SEQUENCE ANALYSIS OF THE UPPER CRETACEOUS TWO MEDICINE AND JUDITH RIVER FORMATIONS, MONTANA: NONMARINE RESPONSE TO THE CLAGGETT AND BEARPAW MARINE CYCLES

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ABSTRACT: **Superb outcrop exposures and abundant subcrop data allow the accurate tracing of two stratigraphic discontinuities updip into fully nonmarine strata of the Campanian Two Medicine and Judith River formations (Western Interior foreland basin, Montana). These throughgoing discontinuities delimit ''regressive'' and ''transgressive'' alluvial equivalents of two third-order sea-level cycles, and provide ground truth for recent conceptual models of alluvial sequence stratigraphy.**

An erosional disconformity interpreted to mark the boundary between regressive and transgressive alluvial deposits crops out in nonmarine strata of the Two Medicine Formation in northwestern Montana. It is embedded in relatively flat-based fluvial sandstone sheets dominated by downstream accretion elements, and is marked by several meters of internal erosional scour, a thick and laterally persistent intraclast lag facies, pervasive oxidation, and a shift from fine- to medium/coarse-grained sandstone. Physical stratigraphic and geochronometric evidence indicate that this fluvial disconformity, which can be traced throughout the outcrop belt, correlates with the widespread 80 Ma sequence boundary developed in distal parts of the Western Interior Basin. The erosional disconformity in the Two Medicine Formation reflects a negative base-level adjustment that occurred during the Telegraph Creek–Eagle regression (R7), and conforms to the standard definition of a sequence boundary. Identification of the 80 Ma sequence boundary in alluvial facies of the Two Medicine Formation is significant in that it is one of very few well-documented examples of a nonmarine sequence boundary, but unlike most others, it is not characterized by a readily apparent facies tract dislocation reflecting a basinward shift in facies (e.g., braided-stream deposits sharply juxtaposed over coastal coal-bearing facies).

A second throughgoing discontinuity embedded within fully nonmarine deposits of the Judith River Formation in central Montana is interpreted to separate regressive and transgressive alluvial deposits that accumulated during the Claggett regression (R8) and subsequent Bearpaw transgression (T9). This discontinuity correlates with the erosional base of a backstepping composite sequence set of shoreface strata, and can be traced inland to the western limit of Judith River strata preserved in central Montana (~ 50 km). The Judith River discontinuity is not erosional, but rather reflects a very abrupt change in alluvial architecture, most notably an abrupt shift from a sand- to a mud-dominated section that can be traced in outcrop and subcrop throughout north-central Montana and into southern Alberta. The throughgoing discontinuity in the Judith River record does not conform to conventional definitions of a sequence boundary, and it apparently did not form in response to a fall in relative sea level. This discontinuity instead appears to record an abrupt increase in the rate of generation of accommodation in the Montana portion of the foreland basin (presumably related to flexural subsidence), and it is provisionally interpreted as the nonmarine equivalent of a third-order transgressive surface coincident with the updip correlative conformity.

INTRODUCTION

Distinctive beds or surfaces that provide a means of correlating marine facies over substantial distances, such as storm beds (Aigner 1985; Lafferty et al. 1994), condensed sections (Jenkyns 1971; Kidwell 1989), flooding surfaces (Plint et al. 1988; Liu and Gastaldo 1992), and bentonite horizons (Huff 1983; Huff and Kolata 1990), tend to be either absent or only locally developed within terrestrial facies successions. Similarly, throughgoing beds or surfaces that tend to punctuate the nonmarine record, such as widespread paleosols (Hanneman and Wideman 1991) and ''eolian super surfaces'' (Blakey et al. 1988; Blakey et al. 1996; Havholm and Kocurek 1994), are generally absent in marine successions. This disparity in the very nature of key beds/surfaces in marine and nonmarine depositional records limits the resolution of marine–nonmarine correlations, and consequently hinders cross-environment reconstructions of geological history.

Sequence analysis has been applied to this problem with varying degrees of success. Recent conceptual treatments of nonmarine sequence stratigraphy underscore the complexity of alluvial depositional systems and their responses to base-level change, and offer insights into the recognition of nonmarine sequence boundaries and alluvial systems tracts (e.g., Schumm 1993; Wescott 1993; Wright and Marriott 1993; Shanley and McCabe 1994). Experimental flume studies also yield data pertinent to unraveling the controls on sequence architecture in coastal-plain settings (Wood et al. 1993a, 1993b). However, empirical studies that link marine and nonmarine records within high-resolution, outcrop-based stratigraphic frameworks are still relatively rare (Shanley and McCabe 1991, 1993; Gibling and Bird 1994; Olsen et al. 1995; Van Wagoner 1995; Blakey et al. 1996; Yoshida et al. 1996; Burns et al. 1997).

This stratigraphic study focuses on nonmarine facies that accumulated during two regressive–transgressive cycles of the Western Interior Seaway. The study interval includes the Campanian Two Medicine and Judith River formations, which together comprise two eastward-thinning clastic tongues of primarily nonmarine sediments in the Western Interior Basin. These rock units and associated marine deposits (Virgelle, Eagle, Claggett, and Bearpaw formations) are widely exposed in outcrop belts that extend across large tracts of northwestern and north–central Montana (Fig. 1). Extensive strike- and dip-oriented surface exposures of interfingering marine and nonmarine strata, coupled with dense well-log coverage, provide a superb opportunity to test conceptual models and to explore nonmarine facies architecture in relation to changes in relative sea level.

This study reveals two distinct varieties of throughgoing nonmarine discontinuities that delimit ''regressive'' and ''transgressive'' alluvial equivalents of third-order sea-level excursions. One discontinuity is interpreted to mark the erosional top of a regressive alluvial sequence and conforms with the standard definition of a sequence boundary. The other is interpreted also to separate regressive and transgressive alluvial deposits, but this discontinuity displays, with no evidence of erosion or significant hiatus. Identification of these discontinuities, and comparison of the regressive and transgressive alluvial facies that they define, brings new and important empirical evidence to bear on the response of alluvial systems to changes in relative sea level (base level). Moreover, this stratigraphic study provides important baseline data for distinguishing subsidence and eustasy in a foreland-basin setting.

GEOLOGICAL SETTING

The basic stratigraphic pattern of fine-grained marine sediment tongues thinning westward and interfingering with eastward-thinning nonmarine and marginal marine clastic tongues typifies Upper Cretaceous deposits

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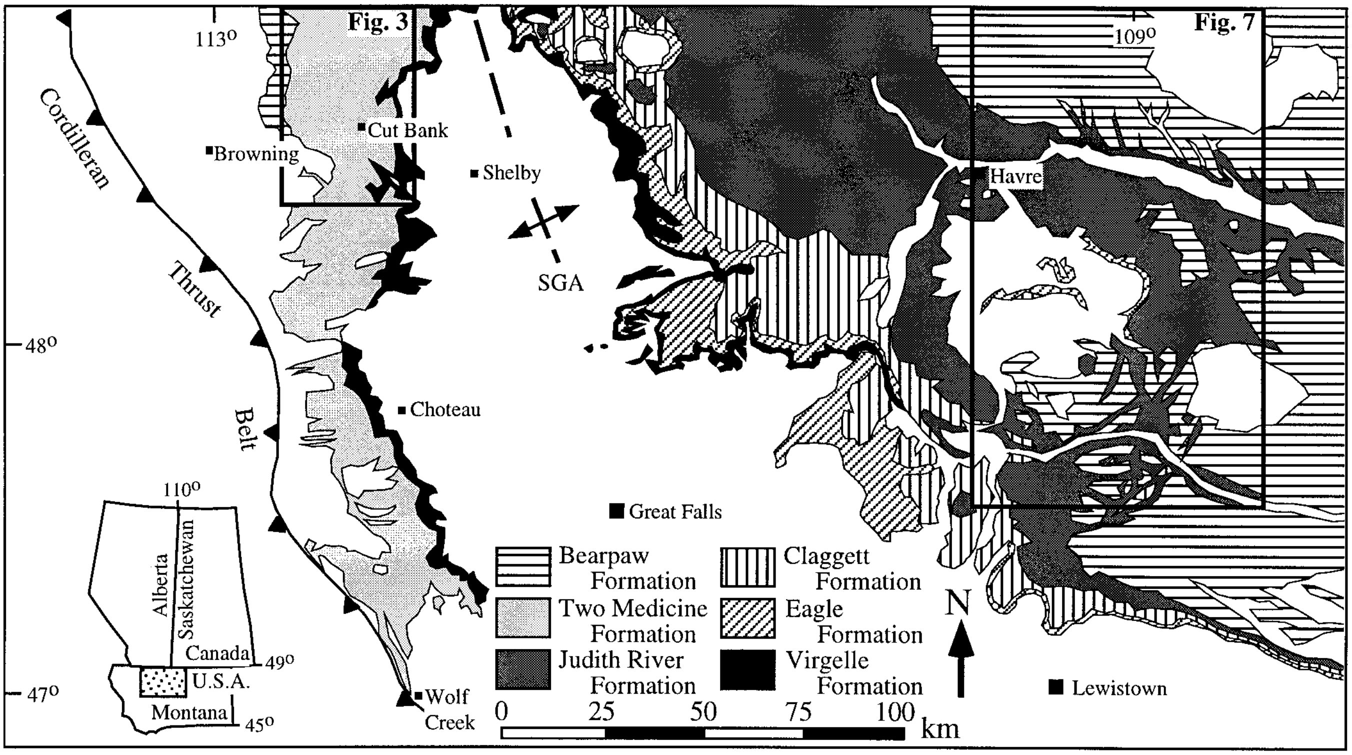

FIG. 1.—Regional outcrop map of Upper Cretaceous rock units in northwestern and north–central Montana (modified from Ross et al. 1955). SGA = Sweetgrass arch. The Virgelle Formation is the basal member of the Eagle Formation on the east side of the Sweetgrass arch.

throughout the Western Interior Basin (Weimer 1960; Waage 1975). This stratigraphy is clearly expressed in the high plains of Montana, where the drainage of the Missouri River and its many tributaries affords spectacular three-dimensional exposures in canyons and widespread badlands. Most Upper Cretaceous (Santonian–Maastrichtian) rock units that crop out within Montana are included within the Montana Group of Eldridge (1889). The heterolithic suite of facies that constitute the Montana Group were deposited during three regressive (R7, R8, and R9 of Kauffman 1977) and two transgressive (T8 and T9 of Kauffman 1977) phases of the Cretaceous Interior Seaway (Fig. 2).

