

Depositional Environments for Strata of Composite Section of Frontier Formation, Madison Range, Southwestern Montana

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By R.G. TYSDAL

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By R.G. Tysdal

ABSTRACT

The Frontier Formation was measured in two partial sections in the Madison Range in order to obtain nearly complete exposures for stratigraphic and sedimentologic interpretation. The two sections form a composite section for the Frontier. The lower section of the Frontier, measured at Lincoln Mountain where it is 102 m (336 ft) thick, is a tripartite succession. The lower part consists mainly of sandstone and bioturbated sandstone deposited in a lower shoreface environment of a delta front facies. These strata are conformable with the underlying Mowry Shale. The middle part is composed of thin interbedded strata laid down in a delta plain setting. Tuff of the middle part forms a marker unit of resistant outcrops and likely was deposited subaerially. Carbonaceous mudstone forms marsh deposits that grade into sandstone interpreted as deposits of a sandflat marginal to a lagoon or bay. At one horizon in the middle part, a gently dipping, planar sandstone that contains a few percent of well-rounded quartz grains crops out and is interpreted as an overwash-fan deposit. Limestone coquina composed of brackish-water bivalves caps the middle part and is interpreted as a deposit of a bay or lagoon. The upper part of the sequence present at Lincoln Mountain is composed of rhythmically interbedded mudstone, silty mudstone, and sandstone deposited in a delta front environment, possibly a mouth-bar deposit. An unconformity, which represents much of the Cenomanian as well as early Turonian time, exists between the delta front deposits and those of the underlying delta plain.

The upper section of the Frontier was measured near the hamlet of Big Sky, where it is about 140 m (459 ft) thick. Strata deposited in interbedded prodelta and delta front facies make up most of the section. Delta front clastic rocks include several units of hummocky cross-stratified sandstone, some of which contain abundant trace fossils, and are interpreted as storm deposits. Thinly interbedded siltstone, fine-grained sandstone, and mudstone are interpreted as deposits of a prodelta slope that formed directly seaward of the lower shoreface of a delta

front. Some of the individual sandstone beds within the prodelta strata show hummocky crossbeds, interpreted as single-event distal storm deposits. Delta front sandstones of the foreshore and backshore record upward shallowing environments.

A delta plain facies forms the upper 25 m (82 ft) of the measured section near Big Sky. The strata consist of carbonaceous to coaly mudstone, siltstone and claystone, and tuff. These rocks include abundant fresh and brackish water megafossils and sedimentary structures indicative of delta plain lakes and brackish water swamps. The tuffs range from well indurated, silicified beds to deeply weathered bentonitic strata. Some of the tuffs were deposited within water, showing ball-and-pillow structures, whereas other beds may have been deposited subaerially. Uppermost strata of the delta plain sequence constitute an estuarine tidal channel deposit that consists, in ascending order, of pebble conglomerate, fine-grained sandstone that contains siltstone to mudstone interbeds, and lenticular bedded mudstone and clayey siltstone. These strata are erosionally based in a mudstone interpreted as a marsh deposit. An unconformity marks the contact of the Frontier Formation with the overlying Cody Shale.

INTRODUCTION

The Madison Range lies in the Rocky Mountain foreland of southwestern Montana (fig. 1) and contains as much as 4,600 m (15,000 ft) of Phanerozoic sedimentary strata, which overlie Archean metamorphic rocks. Geologic studies in the Madison Range were undertaken during evaluation of much of the range for inclusion in the National Wilderness System. An understanding of the Cretaceous strata was a prerequisite to deciphering structural features of the range. Detailed measurement of Cretaceous sections permitted correlation of formations throughout the map area. Study of the Frontier Formation led to recognition of depositional changes, time constraints, and, ultimately, depositional environments of the strata.

Cretaceous rocks, virtually all clastic rocks, make up about half of the Phanerozoic sequence in the Madison Range (fig. 2). Sediments of the Frontier were derived from terrane undergoing folding and thrusting in the Sevier orogenic belt in the hinterland to the west. These sediments were deposited in the western part of the Western Interior Seaway in a deltaic setting, which existed in the region of the Madison Range (McGookey and others, 1972).

The Frontier Formation in the Madison Range generally is poorly exposed, and nowhere is the formation exposed in one continuous sequence. The formation is about 217 m (713 ft) thick in the composite measured section presented here. The lower part of the composite section is exposed at Lincoln Mountain, about 8 km (5 mi) west of Montana State Highway 191 (fig. 1). The upper part of the composite section is exposed in a lengthy roadcut about 3 km (2 mi) west of the village of Big Sky. Exposures

SYSTEM	SERIES	FORMATION
CRETACEOUS	Upper	Telegraph Creek Formation
		Cody Shale
		Frontier Formation
	Lower	Mowry Shale
		Muddy Sandstone
		Thermopolis Shale
		Kootenai Formation

Figure 2. Sequence of Cretaceous formations present directly above and below Frontier Formation in the Madison Range. Queried boundary of Lower and Upper Cretaceous rocks is based on work of Cobban and Kennedy (1989).

showing the contact of the two parts of the composite section were not found during mapping in the range.

The two measured sections are interpreted as comprising a composite section of the Frontier on the basis of their megafaunal content (Tysdal and others, 1990). Megafossils from the top of the Lincoln Mountain section are of the early middle Turonian *Collignonicerus woollgari* faunal zone. Megafossils obtained from near the middle of the Big Sky section are fragmented and not abundant, but they are interpreted to represent the late middle Turonian *Prionocyclus hyatti* faunal zone (W.A. Cobban, in Tysdal and others, 1990). W.A. Cobban (oral commun., 1989) said a possibility exists that the faunal remains could be of forms that are from the older *C. woollgari* zone, but this is not the favored interpretation. If the latter possibility is true, then the two sections could contain some time-equivalent strata, except for uppermost strata of the Big Sky section from which fossils of the *P. hyatti* zone were obtained. The sedimentological interpretations presented here would still pertain, but the lateral relationships of any time-equivalent strata, which would be of different depositional environments, are unknown. The two sections do not share a key bed or like sequences.

Many of the data for this report were obtained from the two measured sections that are graphically displayed in figures 3 and 4. Environments represented in the composite measured section are interpreted within a deltaic framework present in the region at the time of deposition, even though the composite section by itself does not permit the reconstruction of the lateral relationships over long distances. Figure 5 shows a schematic deltaic setting illustrating the depositional environments used for interpretation of the strata present in the composite measured section.

The graphic measured sections of figures 3 and 4 were generated from the Stratigraphic Report Graphic, a stratigraphic applications computer program developed by the U.S. Geological Survey and Petroleum Information Corporation of Denver, Colo. (Petroleum Information Corporation, 1984; Dyman and others, 1985). The program

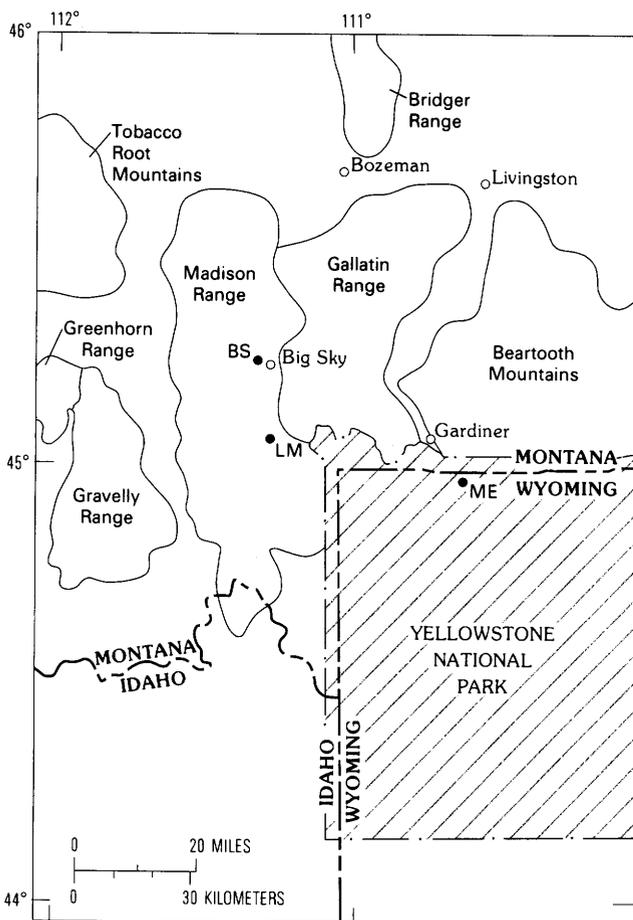


Figure 1. Index map of southwestern Montana showing mountain ranges and locations of measured sections referred to in text. Abbreviations for locations are as follows: LM, Lincoln Mountain; BS, Big Sky; ME, Mount Everts. The Lincoln Mountain locality is site of measured section shown in figure 3, and the Big Sky locality is site of measured section shown in figure 4.

is proprietary to Petroleum Information Corporation, but it is available by contract to the U.S. Geological Survey for a variety of research applications.

Megafossils discussed in this report were identified by W.A. Cobban and, except where specifically noted, their names were published previously in Tysdal and others (1990).

Purpose of Study

The Frontier Formation in the Madison Range affords a key composite measured section for regional stratigraphic correlation. The Madison Range composite section is about 80 km (50 mi) southwest of outcrops near Livingston, Mont.; 55 km (35 mi) west of outcrops at Mount Everts in the northernmost part of Yellowstone National Park; and 200 km (125 mi) northwest of outcrops in the Jackson Hole area of northwestern Wyoming, south of the Park (fig. 1). Frontier strata have been eroded from most of the region between the Madison Range and these other areas, although, locally, Frontier strata are concealed beneath younger sedimentary and volcanic rocks. Strata of the Big Sky measured section are younger than those of sections in some areas to the east, facies differ from some of those present in other areas, and the strata are distant from those of other areas. Frontier strata in the Greenhorn Range, about 55 km (35 mi) west of the Madison Range, are much thicker and were deposited in marginal marine and nonmarine environments (Tysdal and others, 1990). The purpose of this report is to describe the strata of the composite measured section and to interpret their depositional environments.

In this report, "lithologic unit" is used as a nongenetic term to describe a specific kind of rock (for example, sandstone, limestone, tuff); or to describe interbedded rocks of different kinds (for example, interbedded sandstone and mudstone) that, combined, form a distinct rock unit. The term has virtually the same meaning as the informal lithostratigraphic unit called a lithosome (Bates and Jackson, 1987, p. 384), which has fallen into disuse in recent years. The Lincoln Mountain section (fig. 3) and the Big Sky section (fig. 4) each is composed of lithologic units that are numbered sequentially from bottom to top. Depositional environments are interpreted for each of the lithologic units, which are placed within a deltaic framework facies (for example, delta plain facies) as shown in figure 6. Contact relationships for the facies are discussed for each of the measured sections.

Previous Work

The Frontier Formation in the Madison Range was first distinguished from other Cretaceous strata by Tysdal and Simons (1985) during mapping in the central and

southern part of the range. The lower contact of the Frontier was placed at the base of the first sandstone unit above dark-gray mudstone and silty mudstone assigned to the Mowry Shale (Tysdal and others, 1989a, b). A graphic composite section and description of rock units that make up the formation were presented in Tysdal and others (1990).

