



Stratigraphy and depositional environment of the Upper Cretaceous Horsethief Formation northwest of Augusta, Montana
by Carol Jean Bibler

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Earth Science
Montana State University
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Abstract:

The Horsethief Formation (Upper Campanian) crops out in the Northern Disturbed Belt and western Sweetgrass Arch area of Montana, where it was deposited on the western margin of the Western Interior Cretaceous Seaway. Investigation of the depositional environment of the Horsethief in an area extending northwest of Augusta, Montana and southwest of Choteau, Montana indicates that the formation was deposited along a barrier coastline.

Within the study area, the lower part of the Horsethief Formation (Horsethief-Bearpaw Transition Unit) is transgressive in nature. In the northern part of the study area, a nearly complete transgressive sequence is preserved in deposits of the Transition Unit, suggesting that locally, the Bearpaw sea rapidly advanced over terrestrial deposits of the broad Two Medicine coastal plain. Specific depositional environments preserved in the transgressive sequence include, in ascending order, marsh-tidal flat, upper shoreface, and lower shoreface.

The upper part of the Horsethief Formation is regressive. Depositional environments represented in the regressive sequence are upper shoreface, beach foreshore and backshore, tidal inlet, flood tidal delta, and marsh-tidal flat. Marsh-tidal flat deposits of the upper part of the Horsethief Formation interfinger with terrestrial deposits of the overlying St. Mary River Formation, just as marsh-tidal flat deposits of the Horsethief-Bearpaw Transition Unit interfinger with terrestrial deposits of the underlying Two Medicine Formation.

Horsethief Formation sandstones include: 1) volcanarenites, 2) chertarenites, 3) feldspathic volcanarenites, and 4) feldspathic chertarenites. The abundance of volcanic rock fragments increases from bottom to top of the Horsethief, suggesting that the regressive nature of the Upper Horsethief may be due in part to an influx of volcanogenic sediment from the west.

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HORSETHIEF FORMATION, NORTHWEST OF AUGUSTA, MONTANA

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Carol Jean Bibler

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ABSTRACT

The Horsethief Formation (Upper Campanian) crops out in the Northern Disturbed Belt and western Sweetgrass Arch area of Montana, where it was deposited on the western margin of the Western Interior Cretaceous Seaway. Investigation of the depositional environment of the Horsethief in an area extending northwest of Augusta, Montana and southwest of Choteau, Montana indicates that the formation was deposited along a barrier coastline.

Within the study area, the lower part of the Horsethief Formation (Horsethief-Bearpaw Transition Unit) is transgressive in nature. In the northern part of the study area, a nearly complete transgressive sequence is preserved in deposits of the Transition Unit, suggesting that locally, the Bearpaw sea rapidly advanced over terrestrial deposits of the broad Two Medicine coastal plain. Specific depositional environments preserved in the transgressive sequence include, in ascending order, marsh-tidal flat, upper shoreface, and lower shoreface.

The upper part of the Horsethief Formation is regressive. Depositional environments represented in the regressive sequence are upper shoreface, beach foreshore and backshore, tidal inlet, flood tidal delta, and marsh-tidal flat. Marsh-tidal flat deposits of the upper part of the Horsethief Formation interfinger with terrestrial deposits of the overlying St. Mary River Formation, just as marsh-tidal flat deposits of the Horsethief-Bearpaw Transition Unit interfinger with terrestrial deposits of the underlying Two Medicine Formation.

Horsethief Formation sandstones include: 1) volcarenites, 2) chertarenites, 3) feldspathic volcarenites, and 4) feldspathic chertarenites. The abundance of volcanic rock fragments increases from bottom to top of the Horsethief, suggesting that the regressive nature of the Upper Horsethief may be due in part to an influx of volcanogenic sediment from the west.

INTRODUCTION

Purpose

The Upper Cretaceous (Campanian) Horsethief Formation in the Northern Disturbed Belt and Sweetgrass Arch areas of Montana (Fig. 1) consists of sandstones, siltstones, and mudstones which were deposited along the western margin of the Western Interior Cretaceous seaway (Fig. 2). Although depositional environments of Cretaceous strata along the western margin of the Cretaceous seaway are well-documented from other better-studied regions in Wyoming, Utah, and Colorado, sedimentologic investigations in western Montana are lacking. Hence, our understanding of Upper Cretaceous paleogeography in western Montana is incomplete.

Most previous studies involving the Horsethief Formation identify it as "shallow marine" in origin (Cobban, 1955; Viele and Harris, 1965; Gill and Cobban, 1973). This earlier work consists predominantly of relatively broad, regional stratigraphic and mapping investigations. Specific depositional environments of the Horsethief Formation have been interpreted in only one area, located southeast of Augusta, Montana. There, Shepherd (1973) recognized lagoonal-deltaic and barrier-island depositional environments.

West of Choteau, Montana, (Fig. 1), the Horsethief interfingers with the underlying fluvial Two Medicine Formation of Campanian age

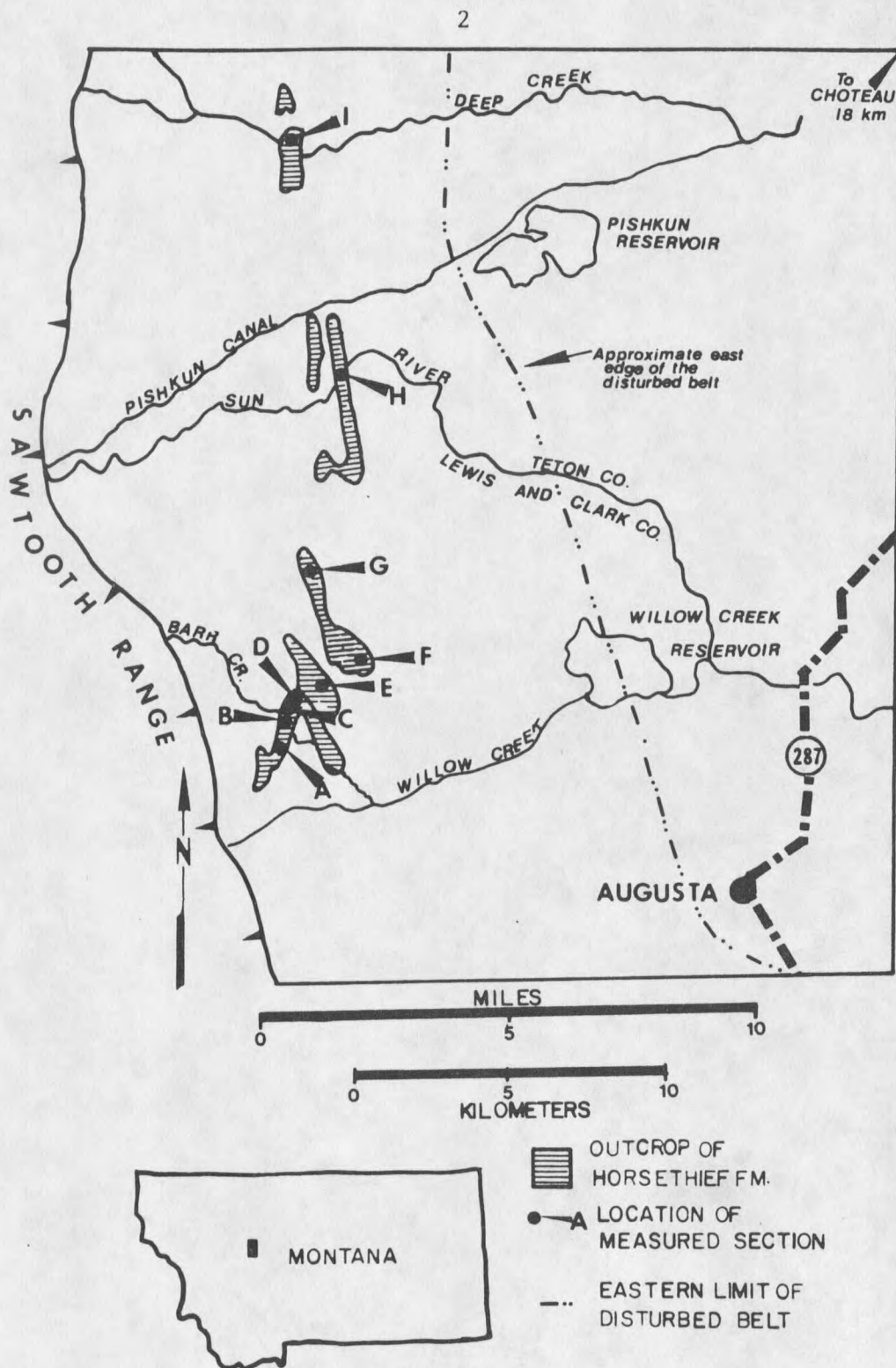


Figure 1. Index map showing outcrops of Horsethief Formation and locations of measured sections, denoted by letters.



Figure 2. Distribution of land and epeiric sea in North America during area. Modified from Gill and Cobban (1973, Fig. 1).

(Fig. 3). There, the Two Medicine contains a unique dinosaur nesting site (Horner, 1984) within fine-grained deposits of a low-energy anastomosing stream fluvial system (Lorenz and Gavin, 1984). The objective of this study is to define the depositional environment of the overlying Horsethief Formation, based upon stratigraphic and lithofacies analysis of exposures northwest of Augusta and southwest of Choteau. This will contribute to our knowledge of paleogeography along the western margin of the Western Interior Cretaceous seaway in Montana, and provide insight into the environment succeeding the broad Two Medicine coastal plain which the dinosaurs inhabited.

Stratigraphy

The Horsethief Formation was deposited as waters of the Cretaceous epeiric sea withdrew from Montana for the last time. In a time-stratigraphic sense, deposition of the Horsethief Formation was concurrent with deposition of the marine Bearpaw Shale to the east (Fig. 3). Similarly, the lower strata of the continental St. Mary River Formation at its western limit of deposition are time equivalent with the upper strata of the Horsethief farther east.

The Horsethief Formation at its type section, 30 km northeast of Browning, Montana and just west of the Sweetgrass Arch, is underlain by the Campanian Bearpaw Shale and overlain by the Maestrichtian St. Mary River Formation (Fig. 3). The underlying Bearpaw Shale is dark gray and contains ferruginous concretions, bentonite, and thin layers of sandstone (Cobban, 1955). The Bearpaw is more than 100 m thick near Browning but thins to a few meters westward (Mudge and Earhart, 1983). It

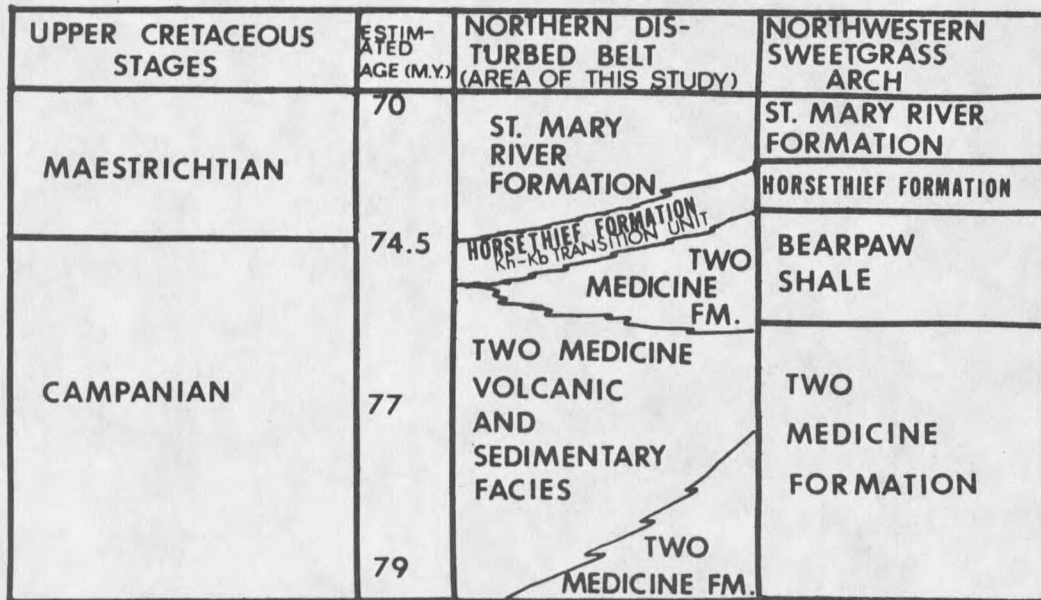


Figure 3. Correlation chart showing relationship of Horsethief Formation to other Upper Cretaceous stratigraphic units, north-central Montana. Age estimates from Kent and Gradstein (1985).

also pinches out rapidly in a southerly direction. South of Dupuyer Creek, which is 28 km north of the study area, the Bearpaw Shale is absent altogether. Near Augusta, lower strata of the Horsethief consist of a series of platy shales and siltstones termed the Bearpaw-Horsethief Transition Unit by Cobban (1955). Mudge and Earhart (1983) altered this terminology, referring to this zone as the Horsethief-Bearpaw Transition Unit, and placed it in the Horsethief Formation (Fig. 3). The present report uses the latter terminology in order to be consistent with recent nomenclature; however, it should be understood that the Transition Unit represents a shallow water sandy facies of the marine transgressive Bearpaw shale, and that it is a

transition between non-marine beds of the Campanian Two Medicine Formation and regressive sandstones of the Horsethief Formation. The Horsethief-Bearpaw Transition Unit thins to the south and is entirely absent south of the study area.

