones.	1.2	13.1
9	Shale, carbonaceous with coaly partings toward the top, forms a brown zone around the hill with coaly streaks in the upper 0.1; light brown to light reddish brown, forms a distinctive key unit; small vertical ledge.	0.4	11.9
8	Mudstone, light olive gray, bentonitic, slope former forms rounded shoulder above terrace held up by Sandstone 4 of unit 7.	1.7	11.5
7	Sandstone 4, sandstone forms large cross-bedded "logs" on the south side of the outlier as well as across the low pass to the east toward the fence lines; light gray, fine to medium grained, ledge former.	1.9	9.8
6	Mudstone same as below becomes increasingly sandy toward the top. Moderately common distinct siderite nodules in the middle; becomes somewhat more yellow gray as sand content increases.	0.4	7.9
5	Mudstone, carbonaceous, forms generally dark band in the gray green mudstone bluff, very clayey, light to medium gray.	0.4	7.5
4	Sandstone grading up to sandy mudstone, light olive gray, weathers the same, slightly lighter near the base, slope zone.	1.5	7.1
3	Mudstone, light olive gray, bentonitic, caps the moderately regular lenses in the amphitheater south of the Z-outlier, near Wounded Toe, siderite concretions become increasingly common toward the top, with some siderite concretions as sandy units but others as black ironstones.	0.6	5.6
2	Sandstone 3, sandstone cross-bedded with numerous interbedded thin mudstone partings, transport direction toward the northeast. Sandstones hard, ledge forming, argillaceous. Mudstones generally 0.1–0.3 m thick, form swollen, bentonitic lines after rains; cross-bed sets generally 2–3 m thick in the light gray green slope zone and semi-ledges. Mudstones become much more common and over 50% of the unit toward the top.	3.1	5.0
1	Sandstone gray green, light olive with carbonaceous streaks with numerous light yellow brown sandstone concretions, forms toadstool park-type topography. Equivalent to unit 20 of Cow Pens section, appendix E.	1.9	1.9

APPENDIX H

McGuire Buttes Section begins 610 m west and 30 m south of northeast corner of section 36, in the small embayment where Z-coal is exposed and extends up to the northeast to Lebo beds at the west end of the western butte, 245 m west and 180 m north of the southeast corner of section 25, T. 22 N, R. 43 E, Bug Creek Quadrangle.

Unit	*Description*	*Unit Thickness (meters)*	*Cumulative Thickness (meters)*

Lebo Formation, eroded top

45	Sandstone, massive, capped by calcareous resistant concretionary layer, forms shear wall with overhanging blocks at the top of McGuire Buttes; channel fill, light yellow gray, weathers essentially the same; lower part only weakly cemented, upper part distinctly	9+	690+

	calcareous; paleocurrent flow almost due east, documented in concretionary top; sand, fine to very fine grained and homogeneous.		
44	Shale, carbonaceous, brown, flaky, moderate reddish brown to light brown, slope former between thick black shale and base of thick, massive sandstone.	0.6	60.0
43	Shale, carbonaceous, U-coal zone, common thick coaly streaks, slope and recessive thick unit. Same unit caps prominent, but small, black buttes along the fence line to the southeast.	1.1	59.4

