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INFLUENCE OF THE ANCESTRAL SWEETGRASS ARCH ON SEDIMENTATION OF THE LOWER CRETACEOUS BOOTLEGGER MEMBER, NORTH-CENTRAL MONTANA

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Abstract: **In north-central Montana the Bootlegger Member of the upper Lower Cretaceous Blackleaf Formation is well exposed near Great Falls and at one locality in the Sweetgrass Hills. In both areas, Bootlegger strata comprise four stratigraphic successions. In the Great Falls study area each succession consists of an upward-coarsening (-shoaling) package of interbedded very fine sandstone and shale grading upward into fine to medium sandstone, abruptly overlain by a transgressive erosion surface and capped in many places by a conglomeratic transgressive lag deposit. The stacking of these successions is attributed to episodic changes of relative sea level, probably related to episodic reactivation of the ancestral Sweetgrass Arch. During episodes of arch uplift accommodation space was reduced and caused the Bootlegger shoreline to prograde eastward. Subsequently, because of arch subsidence and/or the ongoing basinwide eustatic rise, the shoreline migrated westward. Erosion associated with transgressive shoreface retreat was most intense near the crest of the arch. As a result, in the western study area, which lies above the arch crest, successions are thin and typically consist only of inner-shelf strata (Lithofacies 1); strata deposited in shallower environments were removed mainly by later transgressive erosion. By contrast, in the eastern area, farther from the arch crest, the upward-shoaling part of each succession is more completely preserved. At the end of Bootlegger time, however, movement of the arch either ceased or simply could no longer keep pace with the eustatic rise. Consequently, the shoreline continued to transgress westward, and only fossiliferous silt and mud accumulated in a distal shelf environment. This marked a eustatic drowning and termination of rhythmic Bootlegger sedimentation.**

INTRODUCTION

The Cretaceous of western North America was marked by the long-term development of the Cordilleran fold and thrust belt (e.g., Monger et al. 1972). Lithospheric loading associated with the eastward migration of the developing Cordillera depressed the crust immediately to the east and created a narrow asymmetric foreland basin termed the Cretaceous Western Interior Seaway (Price 1973; Beaumont 1981; Jordan 1981). Marine strata that were deposited on the western side of the basin are commonly characterized by vertically stacked, upward-coarsening successions, generally of the order of several meters to a few tens of meters thick (e.g., Leckie and Walker 1982; Beaumont 1984; Cant 1984; Plint and Walker 1987; Plint 1988; Bhattacharya and Walker 1991; Sethi and Leithold 1994). Typically, each succession shows a suite of physical and biogenic sedimentary structures indicating upward-shoaling depositional conditions. In turn these strata are abruptly overlain by deeper-water deposits (e.g., Arnott 1995). These high-frequency depositional events are related to changes of relative sea level, which in turn are controlled by three principal factors: sediment supply, basin subsidence/uplift, and eustasy. A fourth variable, basin physiography, principally influences the internal architecture of depositional sequences (Posamentier and Allen 1993). These factors, in turn, are controlled by a number of causal mechanisms. For example, changes of eustasy can be the result of periodic waxing and waning of continental ice sheets (e.g., Pitman and Golovchenko 1983; Plint 1991; Murakoshi and Masuda 1992), although the paucity of evidence supporting significant ice-sheet development during the Cretaceous (Frakes 1979) makes such an interpretation problematic for Cretaceous successions. Basin uplift/subsidence may be related to intrabasinal or extrabasinal tectonics (Watts 1982; Embry 1990, 1993; Agirrezabala and Garcia-Mondejar 1992; among others), or variations in intraplate stresses (Cloetingh et al. 1987; Cloetingh 1988). Moreover, volumetric fluctuations in sediment supply may be related to climatic change (e.g., Sethi and Leithold 1994) or tectonic events in the adjacent source area (e.g., Arnott and Hein 1986). Intuitively, therefore, using stratigraphic data to interpret which of the many possible mechanisms and/or related factors caused a relative sea-level change is difficult, and in many cases equivocal. Nowhere is the debate more acute than in the Cretaceous of western North America. Here, because of contemporaneous tectonism associated with Cordilleran mountain building, differentiating intrabasinal from extrabasinal tectonics from nontectonic influences, or local versus basinwide versus global-scale change becomes exceedingly problematic. Nevertheless, we propose that during deposition of the upper Lower Cretaceous Bootlegger Member relative sea-level changes were mainly related to epeirogenic movements of the ancestral Sweetgrass Arch. Although the Bootlegger Member was deposited during a period of rising global sea level (Kauffman 1985), the consistent relationship between the regional and vertical distribution of Bootlegger lithofacies and the Sweetgrass Arch suggests that arch movements did at times overwhelm the effect of the eustatic rise.

SWEETGRASS ARCH

The Sweetgrass Arch of north-central Montana is a north-northwest-trending antiform that loses its identity beneath the Alberta Plains (Stebinger 1916; Collier 1929; Romaine 1929). Several studies have suggested that the northeast-trending Bow Island Arch of southern Alberta may represent its northern extension (Fig. 1; Dowling 1917; Michener 1934; Tovell 1958; Herbaly 1974). During the Paleozoic the Sweetgrass Arch formed the western margin of the intracratonic Williston Basin, and it is thought to have influenced regional sedimentation patterns since the Precambrian (Peterson 1966). Beaumont (1981) suggested that the arch originated as a lithospheric upwarp that developed between an ancestral basin to the west and the Williston Basin to the east. Uplift of the arch began before the Late Cambrian and was the result of lithospheric stress relaxation associated with a trend toward isostatic equilibrium (Beaumont 1981, fig. 18).

In north-central Montana the Sweetgrass Arch consists of two elements, South Arch and the Kevin–Sunburst Dome, which are separated along the Marias River Saddle (coincident with the Pendroy Fault Zone; Fig. 1). The crest of the South Arch underlies the western part of the Great Falls study area (Fig. 1). The Sweetgrass Hills study area lies on the eastern limb of the Kevin–Sunburst Dome (Fig. 1).

LOCAL STRATIGRAPHY

In north-central Montana, upper Aptian to lower Cenomanian strata comprise the Kootenai, Blackleaf, and Marias River Formations (Figs. 1, 2). The Kootenai Formation is of continental origin (Cobban et al. 1959, 1976; Cannon 1966; Hopkins 1985). Unconformably overlying the Kootenai Formation is the Blackleaf Formation, which has been subdivided

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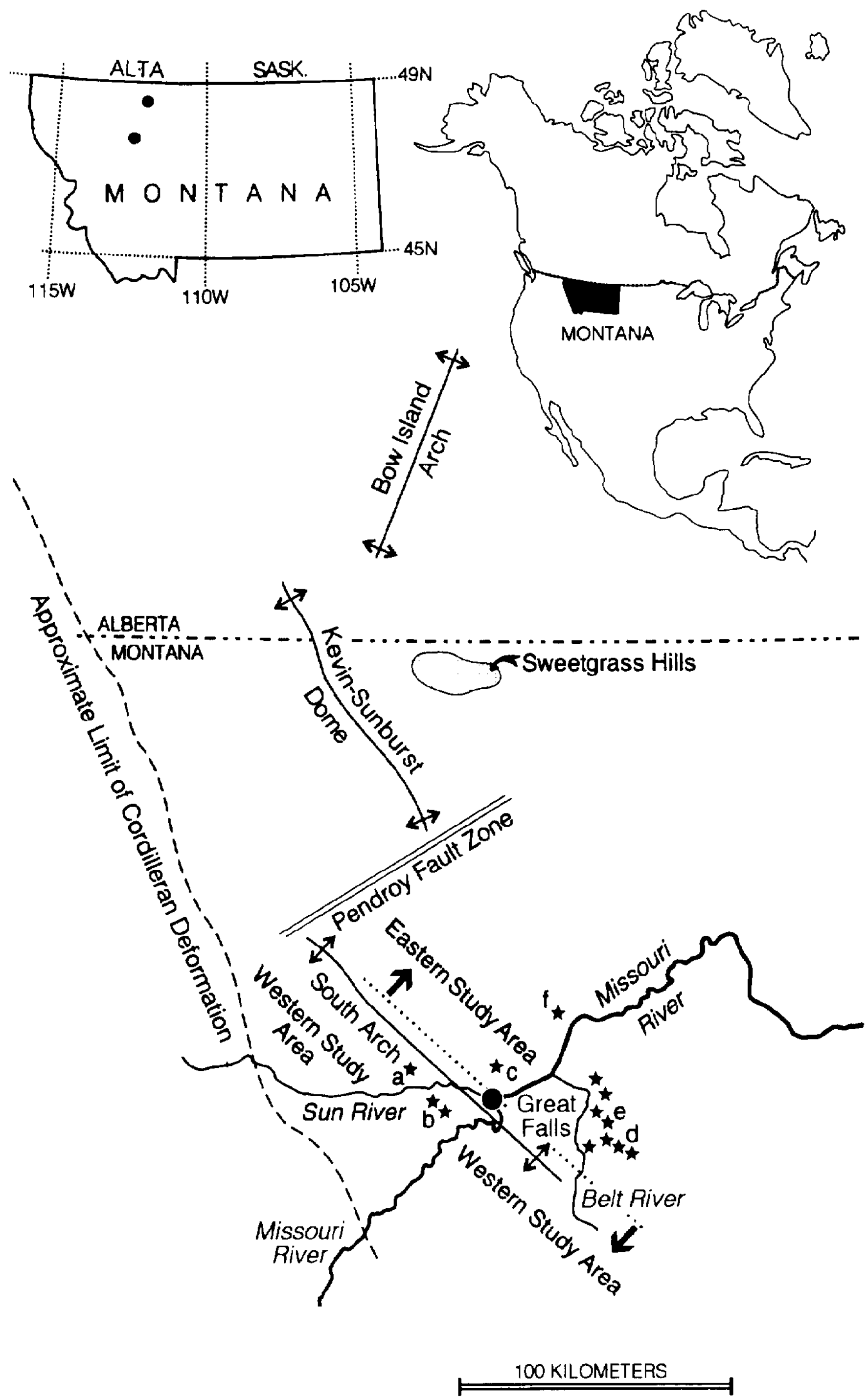