Because of the southerly pinchout of the Bearpaw Shale, the Campanian Two Medicine Formation directly underlies the Horsethief Formation in the study area. Here the Horsethief rests with apparent conformity on the Two Medicine, as the contact, where exposed, is gradational. The absence of the Bearpaw shale in this area thus reflects a lateral facies transition rather than an erosional unconformity.

The Two Medicine Formation is composed predominantly of bentonitic gray to gray-green and red mudstone, with subordinate sandstone (Lorenz and Gavin, 1984). In the vicinity of the study area it is 500 to 600 m thick (Viele and Harris, 1965).

Overlying the Horsethief Formation is the fluvial St. Mary River Formation, which is as much as 366 m thick near the study area (Mudge and Earhart, 1983). Most of the formation is composed of greenish-gray and reddish mudstone with beds of fine to medium-grained sandstone.

Geologic Setting

The Horsethief Formation crops out in a narrow north-northwest trending belt within the foothills of the Sawtooth Range, along the eastern margin of the Northern Montana Disturbed Belt (Fig. 3). The formation is modified by folding and occasional thrust faulting throughout much of this area. Outcrops of the Horsethief are scattered,

as much of it is buried under younger Cretaceous rocks and Quaternary sediments. The study area extends northward along the outcrop belt from the Sun River Game Range, located 15 km northwest of Augusta, Montana to the Salmond Ranch, located 28 km southwest of Choteau, Montana.

Study Methods

Nine exposures of the Horsethief Formation, including the Horsethief-Bearpaw Transition Unit, were studied in detail (Fig. 3) during the field seasons of 1983 and 1984. Five of the exposures, in the southern part of the Sun River Game Range, are closely spaced, while four are relatively scattered. Sections were measured with a Jacob's staff and range from 12 to 240 m in thickness. Cross-bedding orientations were measured wherever the attitude of the beds could be accurately determined, and, in the case of trough cross-beds, where three-dimensional exposure of troughs was available. Troughs were measured by recording the orientation of each limb as well as the perceived axis. A total of 145 dip measurements of both trough and planar cross beds were made.

Lithologic samples were collected from each significant lithologic unit and were studied using a binocular microscope. Fifty thin sections were prepared and analyzed with a petrographic microscope. Seventeen of the thin sections were stained to enable easy recognition of potassium feldspar; their mineralogic composition was determined by point counting 250 points per slide.

LITHOFACIES

The Horsethief Formation can be divided into five major lithofacies on the basis of lithology, sedimentary structures, paleocurrents, and faunal content. Table 1 summarizes the characteristics of these lithofacies and provides references to modern analogues as well as ancient deposits which bear similar interpretations.

Interbedded Sandstone, Siltstone and Mudstone Lithofacies

This lithofacies is comprised predominantly of sandstone beds up to 1 m thick interbedded with subordinate siltstone and mudstone beds, which average 0.5 m thick each. Occasional carbonaceous shale beds are present as well. Sandstones are fine grained, moderately well sorted, grayish white to yellowish brown chert arenites and sublitharenites which are typically horizontally stratified in layers about 3 cm thick, although some are as thin as 0.5 cm. Sandstone layers are sometimes gently undulating in form (Fig. 4). Occasionally, sandstone beds display ripple cross-lamination and rarely, wedge-planar cross-bedding, with cross-bed sets up to 30 cm thick. Some of the sets have erosional lower bounding surfaces with laminations parallel to those surfaces. Cross-stratification is commonly absent, however, resulting in massive beds. Siltstones interbedded with the sandstones are greenish gray to yellowish brown. Dark brownish-gray mudstones which grade in part to

Lithofacies	Interbedded Sandstone, Siltstone, and Mudstone	Trough Cross-Bedded Sandstone	Horizontally Stratified Sandstone	Carbonaceous Shale, Siltstone, and Sandstone	Wedge-Planar Cross-Stratified Sandstone
Lithology	Grayish-white to yellowish brown, fine grained chert-arenites and sublitharenites with interbedded siltstones and mudstones. Bioturbated, trace fossils.	Gray to brown-green, fine to coarse grained chertarenites, volcarenites and sublitharenites. Fossils incl. <u>Ostrea</u> , <u>Diplocraterion</u> , gastropods.	Light gray, reddish brown, or olive green chertarenites, volcarenites and sublitharenites. Fossils incl. <u>Ostrea</u> , <u>Ophiomorpha</u> , plant roots, gastropods.	Gray to black carbonaceous shales; greenish gray to dark brown siltstones and sandstones. Mudballs, volcanic pebbles. Plant rootlet traces, disseminated plant remains, <u>Ostrea</u> beds.	Brownish-green sublitharenites and volcarenites, lens shaped geometry. Occasional <u>Ophiomorpha</u> burrows, plant fragments.
Sedimentary Structures	Horizontal stratification, rare wedge-planar cross bedding, layers sometimes undulating in form.	High angle trough cross-bedding, horizontal cross stratification, ripple cross-lamination, often in vertically repeated sets.	Horizontal to gently dipping stratification.	Flaser bedding, reactivation surfaces, contorted laminae; bioturbation has destroyed many sedimentary structures.	Flood oriented planar cross-beds.
Environments of Deposition	Lower shoreface.	Upper shoreface and tidal inlet channel.	Beach fore-shore and backshore.	Lagoon, marsh, tidal-flat.	Flood-tidal delta.
Modern Analogue	Mustang Island, Texas (Davis, 1978)	Oregon coast (Hunter et al, 1979); Fire Island Inlet (Kumar and Sanders, 1974)	Newport Beach, Oregon (Klein, 1982)	Copano Bay, Texas (Calnan, 1980) Georgia Coast (Frey and Basan, 1978)	South Carolina coast (Hubbard and Barwis, 1976)
Ancient Example with Similar Characteristics	Upper Cretaceous Ferron Sandstone (Cotter, 1975) Upper Cretaceous Blackhawk Fm. (Howard, 1972)	Upper Cretaceous Gallup Sandstone (Campbell, 1971) Upper Cretaceous Fox Hills Sandstone (Land, 1972)	Upper Cretaceous Gallup Sandstone; Upper Cretaceous Fox Hills Sandstone	Upper Cretaceous Fox Hills Sandstone; Late Tertiary Cohansey Sand (Carter, 1978)	Upper Carboniferous of West Virginia (Reinson, 1979)

Table 1. Lithofacies characteristics and interpreted depositional environments of the Horsethief Formation, with modern and ancient analogues.

carbonaceous shales are also present. Individual beds are less than 0.5 m thick. Both sandstones and siltstones contain occasional trace fossils and are bioturbated.

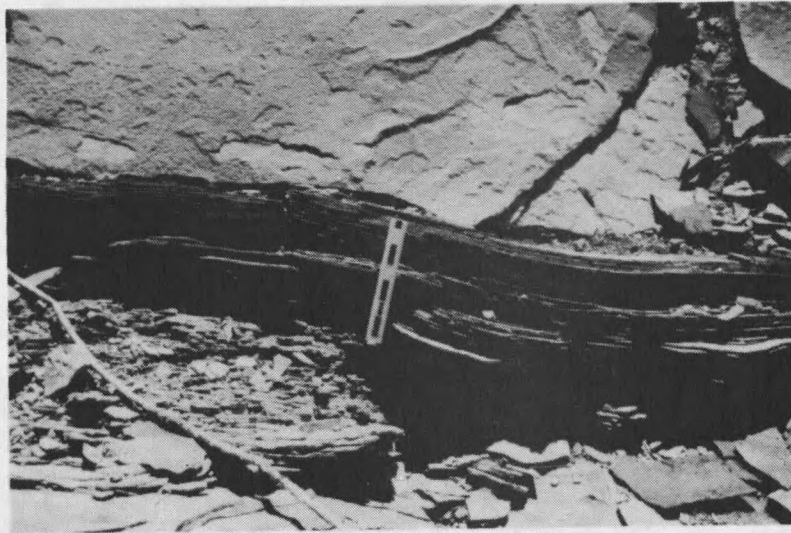


Figure 4. Undulating surfaces of horizontal beds, Interbedded Sandstone, Siltstone and Mudstone Lithofacies, Measured Section I.

Interpretation. Sediments which consist of very fine to fine grained layers of silt and sandy mud are characteristic of modern lower shoreface deposits (Reinson, 1979; Davis, 1978). These sediments reflect the transitional nature of the lower shoreface, where periods of lower energy deposition of silt and mud dominate over higher energy deposition; transport of sand, which is more typical of upper shoreface and foreshore areas, is less frequent. The sandstone beds which are deposited in lower shoreface environments are usually horizontally laminated, because transportation of sand by storm waves typically occurs under upper flow regime plane bed conditions.

The shales, mudstones, and finer siltstones thus reflect low-energy accumulation of suspended sediment, while the sandstones result from traction transport and subsequent deposition during storm events. The gentle undulations in sandstone laminae may reflect periods of increased water velocity, causing ephemeral wave forms to develop on upper flow-regime flat beds (Collinson and Thompson, 1982). Such wave forms are incipient antidunes; they are created when the waveform on the sediment surface is of lower amplitude than the water surface wave. The sediment surface waves move abruptly upflow, causing the water surface waves to break and collapse; this results in a flat water surface from which new waves grow.

Occasional cross-stratification in the sandstones may also result from storm events, or from rip currents. The cross-bed sets with parallel laminations and erosional lower bounding surfaces resemble hummocky cross-strata, but because these structures are largely destroyed by bioturbation it is difficult to positively identify them as such. Bioturbation is common in other Upper Cretaceous rocks interpreted as lower shoreface deposits (Howard, 1972).

Similar burrowed, laminated sandstones which are interbedded with silt and clay have been described in the Lower Cretaceous Muddy Sandstone of southeastern Montana (Berg and Davies, 1968) and in the Upper Cretaceous Ferron Sandstone of Utah (Cotter, 1975); these authors used evidence similar to that described above in interpreting these as lower shoreface sediments, citing the presence of laminated, fine grained sandstones as evidence of occasional rapid influxes of storm-deposited

sand. Thus the Interbedded Sandstone, Siltstone, and Claystone Lithofacies of the Horskethief Formation compares favorably with both ancient and modern examples of lower shoreface deposits.

Trough Cross-Bedded Sandstone Lithofacies

This lithofacies is characterized by gray to brownish-green, fine to coarse-grained sandstones. The sandstones are moderately well sorted, but often display alternating layers (each approximately 15 cm thick) of fine and coarse grains. In several locations, beds in the upper 15 cm of the lithofacies are oxidized to an orange-red color. High-angle trough cross-stratification, with sets averaging 20 cm in thickness, is the dominant sedimentary structure in this lithofacies, but horizontal laminae, ripple cross-laminae, and occasional planar-tabular cross-strata are present as well.

In many areas this facies exhibits sequences characterized by vertical repetition of sedimentary structures (Fig. 5). At the base of each sequence are horizontally stratified sandstone beds, usually less than 1 m thick. These horizontally stratified layers are overlain or truncated by large-scale high angle trough cross-stratified sets up to 2 m thick. Capping the sequence is an approximately 10 cm thick layer of ripple cross-laminated sand; ripples are slightly asymmetric to symmetric and often contain thin laminae filled with carbonaceous detritus or mud. Frequently, deposits consisting of plant debris, fragmented *Ostrea* and marine gastropods are found immediately below these small ripples. Each complete sequence is about 3 m thick, and occurs stacked one upon the other, up to five times in a section.