Many studies in the Madison Range were mapping projects in which Frontier strata were not distinguished from most other Cretaceous rocks. Frontier strata are part of a unit mapped as "Colorado and Montana formations" (Peale, 1896), Colorado Group (Becraft and others, 1970; Garihan and others, 1983), and an unnamed unit (Swanson, 1950). Along the western flank of the central part of the Madison Range, Hadley (1969, 1980) used the name Frontier Formation for a thick succession of strata that included the Frontier Formation as used here, but also he included several formations that underlie and overlie the Frontier. In the east-central part of the Madison Range, much of the previous work constituted fairly detailed thesis studies. Hall (1961), Lauer (1967), Ray (1967), Rose (1967), Bolm (1969), Kehew (1971), and Walsh (1971) used Cretaceous strata undivided or undifferentiated for rocks that included part or all of the Frontier Formation.

Some of the lower Frontier strata at Lincoln Mountain were assigned to the Mowry Shale by Wilson (1970) and Vuke (1982, 1984). Schwartz (1972) assigned the same lower Frontier strata to his Blackleaf Formation unit D, which he equated with the Mowry. Austin and Stoeber (1950) assigned the same Frontier strata to the Aspen(?) Formation, a name used in western Wyoming and eastern Idaho. These assignments of lower Frontier strata to other formations were made, at least in part, to include porcellanitic tuff (fig. 3, lithologic units 13, 14) that lies about 33 m (108 ft) above the base of the Frontier as mapped by Tysdal and Simons (1985) and Tysdal (1990) and as defined in some detail by Tysdal and others (1989a, b; 1990). Pastel-colored porcellanitic and bentonitic strata are common in the lower part of the Mowry Shale, 84 m (274 ft) beneath the base of the Frontier at Lincoln Mountain. The above thesis authors probably thought that the porcellanitic tuff of units 13 and 14 of the Frontier represented additional volcanic material of the Mowry. The pastel strata were assigned to the Vaughn Member of the Mowry Shale by Tysdal and others (1989b).

LINCOLN MOUNTAIN MEASURED SECTION

Delta front and delta plain facies are represented in strata that make up the section of the lower part of the Frontier measured at Lincoln Mountain. The strata are

EXPLANATION	
LITHOLOGY	DESCRIPTION
	Granitic rocks
	Conglomerate
	Sandstone, massive
	Sandstone, laminated
	Sandstone, rippled
	Sandstone, crossbedded
	Limestone
	Siltstone
	Shale
	Mudstone
	Tuff
	Bentonite
	Covered

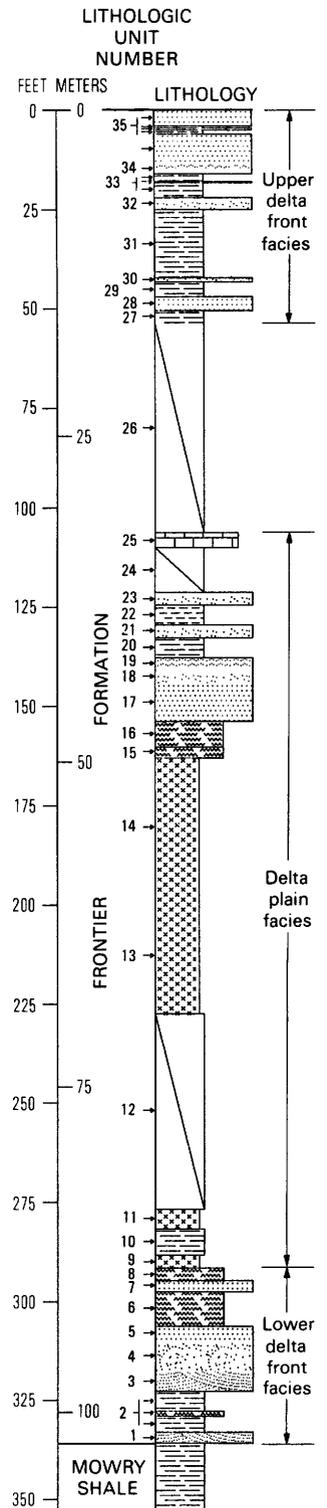


Figure 3. Graphic log of lower part of Frontier Formation, showing facies interpreted for sequences of lithologic units. Arrow to right of each lithologic unit number points to middle of unit. The section was measured in gently dipping strata on Lincoln Mountain, NW¹/₄NW¹/₄ sec. 7, T. 9 S., R. 4 E., Lincoln Mountain 7.5-minute quadrangle.

transitional with the underlying Mowry Shale, but the top of the uppermost strata of the section is a present-day erosional surface. The lithologic unit numbers referenced in the text concerning the measured section at Lincoln Mountain correspond to those in figure 3 and to the those presented in Tysdal and others (1990).

Lower Delta Front Facies

Sandstone and Siltstone

This facies, about 13 m (43 ft) thick, consists of interbedded sandstone and lesser siltstone and mudstone

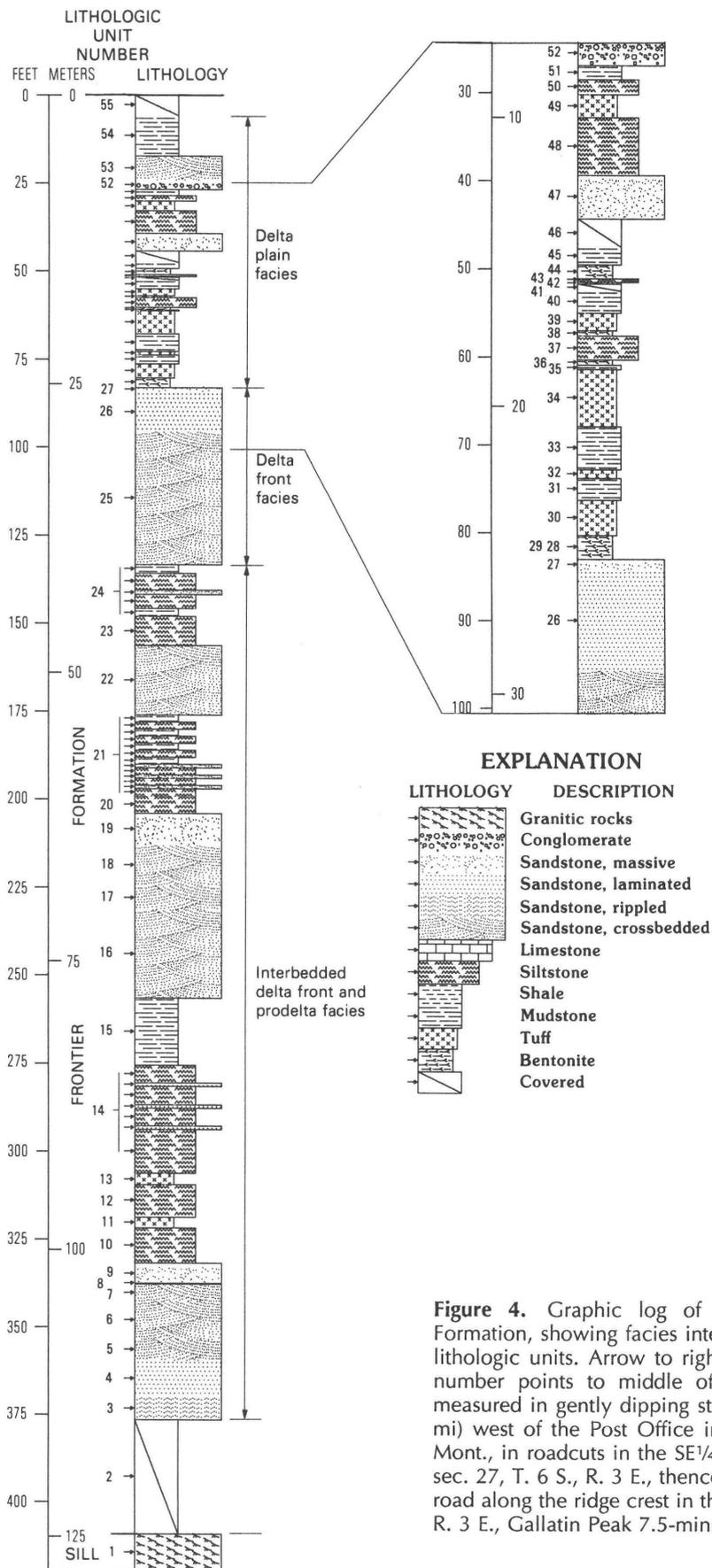


Figure 4. Graphic log of upper part of Frontier Formation, showing facies interpreted for sequences of lithologic units. Arrow to right of each lithologic unit number points to middle of unit. The section was measured in gently dipping strata 3.7–5.6 km (2.3–3.5 mi) west of the Post Office in the village of Big Sky, Mont., in roadcuts in the SE¹/₄ sec. 28 and SW¹/₄SW¹/₄ sec. 27, T. 6 S., R. 3 E., thence southeastward from the road along the ridge crest in the NW¹/₄ sec. 34, T. 7 S., R. 3 E., Gallatin Peak 7.5-minute quadrangle.