FIG. 1.—Location map of the study areas in north-central Montana. The inset map show the location of the two study areas in the state of Montana. Also, the two NNE-SSW-trending elements of the Sweetgrass Arch, the South Arch and the Kevin–Sunburst Dome, are shown. In the Great Falls area the star symbols indicate individual study sites; the small-letter superscripts denote specific study locations: (a) Gordon, (b) Ulm Pishkun, (c) Black Horse Lake, (d) Little Belt Creek, (e) North Willow Creek, and (f) Carter. The arrow at the eastern end of the Sweetgrass Hills indicates the single northern study area. The Great Falls study area has been subdivided into a western and an eastern sector, coinciding closely with the crest of the South Arch. Furthermore, note that the Great Falls study area straddles the crest of the South Arch, whereas the Sweetgrass Hills study area lies far to the east of the Kevin–Sunburst Dome.

into four members: the Flood, Taft Hill, Vaughn, and Bootlegger (Fig. 2; Cobban et al. 1976). A horizon of abundant fish scales and bones separates the Bootlegger Member from the overlying black shales of the lower Upper Cretaceous Floweree Member of the Marias River Formation (Cobban et al. 1959, 1976). Farther to the north in Alberta, a similar fossiliferous interval, called the Fish Scales Formation (Bloch et al. 1993), is interpreted to be a synchronous marker that extends some 800 km from north to south and marks the contact between the Lower and Upper Cretaceous (Stelck and Armstrong 1981). In Montana, however, the Bootlegger fish scales horizon is interpreted to be slightly older (Lang and McGugan 1988).

During the late Albian to early Turonian in the western United States, two basinwide transgressive-regressive packages, the older Kiowa–Skull Creek Cyclothem and the younger Greenhorn Cyclothem, were deposited (Fig. 2; Hattin 1964; Kauffman et al. 1977). In north-central Montana, deposition during the transgressive stage of the Kiowa–Skull Creek Cyclothem is represented by marine deposits of the Flood Member (Vuke

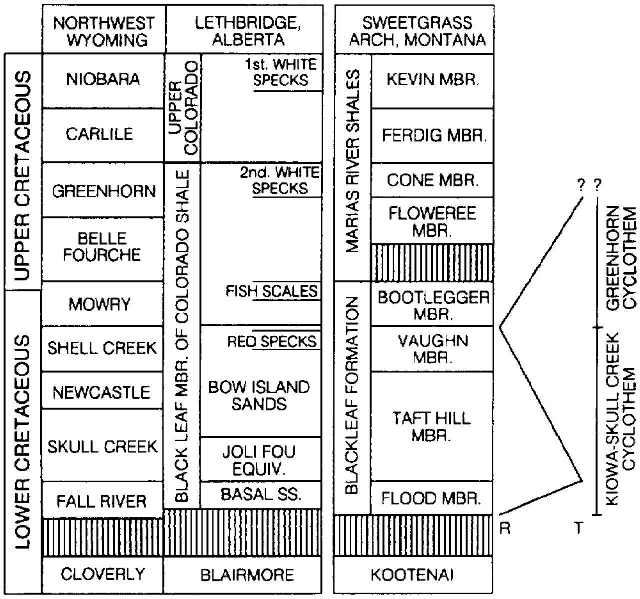

FIG. 2.—Correlation chart of upper Lower Cretaceous to lower Upper Cretaceous strata in west-central North America (modified after Stelck and Armstrong 1981). Also, the sea-level curve for the Western Interior Seaway during the late Early Cretaceous is shown, and indicates two basinwide episodes of sea-level change associated with the Kiowa–Skull Creek and Greenhorn Cyclothems (based on Kauffman 1977). The letters T and R indicate, respectively, rise and fall of relative sea level.

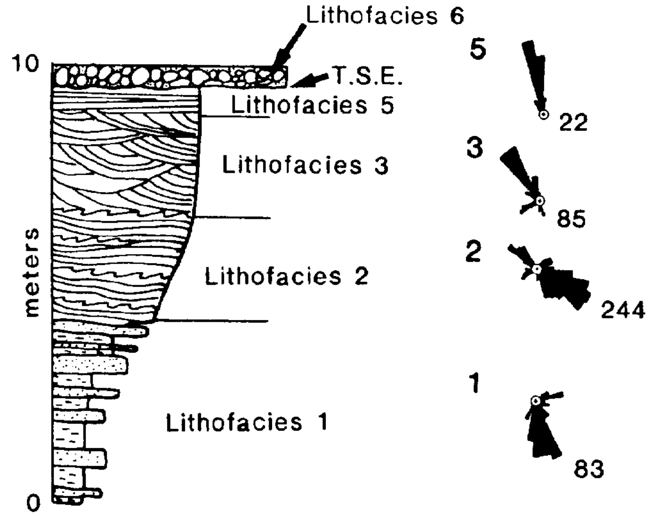

FIG. 3.—An idealized Bootlegger succession. Successions are generally of the order of ten meters to a few tens of meters thick, and when fully developed and preserved, consist of Lithofacies 1 to 5 overlain by a transgressive erosion surface capped by a thin transgressive lag deposit of Lithofacies 6 (see text for details). (Note: Lithofacies 4 is observed only at the Ulm Pishkun and is not considered part of the idealized succession.) In most cases, however, only a part of the idealized succession is observed. Paleocurrent data collected in the Great Falls study area are shown by the rose diagrams; numbers to the upper left indicate lithofacies number, those to the lower right indicate the number of measurements. Note that much of these data represent the measurements of one of the limbs of trough cross-stratified sets.

1984). Subsequent regression deposited the glauconite-rich marine strata of the Taft Hill Member and eventually continental deposits of the Vaughn Member (Cobban 1951; Vuke 1984). Transgression during the early stages of the succeeding Greenhorn Cyclothem deposited nearshore-marine strata of the Bootlegger Member. Continued transgression into the early Late Cretaceous deposited the deep basinal shales of the Floweree Member of the Marias River Formation (Vuke 1984).

Bootlegger Member

In north-central Montana the Bootlegger Member is uppermost Albian to lowermost Cenomanian and consists of marine mudstone, siltstone, sandstone, and rare conglomerate, and is generally 85–100 m thick (Cobban et al. 1976). Westward it onlaps continental deposits of the Vaughn Member and merges eastward with deep basinal shales of the Mowry Member (Fig. 2; Cobban et al. 1959, 1976; Stelck and Armstrong 1981; Lang and McGugan 1988). Although Bootlegger Member strata have not been specifically dated, the base and top of the coeval Mowry Shale has been dated at approximately 95.3–98 Ma and 92–94 Ma, respectively (Folinsbee et al. 1963; Obradovich and Cobban 1975). Deposition of the Bootlegger Member therefore represents approximately 0.7–4 million years of geologic time.

In the Great Falls study area, the Bootlegger Member crops out along laterally continuous, low-relief buttes and comprises four vertically stacked, upward-coarsening successions. Because of the resistant weathering of the sandstone in the upper part of each succession, the Bootlegger Member is easily differentiated from the recessive-weathering, white, bentonitic strata of the underlying Vaughn Member and the recessive-weathering black shale of the overlying Floweree Member. The lower, shale-rich part of each Bootlegger succession is typically poorly exposed.

Bootlegger Member strata are also well exposed 200 km north of Great Falls at one location in the easternmost region of the Sweetgrass Hills (Fig. 1). There the Bootlegger Member and other members of the Blackleaf Formation are continuously exposed in the axis of an overturned anticline; structure in this area is the result of Eocene magmatism (e.g., Marvin et al. 1980). At this location the Bootlegger Member consists of four vertically stacked, upward-coarsening successions (see below). Although this stratigraphic pattern resembles that observed in the Great Falls area, the lack of intervening control makes a 1:1 correlation equivocal. Note, however, that much of the following discussion relates to the Bootlegger strata cropping out in the Great Falls study area.

SEDIMENTOLOGY OF THE BOOTLEGGER MEMBER

In the Great Falls study area the Bootlegger Member can be subdivided into four regionally correlatable successions that range in thickness from several meters to a few tens of meters. Typically each succession shows an upward coarsening and consistently thickens in an eastward, i.e., basinward, direction. Stratigraphically upward the complete succession consists of Lithofacies 1 to 5 overlain abruptly by Lithofacies 6 (Fig. 3).