Figure 5. Beds in the Trough Cross-Bedded Sandstone Lithofacies, showing horizontally laminated sandstone cut by trough cross bedded sandstone and overlain by ripple cross-laminated sandstone, Measured Section B.

Paleocurrent measurements of the cross-bedding and ripple marks reveal a predominantly unimodal, north-northwest trend in Measured Sections B and F, and a bimodal, west-southwest and east-northeast trend for Measured Section C (See Paleocurrents Section).

Ophiomorpha traces (Fig. 6) are common in beds of this lithofacies and Diplocraterion is occasionally present. Fragments of a variety of invertebrate and plant fossils are often concentrated in layers 3 to 30 cm thick. Plant remains include woody-textured fragments as large as 20 cm by 60 cm. The sandstones are chert arenites, volcanarenites, and sublitharenites.

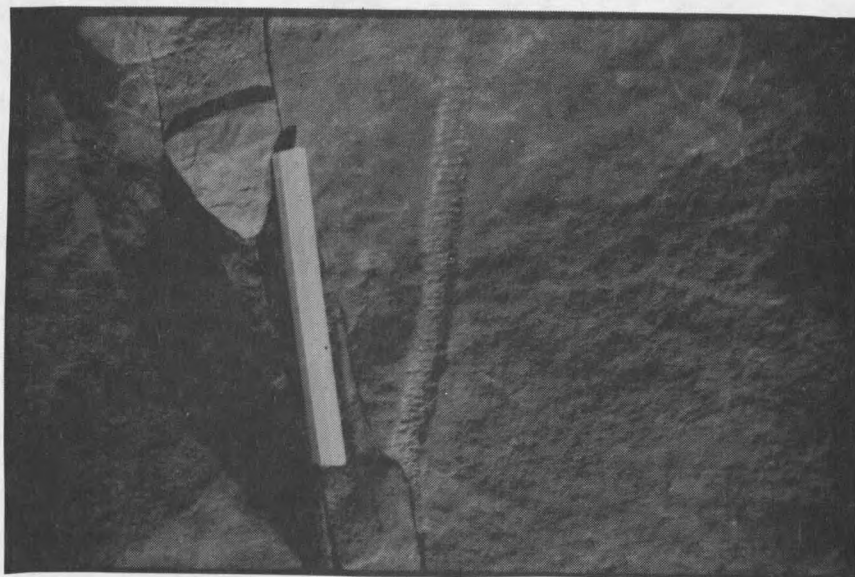


Figure 6. Trace fossil Ophiomorpha in Trough Cross-Bedded Sandstone Lithofacies, showing nodose texture, Measured Section D.

Interpretation. In coastal marine sands, medium to large-scale trough cross-stratification is formed by migration of subaqueous megaripples (dunes), which are characteristic of the upper shoreface (Harms et. al., 1982; Reinson, 1979). The migrating dunes form submerged bar and trough topography typical of the shoreface. The vertical sequence of sedimentary structures and associated bedforms described above may be interpreted in terms of flow regime changes resulting from periodic heavy storms (Reineck and Singh, 1980). During storms, longshore bars of the upper shoreface are leveled by wave erosion, and subsequent deposition of sand occurs in thin horizontal layers on top of the planed-off bar. As the storm recedes, waning flow conditions cause megaripples (dunes) to migrate across these horizontal

layers. Continued waning flow results in deposition of coarser material, such as large plant debris and shell fragments, which were previously held in suspension, and in development of small current ripples. Finally, fine material which was held in suspension is deposited on the rippled surfaces. These cycles were particularly well developed in Measured Sections B and F; they were not evident in Section C.

The trough and tabular-planar cross-stratification which occurs in tidal inlet channels is also characteristic of upper shoreface deposits, so the primary means of distinguishing between the two subenvironments is, in this case, their differing paleoflow directions, together with the greater lateral extent and vertical thickness of the upper shoreface deposits. The unimodal north-northwest trending paleoflow direction present in Measured Sections B and F is interpreted to reflect longshore current, as the general trend of the shoreline during Horsethief time is believed to have been north-northwest (Gill and Cobban, 1973). Longshore currents, which develop in the surf zone, are considered the most important sediment transport agent in the upper shoreface (Reineck and Singh, 1980). The bimodal paleocurrent orientation of Measured Section C is roughly perpendicular to that of Sections B and F and is thus believed to be the result of deposition in a tidal inlet. Inlet-fill deposits may locally replace shoreface deposits (Kumar and Sanders, 1974). The abundance of trough cross-stratification in the deposits interpreted as tidal inlet channels suggests deposition

in the shallower, more marginal portions of the inlet channel (Hubbard and Barwis, 1976).

Burrows formed by calianassid shrimp, which are modern forms of the trace fossil Ophiomorpha, are often present in modern upper shoreface environments (McCubbin, 1982). The orange-red oxidation, confined to the upper 15 cm of the lithofacies, is probably a result of subaerial exposure; the lack of magnetite in these sandstones renders it unlikely that the coloration resulted from oxidation of magnetite. The oxidation therefore suggests a transition between upper shoreface and lower foreshore environments.

The Trough Cross-Bedded Sandstone Lithofacies is thus interpreted to represent deposition in the upper shoreface, and, in the uppermost portion, lower foreshore. In Measured Section B, the upper shoreface deposits have been replaced by deposits of a tidal inlet. This interpretation compares favorably with other ancient examples such as the Upper Cretaceous Gallup Sandstone of New Mexico (Campbell, 1971) and the Fox Hills Sandstone of Wyoming (Land, 1972).

Horizontally Stratified Sandstone Lithofacies

Fine to medium grained sandstones which are light gray, reddish brown, or olive green characterize this lithofacies. Stratification in these sandstones is horizontal to gently dipping (less than 10 degrees)(Fig.7). Individual strata range from 0.5 to 4 cm thick, but are of constant thickness at any given location. This lithofacies is usually less than 1 m thick and typically laterally restricted. Traces



Figure 7. Horizontal lamination in sandstones of the Horizontally Stratified Sandstone Lithofacies, Measured Section B.

of Ophiomorpha are noted in some areas, and plant rootlet traces are sometimes present in the uppermost beds of the lithofacies. Concentrations of whole and/or fragmented shells are occasionally present as well.

Sandstones range from chert arenites to volcarenites. Heavy minerals are abundant in some locations, particularly in the uppermost part of the lithofacies, with magnetite being especially common.

Interpretation. This lithofacies represents beach foreshore and backshore environments. The swash-backwash mechanism of the waves is responsible for the horizontal to subhorizontal laminations of the beach foreshore and backshore (Reinson, 1979; Klein, 1982). Ideally,

foreshore deposits dip gently seaward, while backshore deposits dip gently landward. Because the Horsethief beds have been tilted in the study area, it is not possible to precisely determine the original horizontal position of the beds with sufficient accuracy to determine whether the gently inclined stratification is actually dipping seaward or landward. Thus, it is difficult in this case to distinguish backshore deposits from those of the foreshore on the basis of the direction of inclination of the strata. Generalizations can be made, however, based on the presence of other characteristics. For example, areas of shell concentrations are more common in the beach foreshore, while heavy mineral concentrations and plant rootlet traces suggest deposition in the backshore (Reineck and Singh, 1980). Therefore, the lower beds of this lithofacies were probably deposited in the beach foreshore, while the upper beds are more likely to have been deposited in the backshore.

Fossil beach placers in sandstones of Late Cretaceous age, which consist of heavy mineral concentrations such as those found in beds of this lithofacies, are common in the Rocky Mountain region (Houston and Murphy, 1970). In most of the localities where they exist, they occur near the top of a regressive littoral sandstone overlain by a sequence of carbonaceous shale and fluviatile sandstone. The heavy mineral concentrations in the Horizontally Stratified Sandstone Lithofacies are consistent with this stratigraphic and environmental setting.

Carbonaceous Shale, Siltstone and Sandstone Lithofacies

This lithofacies is characterized by carbonaceous siltstone, claystone, poorly-sorted sandstone and carbonaceous shale with thin coal layers. Shales are gray to black and vary in thickness from 0.5 to 2 m.; siltstones and sandstones are greenish gray to dark brown. The shales are easily eroded and often weather to receded ledges; frequently they are buried and require digging to expose them. Siltstones and sandstones, which range from less than 1 m to 3 m thick, are commonly interbedded with claystone units which average 0.5 m in thickness. Flaser bedding sometimes occurs in those sandstone beds which are overlain by claystones. Mudballs averaging 7 cm in diameter are common in the sandstones in some areas. Occasional volcanic pebbles and cobbles are present in sandstones; small channel-shaped lenses containing pebbles of tuff occur in two of the measured sections.

The predominant sedimentary structures in siltstone and sandstone beds is ripple cross-lamination. Reactivation surfaces are occasionally present. Contorted laminae resulting from water escape are common in some areas (Fig. 8).

The claystones and siltstones are typically bioturbated; vertically oriented plant rootlet traces are common (Fig. 9), as are disseminated plant remains. The sandstones are also bioturbated, with vertically oriented Ophiomorpha being the most commonly readily identifiable trace fossil. Bioturbation has destroyed many sedimentary structures, making accurate paleocurrent determination impossible in beds of this lithofacies.

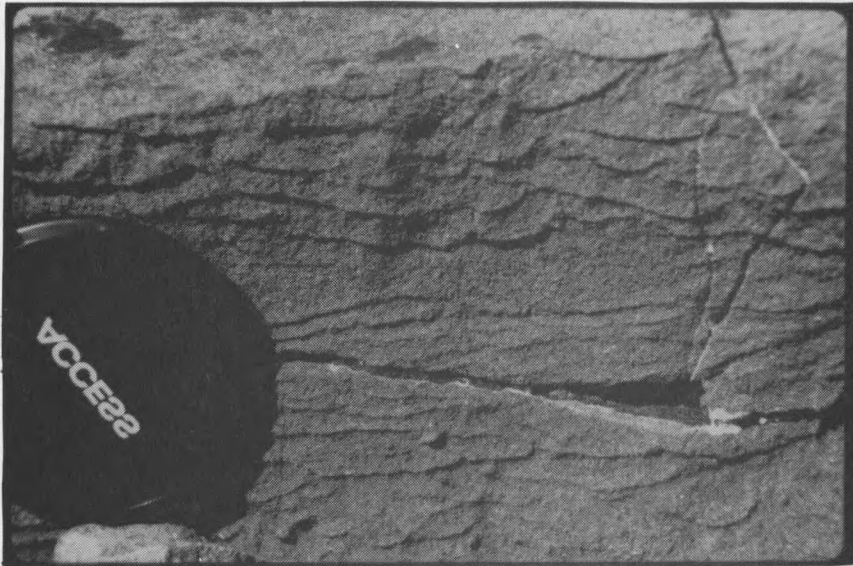


Figure 8. Contorted laminae resulting from water escape in the Carbonaceous Shale, Siltstone, and Sandstone Lithofacies, Measured Section B.



Figure 9. Plant root traces from Carbonaceous Shale, Siltstone, and Sandstone Lithofacies, Measured Section B.

Fine shell hash often occurs on sandstones bedding surfaces. Shales often contain abundant turritellid gastropods, brackish-water Ostrea, and Corbula.

Associated with this lithofacies are beds composed almost entirely of Ostrea, which range in thickness from less than 1 m to more than 4 m (Fig. 10). Most of the shells are articulated, but some are disarticulated and broken, with subangular edges.