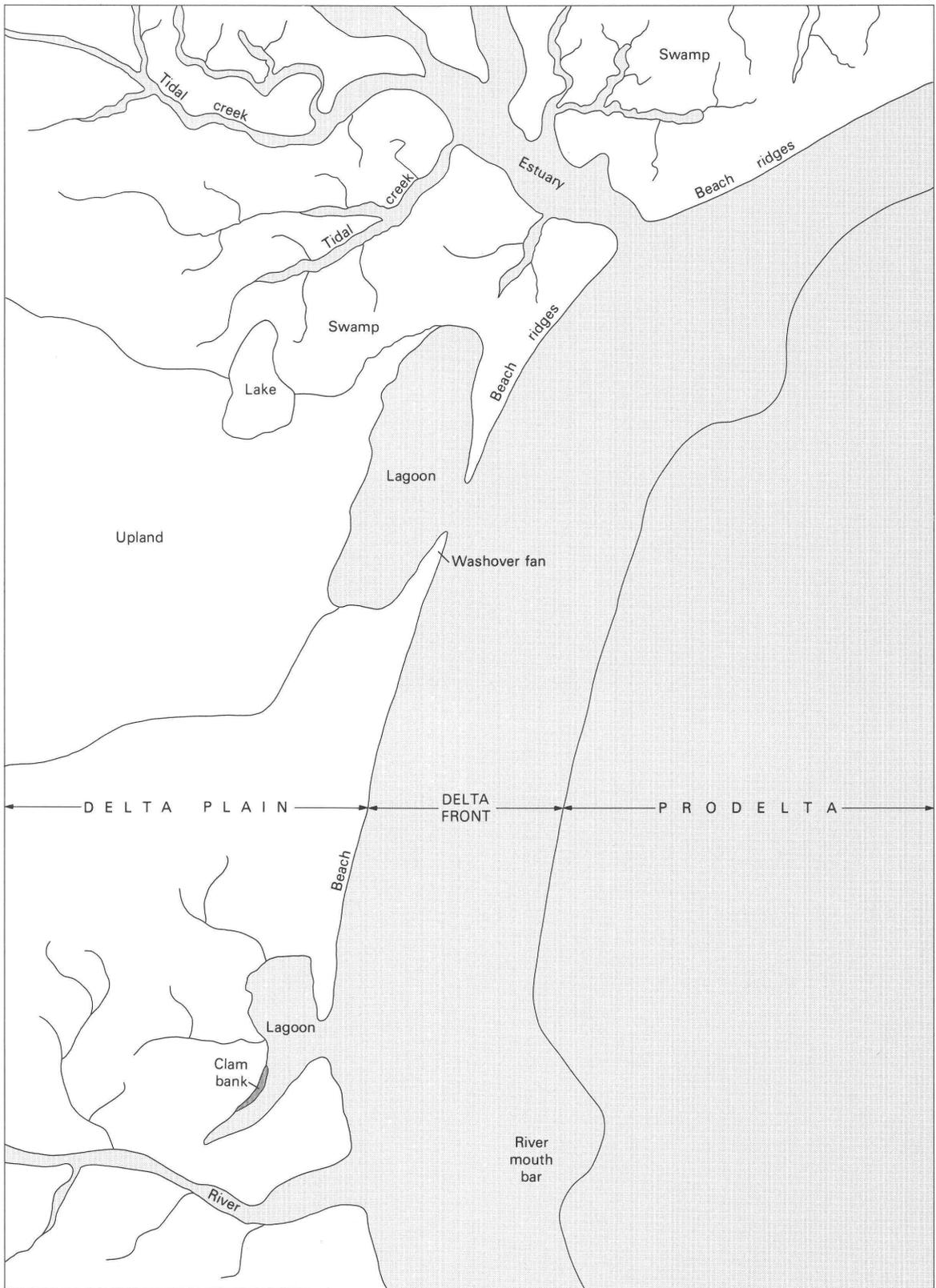


Figure 5. Schematic diagram of a delta showing depositional environments that are interpreted to be represented by strata in the composite measured section of the Frontier Formation in the Madison Range.

DEPOSITIONAL ENVIRONMENT	FACIES
Lake or pond Lagoon Backshore Dune	Delta Plain
Foreshore Upper shoreface Lower shoreface	Delta Front
Offshore	Prodelta

Figure 6. Diagram showing the facies classification scheme used in this report and the corresponding depositional environments interpreted for strata of the Frontier Formation in the Madison Range.

(lithologic units 1–8). The units are generally 1–2 m (3–7 ft) thick and record an abrupt change in grain size from the mudstone and clayey siltstone that characterize the underlying Mowry Shale. The sandstone is greenish gray and is composed of quartz, feldspar, chert, rock fragments, mica, and locally glauconite. Sorting ranges from good to poor, with some strata (fig. 3, lithologic units 4, 5, and 7) consisting of grains that range from very fine to fine and, locally, medium size, along with clay. Beds are commonly thin, planar, and finely laminated. Sandstone of units 1 and 3 is thin to medium bedded and displays both plane beds and low-angle crossbeds. Dark-brown to gray carbonaceous mudstone and clayey siltstone, like that in the upper part of the underlying Mowry Shale, occur locally (unit 2) in the lower part of the sequence. Siltstone and clayey siltstone units are thinly bedded and finely laminated to rippled.

Ophiomorpha burrows are abundant in lithologic unit 5 and so are fragments of megafossils and plants. Bioturbation has disrupted most of the laminae of units 4, 5, and 7. The following megafossils, which are not age-diagnostic, were collected from unit 1 by Tysdal and others (1990): *Oxytoma* sp., *Camptonectes* sp., *Aphrodina* sp., *Goniomya* sp., *Lingula subspatulata* Hall and Meek, a juvenile ammonite of indeterminate species, and fish bones. Unit 6 yielded a palynomorph assemblage of mixed marine and nonmarine fossils (Tysdal and others, 1990). This palynomorph assemblage, and those from the underlying Mowry Shale that were previously assigned to the Albian by Tysdal and others (1989a, b), are considered to be early Cenomanian in age. The early Cenomanian age is based on a reinterpretation of molluscan megafossil data of the Cretaceous Western Interior (Cobban and Kennedy, 1989); assignments for palynomorphs assemblages are based on correlation with the Cretaceous molluscan fossil zones.

Interpretation

Lithologic units 1–8 form a sequence deposited in shallower water than that of the mudstone and clayey siltstone in the underlying Mowry Shale. Intertonguing of lithic units of differing grain size reveals a gradual upward

increase in grain size from underlying Mowry strata and reflects a gradual overall increase in wave energy. The sequence displays physical sedimentological features characteristic of lower shoreface deposits, as described by Reinson (1984) and Leckie and Walker (1982). The lower shoreface is a low energy environment where waves first begin to affect bottom sediments. Sands are generally fine to very fine grained and contain interlayered silt and clay. Laminae are planar but commonly are obliterated by bioturbation. The abundant fossil fragments of differing sizes indicates little reworking by waves.

Megafossils present in the lowermost unit are marine forms. The palynomorphs of unit 6 are a mixed assemblage of marine and nonmarine forms. This grouping of mixed forms is most likely to occur in a nearshore marine setting where nonmarine palynomorphs constitute an admixture, assuming the marine fossils are not recycled. The horizontal boxwork pattern displayed by *Ophiomorpha* (lithologic unit 5)—the burrow of a suspension-feeding animal—also is characteristic of the lower shoreface. *Ophiomorpha* has two general patterns of occurrence: steeply inclined shafts, which predominate in higher energy environments (such as the upper shoreface or foreshore), and boxwork mazes, which characterize lower energy environments (such as the lower shoreface) (Frey and others, 1978).

Delta Plain Facies

This facies totals about 56 m (184 ft) thick and contains thin interbedded lithologic units deposited in several closely related depositional environments of a delta plain.

Tuff

Pale-yellowish-green to medium-gray indurated tuff (fig. 3, lithologic units 9, 11, 13, and 14) forms prominent outcrops in the middle part of the Lincoln Mountain section. Units 13 and 14 together form a marker unit that is about 20 m (66 ft) thick at Lincoln Mountain and is widespread in the central part of the Madison Range. The tuff is glassy (porcellanitic) and breaks with a conchoidal fracture. It is well indurated, although not welded, and contains well preserved shards and some nearly complete bubble structures. Plagioclase phenocrysts are widely dispersed within the tuff; biotite is a minor constituent. None of the phenocrysts or shards, some of which are elongate, show preferred orientation.

Interpretation

Tuffs of units 13 and 14 are interpreted as airfall deposits laid down subaerially on a delta plain. The lack of preferred orientation of the constituents of the tuff, and

preservation of delicate elongate shards and nearly complete bubbles within glass, indicate that the constituents did not undergo sorting by water. The tuffs of units 9 and 11 were not examined in thin section; thus, their internal fabric is unknown, and it is uncertain if the tuffs were deposited subaerially or in water. None of the units show ball-and-pillow structures, which would indicate deposition on a muddy, water-saturated substrate.

Mudstone and Siltstone

Dark-gray to olive-brown mudstone, clayey siltstone, and shale make up most of the strata of lithologic units 10, 15, 16, 20, and 22 (fig. 3). Thin interbeds of bentonite are present in units 10, 15, and 16. Each of the five units is 1–2 m (3–7 ft) thick and is poorly exposed. The rocks contain comminuted carbonaceous debris and generally lack sedimentary structures that are visible in the outcrop or hand specimens. Clayey siltstones contain thin interbeds of finely laminated bentonite (weathered tuff). Unit 16 contains a freshwater gastropod, *Carinorbis* sp., and upper units are closely associated with strata that contain brackish water fossils (see next section), but no fossils were recovered from these other units.

Interpretation

The mudstones and clayey siltstones were laid down where nonmarine and brackish water environments merge and are interpreted as deposits of the lower part of a marsh that fringed a restricted bay or a lagoon. The interlayered bentonites of units 10, 15, and 16 are subaerial tuffs, and unit 16 contains a nonmarine fauna. The upper two lithologic units (20 and 22) of the lithofacies are interbedded with strata that contain a brackish water fauna and are thought to be deposits of a restricted bay. The siltstone of unit 16 is thoroughly burrowed. Preservation of the fine layers of bentonite in some of the lower rock units at Lincoln Mountain suggests a quiet depositional environment that lacked reworking by burrowing organisms or plants. This lack of reworking could indicate deposition in an anoxic environment, such as a pond, or perhaps deposition of the volcanic ash caused temporarily unfavorable living conditions for infauna.

Clayey Sandstone

Sandstone strata included here range from clay-rich to clay-poor and are 1–1.5 m (3–5 ft) thick. Lithologic unit 23 (fig. 3) is a clay-rich sandstone that is dark gray, fine grained, clayey, carbonaceous, and rubbly weathering. Clay-poor sandstone units 18 and 21 are medium and light gray, fine to medium grained, and chert- and quartz-rich. A resistant sandstone bed about 1 m (3 ft) thick (unit 19) forms the most distinctive lithologic unit and includes both clayey

and fairly “clean” sand. Most of the bed is very dark gray to black sandstone that has a matrix of carbonaceous mudstone. The dark sandstone contains abundant brackish water fossils in a near-coquinoid assemblage of *Veloritina?* sp., a gastropod; and *Corbula*, aff. *C. subtrigonalis* Meek and Hayden, and *Melania* sp., which are bivalves. The medium- to light-gray sandstone of the upper few centimeters of unit 19 is slightly calcareous and displays planar to wavy laminations. No megafossils were found in the upper part of unit 19, but nearly vertical burrows of the trace fossil *Skolithos* are present. The animal that produced the trace fossil *Diplocraterion* caused mixing of clay into the sandstone.

Interpretation

The fairly clean sandstones of units 18, 21, and the upper few centimeters of unit 19 are interpreted as intertidal deposits laid down in the foreshore to shoreface of a lagoon or a bay. Sandstones with a claystone matrix of high organic content (carbonaceous) (unit 23 and lower part of unit 19) and the brackish water faunal assemblage of unit 19 both are suggestive of the shallow part of a lagoon or bay, similar to modern lagoons described, for example, by Shepard and Moore (1955), Newman and Munsart (1968), and Warne (1971). The change in composition from a mixed sandstone and mudstone in the lower part of unit 19 to a fairly clean sandstone with vertically oriented trace fossils in the upper part indicates a change in energy conditions. The lower part represents quiet water deposition relative to the upper part that likely was directly affected by waves and (or) currents. The change is abrupt and is consistent with a change from subtidal or lower intertidal to intertidal shoreline (sandflat) deposit of a lagoon or bay. The sandy fossil-bearing strata also could have been deposited in a tidal channel that coursed its way through intertidal deposits (Howard and Frey, 1975; Thorbjarnarson and others, 1985), although this seems less likely.

Finely Laminated Sandstone

Finely laminated sandstone of lithologic unit 17 (fig. 3) is about 10 m (33 ft) thick and is composed of light-greenish-gray sandstone that is fine grained and poorly sorted. Beds are 1–3 cm thick, dip 1–2°, are planar and finely laminated. The sandstone is composed of quartz, chert, feldspar, rock fragments, and glass shards. Some of the quartz grains are well rounded.

Interpretation

The strata are interpreted as a storm washover-fan deposit on the basis of bedding style, primary sedimentary structures, composition, and stratigraphic position. Thin, flat beds that commonly dip 1–4° toward a fan terminus are

the dominant bedding style of washover fans (Hayes, 1967; Schwartz, 1981; Barwis and Hayes, 1985). The strata lie within a regressive sequence. Because washover fans occur at high elevations in a barrier sequence, their preservation potential is greatest in a regressive succession where they can be buried beneath prograding back-barrier sediments. Strata associated with unit 17 are nonmarine, downsection a few meters, and a bay or lagoonal sandstone containing brackish-water fossils a few meters upsection. Lateral exposures are not sufficient to observe intertonguing of the different stratigraphic units.