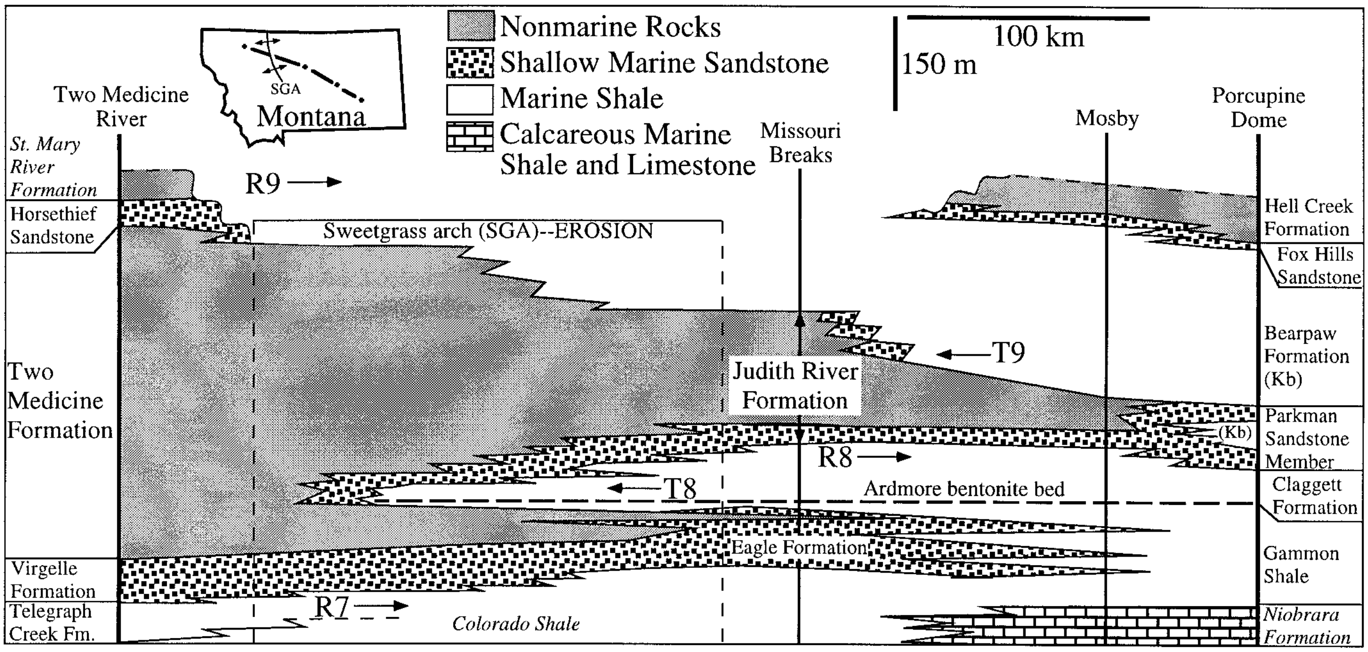

FIG. 2.—Schematic cross section of Montana Group with study interval restored across the Sweetgrass arch. Italicized units are not included within the Montana Group. Modified from Gill and Cobban (1973).

Rocks of the Montana Group described in this report were deposited during two third-order regressive–transgressive cycles (R7–T8 and R8–T9). The Two Medicine Formation, which accumulated during both cycles, comprises the proximal alluvial facies of two eastward-thinning clastic tongues (Fig. 2). The outcrop belt of the Two Medicine Formation extends for approximately 220 km along the eastern edge of the Cordilleran fold-and-thrust belt in northwestern Montana. The Sweetgrass arch, a north–south-trending anticlinal structure over which Upper Cretaceous strata are eroded, separates the Two Medicine Formation from correlative units in central Montana, namely the Eagle, Claggett, Judith River, and Bearpaw formations (Figs. 1, 2).

Shallow-marine sandstones of the Eagle Formation prograded into central Montana during the Telegraph Creek–Eagle regression (R7) (Gill and Cobban 1973; Rice 1980; Hanson and Little 1989). Marine shales of the Claggett Formation, which overlies the Eagle Formation, were deposited during the subsequent transgression (T8) and regression (R8) of the Claggett Sea (Gill and Cobban 1973). Deposition of nonmarine and shallow-marine facies of the Judith River Formation also occurred during R8, as shallow-marine deposits of the Parkman Sandstone Member shifted eastward tracking the regressing Claggett Sea. A variety of nonmarine facies accumulated landward of the Parkman Sandstone strandline. Eastward progradation of the Parkman Sandstone Member of the Judith River Formation ceased with the onset of the Bearpaw transgression (T9). Upper reaches of the Judith River and Two Medicine formations accumulated during the Bearpaw transgressive phase, as did lower parts of the marine Bearpaw Formation.

A highly refined ammonite zonation is available for marine units within the Montana Group (Gill et al. 1972; Gill and Cobban 1973; Obradovich 1993), and correlations indicate that the study interval spans approximately 17 biozones (*Scaphites hippocrepis* II–*Baculites compressus*). Radioisotopic dating of bentonite beds intercalated within these ammonite zones (e.g., Obradovich 1993) suggests that the study interval spans most of the Campanian Stage (using stage boundaries of Gradstein et al. 1995). ^{40}Ar/^{39}Ar analyses of bentonite beds intercalated within nonmarine facies of the Two Medicine and Judith River formations are consistent with a Campanian age designation (Goodwin and Deino 1989; Rogers et al. 1993; Rogers and Swisher 1996).

NONMARINE RECORD OF R7 AND T8

Background

Nonmarine strata of the Two Medicine Formation deposited during the Telegraph Creek–Eagle regression (R7) and subsequent Claggett transgression (T8) are exposed in the formation type area and along Cut Bank Creek south of the town of Cut Bank (Fig. 3). Stebinger (1914) and Cobban (1955) described these strata, and concluded that the lower 60–75 m of the section, which are distinctly sandier than overlying deposits, correlated to the east with prograding shallow-marine facies of the Eagle Formation (Fig. 2).

Lorenz (1981) extended the sand-dominated part of the Two Medicine Formation to approximately 85 m above the base of the section, and noted the laterally extensive nature of the sheet sandstones that characterize lower parts of the Two Medicine Formation. Lorenz (1981) also identified Two Medicine strata that were deposited during transgression of the Claggett Sea (T8). Lorenz's ''Claggett shaley interval'' overlies the sand-dominated part of the section, and consists of approximately 45 m of ''anomalously paralic'' carbonaceous clayshales, lignite beds, and thin sandstones (Lorenz 1981, p. 77). At least eight discrete bentonite beds are figured in schematic sections that span this ''transgressive'' paralic interval (Lorenz 1981; Lorenz and Gavin 1984).

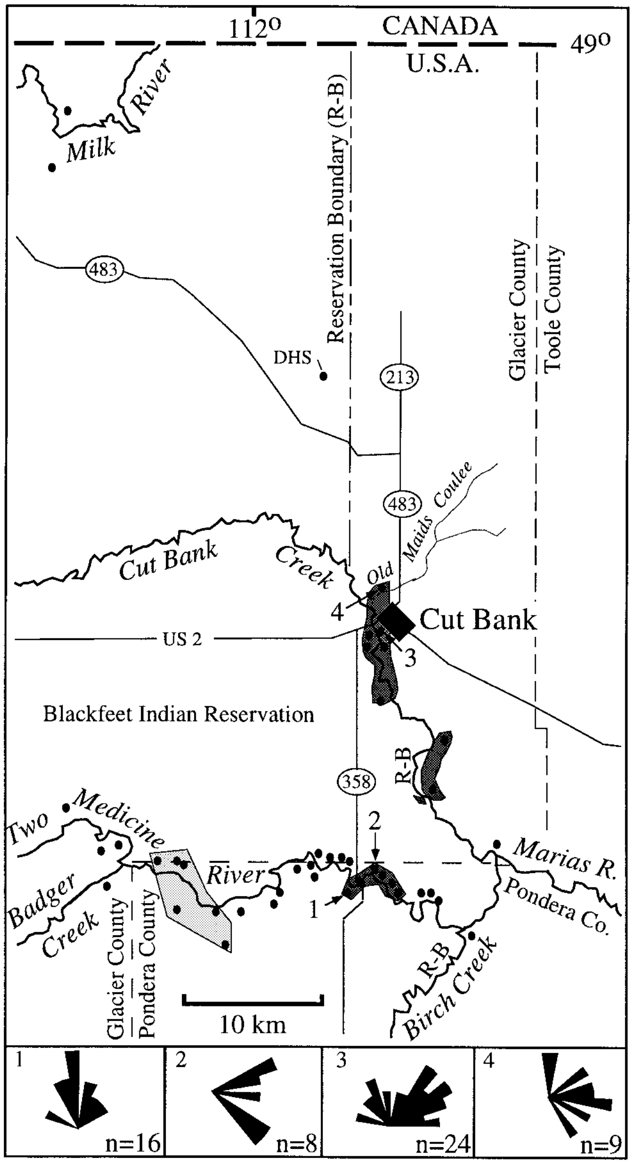

FIG. 3.—Location map of Two Medicine Formation field area. Type area extends along Two Medicine River. Dots indicate locations of measured sections. Dark stipple pattern delimits outcrop belt of the lower disconformity (LD in Rogers 1994). Data for rose diagrams are derived from Localities 1–4. Light stipple pattern delimits outcrop belt of anomalous lacustrine facies tract (the base of which is labeled UD in Rogers 1994). DHS = Dripping Hole Spring.