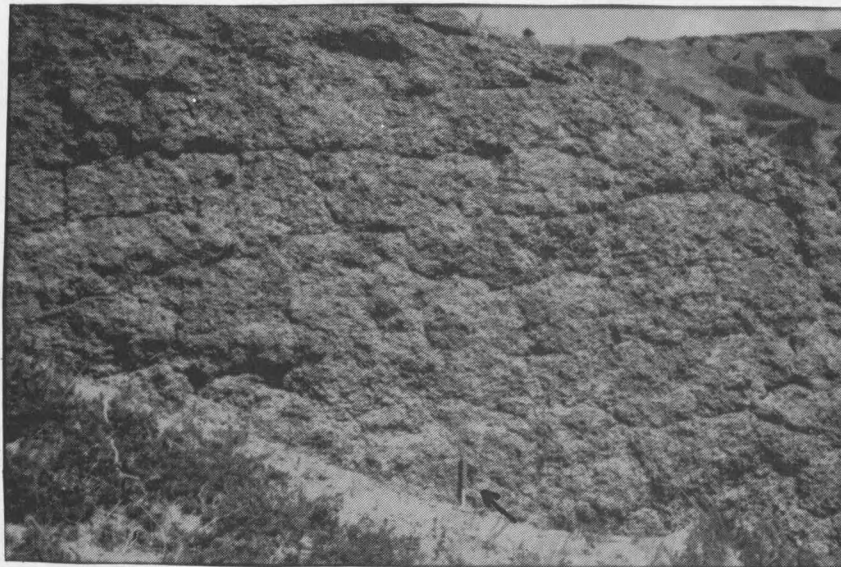


Figure 10. 4 m thick bed composed of whole or nearly whole Ostrea, Measured Section I. Arrow indicates hammer for scale.

In some locations, the upper portion of this lithofacies contains beds with the sedimentary structures and marine to brackish water fossils described above; these beds alternate with pale greenish-white siltstones and mudstones containing numerous freshwater gastropods, identified by the author as Viviparus couseii, occasional bird or dinosaur eggshell fragments, and bone fragments. These beds are 2 to 3 m thick and are interbedded with highly carbonaceous shale beds, up to 3 m thick.

Interpretation. The presence of this lithofacies and its position relative to the shoreface is evidence that barrier islands influenced Horsethief sedimentation in the study area. Fine grained, organic rich facies record subaqueous lagoon and marsh environments (Reinson, 1979; Reineck and Singh, 1980). Plants may flourish in the lee of a barrier island and further act to trap floccules of clay-sized particles (Carter, 1978). Thick coquinid oyster beds, formed by in-place growth and/or by brief transport in estuarine channels, are common in modern bays and lagoons (Calnan, 1980), as well as Cretaceous lagoonal deposits (Land, 1972).

Plant fragments and rootlet traces, wave ripple cross-lamination, and abundant trace fossils are all diagnostic of tidal flats (Weimer and Land, 1972). In addition, contorted laminae resulting from water escape are common on sand flats of back-barrier marshes (Stewart, 1956; Hubbard and Barwis, 1976). Mudballs are formed by bank erosion within channels (Bell, 1940), in this case, tidal channels. Shell hashes are commonly found on surface sediments of modern-day tidal flats, contributed largely by oyster beds on their seaward edge (Hayes, 1976; Land, 1972). Disarticulation of some of the shells in the Ostrea beds indicates that transport has occurred, but the numerous articulated valves suggest very short transport distance.

These characteristics and structures, including the alternating beds containing terrestrial fossils, indicate deposition in a back-barrier tidal-flat marsh complex. The presence of eggshell fragments in non-carbonaceous siltstones and mudstones indicates that not all of

this area was submerged and swampy, as calcareous eggshell should not be preserved in anoxic environments where considerable decay of organic matter and resultant production of acidic conditions was occurring (Carpenter, 1982). Therefore, at least part of this back-barrier environment was emergent and dry for extended periods of time.

Terrestrial sediments entered the back-barrier system via low-gradient fluvial channels, similar to the anastomosing streams which existed in the area during Two Medicine time (Lorenz and Gavin, 1984). The streams entering the Horsethief barrier island system flowed from nearby alluvial plains and volcanic highlands, depositing terrestrial siltstones and shales which interfingered with marine and brackish-water siltstones and sandstones. As the sea retreated, fluvio-lacustrine deposition became increasingly dominant.

Wedge-Planar Cross-Stratified Sandstone Lithofacies

This lithofacies consists of medium to coarse grained, brownish green sandstones which are wedge-planar cross-bedded. Cross-bedding dips, on the average, to the west-southwest; individual cross-bedded sets are about 10 cm thick. The overall geometry of the beds in this lithofacies is lens-shaped; at Measured Section D it is 23 m thick in the center (See Distribution of Facies Section) but pinches out on either side to about 3 m over a distance of about 20 m. Beds located at the same stratigraphic horizon in nearby Section B are not lenticular and are only 5 m thick (Fig. 11). Occasional burrows and shell fragments, as well as rare plant rootlets, are present. The sandstones are sublitharenites and volcanarenites.

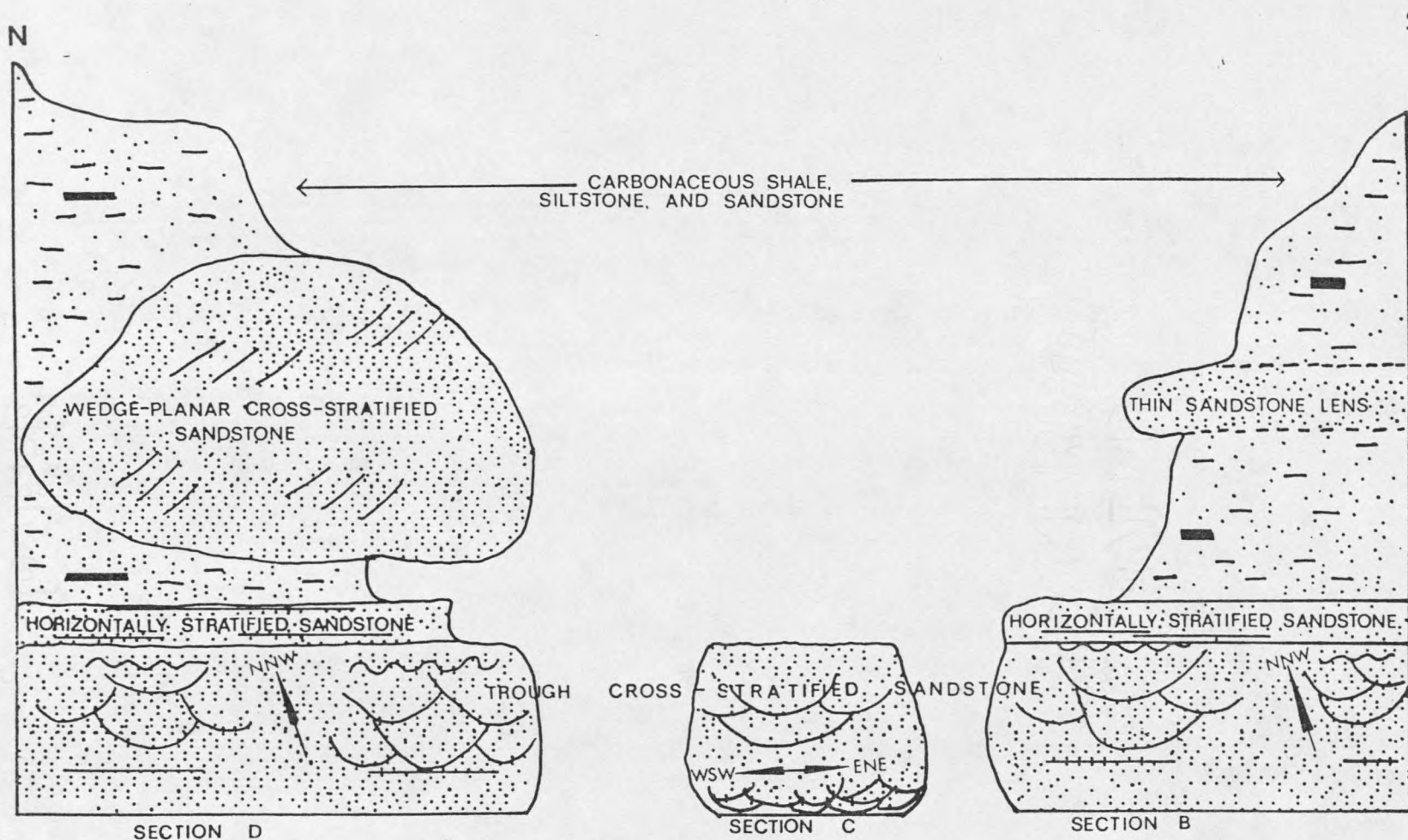


Figure 11. Schematic diagram showing lithofacies relationships in Measured Sections B, C, and D. Drawing not to scale; height of Sections B and D about 50 m.

Interpretation. Flood-oriented planar cross beds are characteristic of flood-tidal delta sequences (Hubbard and Barwis, 1976). The west-southwest orientation of the cross-stratification is roughly perpendicular to the direction of, the estimated shoreline trend (see Paleocurrents Section). The identification of delta sand bodies in the rock record depends largely on their geometry and stratigraphic position relative to surrounding facies (Reinson, 1979). The fact that beds of this lithofacies are much thicker than laterally equivalent sandstone beds (see Distribution of Facies Section), their lens shape, and their stratigraphic position between beds interpreted as upper shoreface deposits and those interpreted as tidal flat-marsh deposits, suggests deposition on a tidal delta. The predominantly shore-oriented cross-stratification specifically indicates that the delta was flood-tidal.

DISTRIBUTION OF FACIES

Stratigraphic sections measured in the course of this study occur in two areas along the outcrop belt: the Salmond Ranch area in the north and the Sun River Game Range area in the south. Four of the five lithofacies are present in each location, but in differing combinations; the Interbedded Sandstone, Siltstone, and Mudstone Lithofacies is absent on the Sun River Game Range but present in the Salmond Ranch Area, while the Salmond Ranch Area contains all but the Wedge-Planar Cross-Stratified Sandstone Lithofacies.

Salmond Ranch Area

Within the Salmond Ranch Area, the Horsethief Formation reaches a maximum thickness of 210 m. The thickest lithofacies present at this locality is the Organic-Rich Shale, Siltstone, and Sandstone Lithofacies, which contains both brackish-water marsh deposits and sediments containing a terrestrial fauna that is very similar in character to the St Mary River Formation. The vertical sequence in Measured Section I (Fig. 12) begins just above the Horsethief-Two Medicine contact and ends where a fault brings the Two Medicine in contact with the uppermost portion of the Horsethief. Although Mudge and Earhart (1983) do not map a contact between the Horsethief and St. Mary River Formations at this location, their descriptions of coal and *Ostrea* beds at that contact, together with the alternating brackish and terrestrial

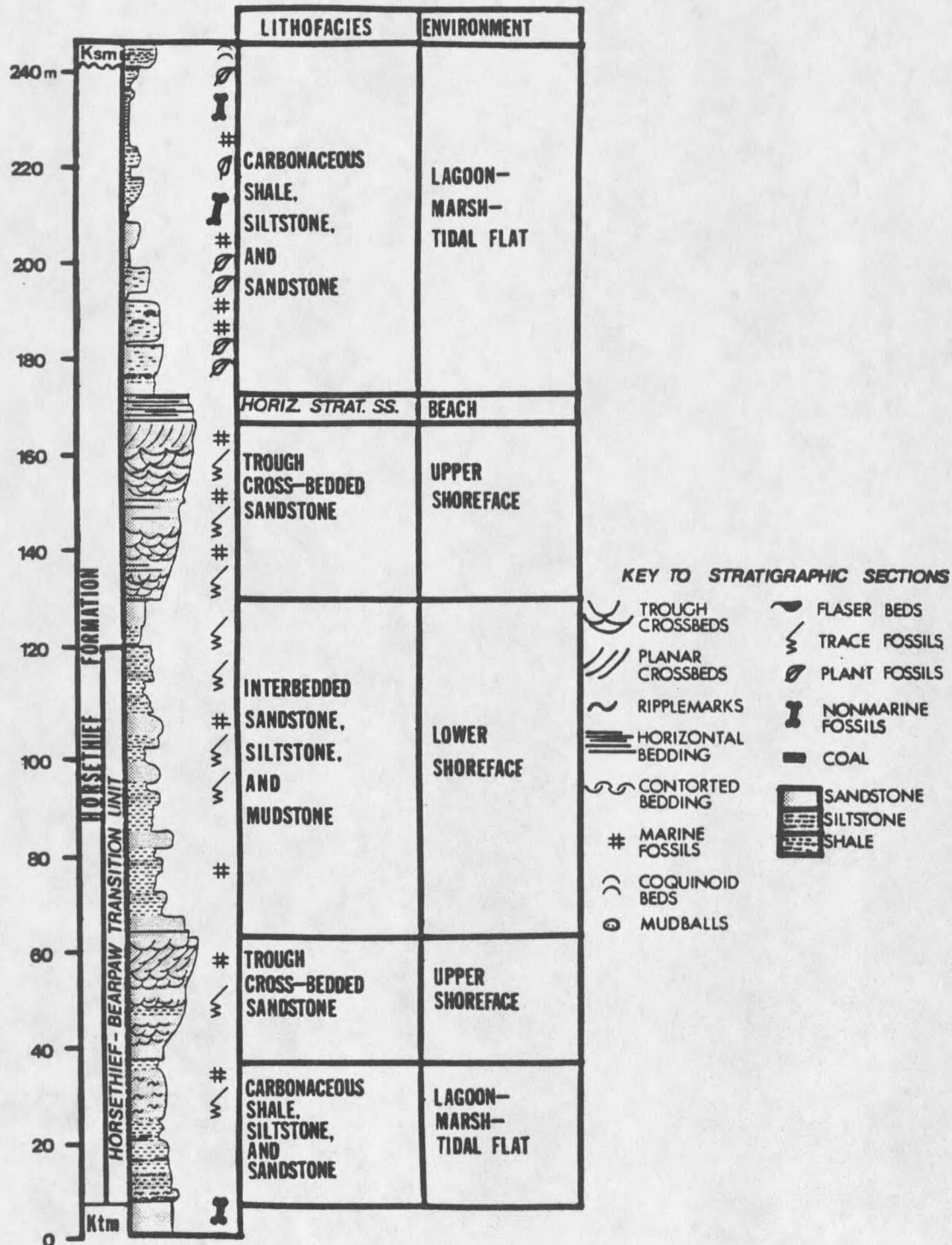


Figure 12. Graphical stratigraphic section; facies and interpreted depositional environments of Measured Section I (Salmond Ranch Area).