Limestone Coquina

The delta plain facies is capped by a prominent bed (fig. 3, lithologic unit 25) of light-gray limestone coquina composed of the brackish water mollusks *Leptesthes* sp., *Veloritina* sp., and *Corbula* sp. in a matrix of micrite. Disarticulated bivalves of the nonmarine mollusk *Protoeliptio hamili* (McLearn) were reported by Wilson (1970) from this unit. Residue of the limestone contains abundant charophytes (W.A. Bryant, USGS, oral commun., 1988). The bed is about 1 m (3 ft) thick and forms a marker unit.

Interpretation

The coquina of unit 25 is interpreted as a brackish-water limestone deposited along the margin of a restricted bay or perhaps along a tidal stream. Charophytes, green algae of which modern species reside only in nonmarine habitats, mixed with the brackish-water mollusks, indicate that fresh water carried materials to the depositional site. The fossils have been reworked into an assemblage of fragmented debris by wave or current action. Brackish-water assemblages of fragmented megafossils are common in the back-barrier bays of the Mississippi delta, where they are concentrated by storm processes (Kosters, 1989).

Upper Delta Front Facies

Rhythmically Interbedded Sandstone and Siltstone or Mudstone

Strata of this facies (fig. 3, lithologic units 27–35) consist of rhythmically interbedded sandstone and mudstone about 16 m (52 ft) thick. (The 16-m- (52-ft-) thick covered interval of unit 26 is not assigned to a facies.) The overall sequence coarsens upward, however. Mudstone comprises a greater volume of strata of the lower part of the sequence composed of units 27–35 and sandstone the greater volume of the upper part. Mudstone ranges from

light gray to dark olive gray, is carbonaceous, thin bedded, and finely laminated. The mudstone is sandy locally, but in the lower part of the sequence some strata are fissile, micaceous, and shaly.

Sandstone ranges from olive-green to gray-green or gray-brown and is composed of quartz, chert, feldspar, and minor glauconite. The grain size commonly is fine to medium, although lithologic unit 35 locally is coarse grained and contains well-rounded chert pebbles in layers as much as 5 cm (2 in.) thick. Most beds are only a few centimeters thick and show planar lamination, but a few beds in the upper part are as much as 50 cm (20 in.) thick. Some sandstone beds are lenticular; others are sharp-based and eroded into underlying sandstone to form composite or amalgamated beds. The 1-m- (3 ft) thick sandstone of unit 28, in the basal part of the sequence, grades from massive in the lower part; through plane-bedded in the middle; to finely laminated, wavy cross-laminated paper-thin layers in the upper part. Tool marks (flute and groove casts), oscillatory ripple marks, and horizontal burrows indicative of the *Cruizana* ichnofacies are common on bedding planes of sandstone in the upper third of the sequence of units 27–35.

The only fossils recovered from units 27–35 are of the middle Turonian mollusk *Collignoniceras woollgari* (Mantell), and some associated fish vertebrae (Tysdal, 1989; Tysdal and others, 1990). The fossils were found on bedding planes of the uppermost sandstone, which also contained tool marks.

Interpretation

Strata that make up the uppermost part of the Lincoln Mountain section are interpreted as delta-front sandstones, possibly distributary mouth-bar deposits, laid down directly shoreward of a prodelta slope. Rhythmic interbedding of fine-grained sandstone and mudstone or siltstone are typical features for this environment, as are graded sandstone beds (unit 28) (Allen, 1965). Most beds lack the grading displayed by unit 28, but both the grading and tool marks, displayed on several beds, would be expected in a setting where sediment was deposited rapidly from a turbid plume of river water debouching onto a delta front. Oscillatory ripple marks and trace fossils of the *Cruizana* ichnofacies both are features common to low wave-energy environments.

Contact Relationships of Facies in Lincoln Mountain Measured Section

The basal contact of the lower delta front facies of the Frontier Formation at Lincoln Mountain clearly is conformable with strata of the underlying Mowry Shale. Strata of the two formations are gradational, and the change

in nomenclature was determined on the basis of a fairly abrupt influx in silt and sand content from mudstone of the Mowry to sandstone assigned to the Frontier (Tysdal and others, 1990).

The contact of the lower delta front facies and the overlying delta plain facies is a hiatus, based on faunal content and interpretation of sedimentary environments. The upsection change in facies—from offshore strata in the upper part of Mowry Shale, to delta front strata (lower shoreface environment) of the Frontier, to delta plain strata of the Frontier—is a regressive sequence. Absence of upper shoreface and foreshore strata between the lower Frontier and delta plain sequences suggests that strata of these environments were deposited and later eroded. This could have been accomplished by a drop in sea level and erosion of the upper shoreface and foreshore deposits. Strata of the delta plain would have shifted seaward. With this interpretation, strata of the delta plain facies are closely related genetically and in time to the underlying Frontier and Mowry strata.

The contact of the regressive delta plain facies with the overlying upper delta front facies at Lincoln Mountain is not exposed. However, the marked contrast in depositional environments—brackish-water deposits of the uppermost delta plain facies to marine deposits of the delta front facies—almost certainly requires that an environmental change exist within the 16-m- (52-ft-) thick covered interval (unit 26) between the two facies. Further, the delta front facies is of middle Turonian age, in contrast to the early Cenomanian age of the regressive strata of the underlying part of the Frontier. The major hiatus between the two facies corresponds to the lacuna of the early Cenomanian–middle Turonian unconformity reported by Merewether and Cobban (1986) in western Wyoming and northward into central Montana (near Townsend, fig. 1).

BIG SKY MEASURED SECTION

Deltaic strata of prodelta, delta front, and delta plain facies crop out in the section of the upper part of the Frontier, measured near Big Sky. A covered interval and a thick granitic sill lie at the base of the section. Rocks beneath the sill, including strata correlatable with the lower section at Lincoln Mountain, are not exposed. The lithologic unit numbers referenced in the text concerning the section measured near Big Sky correspond to those in figure 4 and to those presented in Tysdal and others (1990).

Interbedded Delta Front and Prodelta Facies

Rocks of the lower part of the delta front and upper part of the prodelta facies form repeated lithologies within a

progradational (regressive) marine sequence. The facies is 87 m (285 ft) thick near Big Sky, making up the major part of the measured section.

Rhythmically Interbedded Sandstone and Siltstone or Mudstone

This recurring assemblage of rocks (fig. 4, lithologic units 7, 9, 11, 13, 14, 15, 20, 21, 23, and 24) consists of rhythmically interbedded siltstone or mudstone and lesser amounts of fine-grained sandstone (figs. 7 and 8). Two thin beds of bentonite (lithologic units 10 and 12) occur within the rhythmically interbedded sequence. The rhythmically interbedded strata are 1–7 m (3–23 ft) thick. Lithologic units 7, 9, 11, and 20 contain thin-bedded finely laminated siltstone and mudstone; sandstone is absent. Beds commonly range between 1 cm (0.4 in.) and about 10 cm (4 in.) thick, but a few are as much as 20 cm (8 in.) thick (fig. 9). Some of the sandstone fills erosional scours into the underlying siltstone or mudstone, forming sandstone lenses a few centimeters to tens of centimeters across. Pale-colored fine-grained sandstone traced laterally locally intertongues with dark siltstone, such that the sandstone is really a composite or amalgamated bed. Similar relationships were described by Swift and others (1987) in Cretaceous strata of central Utah.

The thickness and abundance of sandstone beds decrease upward; above unit 19, the lower few meters of these units contain more than 50 percent sandstone. Some sandstone beds only a centimeter or two thick are hummocky cross-stratified, and the clayey siltstone that overlies each sandstone bed reflects this microtopography. In other sandstone beds, hummocks grade laterally and upward into plane-bedded sandstone, which is overlain by siltstone and (or) mudstone. The base of each sandstone bed commonly is sharp, overlying mudstone.

A few groove casts were observed at the base of sandstone beds and graded sandstone beds occur locally. Horizontal burrows were found on a few beds, and vertical burrows occur in hummocky sandstone beds in a few places, but neither type of burrow is common. *Chondrites* burrows are present locally in mudstones that overlie beds of hummocky cross-laminated strata but also are not common.

Ball-and-pillow structures (fig. 10) form a zone about 50 cm (20 in.) thick in the lower part of unit 21 of the rhythmically interbedded strata. These ellipsoidal pillow-shaped structures formed from a bed of fine-grained sandstone that became segmented and foundered into the underlying silty mudstone. In some cases, the segmentation was not completed and some of the pillows are still connected. The pillows are fairly evenly spaced and range from 20–30 cm (8–12 in.) thick and from 100–125 cm (39–49 in.) wide; the length of the structures could not be determined. The laminae within each pillow are concave upward, parallel to the outline of the pillow and parallel to



Figure 7. Rhythmically interbedded sandstone, siltstone, and mudstone of lithologic units 23 and 24 (dark gray) between light-gray hummocky cross-laminated sandstone of lithologic units 22 and 25. Outcrop is about 25 m (82 ft) high roadcut in Big Sky measured section, SW¹/₄SW¹/₄ sec. 27, T. 6 S., R. 3 E., Gallatin Peak 7.5-minute quadrangle.

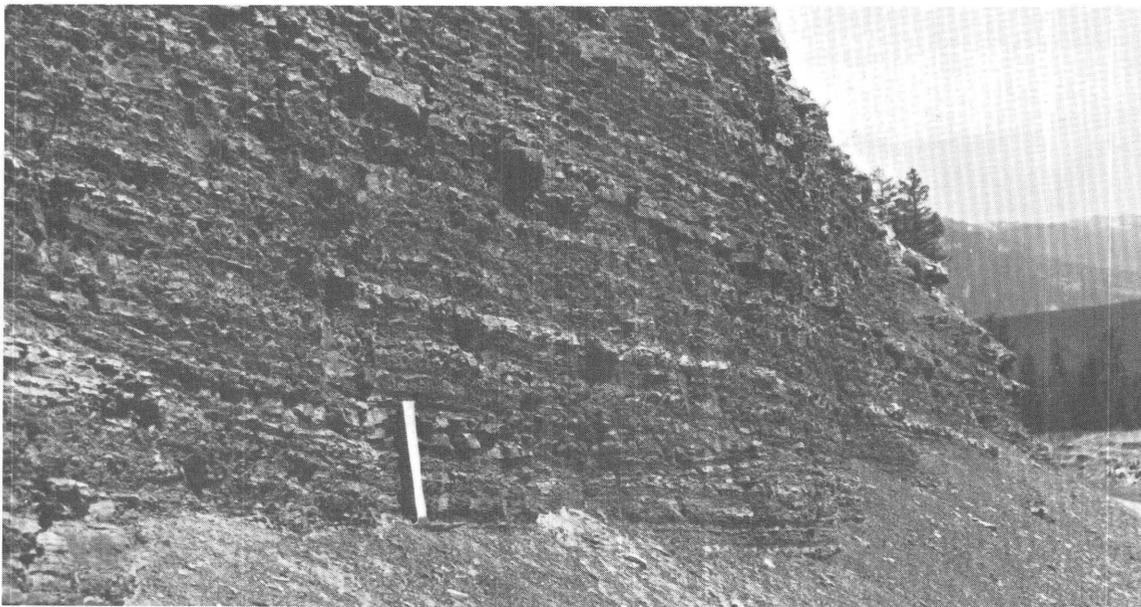


Figure 8. Rhythmically interbedded sandstone, siltstone, and mudstone of lithologic unit 24. Hammer handle is 30 cm (12 in.) long. Outcrop is in roadcut of Big Sky measured section, SW¹/₄SW¹/₄ sec. 27, T. 6 S., R. 3 E., Gallatin Peak 7.5-minute quadrangle.

the flow structure displayed by the surrounding mudstone. The upper part of each pillow has been eroded: nearly vertical laminae in the outer part of each pillow, as well as

the vertical flow structure of the mudstone between the pillows, is overlain by undeformed, nearly horizontally bedded silty mudstone or fine-grained sandstone.