The 80 Ma Sequence Boundary Onshore

Description.—A previously unrecognized throughgoing disconformity crops out 70–80 m above the base of the Two Medicine Formation along the Two Medicine River and Cut Bank Creek (Figs. 3, 4, 5). A preliminary description of this disconformity was published by Rogers (1994, labeled LD).

The disconformity caps a heterolithic succession of nonmarine claystones, siltstones, and fine- to medium-grained sandstones that overlie shoreface deposits of the Virgelle Formation (Figs. 2, 4). Claystone beds in this underlying nonmarine interval are tabular, massive, and often carbonaceous, and display evidence of pedogenesis, including small root traces and slickensides. Siltstone interbeds are typically thin (5–30 cm) tabular sheets characterized by planar and ripple lamination. Thicker sandstone

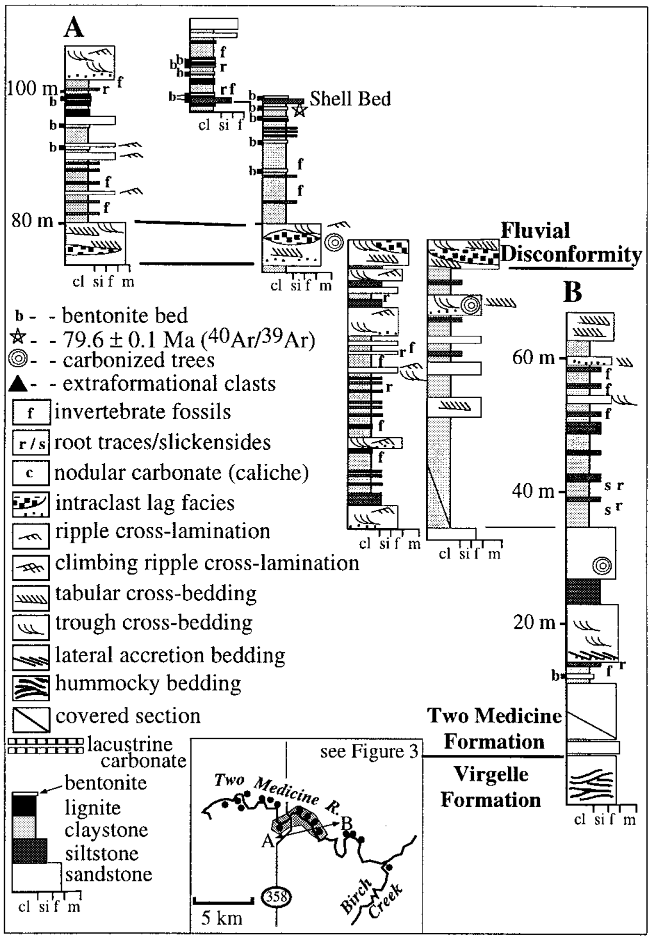

FIG. 4.—Measured sections spanning the fluvial disconformity (80 Ma sequence boundary) along the Two Medicine River. ^{40}Ar/^{39}Ar age is from Rogers et al. (1993). See text for description of fluvial disconformity and shell bed. Key also applies to Figure 12.

bodies display small- to large-scale trough and tabular cross-bedding and ripple cross-lamination. Lateral-accretion bedding is rarely preserved. Several thick (5–10 m) and laterally continuous sandstone sheets crop out within the lower 40 m of the succession. In contrast, the ~ 30 m directly below the disconformity are dominated by finer-grained floodplain facies. Overall, the nonmarine sandstone beds intercalated beneath the disconformity show a thinning- and fining-upward trend, and fine-grained floodplain facies show a diminishing carbon content upsection.

The disconformity is embedded within sandstone bodies that tend to rim exposures along the Two Medicine River and Cut Bank Creek (Fig. 3). Along the river, the disconformity can be tracked throughout the available outcrop belt of its host sandstone sheet, approximately 4 km east–west (≈ depositional dip) and 2 km north–south (≈ depositional strike). Near the town of Cut Bank, the disconformity can be traced more or less continuously for ~ 7 km north–south, from Old Maids Coulee (where it passes northward to cover) to the sharp bend to the east in Cut Bank Creek located ~ 4 km south of town (Fig. 3). Here, the sandstone body that hosts the disconformity pinches out to the south along the east side of the creek. A stratigraphically equivalent sandstone sheet that hosts the same disconformity crops out along the rim of Cut Bank Creek approximately 7 km south of town. This sandstone sheet can be traced to the south approximately 4 km, to the southern limit of Two Medicine exposures on Cut Bank Creek. Throughout the field area, Two Medicine strata dip gently to the west, and accordingly the disconformity drops in elevation from east to west.

Sandstone bodies that contain the disconformity are sheet-like with low-relief basal bounding surfaces. They are dominated by medium- to large-scale wedge-planar and trough cross-bedding (sets typically are 0.2–1.0 m thick), and show rare evidence of lateral accretion, indicating a fluvial origin (Fig. 5A). Paleocurrent data were collected from trough and tabular cross-bed sets at four localities ($n_{total} = 57$), and the mean paleocurrent direction is to the northeast (vector mean ≈ 36°). Individual paleocurrent analyses for each of the four sampling localities are shown in Figure 3. Beds dominated by current-ripple cross-lamination are frequently intercalated with planar laminae in the upper 1–2 m of the sandstone sheets. Climbing ripples are locally developed. Sedimentary structures and stratigraphic architecture indicate that these sheet sandstones accumulated primarily by way of downstream accretion of two- and three-dimensional bedforms, presumably within broad and mobile low-sinuosity channel belts.

The nature of the disconformity embedded in these fluvial sheets varies in character, ranging from a single throughgoing internal erosion surface along the Two Medicine River and southern reaches of Cut Bank Creek to a thick disconformable interval composed of several closely spaced erosional surfaces near Cut Bank (Fig. 5B–D). Although internal scour surfaces are present in fluvial sandstones throughout the Two Medicine Formation, the disconformity is distinguished from all others by (1) several meters of erosional relief (up to 5 m); (2) a thick (up to 1.3 m) and laterally persistent intraclast lag facies that consists of rounded gray and green claystone pebbles, large subrounded to angular bank-collapse blocks, carbonized trees and plant fragments, and scattered fossil bone debris (most other fluvial erosion surfaces in the Two Medicine record are mantled by relatively thin [≤ 0.15 m], localized lags of small claystone and caliche pebbles); and (3) pervasive oxidation, with lag deposits and immediately overlying and underlying strata typically stained orange and red-brown in stark contrast to surrounding drab gray and gray-green facies. In addition, a shift from fine- to medium/coarse-grained sandstone is developed locally across the disconformity (Fig. 5E).

Along the Two Medicine River, the disconformity is overlain by ~ 30 m of fine-grained claystones, siltstones, and lignite beds that contain a low-diversity, brackish-water molluscan fauna (the bivalves *Corbula* and *Corbicula*, a naticid gastropod, and a small whelk). Facies immediately above the disconformity consist primarily of thin gray siltstones and moderately to extremely carbonaceous massive claystones (Fig. 6A). A 10–30 cm thick tabular shell bed that can be traced over at least 4 km^2 crops out ~ 20 m above the disconformity (Figs. 4, 6C). The massive, well indurated matrix of the shell bed is composed of very fine sandstone/siltstone with scattered carbonaceous fragments. Shell debris is for the most part fragmentary, and ranges from loosely to densely packed. This laterally persistent shell-bearing horizon, which was apparently first noticed by Stebinger (1914, p. 63), is interpreted as a ravinement bed associated with marine transgression (Stebinger 1914; Lorenz 1981). A 10 m thick lignite-rich interval overlies the shell bed. At least 9 discrete bentonite beds are intercalated within the fine-grained carbonaceous strata superjacent to the disconformity (Figs. 4, 6B), one of which yielded an ^{40}Ar/^{39}Ar age of 79.6 ± 0.1 Ma (Rogers et al. 1993; Rogers 1994). A plagioclase crystal tuff and an immediately superjacent bentonite bed from the base of this same bentonite-rich interval in the Choteau region (Fig. 1) have yielded ^{40}Ar/^{39}Ar ages of 80.0 ± 0.1 Ma and 79.8 ± 0.1 Ma, respectively (Rogers et al. 1993).