Lithofacies 1: Interbedded Gray-Black Mudstone and Siltstone/Sandstone

Description.—Lithofacies 1 consists of poorly exposed, gray-black bentonitic mudstone and thin siltstone/sandstone interbeds (Fig. 4A). Typically the unit is several meters to a few tens of meters thick. Stratigraphically upward sandstone interbeds become coarser (siltstone to very fine sandstone) and become more abundant and thicker (siltstone beds generally 2.5–5.0 cm thick, and very fine sandstone beds are 10–15 cm thick). Siltstone interbeds are typically ripple cross-stratified, showing symmetrical and asymmetrical types, with the latter indicating southeastward paleoflow (Figs. 3, 7). Sandstone interbeds are commonly quasi-planar laminated (see Arnott 1987; Arnott and Southard 1990; Arnott 1993a).

Biogenic structures also show a progressive upward change. In the lower

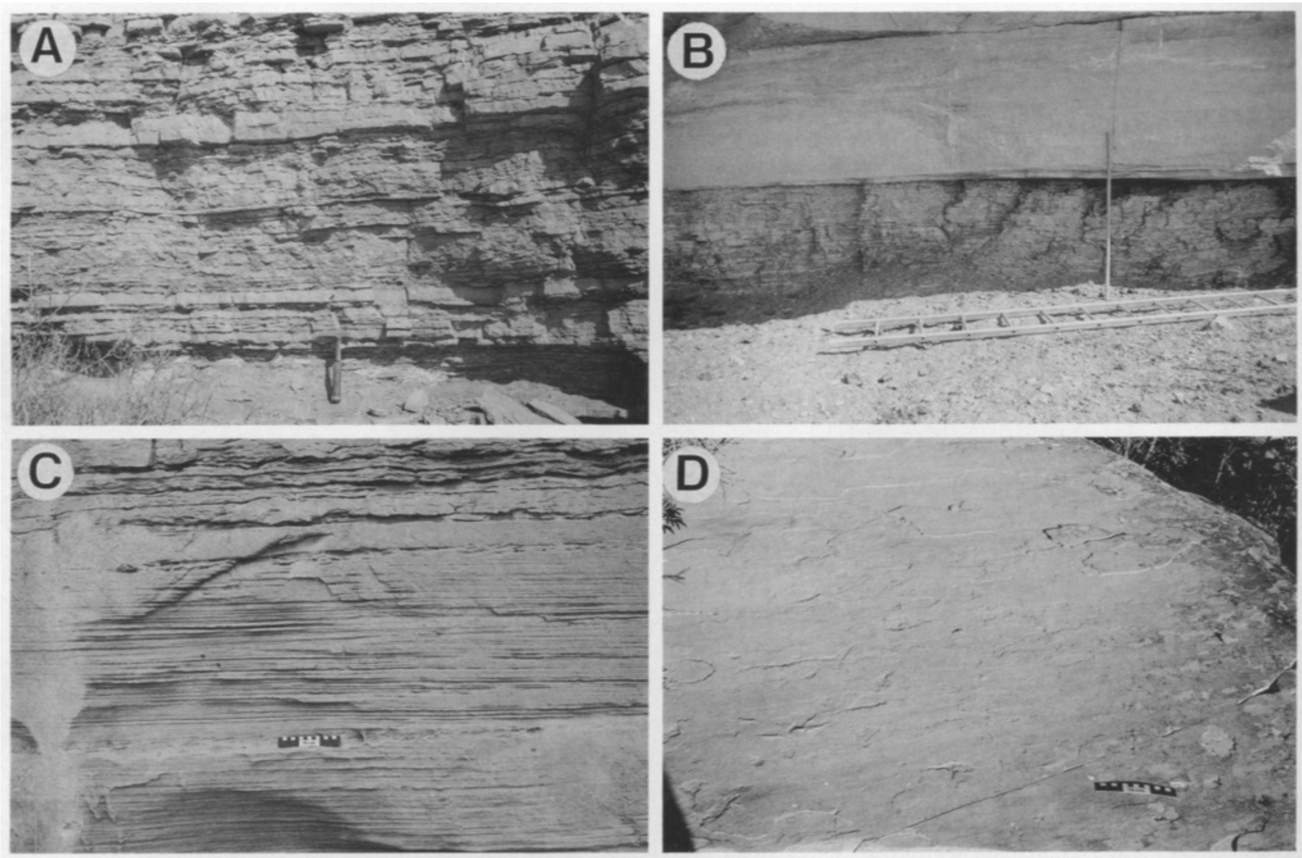

FIG. 4.—**A)** Interbedded very fine sandstone and mudstone strata of Lithofacies 1. Sharp-based, tabular sandstone beds are event beds deposited during high-energy events, most probably associated with storms, in an otherwise quiet, mud-dominated depositional environment (hammer for scale). **B)** Sharp contact between distal inner-shelf deposits (Lithofacies 1) and lower-shoreface strata (Lithofacies 2) at the Ulm Pishkun (staff is 1.5 m long). Unlike the typically gradational contact observed at other locations, this abrupt contact may be indicative of a forced regression (see text for details). **C)** Quasi-planar-laminated sandstone beds of Lithofacies 2 (15 cm ruler for scale). Note the subtle although perceptible undulation of the laminae that make up several laminasets; sets are separated by low-relief scour surfaces. See text and Arnott (1993a) for details. **D)** Parting lineation on the bedding plane of a quasi-planar-laminated sandstone bed (15 cm ruler for scale). Lineation consistently parallels scour marks observed on the bottoms of beds.

mudstone-rich part *Teichichnus*, *Planolites montanus*, and *Chondrites* are dominant. Concomitant with the upward increase in sandstone bed abundance and thickness, trace fossils become more abundant and diverse; forms include *Palaeophycus*, *Thalassinoides*, *Skolithos*, *Cylindrichnus*, *Bergaueria*, *Ophiomorpha*, *Planolites beverlyensis*, and *Asterosoma*.

Interpretation.—Lithofacies 1 is interpreted to represent deposition in a shallow-shelf environment. Sedimentation was dominated by suspension fallout of bentonite-rich mud. Occasionally, however, these conditions were interrupted by brief, higher-energy tractional events that deposited the interbeds of siltstone and very fine sandstone. These events were most probably associated with storms that transported nearshore sediment seaward. The combination of upward thickening and coarsening, the greater abundance of siltstone and sandstone interbeds, and the change from predominately deposit-feeding traces to dwelling burrows indicates upward shoaling as a result of progradation of the local Bootlegger paleoshoreline.

Lithofacies 2: Quasi-Planar-Laminated Sandstone

Description.—Lithofacies 2 typically is present gradationally above deposits of Lithofacies 1 and is generally a few meters to about ten meters thick. At the Ulm Pishkun (Fig. 1), however, Lithofacies 2 abruptly overlies shale-rich strata of Lithofacies 1 (Fig. 4B). Lithofacies 2 is characterized by beds of sharp-based, fine sandstone 5–60 cm thick; units thicker than about 60 cm are invariably amalgamated. These beds have scoured basal contact overlain by a thick quasi-planar-laminated interval capped by a 1–3 cm ripple cross-stratified interval (see Arnott 1993a, fig. 3); hummocky cross-stratification is uncommon. Basal contacts are wavy on a meter scale and replete with bioturbation. Other sole marks include grooves, prod marks, and uncommon flutes and gutter casts. Paleoflow directions of the sole marks are southeastward. The thick middle interval shows quasi-planar lamination (Fig. 4C). Spacings of the undulation range from decimeters to several meters, and heights rarely exceed a few centimeters; spacing-to-height ratios are typically greater than 100:1. Laminae are laterally continuous and generally show no evidence of lateral accretion, but only vertical aggradation. Consequently, most beds consist of a single laminaset, although rare low-angle ($< 5°$) truncation surfaces separate laminasets in some beds. Parting lineation is common on bedding planes and parallels the basal sole marks (Figs. 4D, 7). Grain fabrics analyzed in the plane of bedding show a fairly well developed bimodal distribution bisected by the trend of the lineation (see Arnott 1993a, figs. 7C, D, E). The upper rippled interval in Lithofacies 2 beds consists of two ripple types: In plan view, the first type shows ripple crestlines that are laterally discontinuous and irregular (three-dimensional forms). In cross-section the ripples are asymmetric and indicate southeastward paleoflow (see Arnott 1993a, fig. 8A). In plan view, the second type shows ripple crestlines that are laterally continuous and straight to sinuous (two-dimensional forms); in cross section the ripples are symmetrically or asymmetrically cross-stratified, with asymmetrical types showing northwestward paleoflow (see Arnott 1993a, fig. 8B). Commonly these beds are interbedded with units of interstratified fine sandstone and mudstone 5–30 cm thick. Sandstone beds are 1–5 cm thick and are generally massive with an undulating basal and upper contact.