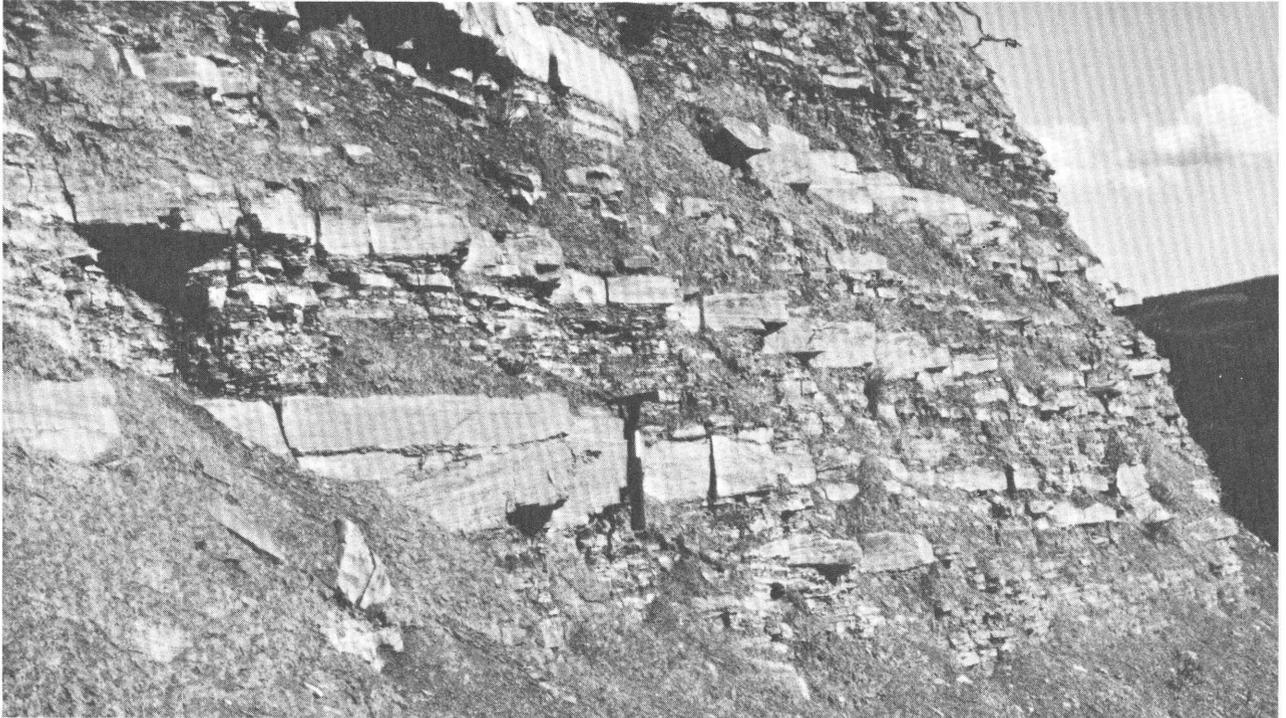


Figure 9. Thick sandstone beds, some of which contain hummocky crossbeds, in rhythmically interbedded strata of lithologic unit 21. Hammer handle is 30 cm (12 in.) long. Outcrop is about 3 m (10 ft) high, in roadcut of Big Sky measured section, SW $\frac{1}{4}$ SW $\frac{1}{4}$ sec. 27, T. 6 S., R. 3 E., Gallatin Peak 7.5-minute quadrangle.

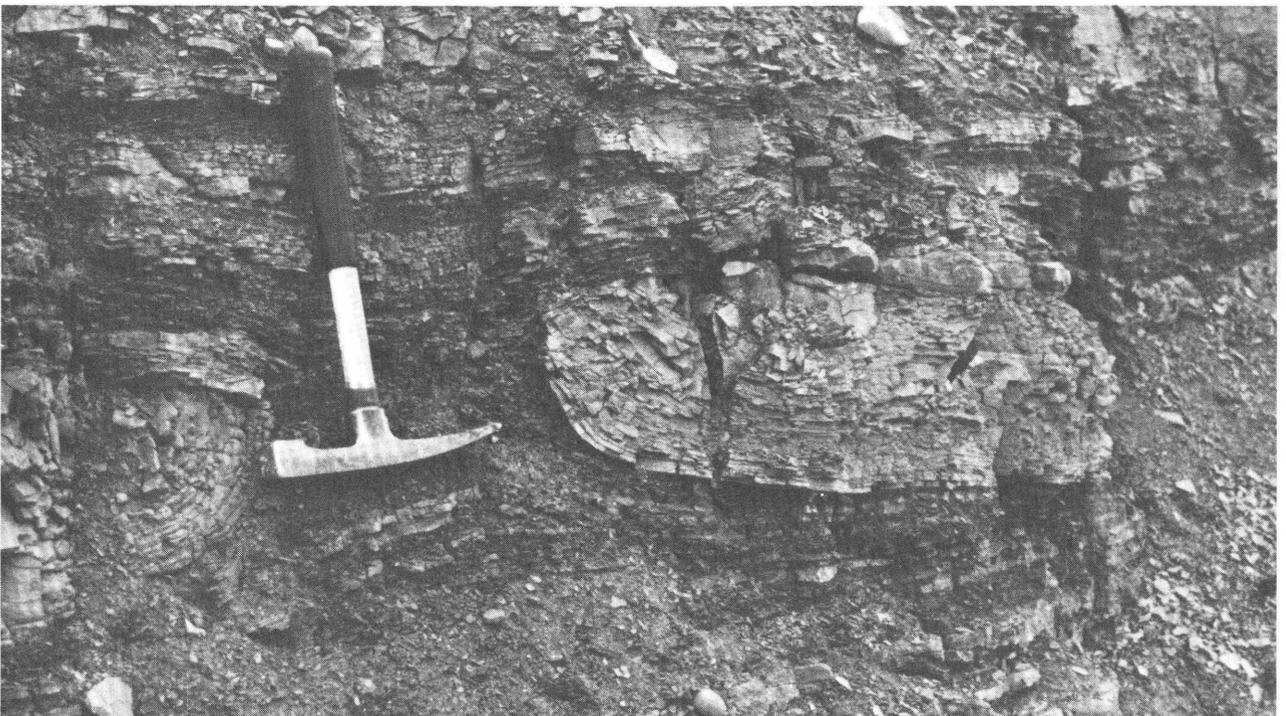


Figure 10. Ball-and-pillow structures in lower part of lithologic unit 21 of rhythmically interbedded strata. Note upturning of sandstone along margins of pillows, opposite both ends of hammer head. Hammer handle is 30 cm (12 in.) long. Outcrop is in roadcut of Big Sky measured section, SE $\frac{1}{4}$ SE $\frac{1}{4}$ sec. 27, T. 6 S., R. 3 E., Gallatin Peak 7.5-minute quadrangle.

Interpretation

The depositional environment of the rhythmically interbedded sandstone and siltstone or mudstone is interpreted to be a prodelta slope, where it is transitional with the lower shoreface environment of the delta front facies. Hummocky cross-stratification (unit 21) in fine-grained sandstone is a storm wave-generated feature; hence, the feature formed above storm wave base but below fair-weather wave base (Harms and others, 1982). The few graded beds and tool marks found may have been produced by storm processes as well.

Ball-and-pillow structures are characteristic of delta-front facies (Howard and Lohrengel, 1969; Hubert and others, 1972). The structures form during soft sediment deformation when a dense sand layer is deposited on top of a less dense, loosely packed water-saturated layer of mud. Gravitational instability causes the less dense water-saturated mud to flow upward, disrupting the sand layer into segments that were deformed into pillow shapes (Allen, 1982, p. 363).

Eroded tops of the ball-and-pillow structures in the Big Sky section indicate that the structures developed shortly after deposition of the sandstone bed from which they formed, and prior to burial beneath the overlying layer of strata. Sandstone of the ball-and-pillow structures was examined for hummocky crossbedding, which would indicate rapid deposition of the sand. Rapid deposition would have facilitated flowage and formation of the ball-and-pillow structures (Chan and Dott, 1986). No hummocky crossbedding was found, although hummocky sandstone lies directly upsection.

Hummocky Crossbedded Sandstone

Sandstone beds of several lithologic units (fig. 4, units 2, 3, 4, 5, 6, 16, 17, 18, 22, and lower part of unit 25) range from 2 to 8 m (6.5 to 26 ft) thick in the measured section of the upper part of the Frontier and all except units 2 and 3 (described and discussed later) show features typical of hummocky cross-stratification as described by Harms and others (1975): (1) crossbed sets display lower bounding surfaces that are erosional, commonly sloping at angles of less than 15°; (2) overlying laminae are parallel to set boundaries, or nearly so; (3) laminae above the erosional base systematically thicken laterally in a set, such that their traces on a vertical surface are fan-like; and (4) the direction of dip of erosional set boundaries are scattered. At Big Sky individual fan-like structures locally can be seen to fill depressions; laminae are nearly parallel to the erosional surface at the base of a crossbed set, gradually fill the erosional scour and decrease in dip until a horizontal dip is attained upward, and then build upward to form a hummock from which the laminae dip outward.

Laminae in the hummocky beds range from less than 1 mm to 1 cm (0.04 to 0.4 in.) thick (fig. 11) and are

alternately cream colored and pale green. Each light-colored lamina is composed of well-sorted fine-grained quartzofeldspathic sand, mica, and minor clay; each pale-green lamina is composed of clay and minor silt and mica. The change from one sediment size to the other is not gradational, rather it is fairly abrupt. Bases of hummocky sandstone sequences are erosive into underlying strata. Where a base is exposed over several tens of meters, contact of the hummocky sandstone sequence cuts into the underlying silty mudstone to a depth of less than 1 m (3 ft). A few thin carbonaceous shale lenses also are present within the unit. These characteristics of hummocky crossbeds generally correspond with those observed by Bourgeois (1980), Hunter and Clifton (1982), and the model of Dott and Bourgeois (1982, 1983) that contains the four bedding types shown in figure 12.

The lowermost hummocky crossbedded sandstone (unit 4) of the Big Sky section is underlain by massive to finely laminated sandstone that is faintly rippled, very fine grained sandstone (unit 3) and a similar lithology (unit 2) that contains some tiny mudchips. It is uncertain if units 2 and 3 are genetically related to the hummocky beds, but they display the same alternating buff and pale-green colors, and the same alternating compositional makeup, as the cross-laminated sandstone. These strata may represent two additional bedding types that Walker and others (1983) believed should be a part of the depositional model for hummocky crossbeds (fig. 12).