characteristics of the beds, leave little doubt that a gradational Horsethief-St. Mary River contact exists in the uppermost part of this section.

The Horsethief-Bearpaw Transition Unit records a transgression (Fig. 12). Water in the area was relatively shallow, as the deposits do not reflect any subenvironment deeper than lower shoreface. The fact that the Horsethief-Bearpaw Transition Unit represents a preserved transgressive deposit is noteworthy, as relatively few complete transgressive sequences are known in the rock record (Kraft, 1978). In particular, preservation of the top portions of transgressive sequences is unusual under conditions of slow sea level rise (Klein, 1982). The Bearpaw transgression was relatively slow, advancing 300 miles in about 3 m.y. (Gill and Cobban, 1973). However, variations in tectonism and sediment supply can locally alter shoreline patterns, causing a rapid transgression to occur within a relatively small area (Kraft, 1978). Preservation of the Horsethief-Bearpaw Transition Unit can probably be attributed to an initial cutoff in sediment supply, locally rapid subsidence, a structural low, or some combination of these factors.

A cutoff in sediment supply, which might be the result of nearby stream channel abandonment, would put an end to local progradation, allowing marine waters to move inland. Similarly, ongoing accumulation of sediment at the mouth of a stream could eventually result in localized compaction and subsidence, forming a depression which the adjacent sea could enter.

Paleostructural influences on Cretaceous sedimentation patterns are documented elsewhere in the Rocky Mountain Region (Weimer, 1980). These studies show that recurrent movement of basement faults creates structurally low areas in which sediments thicken considerably. Basement-controlled tectonic activity in the study area may have created a structural low in the northern part of the area, causing a locally rapid advance of the Bearpaw sea.

As this transgression progressed, water depth and wave energy increased, depositing sandstones in an upper shoreface environment; this was followed by deeper water, lower shoreface conditions, in which horizontally bedded sandstones, siltstones, and mudstones were deposited. The remainder of the Horsethief Formation was deposited under regressive conditions. Terrestrial shales and siltstones of the Two Medicine Formation, which contain dinosaur eggshell and bone fragments, grade into organic-rich deposits of a lagoon-marsh-tidal flat complex. As regression began, the environment returned again to the upper shoreface, barrier beach, and finally, lagoon-marsh-tidal flat regimes. Back-barrier deposits of the uppermost Horsethief Formation interfinger with terrestrial shales and siltstones of the St. Mary River Formation.

Sun River Game Range Area

The maximum thickness of the Horsethief Formation in the Sun River Game Range Area is 65 m, at Measured Section B. The Horsethief-Bearpaw Transition Unit appears to be very thin or absent altogether in this location; burial of the Horsethief-Two Medicine contact makes it impossible to determine this, however. Outcrops in this area are composed

primarily of the Trough Cross Bedded Sandstone Lithofacies and the Carbonaceous Shale, Siltstone and Sandstone Lithofacies; Measured Section B (Fig.13) is typical of the exposures. Measured Section C (Fig.14) is unique in that it is composed entirely of beds of the Trough Cross-Bedded Sandstone Lithofacies; these beds grade laterally into beds of the same lithofacies in Sections B and D, but differ in that the trough axes in Section C are oriented perpendicular to those in Sections B and D (See Paleocurrents Section). Measured Section D (Fig. 15) differs from the other measured sections in the Sun River Game Range Area in that it contains an Ostrea bed and carbonaceous shales at its base. It also contains well-developed beds of the Wedge-Planar Cross-Stratified Sandstone Lithofacies.

The contact between the Horsethief and St. Mary River Formations, identified by a non-resistant carbonaceous shale bed overlain by an Ostrea bed (Mudge and Earhart, 1983), is best exposed in Section H along the Sun River. Elsewhere in the Sun River Game Range Area, it is poorly exposed at best. The main body of measured section B is on the north side of Barr Creek, while the contact between the two formations is actually only exposed on the south side of the creek; at the remainder of the measured sections the contact with the St. Mary River Formation is inferred only by scattered Ostrea shells found at the top of the Horsethief beds.

As shown in Figure 13, the Horsethief Formation at Section B records a regressive sequence. The contact between the Two Medicine and Horsethief Formations is obscured by soil and vegetation at the point

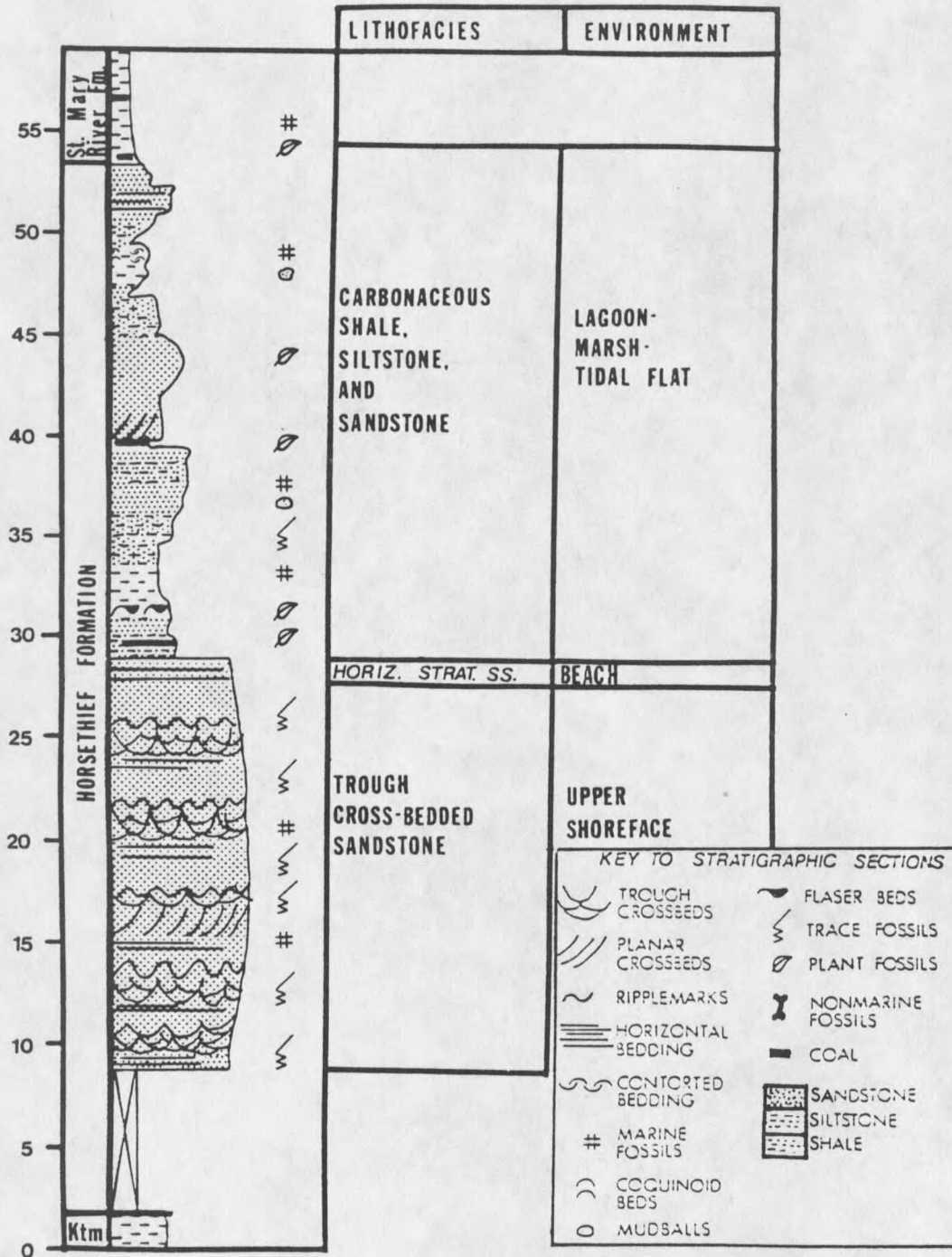


Figure 13. Graphical stratigraphic section; facies and interpreted depositional environments of Measured Section B (Sun River Game Range Area).

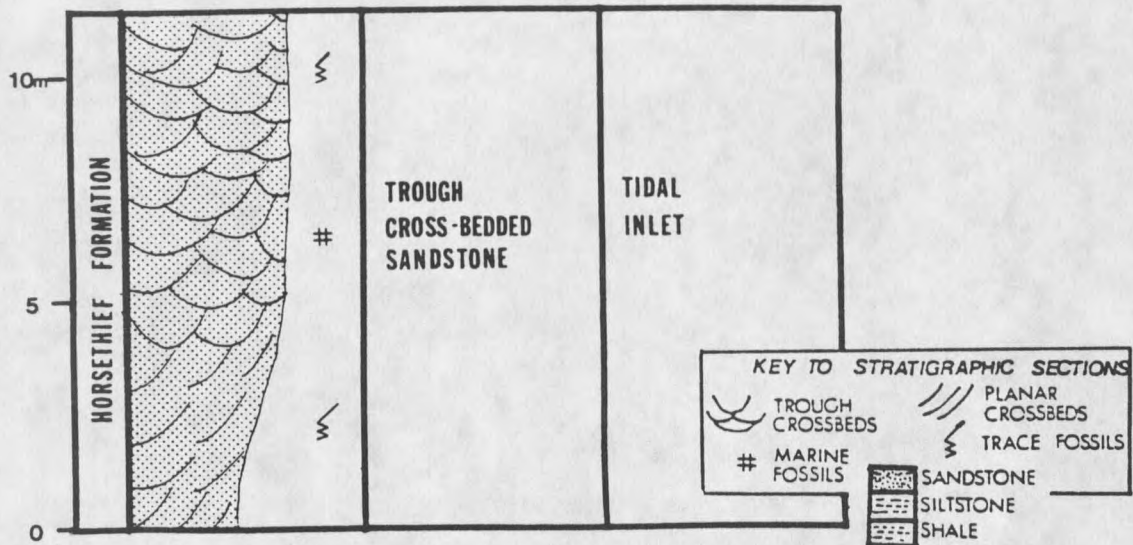


Figure 14. Graphical stratigraphic section; facies and interpreted depositional environments of Measured Section C (Sun River Game Range Area).

where Section B was measured, but the lowermost part of the section probably consisted at least partially of deposits similar to those at the base of nearby Section D. Trough cross-stratified sandstones of the upper shoreface are overlain by laminated barrier beach sandstones, lagoonal shales, and finally, organic-rich shales, siltstones and sandstones which were deposited adjacent to the mainland in a lagoon-marsh-tidal flat complex.