Base Lebo Formation—top Hell Creek Formation

42	Sandstone as unit 39; massive, moderately to poorly exposed in steep bluffs, selenite bearing.	3.6	58.3
41	Claystone, olive gray, weathers light olive gray, semi-ledge zone, silty, capped by a thin 5 cm coal.	0.9	54.7
40	Shale, carbonaceous, grades up to thin coal with coaly streaks in the lower and upper 0.2 m, selenite common, unit forms a prominent shelf below massive thick sandstone that caps the butte.	0.6	53.8
39	Sandstone, light olive gray to yellow gray, massive, poorly cemented, friable, forms steep, prominent, homogeneous slope.	13.5	53.2
38	Coal, V-coal(?), powdery with abundant siderite nodules and clay stringers, forms a prominent recess in hillside, where it is not covered by angular debris from the overlying resistant sandstones.	0.7	39.7
37	Sandstone, same as unit 34.	0.8	39.0
36	Shale, carbonaceous, brownish gray, weathers light brownish gray; carbonaceous shales and coal form a distinct recess beneath sandstone.	0.3	38.2
35	Coal, powdery, with minor brown carbonaceous shale streaks.	0.2	37.9
34	Shale, carbonaceous, brownish gray, weathers light brownish gray.	0.2	37.7
33	Sandstone, yellowish gray to grayish yellow, poorly cemented, only moderately exposed in the gully sides, part of the prominent yellow double sandstone in upper part of the Tullock Formation.	1.0	37.5
32	Shale, carbonaceous, like unit 30, though pale brown to moderate brown, weathering pale brown, some disseminated plant debris.	0.5	36.5
31	Coal and interbedded carbonaceous shale, flaky, dark gray; coal with pink, ashy stringers.	0.3	36.0
30	Shale, carbonaceous, brown to moderate reddish brown, flaky, slope zone but exposed in gullies.	0.2	35.7
29	Sandstone, poorly exposed, like sandstone of unit 23.	3.7	35.5
28	Coal, upper W-coal(?), powdery; units 27 and 28 form a slope and recess between the somewhat more resistant sandstones; both are selenite bearing with small crystals approximately 1 cm across.	0.3	31.8
27	Shale, carbonaceous, brown, moderate slope former like unit 23, becomes distinctly flaky and is very dusky red to blackish red in the upper part beneath unit 28.	0.8	31.5
26	Sandstone, like unit 23, poorly exposed as semi-slope on grassy rounded bluff.	0.8	30.7
25	Shale, brown to moderate brown, carbonaceous, flaky.	0.3	29.9
24	Coal, lower W-coal(?).	0.3	29.6
23	Shale, carbonaceous, pale yellowish brown to pale yellowish brown, flaky; dark, carbonaceous streaks of macerated plant debris increasingly common in the upper part that grades into unit 24. Jarosite stained, particularly in the upper part. Selenite crystals, 1–3 cm long and across, occur in the middle part and are commonly amber colored.	1.1	29.3
22	Sandstone, light olive gray, weathers light olive gray with a siltstone approximately 0.4 m thick at middle; friable, slope zone.	3.1	28.2
21	Sandstone, concretionary, cross-bedded resistant unit eroding to massive blocks several meters across and 1–2 m thick; yellowish gray to pale olive, very fine grained at the base, grades to fine-grained sand at the top; lower and uppermost parts poorly cemented, but middle well cemented with calcium carbonate; few siderite nodules throughout, but in general unit is a persistent, clean sandstone with cross-bed sets to 1 m high. Unit capped by a moderately persistent siderite zone, 0.4–0.5 m thick, that allows the unit to be traced into the gullies to the north. Unit is part of major channel.	3.6	25.1
20	Sandstone same as below but with more common mudstones in upper part.	3.1	21.5