Bioturbated hummocky crossbedded sandstones (units 6 and 18) are poorly sorted and contain abundant organic debris. Most sedimentary structures have been destroyed, although a few hummocky crossbeds are preserved. Some of the hummocky sandstones intertongue with mudstone, showing that the cross stratification is an amalgamation of hummocky strata. Fossil debris is common in unit 18 and includes fish scales and fragments of *Cyprimeria*?; *Inoceramus* sp., possibly *I. flaccidus* White; an oyster fragment, possibly *Pycnodonte*; an ammonite, possibly *Scaphites arcadiensis* Moreman; and the long-ranging brachiopod *Lingula subspatula* Hall. *Ophiomorpha* is the only trace fossil that was identified.

Interpretation

Hummocky crossbedding commonly is attributed to oscillatory motion of storm waves (Harms and others, 1975; Bourgeois, 1980). The hummocky crossbedded sandstones of the Frontier are interpreted as deposits of the lower shoreface, where they were not reworked by fair-weather waves. Sandstone sequences with hummocky crossbedding are sharp based (erosional); whereas, the uppermost part of each sequence is gradational into overlying siltstone, or siltstone or mudstone strata. These data and the intense bioturbation in the uppermost part of sandstone sequences (units 8 and 19) suggest that the hummocky cross-stratified sandstones were deposited rapidly into an environment

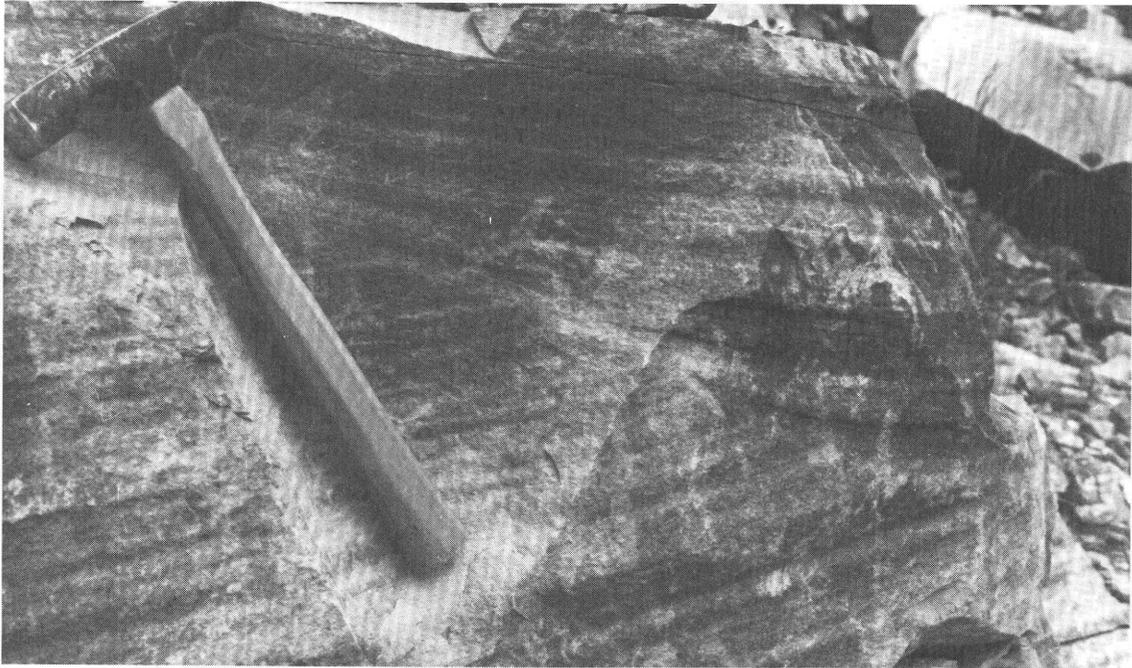


Figure 11. Hummocky cross-laminated sandstone of lithologic unit 6. Hammer head is 20 cm (8 in.) long. Outcrop is in roadcut of Big Sky measured section, NE $\frac{1}{4}$ SE $\frac{1}{4}$ sec. 28, T. 6 S., R. 3 E., Gallatin Peak 7.5-minute quadrangle.

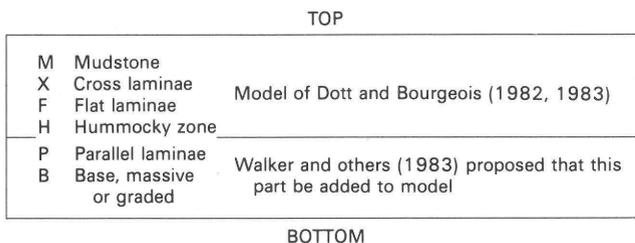


Figure 12. Sequence of sedimentary structures in hummocky crossbedded strata as determined by models of Dott and Bourgeois (1982, 1983) and Walker and others (1983).

normal for siltstone or mudstone—that is, hummocky sandstone is a storm deposit that accumulated seaward of where fair-weather sand deposition would have taken place. This interpretation agrees with the concept of storm generated hummocky beds espoused by Walker and others (1983), and Aigner (1985). Aigner interpreted proximal (near-shore) storm beds as thick bedded and coarse grained, and distal equivalents as mud-dominated and thin, one-event beds. Proximal deposits should be more abundant and thicker than distal storm deposits, and they should show evidence of repeated reworking or amalgamation of several events and ecologic communities.

The thin hummocky sandstone beds in the prodelta strata of unit 21 represent single events. Strata above the single-event hummocky sandstone beds are siltstone or mudstone beds that lack hummocky sands and may have

been deposited still farther offshore. (Alternatively, a cessation of storms or decrease in storm strength could produce the same sequence of siltstone or mudstone.)

Trace fossils present in the hummocky crossbeds are consistent with a lower shoreface depositional environment. In general, *Ophiomorpha* with vertical components ranges throughout the shoreface environment and into the foreshore-shoreface transition zone, and are indicative of relatively high levels of wave or current energy and shifting particulate substrates (Frey and Howard, 1985). In the Big Sky section, burrows of *Ophiomorpha* are present in virtually all of the hummocky cross-stratified sandstone units. Most of these probably were formed below fair-weather wave base where they were not reworked by waves.

Upper shoreface and paralic sediments are absent from the hummocky strata in the Big Sky section and most likely never were deposited after the storm deposits were laid down—only lower shoreface sands ever existed. The existence of “thin” hummocky sandstone beds interbedded within the prodelta strata (described in the previous section) is a strong argument for this interpretation. Further, the occurrence of mudstone layers within the upper part of the hummocky sequences argues for a depositional environment of the lowermost lower shoreface of the delta front.

This interpretation contrasts with that of some workers (for example, Weise, 1980; Bourgeois, 1980), wherein coarsening-upward clastic sequences within deltas represent truncated sequences—that is, offshore and lower shoreface strata are present but upper shoreface, beach, and

delta plain strata have been eroded. In this interpretation, upper shoreface and foreshore strata were reworked, destroyed, during marine transgressions that followed progradation. In the Big Sky section, I found no conglomerates, lag deposits of any kind, or other evidence of erosion or transgression at the top of the hummocky crossbeds or in the overlying prodelta strata, to support the concept of a truncated sequence.

Bioturbated Muddy Fine-Grained Sandstone

Bioturbated muddy fine-grained sandstone to siltstone (fig. 4, lithologic units 8 and 19) directly overlies hummocky crossbedded sandstone in a few places. The units are 1.5–3 m (5–10 ft) thick. The strata are rubbly weathering and lack laterally continuous laminae, although discontinuous shale or mudstone layers a few millimeters thick are present locally. The sandstone and siltstone is thoroughly bioturbated. Unit 19 definitely is gradational through 10–15 cm (4–6 in.) with underlying hummocky sandstone; mudstone or siltstone has been churned by infauna into the uppermost part of the sandstone. No specific trace fossils were identified from this unit.

Interpretation

These rocks are interpreted as deposits of the lowermost shoreface of the delta front facies or uppermost prodelta facies, deposited seaward of the bioturbated hummocky cross-stratified beds that lie directly beneath it. The thorough bioturbation reflects total, repeated reworking of sediments by infauna rather than absence of organisms; intense bioturbation also indicates slow, continuous rates of deposition (Frey and Howard, 1985).

Delta Front Facies

Tabular and Trough Crossbedded Salt-and-Pepper Sandstone

The upper 3–4 m (10–13 ft) of lithologic unit 25 (fig. 4) is pale-yellowish-gray, fine- to medium-grained, and locally coarse-grained and pebbly quartzose cherty sandstone. Tabular and trough crossbeds are abundant and are transitional into hummocky crossbedded sandstone that is present locally in the lower part of the unit. A few thin shale lenses are present in the upper strata. Strata of unit 25 are transitional into the sandstone of unit 26, which appears massive where freshly exposed in roadcuts, but displays gently dipping planar laminated beds where weathered. The sandstone of unit 26 is pale brown to light gray but weathers very light gray to white in an irregular zone 0.1–2.0 m (0.3–7 ft) thick in its uppermost part. It is fine to medium

grained and composed primarily of quartz, chert, and feldspar. Quartz grains range from subangular to well rounded. No heavy minerals, crossbeds, or burrow structures were observed in this unit.

Interpretation

The tabular and trough crossbeds and the wide range of grain sizes in the upper part of unit 25 are common in upper shoreface deposits (Reinson, 1984), or in the lowermost part of the foreshore (Frey and Howard, 1988). The better sorting and very low angle dip of thin, planar beds of unit 26 correspond to features typical of foreshore deposits as described, for example, by Harms and others (1975), Reinson (1984), and Frey and Howard (1988). The sandstone contains grains of a common size grading, but the mix of well-rounded to subangular grains reflects different sorting histories. The few percent of well-rounded quartz grains suggests either reworking of existing sandstone or an admix of windblown grains from dunes or other wind-sorted deposits onshore.

Delta Plain Facies

Strata of delta plain origin comprise a sequence of thin lithologic units, commonly a few centimeters to about 1 m (3 ft) thick. The units include medium-gray “salt-and-pepper” sandstone, dark-gray mudstone and siltstone; coaly and carbonaceous mudstone; and yellowish-green tuff, some of it weathered to mudstone that is light gray or reddish orange. The contact of the delta plain sequence with the underlying marine delta front deposits is marked by a general color contrast from light-gray sandstone of the delta front strata to the dark colors of much of the delta plain sequence.

Bioturbated Salt-and-Pepper Sandstone

Bioturbated sandstone of lithologic unit 27 (fig. 4) is about 0.5 m (1.5 ft) thick and is gradational with the sandstone of the underlying unit 26, but unit 27 differs in that it mainly is composed of quartz, with only a few grains of chert and feldspar. Most of the quartz grains are angular to subangular, but 15–20 percent of them are well rounded, in contrast to a much smaller percentage of rounded grains in unit 26. Some of the well-rounded grains are frosted. In addition, sandstone of unit 27 contains some clay, giving it a medium-gray color, and is thoroughly bioturbated by plant roots. Unit 27 also contains abundant tubular fractures filled with a white noncalcareous material. A thin section shows a rootlet-like structure composed of carbonaceous material (charcoal?) that defines the two walls of the tubular structure; the structure was not disturbed by compaction. The thin section also shows isolated grains of the same carbonaceous material.