Strata of Lithofacies 2 contain an abundant and diverse trace-fossil assemblage, including *Thalassinoides, Ophiomorpha, Skolithos, Cylindrichnus, Arenicolites, Diplocraterion, Asterosoma, Bergaueria, Lockeia, Palaeophycus, Polykladichnus, Planolites beverylensis,* and escape structures. In addition, *Teichichnus* and *Planolites montanus* burrows are present, but are preferentially observed in the interbedded rippled sandstone and mudstone units.

Interpretation.—Strata of Lithofacies 2 are interpreted to have been deposited on the lower shoreface. The typical gradational lower contact with strata of Lithofacies 1 indicates normal shoreline progradation. At the Ulm Pishkun, however, the sharp basal contact between lower-shoreface and distal inner-shelf deposits was the result of a fall of relative sea level. Similar successions have been termed sharp-based shorefaces (Plint 1988), and are attributed to forced regression (Posamentier et al. 1992). Quasi-planar-laminated sandstone beds are interpreted to represent deposition from waning, storm-related combined flows (cf. Arnott 1993a). Initially flows were characterized by seafloor erosion, followed by sediment deposition and bed aggradation. During much of the depositional event combined-flow plane bed was the principal stable bed form. The thick, quasi-planar-laminated interval represents deposition under these conditions. As flow strength waned, three-dimensional, combined-flow ripples became the stable bed configuration; under these conditions the thin upper interval of ripple cross-stratification showing offshore (southeastward) paleoflow was deposited. Symmetrical and asymmetrical two-dimensional ripples showing northwestward (onshore) paleoflow directions are interpreted as wave ripples that postdated deposition of the quasi-planar-laminated interval, and were the result of seafloor reworking by waves. Mudstone strata represent deposition by interstorm suspension fallout. During these periods the indigenous deposit-feeding tracemakers of the *Cruziana* ichnofacies returned and replaced the opportunistic suspension-feeding burrowers of the *Skolithos* ichnofacies that colonized the seafloor immediately following the storm event (cf. Pemberton and Frey 1984).

Lithofacies 3: Medium-Scale Cross-Stratified Sandstone

Description.—Where present, Lithofacies 3 gradationally overlies Lithofacies 2 and is commonly 2–4 m thick. It consists of medium-scale cross-stratified fine and, less commonly, medium sandstone (Fig. 5A); sets are typically 20–40 cm thick. Trough cross-stratification is common, but planar-tabular cross-stratification is rare. Paleoflow directions are typically northwestward; southeastward directions are less common (Figs. 3, 7). In addition, interbedded quasi-planar-laminated sandstone beds with dispersed chert pebbles and granules are common. Biogenic structures are markedly less abundant and less diverse compared with Lithofacies 2 and include *Palaeophycus tubularis, Planolites beverlyensis, Ophiomorpha nodosa, Thalassinoides suevicis, Skolithos, Bergaueria,* and *Lockeia.*

Interpretation.—Lithofacies 3 is interpreted to have been deposited on the upper shoreface. Medium-scale cross-stratification is common in this environment, and is related to the landward migration of medium-scale asymmetric dunes due to a shear-stress asymmetry caused by shoaling surface gravity waves (e.g., Clifton et al. 1971; Vos and Hobday 1977; Clifton 1981; Arnott 1993b; Osborne and Vincent 1993). Interbeds of quasi-planar-laminated sandstone, commonly with dispersed chert pebbles and granules, most probably indicate high-energy combined-flow deposition associated with episodic storms (cf. Arnott 1993a). Similarly, southeastward-trending, medium-scale cross-stratification is interpreted to represent the remnants of storm-related, seaward-migrating combined-flow dunes (see Arnott and Southard 1990).

Lithofacies 4: Medium-Scale Cross-Stratified Sandstone with Mudstone Rip-Ups

Description.—Lithofacies 4, observed only at the Ulm Pishkun (Fig. 1), is 0–8 m thick. Laterally along the outcrop the basal contact cuts stratigraphically downward, truncating strata of Lithofacies 3 and bottoming out in Lithofacies 2 strata (Fig. 5B). Scours several centimeters deep and several decimeters wide are common locally along the basal contact. Lithofacies 4 consists of medium-scale cross-stratified fine and medium sandstone; sets are typically 10–30 cm thick. Thin mudstone intraclasts are common and are typically concentrated in the lower part of cross-stratified sets (Fig. 5C); mudstone drapes are rare. Paleocurrent directions are predominantly northwestward, although southeastward directions are common (Fig. 7). Trace fossils are abundant and dominated by robust *Thalassinoides, Rosselia,* and *Paleophycus* burrows. In addition, *Glossifungites* burrows are abundant along one stratigraphic horizon.

Interpretation.—Strata of Lithofacies 4 are interpreted as a tidal-channel fill. The sharp basal contact truncating upper-shoreface strata of Lithofacies 3 and bottoming out in lower-shoreface deposits of Lithofacies 2 represents an erosion surface created by a laterally migrating tidal channel (Kumar and Sanders 1974). Medium-scale cross-bedding showing bidirectional paleoflow is interpreted to represent subaqueous dunes that migrated under reversing tidal currents, although dune migration was preferentially in a flood, or northwestward direction. In addition, the presence of mudstone drapes on medium-scale cross-strata is interpreted to indicate fine-grained suspension deposition associated with reversing tidal currents (cf. Nio and Yang 1988). Furthermore, abundant mudstone intraclasts most probably represent locally eroded fine-grained slack-water deposits that during slipface avalanching became concentrated near the toesets of migrating subaqueous dunes.

The diversity and robustness of the trace-fossil assemblage suggests open-marine conditions. Soft-ground burrows are most common, but firm-ground burrows, most notably *Diplocraterion,* are abundant along one horizon within the channel fill. In this bed both soft-ground and firm-ground burrows are observed. This suggests that the sediment was initially burrowed by soft-ground burrowers, was subsequently partially lithified, and was then bioturbated by firm-ground burrowers. Exposure of the partially lithified sediment surface may have coincided with a significant erosional event that removed the overlying sediment and reexposed the previously buried surface at the sea bed (cf. Vossler and Pemberton 1988). Erosion may have been the result of a severe storm that might have coincided with a spring tide. Subsequently, the partially lithified sediment now exposed at the sea floor was burrowed by firm-ground burrowers. Eventually this surface was covered with unconsolidated sand, and consequently soft-ground burrowers returned.

Lithofacies 5: Massive and Planar-Laminated Sandstone

Description.—Strata of Lithofacies 5 were not observed at most study locations (see below). However, when present, Lithofacies 5 sharply overlies strata of Lithofacies 3 or 4 and, in turn, is abruptly overlain by deposits of Lithofacies 1 or 6. Beds consist typically of massive or planar-laminated, well-sorted, fine sandstone that at some locations shows a distinctive flaggy-weathering character (Fig. 5D). Beds are typically 1–2 cm thick and form cosets 5–10 cm thick separated by low-angle (< 5°) truncation surfaces. Parting lineation is typically well developed on exposed bedding surfaces. Bioturbation is rare, but when present is dominated by *Planolites montanus.* Trough cross-stratified beds 15–30 cm thick are observed locally; foresets dip typically toward the north-northwest (Figs. 3, 7).

Interpretation.—Strata of Lithofacies 5 are interpreted as foreshore deposits. In large part this interpretation is based on lithofacies association:

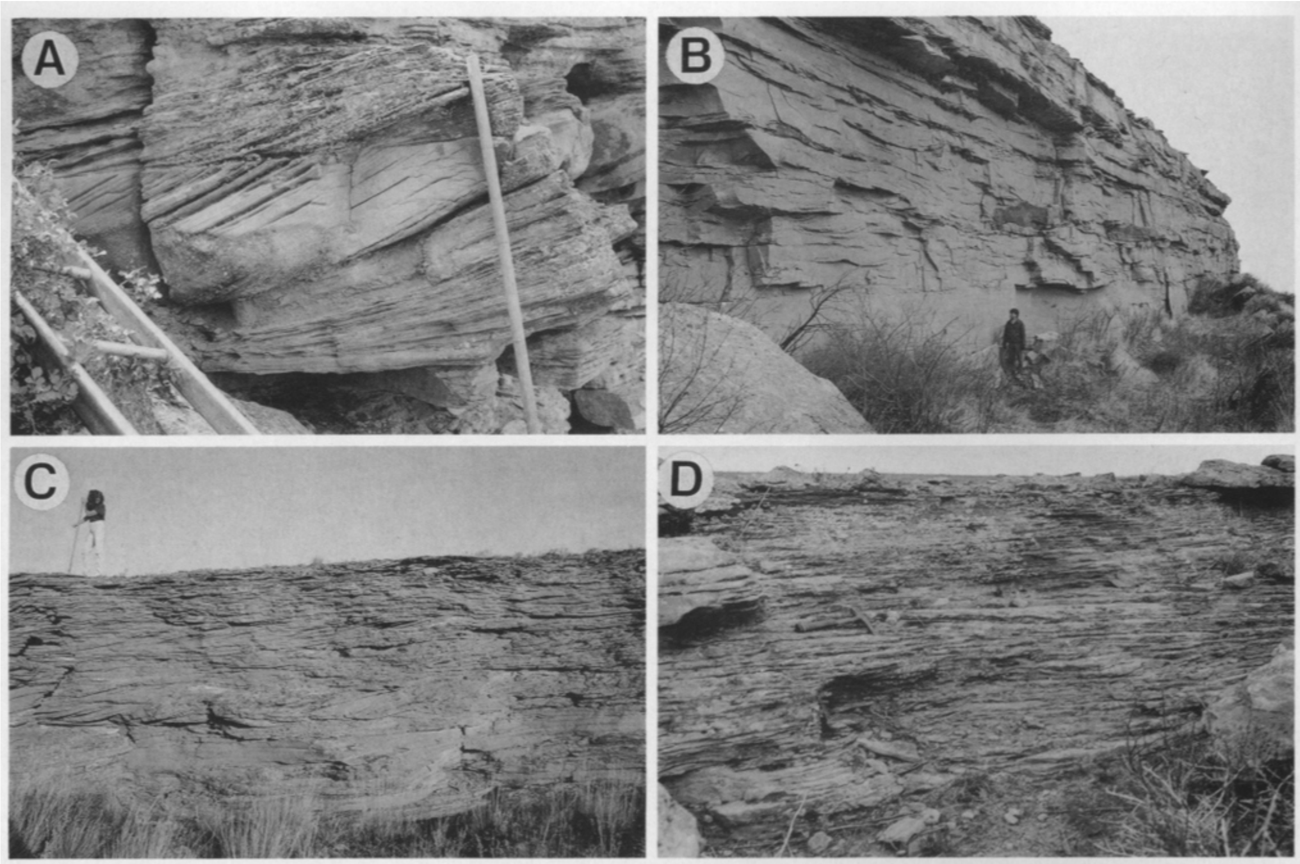

FIG. 5.—A) Medium-scale cross-stratified sandstones of Lithofacies 3 (gradations on the staff are 25 cm apart). Center of the photo shows two cross-sets separated by a throughgoing erosion (reactivation) surface; the upper laminae downlap onto the surface. This lithofacies lies gradationally above Lithofacies 2 and is interpreted to represent upper-shoreface deposits in a typical upward-shoaling succession. **B)** Sharp contact observed between Lithofacies 2 and 4 at the Ulm Pishkun (person for scale). This is interpreted as a scour surface formed at the base of a laterally migrating tidal channel; the channel was subsequently filled with the cross-stratified sandstones observable above the surface. **C)** Detail of the tidal-channel fill observed at the Ulm Pishkun (person for scale). The fill is dominated by medium-scale cross-stratified sandstones that show bidirectional paleocurrent directions. In addition, abundant mudstone rip-up clasts and rare mudstone drapes are observed. **D)** Massive and planar-laminated sandstones of Lithofacies 5 (hammer for scale). Note the low-angle truncation surfaces between flaggy-weathering sets. In an idealized succession (Fig. 3), strata of Lithofacies 4 are present at the top of the shoaling-upward unit, and are interpreted as foreshore deposits.

Lithofacies 5 is present above upper-shoreface or tidal-channel deposits of Lithofacies 3 and 4, respectively, and below transgressive deposits of Lithofacies 6; the sharp upper contact with Lithofacies 6 strata is interpreted to be a transgressive erosion surface associated with a rise of relative sea level (see below). Moreover, the strata are planar-laminated with well-developed parting lineation. These sedimentary structures are common in foreshore deposits and are attributed to deposition by high-energy, swash-backwash processes (e.g., Clifton 1969; Clifton et al. 1971). Inverse grading, although common in swash-laminated sandstones (e.g., Clifton 1969), was not readily apparent in the field, possibly owing to the well-sorted nature of the sandstone. Thin sections oriented perpendicular to bedding were not analyzed. The low-angle ($< 5°$) truncation surfaces that bound the planar-laminated cosets are the result of foreshore erosion during storms (cf. Clifton 1981). Local trough cross-stratified units most probably represent obliquely landward-migrating (north-northwest) subaqueous dunes in a foreshore environment (e.g., Clifton et al. 1971; Clifton 1981).

Lithofacies 6: Anomalously Coarse-Grained Deposits

Description.—Lithofacies 6 may overlie any of the lithofacies units discussed above, and in many cases interrupts the idealized upward-shoaling succession of Lithofacies 1 to Lithofacies 5. Strata consist typically of black chert-pebble conglomerate. The conglomerate tends to be thin, ranging from one or two pebbles thick to beds up to 15 cm thick. Commonly, conglomerate beds are massive and clast-supported, or contain dispersed chert pebbles within a mudstone or sandstone matrix. Thick beds show crude normal grading.

Lithofacies 6 is typically bounded by abrupt and commonly planar surfaces. At Little Belt Creek and North Willow Creek (Fig. 1), however, the basal surface is undulatory with an average spacing of 1 m and and average height of 7 cm (Fig. 6A). Crestlines of the undulations are oriented north-northeast/south-southwest (18°–198°). Overlying the basal surface are the coarsest-grained deposits observed in the Bootlegger Member in the study area; note that pebbles are rare in the underlying strata. Chert pebbles up to 6.5 cm in long-axis length (average long-axis length of the 10 largest clasts is 5.5 cm) are common and are preferentially oriented with their long axes subparallel to the trend of the undulation. In addition the coarsest pebbles are concentrated on the eastward side of the undulation crests; finer-grained pebbles are concentrated in the troughs and westward side of the crests.

At Black Horse Lake (Fig. 1), Lithofacies 6 is a 2 m thick unit of medium-scale cross-stratified, medium to coarse sandstone with dispersed pebbles. These strata abruptly overlie strata of Lithofacies 1 and form a lensoid

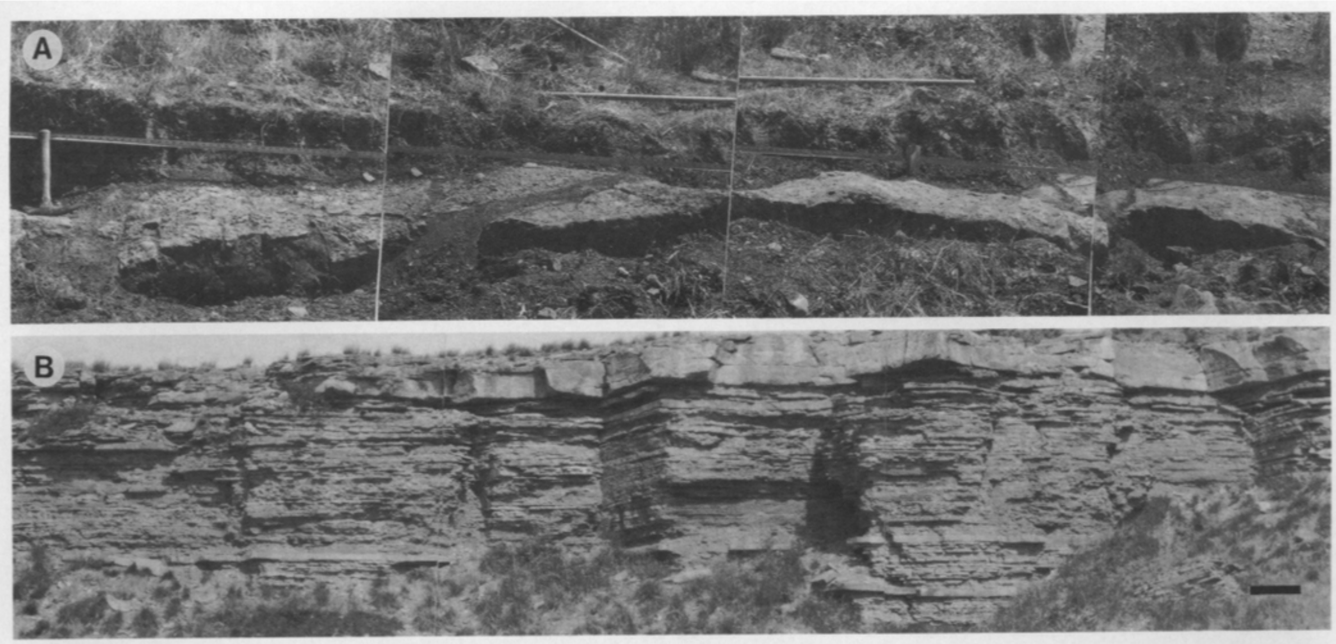

FIG. 6.—**A)** Wavy contact at the base of Lithofacies 6 at the Little Belt Creek section. The undulation has meter spacing and several centimeter height, and crestlines are oriented subparallel to the paleoshoreline trend (hammer for scale; tape measure is in centimeters). The surface is veneered with large black-chert pebbles (maximum a-axis length 7 cm); pebble fabric is invariably long axis parallel to the crestline trend. This surface is interpreted as a transgressive erosion surface on which large-scale wave ripples formed. The surface was then buried by a thin, coarse-grained transgressive lag deposit. **B)** Anomalously coarse-grained, lensoid-shaped unit that truncates a shoaling-upward succession at Black Horse Lake (scale bar is 1 m long). Only one side of the feature is shown, but it pinches out farther to the right. This unit is interpreted as a subtidal shoal related to transgressive erosional processes during an episode of rising relative sea level.

body (Fig. 6B). In addition, the magnetic susceptibility of these strata is an order of magnitude higher than other Bootlegger strata (magnetic susceptibility is a measure of the abundance of magnetic minerals present in the sample, principally magnetite).