Near Cut Bank, the disconformity is overlain by a few meters of laminated siltstones and carbonaceous claystones (with two thin intercalated bentonite seams), which are in turn overlain by sheet sandstones characterized by hummocky bedding, the marine trace fossils *Cylindrichnus* and *Terebellina,* and localized lags of oyster debris and flattened siderite pebbles (Fig. 6D). These shoreface strata can be traced approximately 20 km north–south, from the vicinity of Dripping Hole Spring to ~ 4 km south of Cut Bank (Fig. 3).

Interpretation and Correlation.—A fall in base level is consistent with the pattern of regional erosion and fluvial cannibalization recorded by the

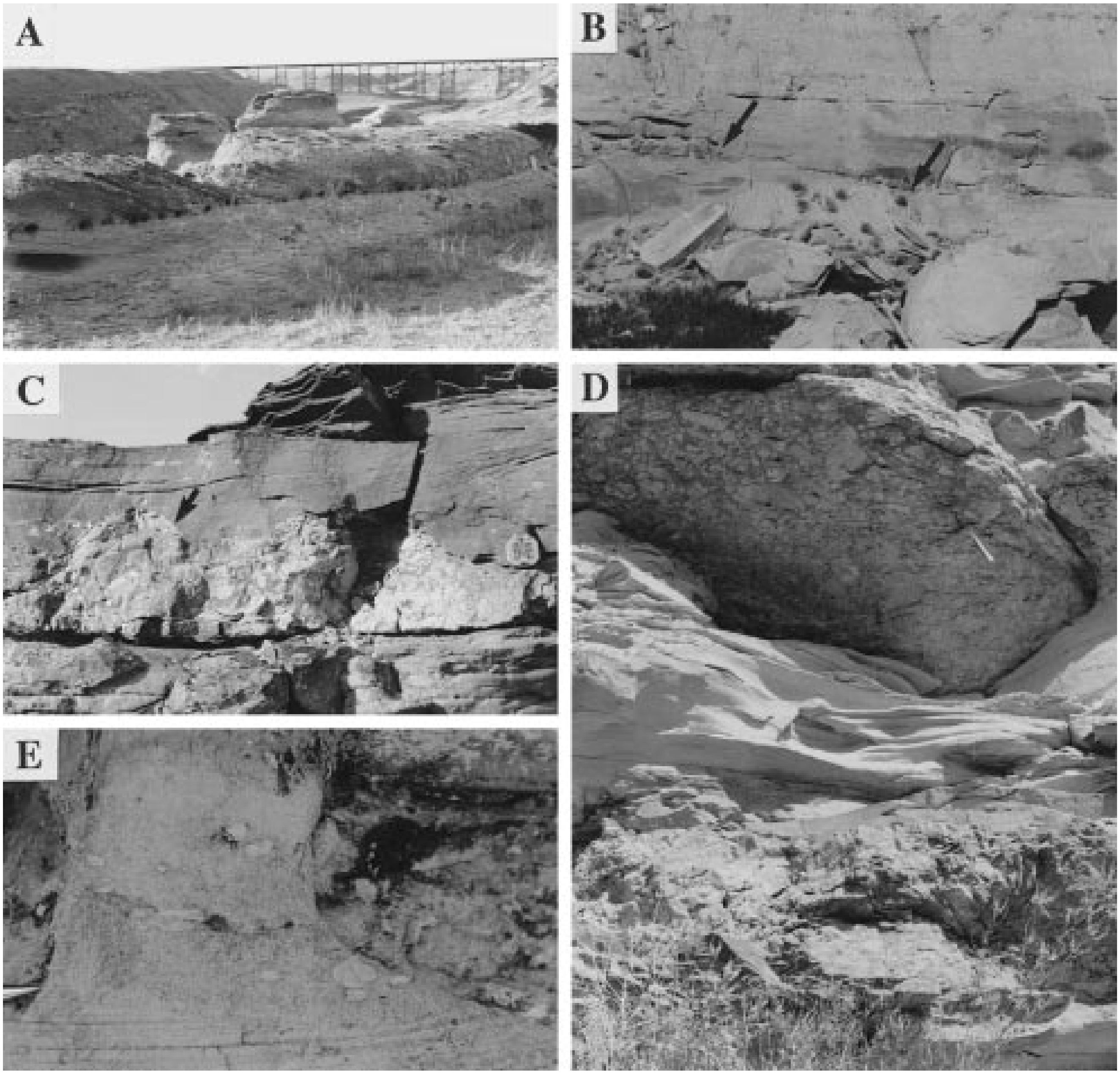

FIG. 5.—Outcrop photographs of fluvial disconformity (80 Ma sequence boundary) interpreted to mark the boundary between regressive (R7) and transgressive (T8) alluvial deposits in the Two Medicine Formation. **A)** Medium- to large-scale tabular and trough cross-bed sets characterize the host sandstone sheet near the town of Cut Bank (Locality 3, Fig. 3; field notebook for scale). **B)** Arrows point to downcutting erosional disconformity embedded in sandstone sheet along the Two Medicine River. Here, the disconformity exhibits up to 5 m of erosional relief. Left arrow points to oxidized deposits truncated by erosional surface. **C)** View of lag facies with rounded bank-collapse block (arrow). **D)** Superposed intraclast lags (up to four) characterize the northern sandstone sheet that crops out along Cut Bank Creek (see Figure 3). **E)** An increase in grain size, from fine to medium/coarse sandstone, is developed locally across the disconformity within the host sandstone sheet. The sandstone matrix of the lag facies is typically coarser grained than surrounding fluvial beds.

patchy but extremely persistent intraclast lags marking the disconformity. Base level did not fall dramatically, as evidenced by the lack of gullying or erosional beveling of strata beneath the essentially flat-based host sandstone sheets. It also appears as though local base level may have fluctuated somewhat during generation of the disconformity, which would account for the multiple episodes of erosion and aggradation apparent in the thick multistory sandstone sheet exposed on Cut Bank Creek near the town of Cut Bank (Figs. 3, 5D). An indisputable rise in relative sea level followed this negative base-level adjustment (Fig. 6).

Physical stratigraphic and geochronometric evidence indicates that the fluvial disconformity described above correlates with a widespread unconformity developed in distal parts of the Western Interior Basin. That unconformity is embedded within marine deposits of the Niobrara Formation and Pierre Shale in parts of North Dakota, South Dakota, and Nebraska, and is characterized by variable relief ranging up to a few tens of meters (DeGraw 1975; Shurr and Reiskind 1984; Weimer 1988). DeGraw (1975) described north–south-trending trellis drainage patterns on the unconformity in Nebraska, and concluded that the Western Interior Seaway with-