Interpretation

The sandstone of unit 27 represents a backshore deposit, landward of the uppermost reach of waves of the foreshore environment. The association of angular to sub-angular and rounded grains, tubular root-like structures in vertical (growth) position, bioturbation by plants, and finely comminuted carbonaceous debris suggests deposition where the sand was stabilized by vegetation. Retallack (1988) described root traces in growth position as being one of the most diagnostic features of paleosols. The well-rounded quartz grains, particularly the frosted ones, are suggestive of a wind-blown origin, but the mix with angular grains indicates the preserved sandstone is not a dune.

Carbonaceous Mudstone

Dark-gray carbonaceous mudstone and coaly carbonaceous mudstone (fig. 4, lithologic units 31, 35, 37, 40, 45) occur at several horizons in the delta plain strata of the Big Sky section. Lithologic unit 37 also contains a large percentage of clayey siltstone and is shown as siltstone in figure 4. The rest of the units are thin bedded and display very fine laminations. Burrowing is evident locally. A mudstone believed to part of unit 35, but on the opposite side of the road from the measured section and not traceable across the road, yielded the freshwater clams *Protelliptio* n. sp. and *Plesielliptio* n. sp., and the freshwater snail *Cairn-arbis* sp. The coaly carbonaceous mudstone of unit 37, which gradationally overlies carbonaceous clayey, cross-bedded, siltstone of the unit, yielded crushed unionid bivalves. The fossils of both assemblages are disarticulated and abraded.

Interpretation

The coaly carbonaceous mudstone of unit 37 represents a heavily vegetated environment with little coarse clastic input. The carbonaceous material in the mudstone is not rooted but is debris that likely was transported into the depositional site. The unionid bivalves indicate the depositional site was a coastal freshwater swamp. The ripple crossbedded carbonaceous muddy siltstone of unit 37 could represent an overbank deposit or even a small delta where a stream debouched into the freshwater swamp.

The very fine laminations of carbonaceous strata of lithologic units 31, 35, 40, and 45 record deposition in quiet water where only occasional wave and current action are characteristic, reducing conditions are common, and burrowing organisms exist. Fragmental accumulations of mollusks, which churned through sediment mixing sand and silt into adjoining clays, probably reflects wave action along a lake shore. The silty and sandy strata are not typical of lake sediments (Krinitzky and Smith, 1969) but represent a

lacustrine delta where a stream entered a lake. These strata are much like those described and pictured by Coleman (1966), Krinitzky and Smith (1969), and Krinitzky (1970) from lake deposits of the Mississippi River delta plain, Louisiana.

The *Plesielliptio* sp. fauna of unit 35 indicate a freshwater lake environment. Shells of the fauna are disarticulated, but they are not severely abraded. The fauna could have lived in a paleoecological environment different from that indicated by the carbonaceous mudstone in which they were preserved, having been transported from a fluvial environment into a lake. Hanley (1976) found mollusks of the genera *Plesielliptio* sp. to occupy a fluvatile habitat near freshwater lakes and transported specimens were found in lakeshore sediments. Hanley and Flores (1987) found non-transported specimens of *Plesielliptio* were most common in very shallow water, near-shore lake settings, although the fauna also were found offshore in small lakes.

Clayey Siltstone and Mudstone

These strata (fig. 4, lithologic units 33, 43, 48, and 50) are dark-gray clayey siltstone, black carbonaceous mudstone, and coaly mudstone. They contain abundant detrital plant debris. The mudstone appears massive. Unit 43 contains very small crystals of pyrite and dispersed 1–2 mm (0.04–0.08 in.) fragments of calcareous shell debris. Unit 33 consists of coaly mudstone that gradationally overlies siltstone containing small-scale ripple crossbeds. The coaly mudstone of unit 33 and the siltstone of unit 43 both yielded disarticulated, abraded shells of *Brachiodontes* sp., *Anomia* sp., and *Corbula* sp., which are brackish water genera.

Interpretation

The sedimentological and compositional features of these strata conform to those of poorly drained swamp deposits as described and pictured by Coleman (1966), Krinitzky and Smith (1969) and Krinitzky (1970). The carbonaceous material in the rock units is not rooted but is debris that likely was transported into the depositional site during floods. The faunal assemblage of units 33 and 43 are brackish water forms. The abraded and disarticulated fossils of both units could have been transported into their depositional sites or simply reworked within them.

Tuff and Bentonite

Tuff and bentonite are interstratified with the delta plain sequence and form beds 0.2–2.0 m (0.7–6.6 ft) thick. Tuff beds (fig. 4, lithologic units 30, 32, 34, 39, 43, and 49) are pale-greenish-gray to pale-yellowish-green. Some of the tuff beds are hard, due to silicification, and contain very small plagioclase phenocrysts. At least one of the beds is graded and contains lithophysae. Other tuffaceous beds are

deeply weathered and are more properly called bentonite (fig. 4, lithologic units 28, 29, 31, 36, 38, and 44). The bentonite ranges from very light gray to reddish orange. X-ray diffraction examination of two of the bentonites shows presence of montmorillonite clay. All colors of the tuff and bentonite contrast strongly with the dark grays of the carbonaceous clayey sandstone, siltstone, and mudstone of the sequence. Contacts of the tuff and bentonite beds with overlying and underlying strata are sharp. No root structures were observed in any of the tuff or bentonite beds, and no bioturbation-mixing of the tuff or bentonite with underlying or overlying dark-gray mudstone or siltstone was observed.

Interpretation

The characteristics displayed by the tuff and bentonite are consistent with their airfall deposition into shallow water lakes or swamps that lacked reworking by waves, and (or) on land that lay adjacent to the water bodies. Only one of the tuff beds in the Big Sky measured section showed convincing evidence of reworking by water. A 0.5 m (1.6 ft) thick bed of tuff about 13 km (8 mi) west-southwest of the Big Sky section definitely was deposited in water, as indicated by ball-and-pillow structures (fig. 13). Inundation of land adjacent to the water bodies during floods, or a relative rise in sea level, could account for accumulation of overlying deltaic sediments. The deep weathering of tuff to form bentonite may reflect oxidation shortly after the time

of deposition, but such effects also could have taken place recently. No soil textures indicative of weathering shortly after deposition were observed.

Laminated and Burrowed Sandstone

Sandstone of lithologic unit 47 (fig. 4) is light gray, fine to medium grained, and composed of well-rounded and angular to subangular grains of quartz, some feldspar (chiefly potassium feldspar), and chert. In one location the sandstone is poorly sorted, contains wispy mudstone flasers, and is thoroughly burrowed. The main burrow structure is of the trace fossil *Ophiomorpha irregulaire*, which is filled almost entirely of carbonaceous mudstone. Also observed were a few burrows of *Teichichnus*, another horizontal trace fossil formed by a deposit-feeding animal.

In another location the sandstone is well sorted and displays parallel laminations. Rip-up mud clasts a few millimeters to about a centimeter across are associated with similar sized fragments of clams. Fragments of *Crassostrea* sp., an oyster, and *Corbula* sp., another bivalve, were found at this location. U-shaped burrows of the trace fossil *Diplocraterion*, a vertically oriented dwelling structure, were the only trace fossils found in these strata.

Interpretation

The depositional environment interpreted for this unit is a bay or lagoon, or partially enclosed distributary river

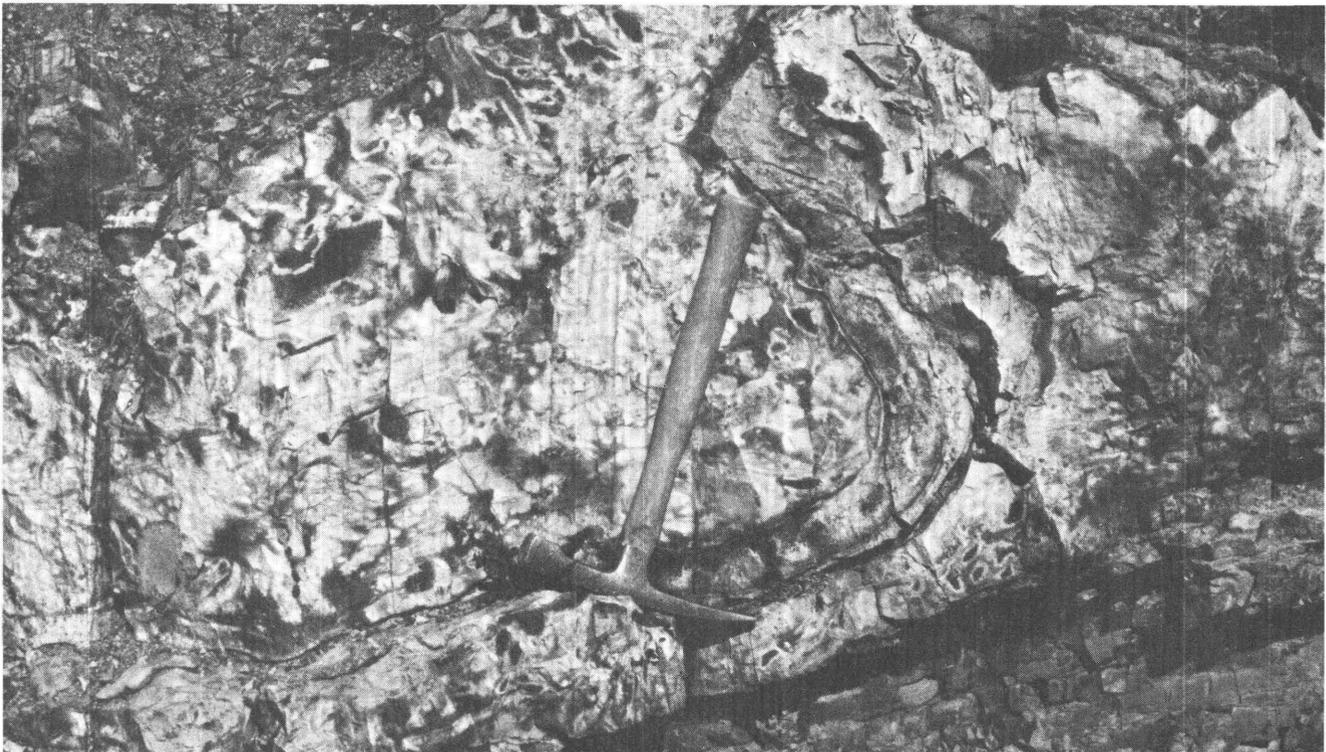


Figure 13. Pillow structure in tuff bed of delta plain strata in upper part of Frontier Formation. Outcrop is at head of Muddy Creek, 13 km (8 mi) southwest of the Big Sky measured section. Hammer handle is 30 cm (12 in.) long.

mouth, such as at the seaward edge of the delta plain of the Niger delta where barrier spits restrict entrance to the rivers and form small estuaries that undergo tidal reversal (Allen, 1965). The low diversity of trace fossils, the horizontal versus vertical forms, the contrasting abundances of trace fossils, and the strata known to directly overlie and underlie the sandstone unit support this interpretation. An open marine setting likely would have produced a sandstone that differed little in the character of its ichnofauna from one place to another.