Measured Section D reflects a similar sequence, except that the Two Medicine is not exposed at all and the lower part of the Horsethief Formation consists of organic-rich shale, siltstone and sandstone deposits similar to those at the base of the Horsethief-Bearpaw Transition Unit in Measured Section I. The regressive portion of the sequence

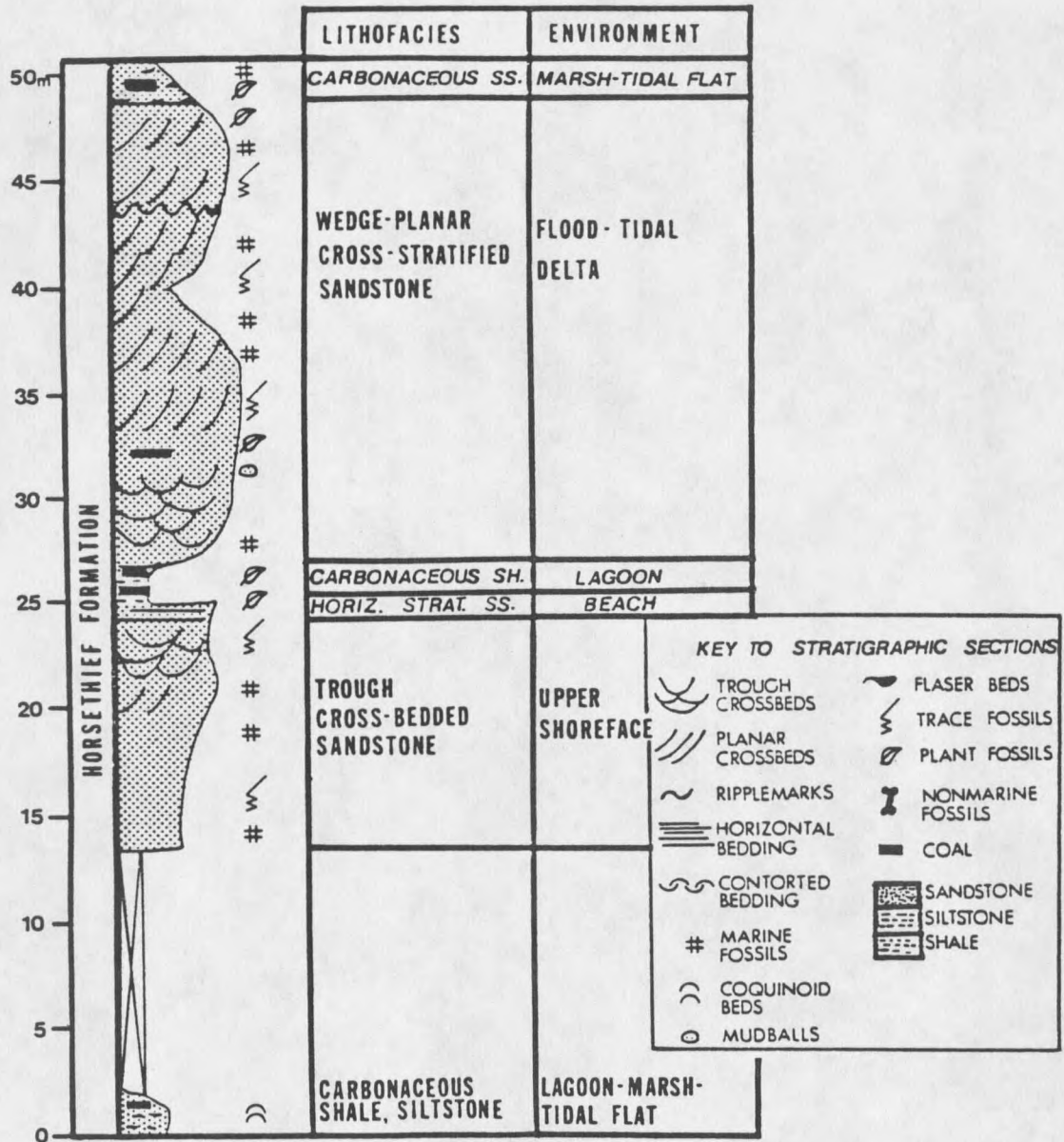


Figure 15. Graphical stratigraphic section; facies and interpreted depositional environments of Measured Section D (Sun River Game Range Area).

begins above a 14 m thick buried interval; the sequence encountered is nearly identical to that in Measured Section B, except that it contains a 26 m thick section of wedge planar sandstone which was probably deposited just landward of a barrier inlet as a flood-tidal delta. With continued regression, the flood-tidal delta sands were overlain by the organic-rich sands of a marsh-tidal flat complex.

Figure 1 shows the relatively close spacing of Measured Sections B, C, and D. Section C is a relatively thin sandstone section which grades laterally into the upper shoreface deposits of Sections B and D. (Fig. 11). The fact that this interval is stratigraphically equivalent to sandstones interpreted as upper shoreface deposits, together with its bimodal cross-stratification, suggests that the sandstone of Section C was deposited in a tidal inlet channel.

PALEOCURRENTS

Four locations contain beds suitable for paleocurrent measurements: the Trough Cross-Bedded Lithofacies of Measured Sections B, C, and F, and the Wedge-Planar Cross-Stratified Sandstone Lithofacies of Section D.

In Measured Sections B and D, the Trough Cross-Bedded Sandstone Lithofacies is characterized by a unimodal distribution of north-northwesterly oriented paleocurrent azimuths based upon 30 measurements of crossbeds and ripple marks at each location (Fig. 16). Paleocurrents of the same lithofacies in Measured Section C trend bimodally west-southwest and east-northeast, and those of the Wedge-Planar Cross-Stratified Sandstone Lithofacies are characterized by a strong west-southwest mode.

These paleocurrent trends may not necessarily accurately reflect the shoreline during Horsethief time, as the region may have undergone rotation about a vertical axis since then due to the buttressing effect of foreland uplifts upon developing thrust sheets. Grubbs and Van Der Voo (1976) used paleomagnetic data to document rotation in the Wyoming Thrust Belt; however, no such studies have been done in the Northern Montana Disturbed Belt. It is therefore not known whether significant rotation about a vertical axis has taken place in the study area.

Regardless of whether or not rotation has occurred, the fact that the orientations of these paleocurrent azimuths agree favorably with

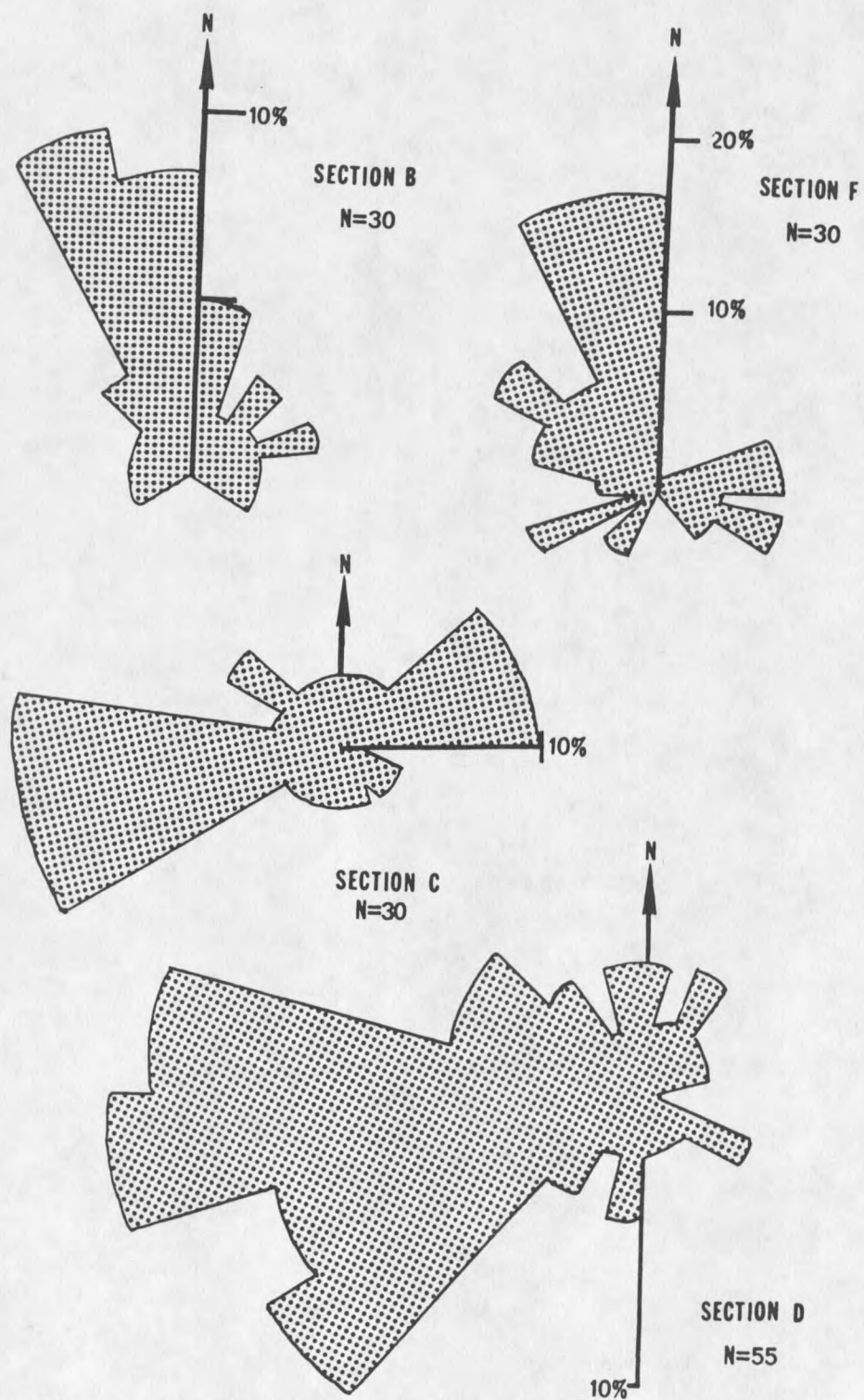


Figure 16. Paleocurrent directions of the Horsethief Formation, Measured Sections B, C, D, and F.

the general trend of the strandline as estimated by Gill and Cobban (1973) may only be coincidental, as local irregularities in the trend of any coastline are certainly the norm. What is significant in this case is the orientation of the paleocurrent azimuths of a given lithofacies with respect to those of another lithofacies; i.e., the current directions of lithofacies interpreted as representing tidal inlet and tidal delta environments are perpendicular to those representing upper shoreface environments. For example, if the shoreline in the study area actually trended east-west, then the tidal inlet currents would have trended north-south; but in any case, they would remain perpendicular to each other, as rotation, if it did occur, would affect the entire area in a consistent manner.

PETROLOGY

The sandstones of the Horsethief Formation vary considerably in mineralogic composition and texture. They are generally immature and highly altered. Volcanic rock fragments are found throughout the Horsethief Formation and in general, the percentage of volcanic rock fragments increases upsection, accompanied by a decrease in the percentage of quartz and feldspar (Fig.17). Volcanic rock fragments (VRF's) constitute between 4 and 93 percent of the detrital grains (matrix and cement excluded). VRF's are grouped into three categories: those consisting primarily of vitrophyre (volcanic glass); those consisting primarily of microliths (predominantly feldspar); and those consisting primarily of phenocrysts (predominantly feldspar and quartz). Detrital quartz ranges from 0 to 56 percent and feldspar varies from 6 to 21 percent. Chert is rare or absent in the samples containing a high percentage of volcanic rock fragments, but sandstones containing fewer volcanic rock fragments contain up to 38% chert. Magnetite is a common accessory mineral in sandstones deposited in the beach facies. Using Folk's (1980) sandstone classification, Horsethief sandstones can be placed into four groups: volcarenites, chertarenites, feldspathic volcarenites, and feldspathic chertarenites.