Finally, throughout the study area, but near the top of the Bootlegger Member, Lithofacies 6 strata contain abundant fish scales, fish bones, and other hard-body fossils, including the ammonites *Neogastroplites americanus, Posidonia nahwasi nahwasi,* and *Epengonoceras* (C.R. Stelck, personal communication). Elsewhere, hard-body fossils are generally absent from the Bootlegger Member. In the western Great Falls study area these strata consist of interbedded fossiliferous coarse to granule sandstone and fossiliferous shale. By contrast, in the eastern study area they consist of interbedded fossiliferous siltstone and shale.

Interpretation.—By three principal criteria, strata of Lithofacies 6 are interpreted to be transgressive deposits emplaced during an episode of rising relative sea level (see below): (1) Lithofacies 6 strata typically abruptly overlie an interrupted regressive succession; (2) Lithofacies 6 strata are anomalously coarse grained and/or fossiliferous; and (3) Lithofacies 6 is in turn abruptly overlain by strata of Lithofacies 1. The sharp, typically planar contact at the base of Lithofacies 6 represents a transgressive surface of erosion, or ravinement surface, related to erosive shoreface retreat (Swift 1975). Erosion removed some part of the underlying regressive succession, and as a result interrupted the normal upward succession of lithofacies. Eroded sediments were reworked, with coarse-grained, pebble-size sediment being deposited on the erosional or transgressive surface as thin, areally extensive chert-pebble conglomerates interpreted to be transgressive lags. Finer-grained sediment, on the other hand, was selectively winnowed and transported elsewhere. At one stratigraphic horizon, however, the transgressive surface at Little Belt Creek and North Willow Creek is undulatory and overlain by a bed of very coarse chert-pebble conglomerate up to 15 cm thick; the possible significance of this contact is discussed in the next section. Crestlines of the undulations are oriented north-northeast/south-southwest, i.e., parallel to the inferred paleoshoreline trend. This surface is interpreted to represent the form-sets of large-scale wave ripples that were formed on the transgressive erosion surface (cf. Yorath et al. 1979; Leckie and Walker 1982; Leckie 1988; Cheel and Leckie 1992). Earlier authors have commonly reported the subparallel relationship between wave-ripple crests and the inferred paleoshoreline trend (see review by Leckie and Krystinik 1989). Strong oscillatory currents, most probably related to storms, would have molded the sandy seafloor into large-scale

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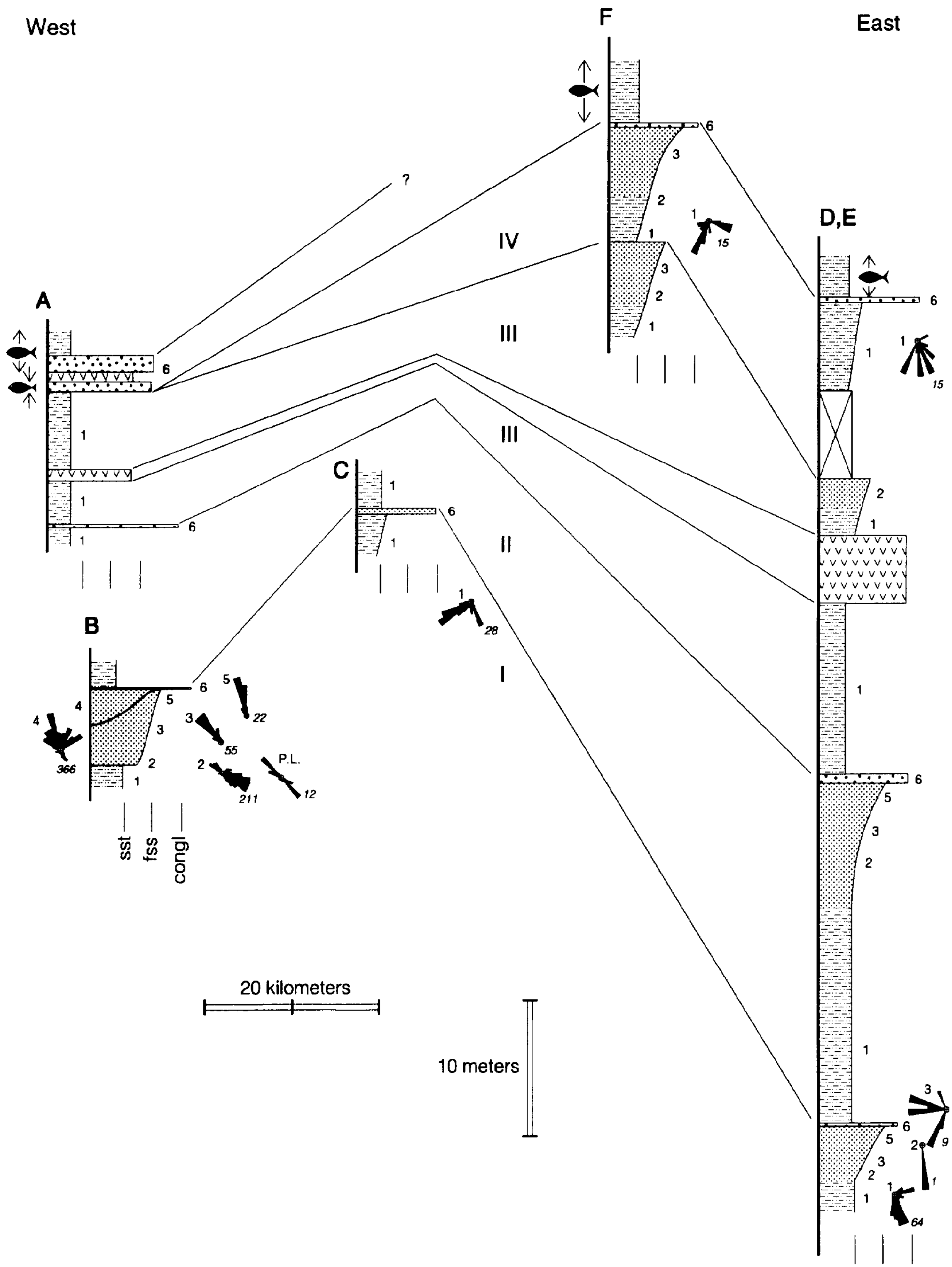
FIG. 7.—Stratigraphic cross section showing the regional correlation of the Bootlegger strata measured at some of the principal study sites in the Great Falls area (Sites D, E is a compilation of data from Belt Butte and North Willow Creek). See Figure 1 for the location of each site. Vertical axis, height above the base of the outcrop; horizontal axis, grain size (see cross section B; sst, siltstone; fss, fine sandstone; congl, conglomerate). As discussed in the text, the Bootlegger Member has been subdivided into four regionally correlatable successions (I–IV). Numbers to the right of each cross section indicate the exposed lithofacies (1–6); see text for details. Other symbols used are: V, bentonite; P.L., parting lineation; fish symbol, fish skeletal debris. Also, paleocurrent data are shown as rose diagrams (north is toward the top). Each rose diagram represents the data collected from one lithofacies; the number to the upper left designates the lithofacies, and the number to the lower right indicates the number of data points (measurements). Also shown is the Arrow Creek Bentonite, a regionally extensive unit that is up to 11 m thick in the study area and thickens eastward (see Reeside and Cobban 1960 for discussion). Note that because of lack of exposure between locations A and B the second Bootlegger succession (II) is not observed, and as a result is of unknown thickness in this area.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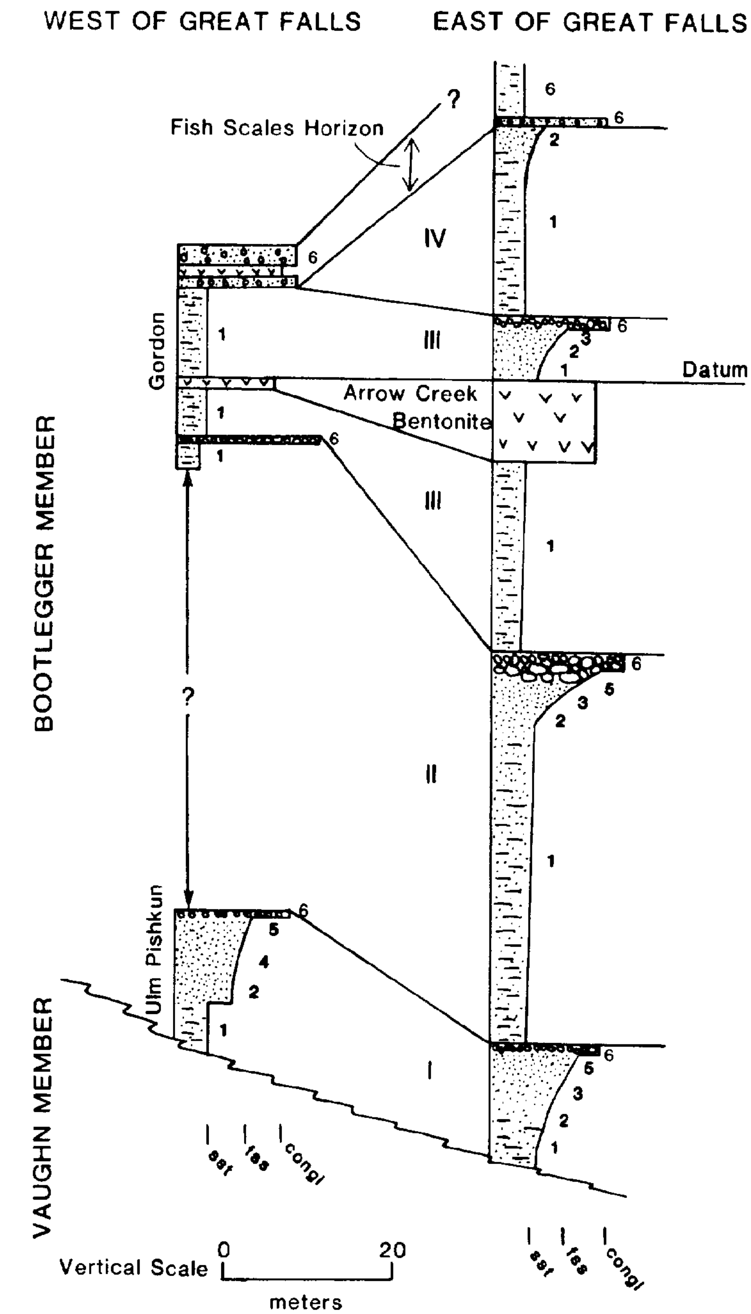