The sandstone of unit 47 contains contrasting types of trace fossils at two locations less than 0.8 km (0.5 mi) apart. The restriction of specific types of trace fossils to different areas of the same rock unit reflects contrasting environments. The U-shaped traces of *Diplocraterion* are indicative of a moderate to high energy environment. The traces are truncated by laminae of mudstone and carbonaceous debris indicating that the lamination of the sandstone records successive depositional events. The sediment and trace fauna are indicative of the *Skolithos* ichnofacies, which is characterized by moderate to high energy conditions and shifting sediments (Ekdale and others, 1984). In contrast, the area of the sandstone that is thoroughly bioturbated by the horizontal burrows of *Ophiomorpha* and *Teichichnus* indicates a moderate to low energy environment of the *Cruizana* ichnofacies. This mix of trace fauna representing the *Skolithos* and *Cruizana* ichnofacies at a locality is suggestive of a brackish water environment (Howard and Frey, 1985; Ekdale and others, 1984).

A tidal sand-flat in a protected back-barrier environment provides a likely depositional model for the sandstone and the trace fauna. The well-laminated, least burrowed area of the sandstone was deposited closest to the low tideline where it was subjected to continuous current and wave action. The extensively burrowed sandstone, with its mud flasers, is characteristic of a middle tidal flat (mixed flat) (Duc and Tye, 1987), which is commonly inhabited by abundant deposit-feeding organisms that rework the substrate and obscure the original bedding (Ekdale and others, 1984). Such an environmental setting characteristically contains only a few species that can adapt to the extreme variation of environmental conditions, although such species may occur in high densities (Ekdale and others, 1984; Benyon and others, 1988). The well-rounded quartz grains in the sandstone indicate deposition proximate to a beach or a dunes, either (or both) of which subsequently was eroded. Duc and Tye (1987) reported that back-barrier sand flats of Kiawah Island, South Carolina, periodically received washover material, including shell debris, which later was reworked. The stratigraphic position of unit 47, within a delta plain sequence of lagoonal, swamp, and marsh deposits, is an appropriate setting for washover deposits (Hennessy and Zarillo, 1987).

Claystone

Claystone (fig. 4, lithologic unit 51) is pale gray green, massive, hard, and appears homogeneous in hand specimen. It lacks laminations or evidence of primary soil structures. Thin section examination shows a few widely dispersed silt grains, minor comminuted and dispersed organic debris, and bioturbation, perhaps by both plants and animals. The mottled, churned appearance visible in thin section suggests burrowing by animals. Later cross-cutting tubular structures probably are rootlets. The rootlets are filled with claystone of slightly different composition from that of the claystone outside the rootlets.

Interpretation

The claystone is interpreted to be a marsh deposit, displaying characteristics of modern marsh sediment described by Edwards and Frey (1977), Basan and Frey (1977), and Kisters (1989). These authors recognized three classes of marsh: low, transitional, and high. Unit 51 has the characteristics of the low marsh sediment. It is highly clayey silt to sandy mud that is essentially homogeneous, having been thoroughly reworked by animals and plant roots. Laminations are rare.

Conglomerate, Sandstone, and Lenticular-Bedded Siltstone

A ledge of conglomerate, sandstone, and lenticular-bedded siltstone to mudstone forms a prominent fining-upward sequence about 6.5 m (21 ft) thick at the top of the Big Sky measured section (fig. 14). The conglomerate forms a discontinuous bed (fig. 4, lithologic unit 52) at the base of the sequence and is composed of well-rounded pebbles 0.5–6 cm (0.2–2.4 in.) in diameter in a sandstone matrix. The matrix is pale-brown, calcareous, fine- to coarse-grained sandstone that is mainly composed of angular to well-rounded quartz grains in mudstone. No shell fragments were found in the conglomerate. The pebbles consist of dark-gray chert (70 percent), light- to dark-gray quartzite (25 percent), and other compositions (5 percent). Some of the chert contains silicified pelmatozoan debris and is probably from the Mississippian Madison Group, but the major part of the chert likely is from the Permian Phosphoria (or Shedhorn) Formation. Pebbles from these formations also are present in pre-Frontier Mesozoic strata of the Madison Range. The pebbly sandstone is lenticular, ranges up to 15 cm (6 in.) thick, and extends for several meters along the strike of the outcrop. The base is erosional.

Sandstone (lithologic unit 53) directly overlies the conglomerate. The sandstone unit is about 2.8 m (9 ft) thick, is ripple laminated and trough crossbedded, and contains interlayered discontinuous lenses of mudstone. Sandstone



Figure 14. Tidal estuarine deposit of lithologic units 52 (covered), 53, and 54, underlain by mudstone of lithologic unit 51 (covered). Outcrop is in uppermost part of Big Sky measured section, along ridge crest in SW¹/₄NE¹/₄ sec. 28, T. 6 S., R. 3 E., Gallatin Peak 7.5-minute quadrangle.

beds are about 10–30 cm (4–12 in.) thick, and the base of each commonly is erosional. The sandstone is fine grained and is composed of quartz, feldspar, and minor biotite; finely comminuted organic debris is common, but no shell material was found. A few horizontal burrows are present locally where the sandstone contains a large amount of mud. In the lower part of unit 53, mudstone makes up about 25 percent of the rock. Ripple cross-laminated sandstone layers 0.5–2 cm (1.3–5 in.) thick are separated by mudstone layers that are about 0.5 cm (0.4 in.) thick. Some of the mud layers are drapes: they are present only at the toe of a cross lamina, decreasing in thickness and pinching out upward in the crossbed. Within areas of trough crossbeds, mainly in the upper part of unit 53, medium- to dark-gray mudstone alternates with sandstone. The mudstone content of the cross-laminated sandstone increases in the upper part of the trough, and in some places grades into horizontally laminated mudstone and silty mudstone that forms discontinuous lenses between trough cross-stratified

sandstone beds. The lenses are as much as 15 cm (6 in.) thick and pinch and swell, both along and normal to strike. Some mudstone layers extend for several meters along strike, although most extend only a meter or two; their extent was not determined normal to strike owing to limited exposures. The lenses occur at irregular stratigraphic intervals and are overlain by sandstone beds that have erosional bases. Unit 53 is gradational into unit 54.

Strata (unit 54) in the upper part of the ledge-forming sequence are 3.0 m (10 ft) thick and are composed of lenticular bedded mudstone and clayey siltstone. Locally discontinuous, isolated lenses of cross-laminated fine-grained sandstone, the record of ripples that migrated across a mud substrate, are present within the mudstone. The sandstone layers are 0.1–1 cm (0.04–0.4 in.) thick, and mudstone layers range up to 3 cm (1.2 in.) thick. The contact of sandstone and mudstone layers is sharp. The unit has been burrowed, but no identifiable forms were found. Molds of a few burrows, as much as 1 cm (0.4 in.) across

and 5 cm (2 in.) long, were found weathered out on the ground surface and also were unidentifiable.

Upper strata of the lenticular-bedded unit yielded the following megafossils, reported previously by Tysdal and others (1990): *Inoceramus lamarcki stumckeii* Heinz, and *I. flaccidus* White, which are clams; *Rhynchostreon suborbiculatum* (Lamarck), an oyster; *Scaphites carlilensis* Morrow, and *Baculites* sp., which are ammonites. The fossils are marine and marginal marine forms and constitute a late-middle Turonian assemblage. None of the clams, which constitute most of the specimens, were in growth position and all were disarticulated, consisting of large pieces of individual valves.

Interpretation

The sequence formed by lithologic units 52–54 is interpreted as a tidal estuarine deposit because it has characteristics of the subtidal part of a point bar and because it contains a mixed assemblage of open marine and marginal marine fauna. It has characteristics of modern back-barrier tidal streams of the microtidal Niger delta. The upward changing sequence of intermittent lag gravel, interbedded cross-laminated sandstone and mudstone lenses, and overlying interbeds of siltstone and mudstone are characteristic of tidal estuarine deposits described by Howard and Frey (1985) in modern deposits of Georgia tidal estuaries that have rivers flowing into their headwaters.

Interbedded sandstone and mudstone constitute the most prominent feature of unit 53 and record contrasting depositional conditions. Rippled and trough cross-laminated sandstone reflect stronger current conditions than the laminated mudstone that contains horizontal trace fossils, which reflect weak currents. The laminated mudstone likely was deposited in the uppermost part of an estuary, or in a tidal stream that flowed into an estuary. In such a location, fine sediment settles out when water flow is inhibited by slack tides (Dorjes and Howard, 1975) and clay-silt flocules suspended in the brackish waters are deposited, forming cohesive muds that are difficult to erode (Allen, 1965). Thin clay beds occur throughout the cross-laminated sand of tidal channel deposits (Oomkens, 1974), and grain-size contrasts between the layers of tidal creeks are much more marked than in any other layered deposit in the Niger delta (Allen, 1965).

The upward fining of grain size of the Big Sky strata is reflected in the lenticular beds of unit 54, which indicate decreasing transport power. The marine and marginal marine megafossils of these strata is an argument in support of a subtidal origin. These strata represent subtidal accretionary deposits.

None of the cross-laminated strata of unit 53 show rhythmically interlayering reflective of inequal diurnal tides, as reported by Visser (1980) in a mesotidal Dutch tidal flat. There, thin mud laminae form a couplet of two

mud layers separated by a thin sandstone layer, each couplet separated by a thick sand layer called a tidal bundle. Such tidal bedding patterns have not been reported from microtidal environments, the tidal range commonly considered applicable to deposits of the Cretaceous Western Interior Sea. No herringbone crossbedding, indicative of reversing current flow, was found either.

Contact Relationships of Facies in Big Sky Measured Section

The relationship of the upper delta front strata at the top of the Lincoln Mountain measured section to the interbedded lower delta front and upper prodelta rocks of the Big Sky measured section is not known because the contact of the two sequences has not been observed at either location or elsewhere in the range. The lower Frontier strata are concealed in the area of Big Sky, and upper Frontier strata that are the time-equivalent of the Big Sky section have been eroded from the general area of Lincoln Mountain.

An unconformity occurs at the top of the Frontier in the Madison Range. Uppermost delta plain rocks of the Frontier are overlain by offshore (prodelta) mudstone of the Cody Shale, which contains late Coniacian megafossils. Several Western Interior molluscan fossil zones are unrepresented between the late-middle Turonian fauna at the top of the Frontier and the late Coniacian fauna of the basal Cody. The faunal and stratigraphic break correspond to the time of an unconformity recognized by Merewether and Cobban (1986) throughout northwestern Wyoming and adjacent southwestern and south-central Montana.

CONCLUSIONS

The section for the Frontier Formation in the Madison Range consists of two measured sequences that, combined, form a composite section. The lower part of the composite section, at Lincoln Mountain, consists of a regressive sequence of delta front strata that are overlain by delta plain strata. These rocks early Cenomanian rocks are separated by an unconformity from middle Turonian delta front deposits in the uppermost part of the Lincoln Mountain section. The upper part of the composite measured section, near Big Sky, consists of a regressive sequence of late-middle Turonian lower delta front hummocky crossbedded sandstone and intertonguing prodelta strata. This sequence is overlain by sandstone of the upper delta front (shoreface) and lower delta plain facies. The uppermost 25 m (82 ft) of the Big Sky section of the Frontier is interpreted as a delta plain sequence composed mainly of mudstone and siltstone.

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