Because of diagenetic changes, it was extremely difficult to distinguish between matrix and cement (and, in many cases, between matrix and grains) in the volcanic-rich samples. Therefore, matrix and

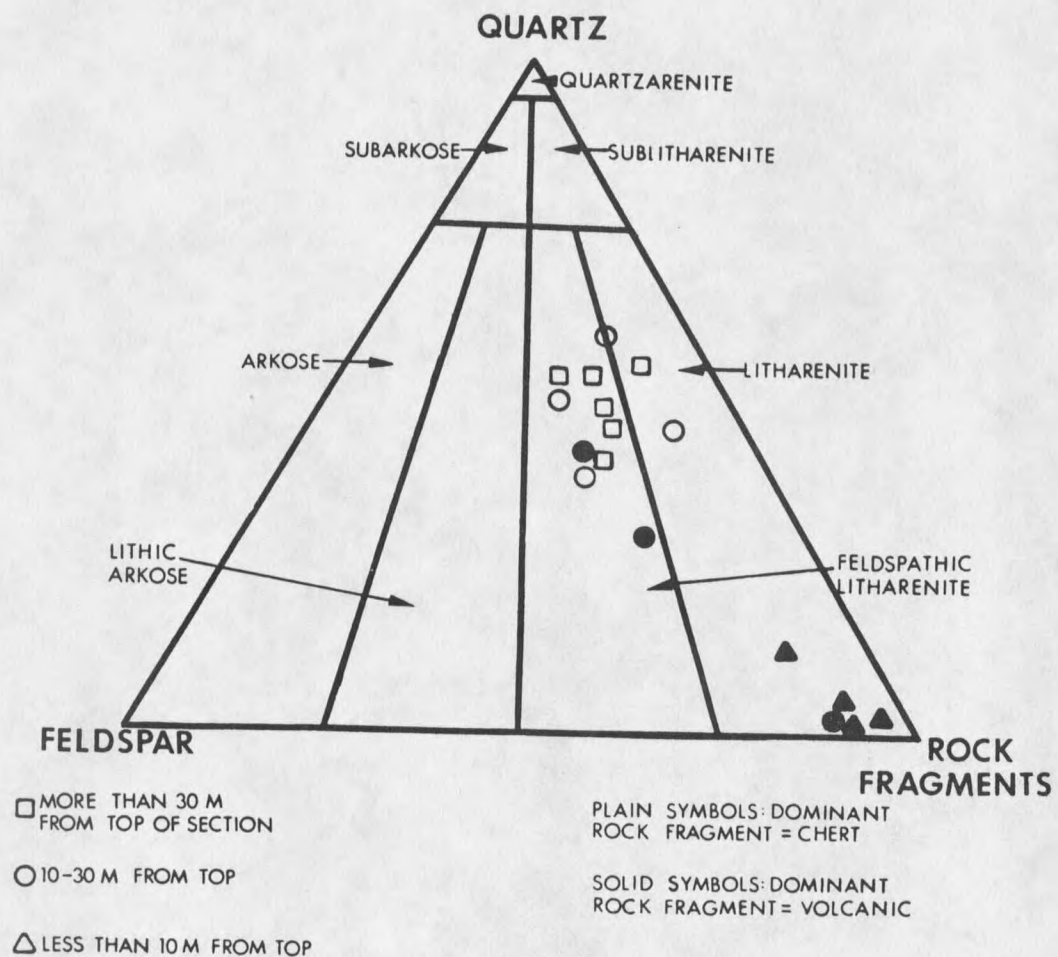


Figure 17. Q-F-RF ternary diagram showing composition of Horsethief Sandstones with respect to location within section.

cement were counted as a single component in point counts. Silica is a common cementing material in all the sandstone types, while carbonate cement is more frequently noted in the volcanic-lean sediments and chlorite cement more abundant in the volcanic-rich sandstone. Other matrix materials include clay and iron oxide.

Texturally, volcanic-rich sandstones tend to be much coarser and in some areas contain rounded pebbles and cobbles up to 7 cm in diameter. Petrographic examination of several typical cobbles revealed compositions to be andesite and trachyandesite.

The sandstones of the Horsethief Formation range in color from light gray to greenish black. In general, the color changes upsection, with light colored, volcanic-lean rocks in the lower part of the formation, and dark-colored, volcanic-rich rocks at the top.

HORSETHIEF DEPOSITIONAL HISTORY

During late Campanian time, a broad coastal plain extended from the Sevier orogenic highlands eastward to the western shore of the Cretaceous Interior (Bearpaw) Sea. Rivers and lakes were common on this plain, whose fauna included the dinosaurs that nested west of what is now Choteau, Montana. The Bearpaw sea was slowly transgressing westward across this plain, and by the latter part of late Campanian time, its westernmost shore extended from the vicinity of the Sun River toward the northwest, inundating the dinosaur nesting area on the Two Medicine coastal plain. The shallow-water Horsethief-Bearpaw Transition Unit, which thins from north to south, was deposited on the southwestern shore of this sea (Cobban, 1955) in marsh-tidal flat and shoreface environments. On the Two Medicine River, 80 km northwest of the study area, Cobban (1955) recorded a thickness of 130 m for the Transition Unit; it is 108 m thick in the northern part of the study area and, though mostly covered in the southern part of the study area, no more than 13 m thick there. South of the study area the Transition Unit is absent altogether. The Horsethief-Bearpaw Transition Unit has not been examined in detail to the north of the study area, but lack of identification of the unit in general geologic studies north of the Two Medicine River implies that it also thins to the north. The southward thinning of the Horsethief-Bearpaw Transition Unit may well be an

extension of the southward thinning trend of the Bearpaw Shale (Fig. 18).

The apparent limited extent of preservation of the transition unit requires some explanation. Regional topography may have been lower in the area where the transition unit is thick. Alternatively, subsidence was more rapid in this region of greater thickness. In either case, it appears that transgressive waters advanced more rapidly into the area where the Transition Unit is now thick, probably inundating that area earlier and remaining longer. The southern part of the study area was therefore at the limit of the region where deposits of the transgression were preserved. Where the deposit is absent or very thin, waters probably inundated the area more slowly and retreated soon after their arrival, leaving only a scant record of the transgression.

The study area was located on a coastal plain which received sediments from low-gradient, anastomosing streams flowing from the rising Sevier orogenic highland to the west (Lorenz and Gavin, 1984) (Fig. 19). Sediments were reworked by waves and tides and were transported by longshore currents, apparently flowing roughly north-northwest. Wave energy was significant along the shoreface of this coastline during storms but was greatly diminished landward due to the protection of barrier islands. Evidence for this includes high-angle cross-bedded beach sandstones overlain by lagoonal carbonaceous shales and *Ostrea* beds, which in turn grade into continental-fluvial deposits. Tidal processes formed tidal deltas, channels, and tidal flats.

Large-scale deltaic sedimentation does not appear to have

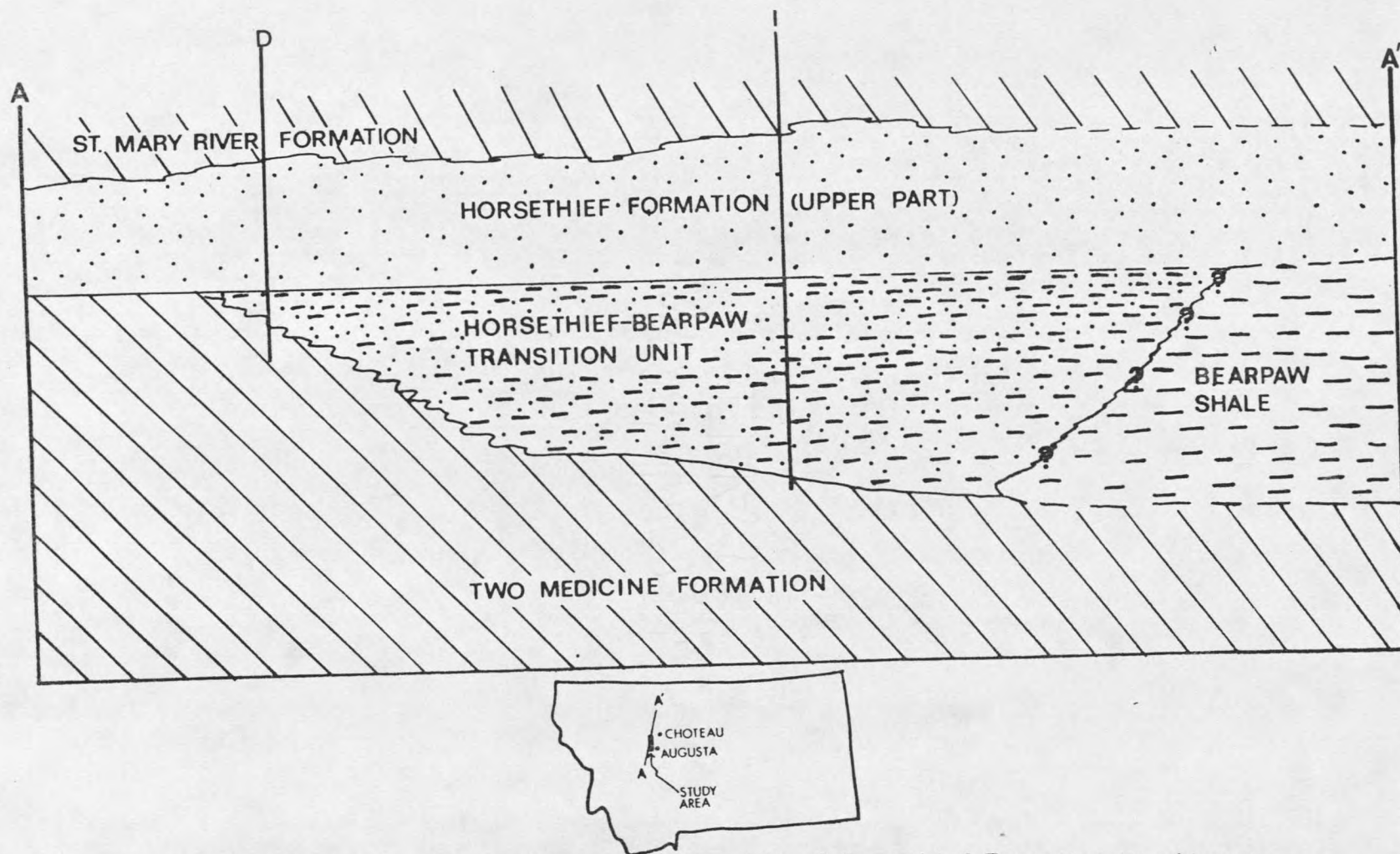


Figure 18. Schematic diagram showing relationship of Horsethief Formation to adjacent units along cross-section A-A'. Letters D, I refer to measured sections. Drawing not to scale.

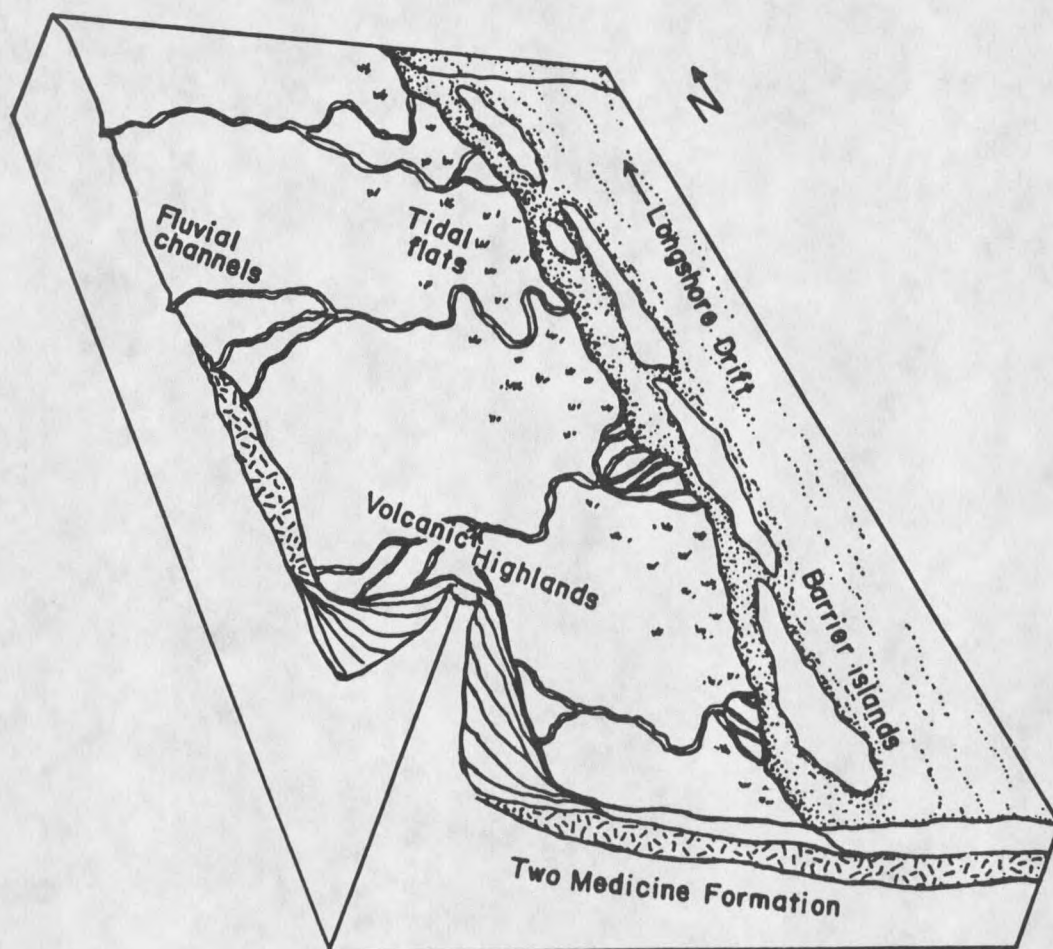


Figure 19. Block diagram showing a generalized paleogeographic reconstruction of the depositional environment and facies relationships during deposition of the Upper Cretaceous Horsethief Formation of west-central Montana.

dominated the coastline in the study area. Thick sheet sandstones with multiple coarsening-upward sequences characteristic of delta-front sandstones are absent from the study area, probably because stream channels entering the Horsethief sea were small and low-gradient, similar to those described by Lorenz and Gavin (1984). Therefore, while deltas were probably formed at the mouths of some of these streams, they would have been small. Barrier-island sedimentation was clearly dominant over deltaic sedimentation in the study area.