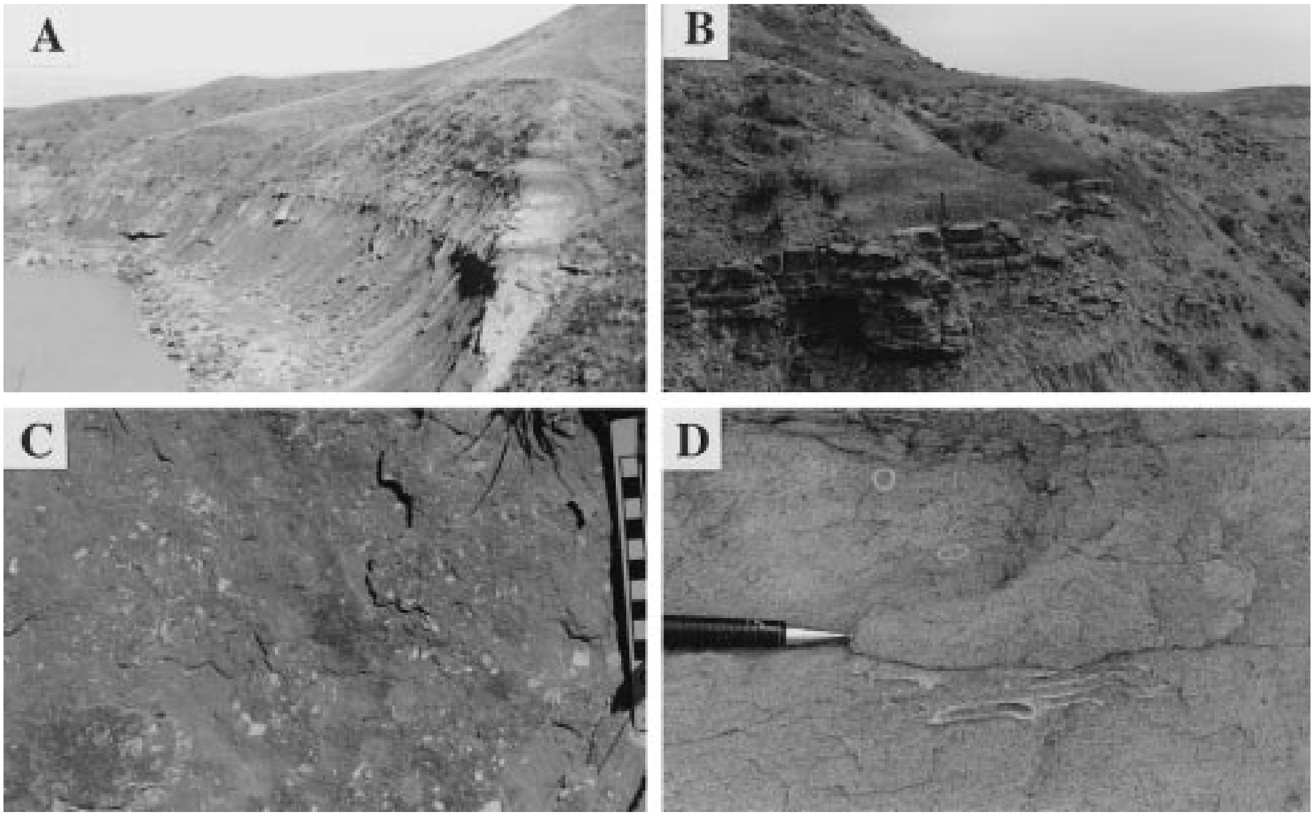

FIG. 6.—Outcrop photographs of T8-equivalent deposits overlying the Two Medicine fluvial disconformity. **A)** Top of fluvial sandstone sheet that hosts 80 Ma sequence boundary is exposed at river level. Overlying paralic facies are fine-grained and carbonaceous. **B)** At least nine discrete bentonite beds are intercalated in T8-equivalent facies. Popcorn weathering due to the swelling of smectite facilitates identification (hammer rests at base of bentonite). **C)** Bedding-plane view of a tabular shell bed (~ 30 cm thick) that crops out ~ 20 m above the disconformity along the Two Medicine River. This shell bed, which can be traced for ~ 4 km², preserves fragmentary remains of brackish and marine invertebrate taxa (*Corbula, Corbicula,* naticid gastropods). It is interpreted as a transgressive lag associated with T8. **D)** Hummocky shoreface deposits overlie the disconformity on northern reaches of Cut Bank Creek and in the vicinity of Dripping Hole Spring. The shallow-marine trace fossil *Terebellina* is common in these shoreface sandstones.

drew and exposed considerable portions of the Niobrara carbonate ramp to subaerial erosion. Van Wagoner et al. (1990) described the same unconformity in the Powder River Basin of eastern Wyoming at the top of the Gammon Ferruginous Member of the Pierre Shale, and characterized it as a type 1 sequence boundary (the 80 Ma sequence boundary). The age of the sequence boundary can be determined biostratigraphically and radioisotopically. It falls at the base of the *Baculites obtusus* ammonite zone (Gill and Cobban 1973), which places it in the lower Campanian. More importantly, it is overlain by the Ardmore bentonite bed, a regionally extensive marker horizon that consists of several discrete bentonite beds that crop out near the base of the Claggett and Pierre formations. Radioisotopic dating of the Ardmore bentonite bed in the Elk Basin of northern Wyoming indicates an age of 80.54 ± 0.55 Ma (Obradovich 1993).

The Two Medicine disconformity appears to be the terrestrial expression of the 80 Ma sequence boundary. It is clearly erosional in origin, it is situated stratigraphically where previous workers have reconstructed a turnaround from regressive to transgressive phases (Stebinger 1914; Cobban 1955; Lorenz 1981), and it is overlain by a series of closely spaced bentonite beds that correlate stratigraphically and radioisotopically with the marine Ardmore bentonite bed.

NONMARINE RECORD OF R8 AND T9

Background

Strandline reconstructions (e.g., Gill and Cobban 1973) indicate that Two Medicine strata in the type area accumulated 300–350 km inland of contemporaneous shoreline deposits at the onset of the Bearpaw transgression (T9). This upland alluvial setting renders the recognition of facies deposited during the Claggett regression (R8) and the subsequent Bearpaw transgression (T9) problematic. An additional complicating factor has been the generally held belief that the Bearpaw transgression in the plains of Montana and southern Alberta was a very rapid event that left a meager depositional record (Folinsbee et al. 1964; McLean 1971; Lorenz 1981; Braun 1983). On the basis of this reasoning, Lorenz and Gavin (1984) interpreted all Two Medicine strata in the type area above the ‘‘Claggett shaley interval’’ as regressive equivalents of R8. However, this reconstruction is incompatible with the stratigraphy of the Judith River Formation, the distal nonmarine equivalent of the Two Medicine Formation that crops out on the east side of the Sweetgrass arch (Figs. 1, 2). Recent stratigraphic work (Rogers 1995) indicates that the upper ~ 100 m of the Judith River Formation in its type area (Missouri Breaks, north-central Montana) accumulated during the Bearpaw transgression (T9).

Inland Traceability of R8/T9 Alluvial Facies

Approximately 180 m of Judith River strata are exposed in the Missouri Breaks type area (Fig. 7), and at several locations the complete section can be observed. The basal ~ 20 m of the Judith River Formation consists of shoreface and foreshore deposits of the Parkman Sandstone Member (Gill and Cobban 1973), which forms a tan sheet siltstone/sandstone body at the base of the Judith River section that extends across the type area (Fig. 8). In westernmost reaches of the type area, near the confluence of the Judith

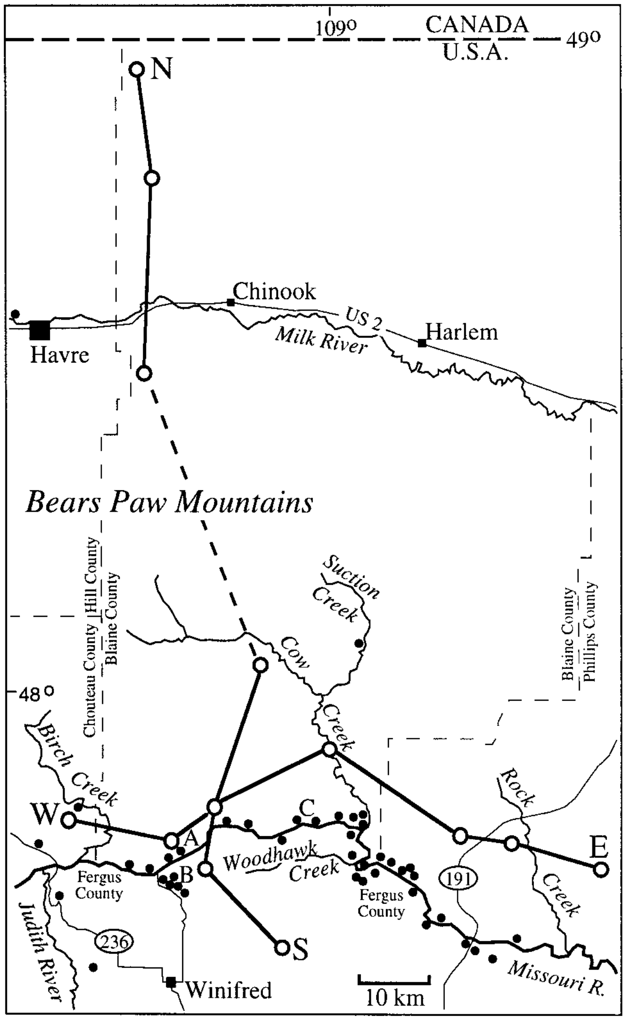

FIG. 7.—Location map of Judith River Formation type area along the Missouri River (Missouri Breaks) and the Havre region. Dots indicate locations of measured sections, open circles indicate locations of well logs used in subcrop cross sections (Fig. 8). Letters A–C refer to localities in Figure 9.

and Missouri rivers (Fig. 7), a tongue of shoreface strata crops out within silty clayshales of the Claggett Formation several meters beneath the main Parkman Sandstone Member sheet (Fig. 8). This eastward-thinning tongue of shallow-marine sediment presumably represents the leading edge of an underlying prograding sandstone body (post-Cretaceous erosion prohibits westward tracking of this sandstone body). The Parkman Sandstone Member is poorly exposed in the eastern half of the type area, but well logs indicate that its base steps 10–15 m upsection a few kilometers to the east of the mouth of Rock Creek (Figs. 7, 8). Well logs further indicate that prograding shallow marine facies of the Parkman Sandstone Member pinch out in marine shales of the Pierre Formation in the vicinity of Porcupine Dome in east-central Montana (Weimer 1963).

Onset of the Bearpaw transgression (T9) is obvious in the eastern, seaward part of the type area, where shoreface strata and carbonaceous paralic facies are sharply juxtaposed over alluvial deposits that presumably accumulated landward (updip) of the Parkman Sandstone strandline (Rogers 1993a) (Fig. 8). These shallow-marine deposits constitute a transgressive composite sequence set (*sensu* Mitchum and Van Wagoner 1991; Van Wagoner 1995) that is divisible into three backstepping fourth-order sequences (Rogers 1995). The erosional base of this composite sequence set can be correlated updip into fully nonmarine facies of the Judith River Formation (Figs. 8, 9). The throughgoing discontinuity that correlates updip is not erosional, but rather reflects a very abrupt change in alluvial architecture, the most striking evidence of which is a regional shift from a sandstone-dominated regressive alluvial suite to a mud-dominated transgressive alluvial suite. In many localities this abrupt lithofacies adjustment can be accurately positioned in surface exposures (Fig. 9). However, the discontinuity is best traced in subcrop, where regressive–transgressive turnaround is readily defined by an abrupt drop to the shale baseline (SP) and a coincident strong leftward deflection in resistivity (Fig. 8). Gamma logs also define the discontinuity, with an abrupt increase in radiation intensity coinciding with the regional shift to a mud-dominated section. This discontinuity can be traced in outcrop and subcrop to the western limit of Judith River deposits preserved in the type area (~ 50 km inland), and can also be traced northward ~ 130 km to the international border (Fig. 8). There is no evidence of significant relief on the discontinuity in subcrop, nor is there evidence for erosion or hiatus in outcrop.