FIG. 8.—Summary cross section showing the stratigraphic correlation of Bootlegger successions in the eastern and western Great Falls study area. Grain size is plotted along the horizontal axis (sst, siltstone; fss, fine sandstone; congl, conglomerate). Numbers to the right of each stratigraphic column denote the specific lithofacies (1–6; see text for details); Roman numerals in the center of the diagram indicate the individual Bootlegger successions (I–IV); V, bentonite. Stratigraphic datum is the areally extensive Arrow Creek Bentonite. Because of poor exposure in the western study area only two outcrops were measured: Ulm Pishkun and Gordon (see Figure 1 for locations). The stratigraphic section shown for the eastern Great Falls study area is a compilation of measured sections. Note the consistent thickening and more complete preservation of the Bootlegger successions in the eastern study area, and the lack of unit IV strata in the western study area.

wave ripples. At the same time, the coarsest gravel was preferentially concentrated on the seaward (eastward) side of the crest as a result of a landward asymmetry of shear stress produced by shoaling surface gravity waves. Finer-grained gravels accumulated in the intervening troughs and on the landward (westward) side of the crests.

At Black Horse Lake, the lens-shaped unit composed of cross-stratified, medium to coarse sandstone is interpreted to be a subtidal-shoal deposit that developed on the transgressive erosion surface. Similar deposits have been reported from the Holocene Mississippi River delta (Penland et al. 1988). The high magnetic susceptibility of the Bootlegger strata is interpreted to be the result of sea-bed reworking and the concentrating of heavy minerals, particularly magnetite, during the transgression.

Finally, near the top of the Bootlegger Member, fossiliferous strata of Lithofacies 6 are interpreted to be transgressive deposits deposited on a distal shelf. Transgression locally (regionally?) deepened the depocenter and caused it to become starved of new sand and coarser-grained terrigenous sediment. Typically only suspended mud was transported into the area. Because of the low sedimentation rate of terrigenous material, fish skeletal debris and other hard-body fossils were the primary source of sediment, and formed a regionally extensive, fossiliferous horizon (see below). Nevertheless, rare major storms may have deposited thin coarse-grained layers, particularly toward the west (landward). The coarse-grained, fossiliferous strata of Lithofacies 6 in the western study area are probably the result of reworked thin, coarse-grained storm deposits and intercalated fossiliferous mud.

DEPOSITIONAL HISTORY AND CONTROLS ON SEDIMENTATION

In the Great Falls study area, Bootlegger successions consist of an upward-shoaling interval overlain by a transgressive erosion surface, and capped in many places by a transgressive deposit (Fig. 3). Note that although the paleocurrent data suggest that the Bootlegger shoreline was oriented northeast-southwest, this was probably only a local deflection of the predominantly east-west-trending late Albian shoreline, with the Mowry Sea basin lying to the east (e.g., Williams and Stelck 1975, fig. 4). For convenience, therefore, the following discussion will consider eastward and westward to be basinward and landward, respectively. The upward-shoaling interval of each Bootlegger succession records deposition during basinward progradation of the local Bootlegger shoreline. The fact that each succession begins with shallow-shelf deposits indicates that at the time of initial progradation the Bootlegger paleoshoreline lay to the west. In the western study area these strata are commonly overlain by transgressive deposits of Lithofacies 6 (Figs. 7, 8). In the eastern study area, on the other hand, successions are typically more complete and commonly consist of lower-shoreface, upper-shoreface, and rare foreshore deposits (Figs. 7, 8). This indicates that before transgression the Bootlegger paleoshoreline commonly prograded eastward at least as far as the eastern Great Falls study area. Progradation was subsequently terminated by a rise of relative sea level and an ensuing marine transgression. Erosion associated with shoreface retreat destroyed some part of the underlying upward-shoaling succession and in its wake left a transgressive erosion surface, commonly capped by a thin, coarse-grained transgressive deposit.

In the Sweetgrass Hills area, on the other hand, Bootlegger successions consist only of Lithofacies 1 gradationally overlain by Lithofacies 2, in turn sharply overlain by Lithofacies 1 (Fig. 9). The gradational contact between Lithofacies 1 and 2 indicates eastward shoreline progradation, and the sharp upper contact with Lithofacies 1 indicates subsequent transgression. This suggests that at no time did the shoreline prograde into the area, but rather was consistently located to the west (landward). Nevertheless, in both the Great Falls and Sweetgrass Hills study areas this depositional history of progradation followed by transgression was repeated four times. However, as noted above, because of the lack of intervening stratigraphic control the correlatability of the units remains uncertain.

Although the foregoing depositional history is generally applicable, it may not strictly apply to the transgressive conglomeratic deposit cropping out above the third Bootlegger succession (see Figs. 6A, 7). At many locations this conglomerate contains chert pebbles commonly several centimeters long, and as such is markedly coarser-grained than any other transgressive deposit. In addition, chert pebbles are rare in the upper-shoreface and foreshore deposits immediately below the transgressive surface. Intuitively, if the source of the pebbles was from erosion of the underlying strata, then presumably pebbles should be more common in these strata. It could be argued, however, that the main source of pebbles was conglomeratic nonmarine deposits that were eroded during transgression, but the paucity of pebbles in very shallow-marine strata (upper shoreface and foreshore) immediately below the transgressive surface remains problematic. A second possibility is that the transgressive surface actually represents an erosion/transgression (E/T) surface as described by Plint et al. (1986), therein involving an initial fall of relative sea level followed by rise of relative sea level and transgression. This would indicate a significant break between strata on either side of the E/T surface, and thus help to resolve the lithological dilemma. However, owing to the lack of stratigraphic data farther into the basin (eastward) this hypothesis remains equivocal and awaits future investigation. Nevertheless, earlier work by Davis and Byers (1989) has suggested two possible episodes of relative

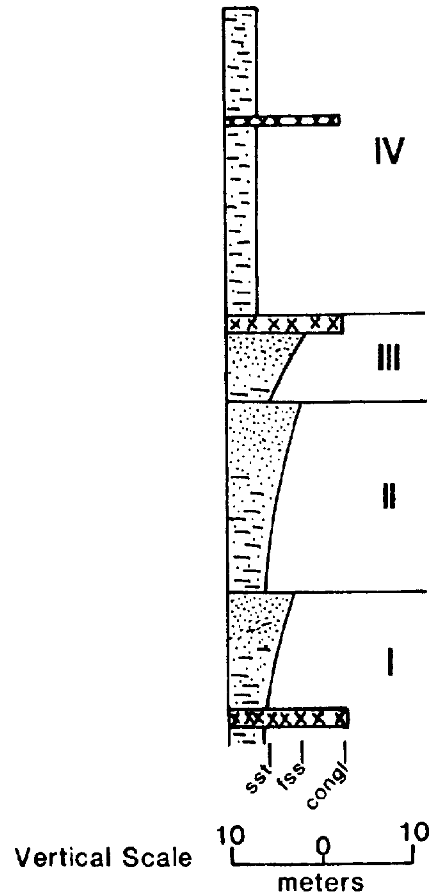


FIG. 9.—Stratigraphic column showing the Bootlegger successions (I–IV) in the Sweetgrass Hills study area. Symbols: sst, siltstone; fss, fine sandstone; congl, conglomerate; XX, Tertiary intrusives. Succession I lies 12.5 m above the top of the Vaughn Member. The thickness of succession IV is uncertain because the upper part is covered. Here, just as in the Great Falls study area, the Bootlegger Member consists of four successions, but because of the lack of intervening control, correlations are equivocal.

sea-level fall during deposition of the Mowry Shale in western Wyoming. As a result, one or possibly both events may correlate with the potential E/T surface in the Bootlegger strata. Again this correlation is equivocal and requires more extensive stratigraphic detail.