The presence of barriers in combination with tidal deltas and inlets suggests that the paleotidal range was upper microtidal to lower mesotidal, or 2 to 3 m (Hayes, 1976). A numerical model of tides in the Cretaceous Seaway of North America (Slater, 1985) suggests that independent tides in the seaway had a range of less than 1 m, but that local bathymetry and interaction with the Arctic Ocean and Gulf of Mexico may have amplified this range.

During the latter stages of Horsethief deposition, there was a significant change in the composition of the sediments. Chertarenites, derived from reworking of older stratigraphic units in highlands to the west, were replaced by highly immature volcarenites. This shift was apparently the result of increased volcanic activity, but the exact location of the volcanism is uncertain. The Elkhorn Mountains Volcanics, located 130 km southwest of the study area, are the nearest Cretaceous volcanic rocks. The coarseness, angularity, and composition of the Horsethief volcanoclastic material suggests it was not transported a great distance. Viele and Harris (1965) have suggested that during Late Cretaceous time, Elkhorn volcanism extended as far

north as the Sun River, and that the volcanoes have since been eroded or buried by thrust sheets.

The volcanic and volcanoclastic facies of the Two Medicine Formation (which Viele and Harris term the Big Skunk Formation) is further evidence for nearby volcanism. Cropping out 16 km south of the study area, this facies of the Two Medicine includes volcanic conglomerates and tuffs, may be up to 1500 m thick (Mudge and Earhart, 1983) and petrologically resembles the calc-alkalic volcanic rocks of the Elkhorn Mountains (Viele and Harris, 1965). As with the Horsethief volcanoclastic sandstones, Two Medicine volcanoclastic deposits appear to be too immature to have been transported a large distance from the present-day Elkhorn Mountains. The Adel Mountains Volcanics, located 45 km southeast of the study area, are currently believed to be of Paleocene age (Mudge and Earhart, 1983) and thus must be ruled out as a possible source.

The lithology of the Upper Two Medicine and Horsethief rocks suggests that volcanism in the vicinity of the study area was somewhat sporadic; it was contributing large amounts of sediments during late Two Medicine time and relatively little during early Horsethief time. During late Horsethief time volcanism was apparently renewed. Sedimentation was more rapid during periods of increased volcanism; south of the study area, for example, a volcanic conglomerate facies of the Horsethief Formation provides evidence that sheet mudflows transported cobbles directly into the Horsethief sea (Viele and Harris, 1965).

The influx of volcanic sediments was probably responsible for the local progradation of the barrier island-tidal marsh complex, and contributed to the final withdrawal of marine waters from this area. Eventually, terrestrial sedimentation dominated, resulting in deposition of the shales and sandstones of the St. Mary River Formation.

CONCLUSIONS

Deposits of the Horsethief Formation west and northwest of Augusta, Montana represent the sedimentary record of a barrier island coastal zone. The lithofacies interpretations are as follows:

Interbedded Sandstone, Siltstone, and Mudstone--Lower Shoreface Environment

Trough Cross-Bedded Sandstone--Upper Shoreface and Tidal Inlet Environments

Horizontally Stratified Sandstone--Beach Foreshore and Backshore Environment

Carbonaceous Shale, Siltstone and Sandstone--Lagoon, Marsh, Tidal Flat Environments

Wedge Planar Cross-Stratified Sandstone--Flood Tidal Delta Environment

Within the study area, the lowermost strata of the Horsethief Formation, termed the Horsethief-Bearpaw Transition Unit, record a shallow transgressive sequence; conversely, the upper part of the Horsethief Formation is regressive. The transgressive sequence was deposited as the western edge of the Bearpaw sea encroached on a coastal plain at the close of Two Medicine time. It is preserved in an area which was probably low or more rapidly subsiding. In areas north and south of the study area, the Transition Unit is apparently thinning or

absent altogether. The regressive sequence accumulated while volcanic activity in the vicinity of the study area increased toward the end of Horsethief deposition, contributing large amounts of volcanoclastic sediment to the prograding barrier island system.

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APPENDIX

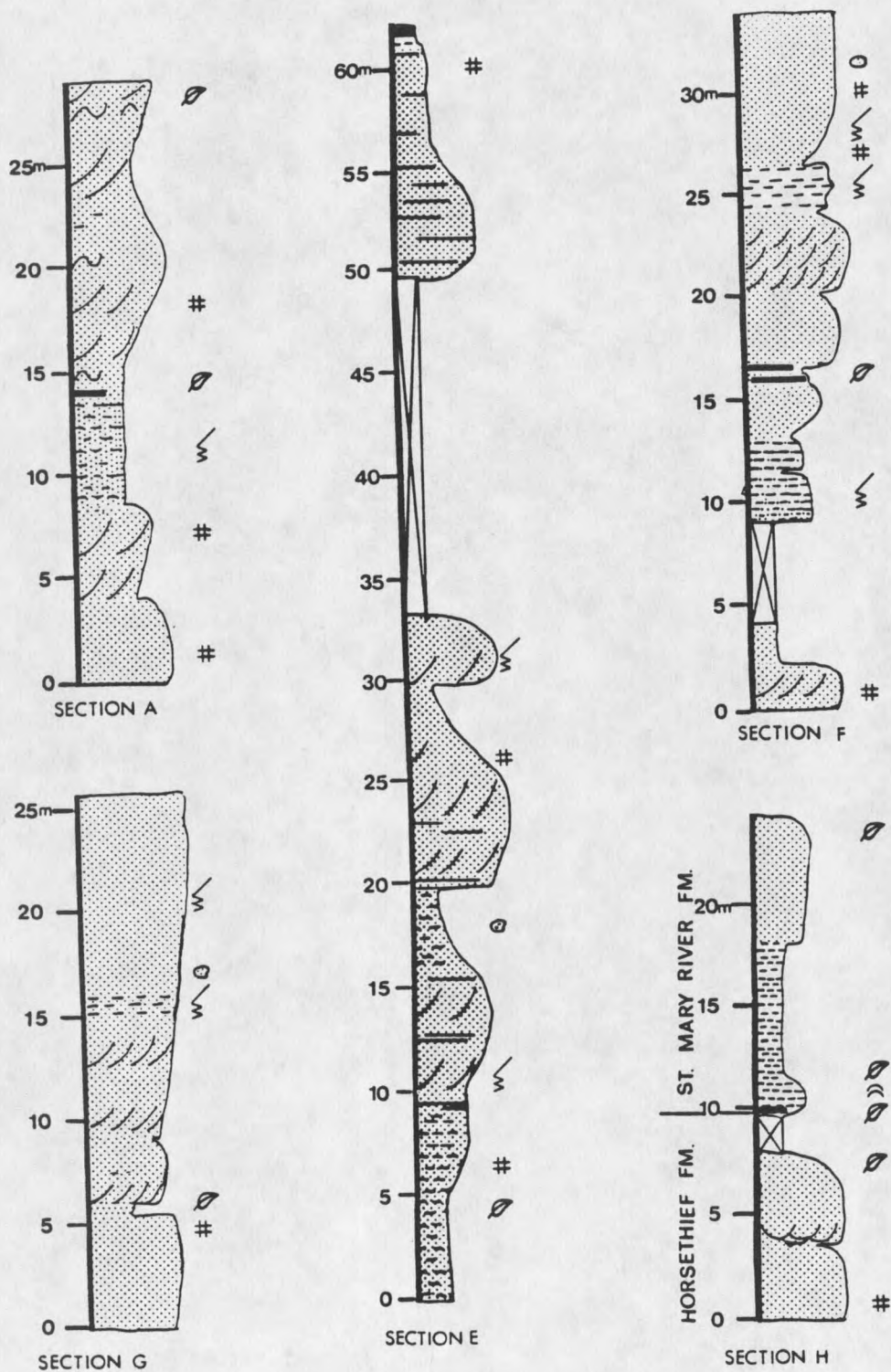


Figure 20. Measured sections not described in text.

SAMPLE NO.	7-11	7-112	7-116	7-25	7-21	8-10	8-23	8-234	8-231	8-17	8-232	8-13	7-4	7-5	8-4	8-5	8-14
SECTION NO.	A	A	A	B	B	C	D	D	D	D	E	F	F	G	H	I	I
DISTANCE FROM TOP OF SECTION (m)	23	28	5	4	52	25	51	50	22	18	2	33	6	13	7	90	230
QUARTZ	66	72	4	8	66	73	79	57	62	14	1	92	4	55	4	40	60
PLAGIOCLASE	9	9	5	3	12	7	14	4	10	6	3	10	4	11	3	3	3
K-FELDSPAR	4	5	4	1	3	3	3	2	8	2	1	2	2	11	3	2	2
OPAQUES	Oth 45	Oth 13	Oth 29	Oth 5	M 37	Oth 12	Oth 27	M 67	Oth 45	Oth 90	Oth 38	Oth 20	Oth 96	Oth 10	Oth 20	Oth 69	Oth 20
VRF'S, MOSTLY VITROPHYRE	6	5	4	67	3	0	5	3	2	4	1	0	3	15	17	2	2
VRF'S, MOSTLY MICROLITES	10	10	97	3	6	4	6	5	9	7	25	5	3	4	61	5	1
VRF'S MOSTLY PHENOCRYSTS	5	5	19	44	4	0	8	3	7	54	92	7	75	0	77	3	3
MUSCOVITE	3	6	4	3	3	4	3	4	1	2	0	3	2	10	0	4	3
BIOTITE	2	4	2	3	5	1	2	3	2	4	0	0	1	15	0	2	2
PYROXENE	1	2	4	3	3	0	0	2	1	2	0	0	2	4	0	0	0
HORNBLFENDE	1	4	3	2	1	0	1	0	2	1	0	0	1	3	0	0	0
CARBONATE CEMENT & MATRIX	10	30	27	60	35	75	30	34	30	5	12	5	2	35	20	46	90
CHLORITE CEMENT & MATRIX	16	6	28	15	6	0	10	9	2	4	34	10	47	20	25	16	2
UNDIFFERENTIATED CEMENT & MATRIX	31	31	20	19	22	30	27	37	50	37	40	20	2	25	20	30	45
CHERT	38	42	1	2	38	41	39	19	15	12	3	76	3	30	0	22	17
OTHER OR UNKNOWN	2	4	0	6	7	0	0	0	2	5	0	0	3	12	0	6	0
MEAN QUARTZ GRAIN SIZE (mm)	.27	.39	.20	.12	.21	.24	.23	.23	.25	.16	.23	.31	.25	.21	.10	.25	.10

M= Magnetite
Oth=Other Opaques

Table 2. Point count data.

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