Regressive vs. Transgressive Alluvial Facies

Outcrop Expression.—On the basis of the throughgoing nature of the discontinuity just described, it is now possible to subdivide the nonmarine Judith River record into regressive and transgressive alluvial suites. In outcrop, the regressive (R8) alluvial suite is tan and light gray because of the thick fluvial sandstone sheets that dominate the succession; the blocky sand-dominated slopes of the regressive alluvial suite provide foothold for vegetation. In contrast, the overlying transgressive (T9) alluvial suite is dominated by fine-grained gray-green and dark gray to black floodplain mudstones, and vegetation is more sparse on the markedly steeper slopes (Fig. 9). Color banding is also better developed in the transgressive record, and this presumably reflects enhanced preservation of discrete paleosol horizons and the intercalation of numerous brown, gray, and black carbonaceous beds and orange ironstone horizons.

Sedimentology.—Fluvial sandstones of the Judith River Formation are generally poorly lithified and moderately to well sorted, and tend to be finer grained in the transgressive suite. The grain size of five wet-sieved samples from the regressive alluvial suite ranges from fine to medium, while the grain size of five samples from the transgressive alluvial suite ranges from very fine to fine. Rounded metamorphic pebbles and one large metamorphic boulder were recovered from basal lags of two sandstone bodies in the transgressive alluvial suite (Fig. 10H). Sandstones throughout the formation are loosely cemented with calcite and clay minerals, and there is no apparent difference in cementation history between regressive and transgressive alluvial deposits.

The regressive alluvial suite is dominated by 5–10 m thick multistory sandstone sheets (Figs. 9, 10A). Internal scour surfaces are common, and are typically marked by lags of clay and ironstone pebbles and fossil bone and shell debris. Individual stories are commonly composed of thinning-upward sets of medium- to large-scale trough cross-bedding (Fig. 10B), and, unless truncated, are usually capped by ripple-laminated and planar-laminated beds. Tabular cross-bed sets are interspersed with trough sets, and lateral accretion bedding is relatively rare. Sandstone bodies of the regressive alluvial suite are interpreted to represent deposits of wide and relatively shallow low-sinuosity channels.

Sandstone sheets and ribbons of the transgressive alluvial suite are typically thinner than their regressive counterparts, and lateral accretion deposits (including inclined heterolithic strata) are more common (Fig. 10D, E). However, fluvial sandstone bodies are still dominated by medium- to large-scale trough cross-beds. Thin laminae of clay and/or carbonaceous debris frequently drape foresets and toesets, and these fine-grained drapes are in some instances distinctly paired (Fig. 10F). Increased evidence of lateral accretion suggests that many sandstone bodies of the transgressive alluvial suite were deposited within fairly sinuous channels. Inclined heterolithic stratification (IHS) and clay/carbon-draped foresets, along with

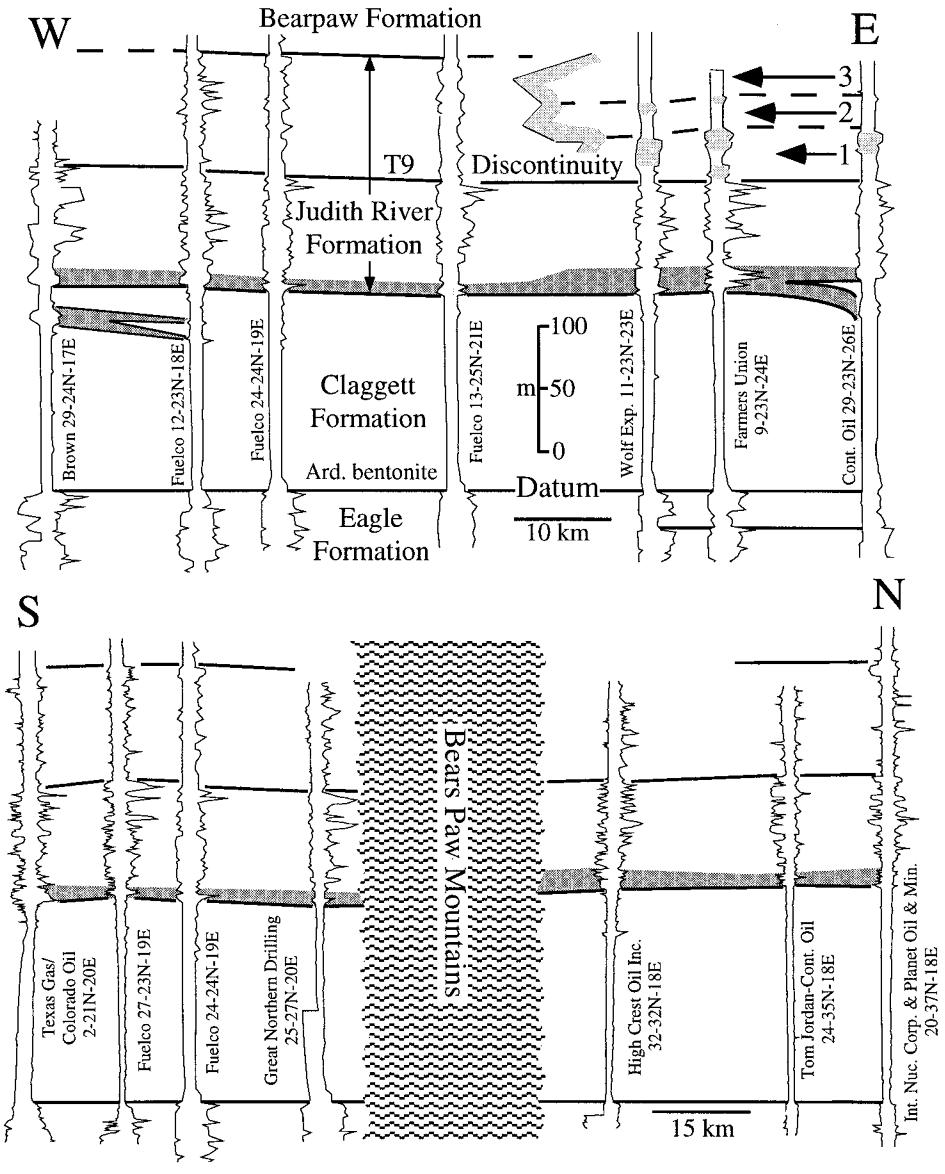

FIG. 8.—Well-log (SP and resistivity) cross sections extending across the Judith River Formation type area (W–E) and from the type area north to the international border (S–N). A backstepping composite sequence set of shoreface strata (light stipple), which is well exposed in eastern reaches of the type area, accumulated during T9 (Bearpaw transgression). The basal transgressive surface of this sequence set can be traced inland throughout north-central Montana. This discontinuity delimits regressive and transgressive alluvial equivalents of R8 and T9. Dark stipple at the base of the Judith River section defines the prograding Parkman Sandstone Member.

rare silicified logs with *Teredolites* borings (Fig. 10G), further suggest that these channels were tidally influenced (Thomas et al. 1987; Shanley et al. 1992).

Fine-grained interchannel facies were deposited in a variety of environments on the Judith River alluvial plain. Floodplain facies of the transgressive alluvial suite are highly carbonaceous (Fig. 10C), which suggests that hydromorphic conditions prevailed during deposition. Fissile lignite beds and brown carbonaceous claystones that accumulated in coastal swamps and floodbasin lakes are particularly abundant. Comparable carbonaceous facies are restricted to the lower 10–15 m of the regressive alluvial suite, and are situated immediately above the Parkman Sandstone Member (Fig. 10A). Sideritic ironstone nodules and tabular ironstone beds are developed throughout the Judith River Formation, but they, too, are more abundant within the transgressive alluvial suite. Bentonite beds are also more abundant within the transgressive alluvial suite.

Channel/Floodplain Ratio and Sandstone Body Thickness.—Channel/floodplain ratio was calculated for eight measured sections that span either one or both boundaries of the Judith River Formation in the type area (Fig. 11). The position of regressive–transgressive turnaround in each surface section was based upon measured distance from either the lower or upper formation boundary and reconciled with thickness data from nearby well logs (well logs selected from throughout the type area indicate that the T9 discontinuity lies on average 85 m above the base and 97 m below the top of the Judith River Formation). For each measured section, total thickness of all fluvial sandstones was divided by total thickness of all fine-grained floodplain facies. Sandstone bodies $\leq$ 0.25 m thick were included with floodplain facies in the analysis.

The ratio of channel to floodplain facies varies significantly between regressive and transgressive alluvial suites of the Judith River Formation ($P \leq 0.002$, Mann–Whitney U test). Channel/floodplain ratios for the regressive alluvial suite range from 0.88 to 2.70, with a median value of 1.13, whereas channel/floodplain ratios for the transgressive alluvial suite range from 0.39 to 0.84, with a median value of 0.51 (Fig. 11). The thickness of sandstone bodies also varies significantly between regressive and transgressive alluvial suites ($P \leq 0.0143$. Mann–Whitney U test). The median thickness of 45 sandstone bodies registered in measured sections spanning the regressive alluvial suite is 3.10 m, whereas the median thickness of 55 sandstone bodies logged within the transgressive alluvial suite is 2.20 m (Fig. 11).