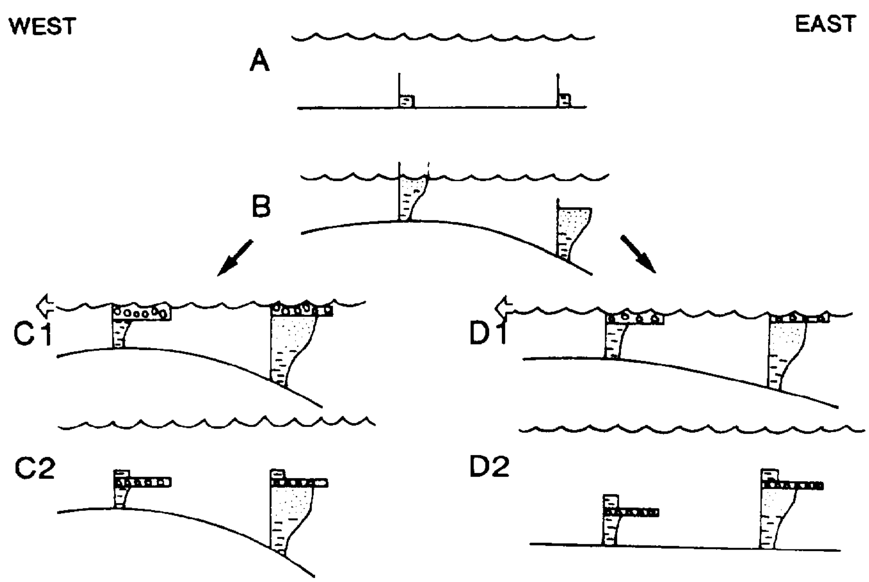
In addition to the areal variability of Bootlegger lithofacies and stratal thickness discussed above, the nature of the fossiliferous transgressive strata cropping out near the top of the Bootlegger Member in the Great Falls study area also show a consistent west-to-east variation. In the western study area these strata are composed of interbedded fossiliferous coarse-grained/granule sandstone. In the east, however, they consist of interbedded fossiliferous shale and siltstone. Moreover, the thickness of the unit is much greater in the east than in the west (Fig. 8).

With the foregoing in mind, the question, therefore, is to explain not only the consistent east-west variation in the Bootlegger stratigraphy but also the cause of the numerous, short-term changes of relative sea level.

Proposed Mechanism

A number of plausible mechanisms could account for the origin of the Bootlegger successions, including: (1) temporal variations in sediment supply; (2) eustasy; and (3) episodic epeirogenic movements of the Sweet-

FIG. 10.—The depositional history of each Bootlegger succession in the Great Falls study area (diagram is oriented east-west). Stratigraphic columns on the left and right of each diagram represent the western and eastern study areas, respectively. Because of two possible explanations (see below and text for details), the diagram diverges into C1-D1 and C2-D2. **A)** Each Bootlegger succession begins with the paleoshoreline to the (north)west of the study area. Deposition of fine-grained sediment from suspension predominated. **B)** Uplift of the Sweetgrass Arch decreased accommodation space and caused the Bootlegger paleoshoreline to migrate basinward, or (south)eastward. **C/D)** Subsequent rise of relative sea level displaced the Bootlegger paleoshoreline (north)westward (open arrow). Transgression created a transgressive erosion surface that in many places was capped by a thin, coarse-grained lag deposit. However, two different mechanisms can account for the rise of relative sea level: C1-D1 (eustatic rise) and C2-D2 (arch subsidence). (C1-D1): Because of the (Greenhorn) eustatic rise, progradational conditions were eventually overcome by the rising sea level, which displaced the paleoshoreline westward and returned the study area to quiet-water deposition of mud. (C2-D2): the rise of relative sea level that terminated shoreline progradation was due to subsidence of the previously uplifted arch. This caused the paleoshoreline to migrate westward and reinitiated quiet-water sedimentation throughout the study area.



grass Arch. However, any mechanism must address four fundamental issues: (1) Bootlegger successions are consistently thicker in the eastern Great Falls study area (basinward) than in the west; (2) typically only inner-shelf deposits at the base of an upward-shoaling Bootlegger succession are preserved in the western study area; (3) in the western study area fossiliferous strata cropping out at the top of the Bootlegger Member are coarser-grained and thinner than correlative units in the east; and (4) the Bootlegger Member was deposited in approximately 0.7–4 million years. Only the last control, epeirogenic movements of the Sweetgrass Arch, can adequately resolve most of these issues. It is proposed that relative sea level fell during periods of arch uplift, and because of reduced accommodation space the Bootlegger shoreline prograded eastward (Fig. 10A, B). Subsequently, progradation was terminated by an ensuing rise of relative sea level that displaced the Bootlegger shoreline westward (Fig. 10C1, C2). This event was the result of arch subsidence and/or the ongoing basinwide Greenhorn transgression (Fig. 10D1, D2). Erosion by transgressive shoreface retreat would have been most intense in topographically elevated areas, which in this case coincided with the area near the axis of the Sweetgrass Arch. In the western Great Falls study area, therefore, transgressive erosion eroded shallower-water sediments that had previously been deposited above Lithofacies 1. Subsequently, transgressive deposits of Lithofacies 6 were deposited. In the eastern area, farther from the arch axis, the extent of transgressive erosion was less, and more of the upward-shoaling succession was preserved.

We propose that the Bootlegger successions resulted from episodic reactivation of the ancestral Sweetgrass Arch. It is important to note that convergence rates along the western margin of North America increased during the late Albian (Engebretson et al. 1982). From Idaho to southern Alberta this activity resulted in widespread igneous intrusion and volcanism, including increased rates of intrusion of the Coast Plutonic and Idaho Batholith complexes, and increased activity of the Crowsnest volcanics (McGookey et al. 1972; Kauffman 1977). Within the study areas, abundant bentonites in both the Vaughn and Bootlegger members suggest that deposition was coincident with tectonism. It seems likely, therefore, that during Bootlegger time the lithosphere in north-central Montana and southern Alberta was strained and possibly anomalously heated. In addition, Lorenz (1982) pointed out that at this time the arch was an optimum distance from the Cordillera to have acted as a peripheral forebulge; locally elevated crustal temperatures would have reduced flexural rigidity and increased the height of forebulge uplift (e.g., Beaumont 1981, fig. 9). Lorenz went on to note that even with eastward encroachment of the Cordilleran mountain front the peripheral bulge remained stationary, and therefore acted differently from that predicted by either purely elastic (Turcotte 1979; Jordan 1981) or viscoelastic (Beaumont 1981; Quinlan and Beaumont 1984) models of lithospheric flexure. On the basis of the work of Goetze and Evans (1979), Lorenz (1982) proposed that because of its earlier Precambrian and Paleozoic activity the arch represented a crustal inhomogeneity that was susceptible to later flexure. We propose that during deposition of the Bootlegger Member uplift of the arch coincided with episodes of Cordilleran thrusting (loading) and consequent lithospheric flexure. Nevertheless, by the end of Bootlegger time epeirogenic movements of the arch had either ceased or simply could no longer outpace the Greenhorn transgression. As a result the Bootlegger shoreline continued to transgress westward, and the study areas became part of a sediment-starved shelf. In the western Great Falls study area, prolonged reworking and sediment starvation of the seafloor gradually developed the coarse-grained fossiliferous sandstone that caps the Bootlegger Member, suggesting that throughout late Bootlegger time the arch continued to be topographically elevated. In the eastern study area, on the other hand, because of deeper-water conditions, suspension deposition of fine-grained terrigenous sediment and fossil debris dominated, and the thick succession of fossiliferous shale and siltstone was deposited. Continued transgression into the early Late Cretaceous culminated in deposition of the basinal shales of the Floweree Member of the Marias River Formation throughout north-central Montana.

CONCLUSIONS

In the Great Falls and Sweetgrass Hills study areas the upper Albian to lower Cenomanian Bootlegger Member consists of four stratigraphic successions, each consisting of an upward-shoaling unit overlain by a transgressive surface of erosion and capped commonly by transgressive deposits. In the Great Falls area, the geometry and nature of the Bootlegger strata are best explained by invoking reactivation of the ancestral Sweetgrass Arch. During episodes of arch uplift, relative sea level fell, reducing accommodation space and causing the Bootlegger shoreline to prograde eastward. Subsequently, as a result of arch subsidence and/or the ongoing Greenhorn transgression, relative sea level rose and caused the shoreline to transgress westward. Erosion by transgressive shoreface retreat was most intense near the crest of the Sweetgrass Arch, because of its topographically higher position. In the western Great Falls study area this resulted in removal of shallower-water sediments originally deposited above shallow-shelf strata of Lithofacies 1. Conversely, in the eastern area, farther from the arch crest, each upward-coarsening (shoaling) Bootlegger succession shows more complete preservation. Near the end of Bootlegger time, however, arch movements either ceased or could no longer outpace the effect of the Greenhorn transgression, and as a result the Bootlegger shoreline continued to transgress westward, leaving the study areas in a distal setting on a sediment-starved shelf.

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