19	Sandstone with thin clay partings, forms vertical wall or irregular badlands, very pale orange to pale yellowish gray with some bands of grayish orange or dark yellowish orange on fresh surface, weathers somewhat lighter; most orange zones are thin concretionary siderite bands that produce striping. Unit subdivided into four major laminated subunits, separated by carbonaceous or bentonitic mudstones and claystones that are somewhat darker bands on the vertical wall; moderately well bedded in 10–15-cm-thick depositional units.	2.4	18.4
18	Mudstone, dusky yellow to yellowish gray, weathers yellowish gray; ledge former capped by interbedded gray mudstone and claystone. Locally the unit forms a prominent bluff and elsewhere a rectangularly jointed castellate surface, like unit 17 below.	1.2	16.0
17	Mudstone with sandstone and claystone interbeds in striped layers, erodes to a castellate surface; mudstones, moderate to light yellowish brown or light olive brown; bentonitic claystone, light olive gray. Unit capped by a thin bentonitic, moderately yellow brown claystone marker around the hillside. Lower part of unit is prominent, light gray, sandy claystone.	1.4	14.8
16	Sandstone, prominent ledge former, massive, forms vertical to massive walls with numerous limonite and calcareous concretions scattered throughout in strongly cross-bedded accretionary units, which here add on directly eastward. Point-bar lenses of mudstone particularly common in lower part. Large siderite concretions up to 1 m in diameter and 0.3–0.4 m thick mark top of unit.	1.5	13.4
15	X-coal, with 3–4-cm-thick, brown, carbonaceous shale partings, particularly in the lower part; coal grades upward from somewhat moderate quality coal into good quality coal; zone forms a prominent recess below overlying massive sandstone; 1 cm thick, pink ashy units occur as discontinuous partings in the coal, particularly near the base. Upper surface of the coal is one of the abrupt regional surfaces where floods of sand buried the coal over much of the quadrangle.	0.3	11.9
14	Sandstone, grades up into carbonaceous shale; sandstone, yellowish gray, forms prominent bleached zone; grades from unit 13.	0.5	11.6
13	Shale, carbonaceous, like unit 11 with interbedded sandstone, forms prominent brown band below X-coal.	0.4	11.1
12	Sandstone with interbedded carbonaceous shale, shoulder former; sandstone pale yellowish brown, carbonaceous shale pale brown to moderate brown with darker brown carbonaceous streaks and indeterminate coaly plant debris.	0.5	10.7
11	Coal, with 2–3 cm brown, carbonaceous shale at the base; coal of moderate quality but with numerous clay partings in lower half; has abrupt contact with unit 12.	0.4	10.2
10	Siltstone, light yellowish gray to light brown, somewhat less massive and more platy in the upper half, rounded shoulder former.	0.4	10.2
9	Sandstone, light olive gray, weathers light yellowish gray; distinctive salt-and-pepper sand; massive semi-ledge zone with ill-defined cross-beds; argillaceous, poorly cemented.	1.0	9.4
8	Claystone, becomes somewhat sandy in upper part and grades into unit 9; siderite bands discontinuous; forms small rounded badland shoulder.	0.5	8.4
7	Claystone, sideritic, characteristic "zebra" beds, yellowish gray to dusky yellow with light brown to dark yellowish orange concretionary siderite bands; unit capped by a prominent, persistent, siderite band 5–6 cm thick; unit forms a persistent small ledge.	0.4	7.9
6	Claystone, yellowish gray to dusky yellow with some light brown to light orange brown bands; contains silty partings and isolated small siderite concretions; forms a prominent banded ledge of "zebra" beds. Claystone layers 0.1–0.2 m thick with carbonaceous and woody coalified partings; becomes siltier upward.	2.0	7.5
5	Shale, dark brown to dark yellowish brown, weathers grayish orange pink to pale yellowish brown with carbonaceous streaks and macerated plant debris; forms a low slope zone. Minor selenite and jarosite throughout, with a few thin discontinuous coaly partings.	0.4	5.5

4	Coal, Z-coal, powdery but contains vitrain bits; 3–5 cm carbonaceous brown shale at the base, forms a prominent recess.	0.3	5.1

Base Tullock Formation, top Hell Creek Formation

3	Claystone, brownish gray, weathers light brownish gray with popcorn surface, forms small shoulder above slope of unit 2; bentonitic. Unit is bleached to the west in the embayment and is locally light gray along the traverse, with thin sandy partings that are light olive gray and weather yellowish gray; grades up to dark yellowish brown to pale brown, somewhat silty, claystone.	0.3	4.8
2	Mudstone, with thin sandstone and claystone partings in laminated micro-cross-beds and minutely slumped units; mainly yellowish gray with some laminae pale yellowish brown or dark yellowish orange; siderite concentrated at some laminae, like "zebra" beds except with strong cross-bedding. Unit forms slope and grades from sandstone at the base into a bentonitic claystone at the top.	1.5	4.5
1	Sandstone, light yellowish gray to pale olive, salt-and-pepper, weathers light yellowish gray; fine grained, moderately dirty with subangular to subrounded grains; moderately cemented, forms a badland slope above flat valley fill. Large cross-bed sets and numerous concretions common, particularly near the top. Calcareous, ripple marked leveelike sandstone caps the unit, weathers dark yellowish orange to light brown. Base not exposed.	3.0	3.0

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