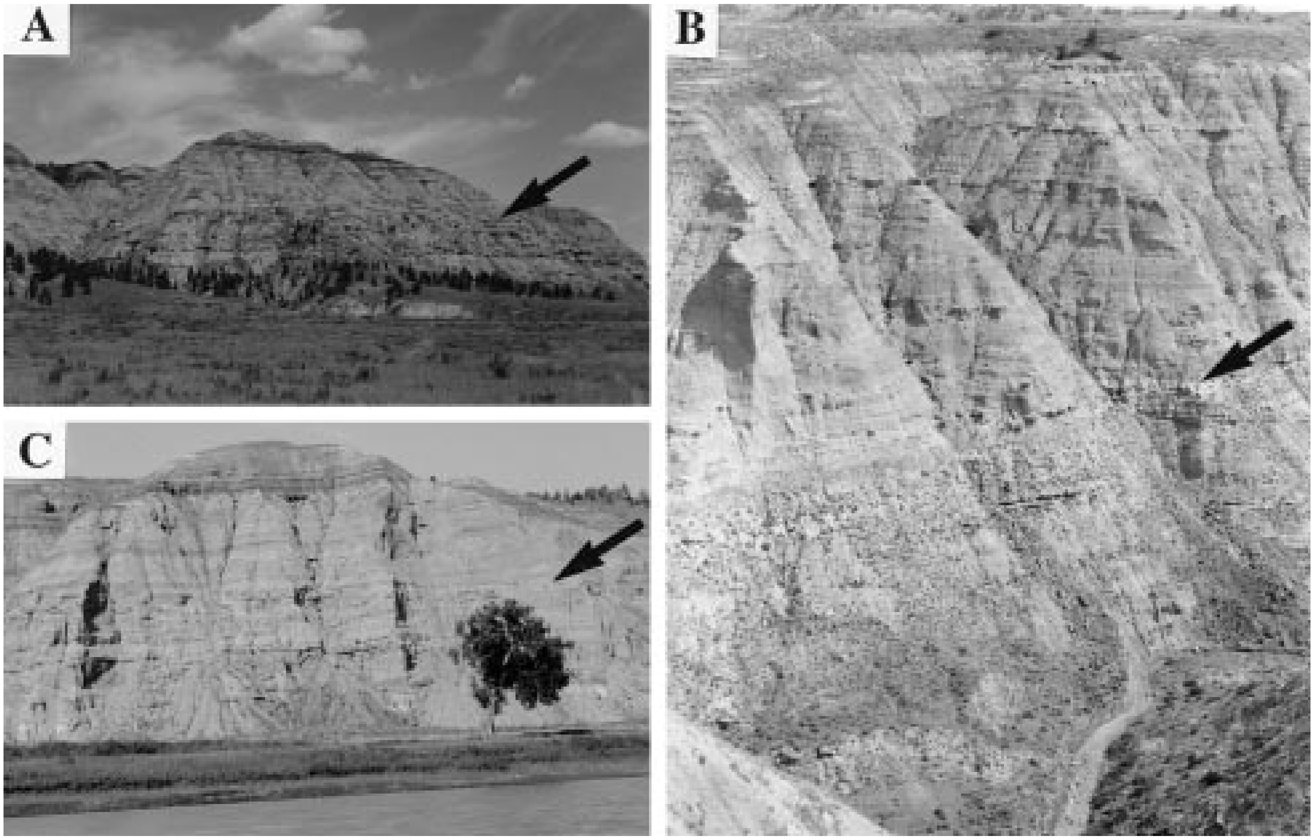

FIG. 9.—Outcrop photographs of regional discontinuity interpreted to separate R8 and T9 equivalent facies in the Judith River Formation type area. **A–C)** Arrows indicate position of abrupt shift from a sandstone-dominated alluvial record (R8) to a mudstone-dominated alluvial record (T9). This discontinuity correlates to the east with the erosional base of a backstepping composite sequence set (see Figure 8). Locations of localities A–C are indicated by corresponding letters in Figure 7.

Tentative Correlation with Two Medicine Formation

Post-Cretaceous erosion over the Sweetgrass arch prohibits direct physical tracing of the Judith River T9 discontinuity into upland alluvial facies of the Two Medicine Formation in northwestern Montana (Figs. 1, 2). However, given the geometry and asymmetric subsidence profile of a foreland basin, and the thickness and age of T9-equivalent facies preserved in the Judith River Formation, it is highly likely that nonmarine facies equivalents of both R8 and T9 are represented in source-area-proximal Two Medicine strata.

Approximately 410 m of interbedded fluvial and floodplain deposits crop out above the ‘‘Claggett shaley interval’’ in the Two Medicine Formation type area (Fig. 12). Lorenz and Gavin (1984, p. 178) described an ‘‘anomalous 55 m thick lithologic suite’’ approximately 230–240 m above the top of the ‘‘Claggett shaley interval’’. In their description, the base of this stratigraphic interval consists of ~ 10 m of crudely bedded carbonate that is locally silicified. Overlying the basal carbonate zone is approximately 40–45 m of fine-grained alluvial strata characterized by gray lacustrine clayshales and very few sandstone beds.

Recent work in the Two Medicine Formation confirms their observations. There is indeed an abrupt shift from fluvial and floodplain deposits to lacustrine carbonate facies ~ 230 m above the ‘‘Claggett shaley interval’’ (Fig. 13A–D; the base of this lacustrine carbonate facies tract was labeled UD in Rogers 1994). The ~ 20 m thick interval of bedded lacustrine carbonate and associated lacustrine shales can be traced throughout available exposures in badlands of the Two Medicine River drainage (~ 15 km^2, Fig. 3), and consists of thin (10–30 cm) beds of micrite intercalated with darker gray and gray-green horizons of noncalcareous shale (Figs. 12, 13C). The micrite facies is massive with scattered quartz grains and clay granules, and rare calcite vugs and chert stringers. Three anomalously coarse-grained volcaniclastic sandstone beds with polymictic lags that include quartzite, carbonate, sandstone, and bone pebbles are associated with the lacustrine carbonate interval (Rogers 1994). The extraformational quartzite clasts (Fig. 13E), along with the ‘‘anomalous’’ lacustrine carbonate interval are unique within the Two Medicine section exposed in the type area (Figs. 12, 13). Fluvial facies above the lacustrine carbonate interval are finer grained than underlying fluvial deposits, and include abundant lacustrine clayshales and thin ripple-laminated siltstones.

Several lines of evidence indicate that this anomalous lacustrine carbonate interval in the Two Medicine Formation type area correlates with the throughgoing discontinuity that marks the onset of T9 in the Judith River Formation (Fig. 14). First, associated facies in both areas indicate flooding of the basin, with the proximal alluvial record (Two Medicine Formation) shifting to widespread shallow lacustrine deposits, and the more distal coastal plain record (Judith River Formation) showing evidence of marine transgression. The channel/floodplain ratio of fluvial facies drops substantially across both boundaries as well (Figs. 11, 12), which is interpreted to reflect a regional rate increase in the generation of accommodation (Bridge and Leeder 1979; Bridge and Mackey 1993; Wright and Marriott 1993; Heller and Paola 1996). Concentrations of vertebrate fossils (dinosaur bonebeds in the Two Medicine Formation and microvertebrate sites in the Judith River Formation) are also much more abundant in strata that crop out above the lacustrine carbonate interval and the Judith River T9 discontinuity (Rogers 1993b, 1995; Rogers and Eberth 1996).

Radioisotopic age data are also consistent with correlation (Fig. 14). Recent ^{40}Ar/^{39}Ar analyses in the Judith River Formation indicate that the T9 discontinuity formed ~ 75.4 Ma (Rogers and Swisher 1996). The la-

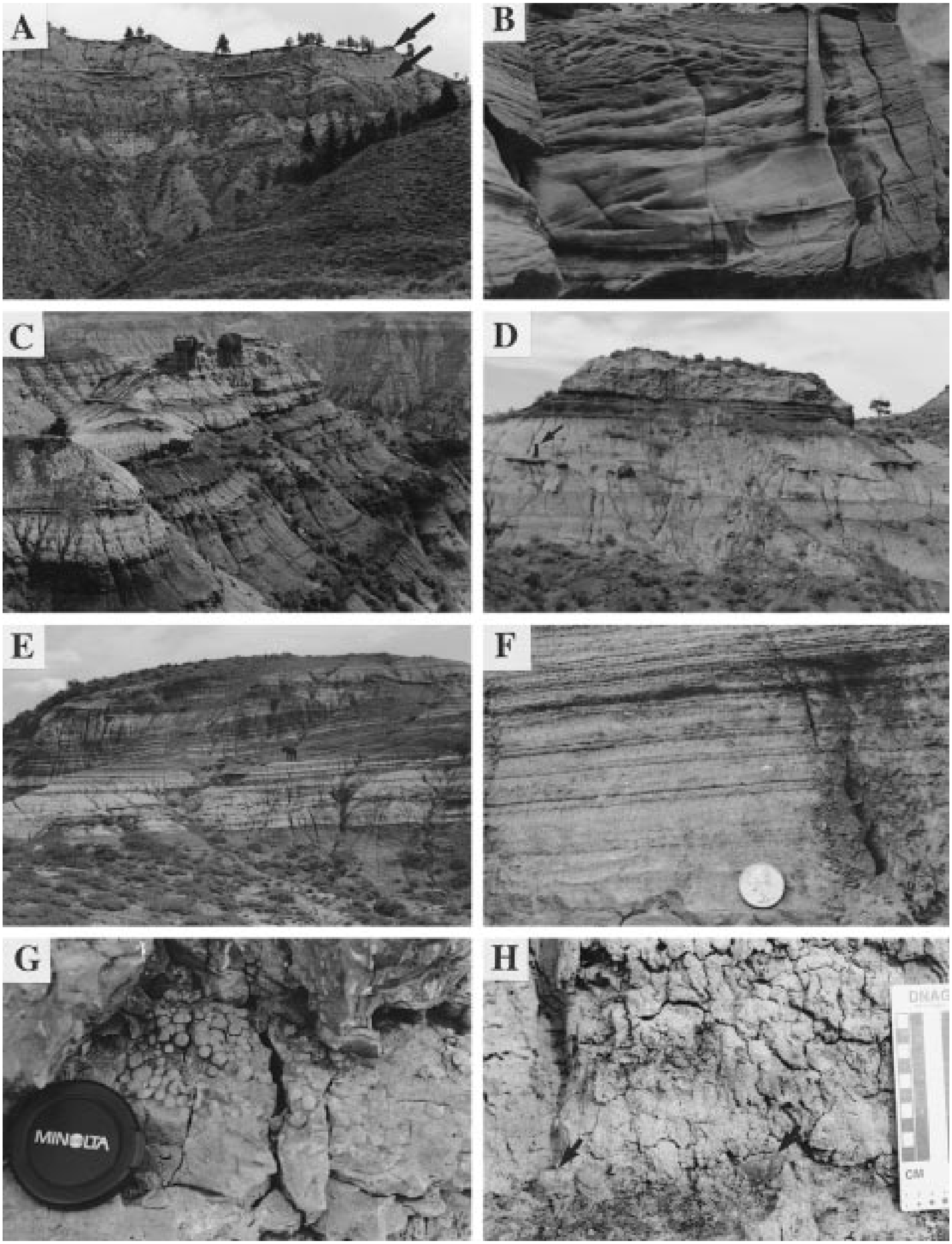

FIG. 10.—Outcrop photographs of regressive (R8) and transgressive (T9) alluvial facies of the Judith River Formation. **A)** Multistory fluvial sandstone sheets (arrows) dominate the regressive alluvial suite. View is approximately parallel to depositional strike. The lower fluvial sheet overlies carbonaceous facies, which in turn overlie shoreface deposits of the Parkman Sandstone Member. **B)** Sandstone sheets of the regressive alluvial suite are characterized by thinning-upward sets of medium- to large-scale trough cross-stratification. **C)** Interchannel facies of the transgressive alluvial suite are more carbonaceous, and preserve more ironstone horizons and bentonite beds,

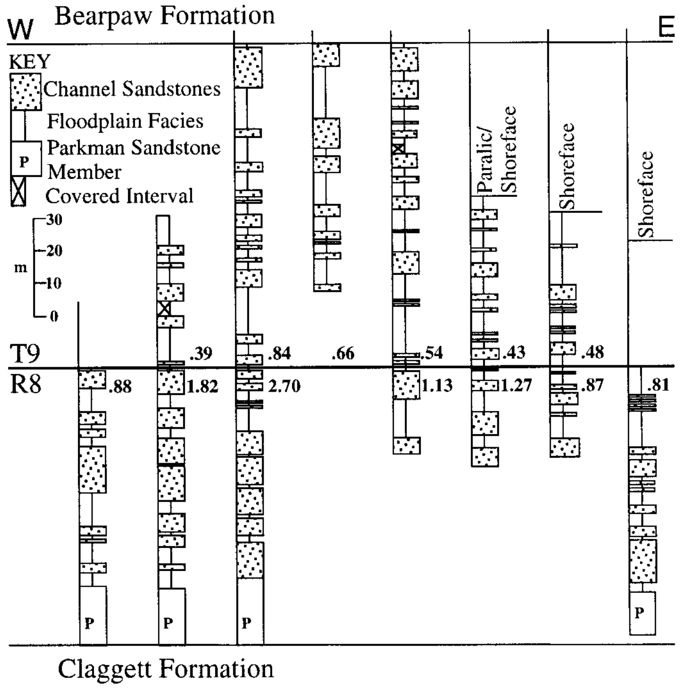

FIG. 11.—Significant differences in channel/floodplain ratio and sandstone body thickness are developed across the T9 discontinuity in the Judith River Formation type area. Channel/floodplain ratios for the regressive alluvial suite range from 0.88 to 2.70 (median 1.13), whereas channel/floodplain ratios for the transgressive alluvial suite range from 0.39 to 0.84 (median 0.51). The median thickness of sandstone bodies logged in the regressive alluvial suite is 3.10 m, whereas the median thickness of sandstone bodies logged in the transgressive alluvial suite is 2.20 m.

custrine carbonate interval in the Two Medicine Formation is situated between bentonite beds with ^{40}Ar/^{39}Ar ages of 79.6 Ma ± 0.3 (~ 240 m below) and 74.1 Ma ± 0.7 (~ 130 m above) (Rogers et al. 1993). Simple interpolation of an age for the lacustrine interval is probably inappropriate because net rates of sediment accumulation presumably changed across the interval (as evidenced by changes in channel/floodplain ratio and the richness of the Two Medicine fossil record), but the dates clearly bracket the same period of time as the discontinuity in the Judith River record. Last, it seems reasonable to postulate that an abrupt increase in the rate of generation of accommodation (subsidence) within a foreland basin that hosts an epicontinental sea could lead to transgression in the coastal-plain lowlands and concomitant lacustrine flooding in coeval upland settings. The temporary establishment of widespread lakes in the source-area-proximal uplands presumably reflects different hydrologic/sedimentary response times of fluvial and lacustrine systems, with the progradation of alluvial aprons delayed because of temporary trapping in the proximal foredeep (Eyer 1969; Blair 1987; Heller et al. 1988).

COMPARISON WITH STANDARD SEQUENCE STRATIGRAPHIC MODELS

Sequence Boundaries

Sequence-bounding unconformities are usually defined as surfaces of subaerial erosion marked by a basinward shift in facies and a vertical change in parasequence stacking patterns, and are generally interpreted to result from a relative fall of sea level (Van Wagoner et al. 1990; Christie-Blick and Driscoll 1995; Van Wagoner 1995). However, basinward shifts in facies and changes in parasequence stacking patterns are likely to be ambiguous in updip fluvial settings (e.g., Yoshida et al. 1996).

The 80 Ma erosional disconformity in the Two Medicine record (LD in Rogers 1994) largely conforms to the standard definition of a sequence boundary. The Two Medicine disconformity shows evidence of subaerial exposure/hiatus (oxidation), erosion, and an upsection change in facies (Figs. 5, 6) suggestive of a change in parasequence stacking patterns. Fluvial incision during generation of the disconformity was inhibited perhaps by subsidence within the proximal foreland basin setting (Jordan and Flemings 1991; Posamentier and Allen 1993). This interpretation is consistent with the substantial evidence for contemporaneous subaerial erosion and valley incision in more distal reaches of the basin (DeGraw 1975; Shurr and Reiskind 1984; Van Wagoner et al. 1990), where subsidence rates would presumably be lower. The relatively minor fluvial incision that characterizes the Two Medicine disconformity might also reflect the low-relief ramp physiography of the western margin of the Western Interior foreland basin. In a ramp setting, a fall in base level (sea level) would not significantly alter fluvial gradients, and would therefore not necessarily prompt headward erosion and valley incision (Schumm 1993; Wescott 1993; Shanley and McCabe 1994).

The identification of the 80 Ma sequence boundary (Van Wagoner et al. 1990) within the Two Medicine Formation is significant in that it is one of very few well documented examples of a nonmarine sequence boundary. Moreover, most other examples of nonmarine sequence boundaries are characterized by striking dislocations of facies tracts, with upland fluvial facies (usually braided-stream deposits) sharply juxtaposed over coastal-plain facies. For example, the Castlegate (Van Wagoner et al. 1990; Olsen et al. 1995; Yoshida et al. 1996) and Calico (Shanley and McCabe 1991) sequence boundaries are defined by the sharp juxtaposition of braided-fluvial facies over carbonaceous coastal-plain facies. In contrast, the Two

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than their regressive counterparts. **D)** Lateral accretion bedding is more common in the transgressive alluvial suite. Beds are accreting to the right in this exposure. Lignitic facies overlie the laterally accreting sandstone body. Dog (arrow) is ~ 80 cm tall. **E)** Inclined heterolithic stratification (IHS) is locally developed in the transgressive alluvial suite. This facies presumably represents lateral accretion on low-inclination point-bar surfaces within tidally influenced channels. **F)** Clay and carbon laminae often drape toesets and foresets in the transgressive alluvial suite. These laminae are occasionally distinctly paired, and when paired, are interpreted as tidal bundles reflecting semidiurnal tidal fluctuations. **G)** Rare logs preserved in channel facies of the transgressive alluvial suite exhibit *Teredolites* borings. **H)** Rare metamorphic pebbles (arrows) are recovered from channel-lag facies in the transgressive alluvial suite.

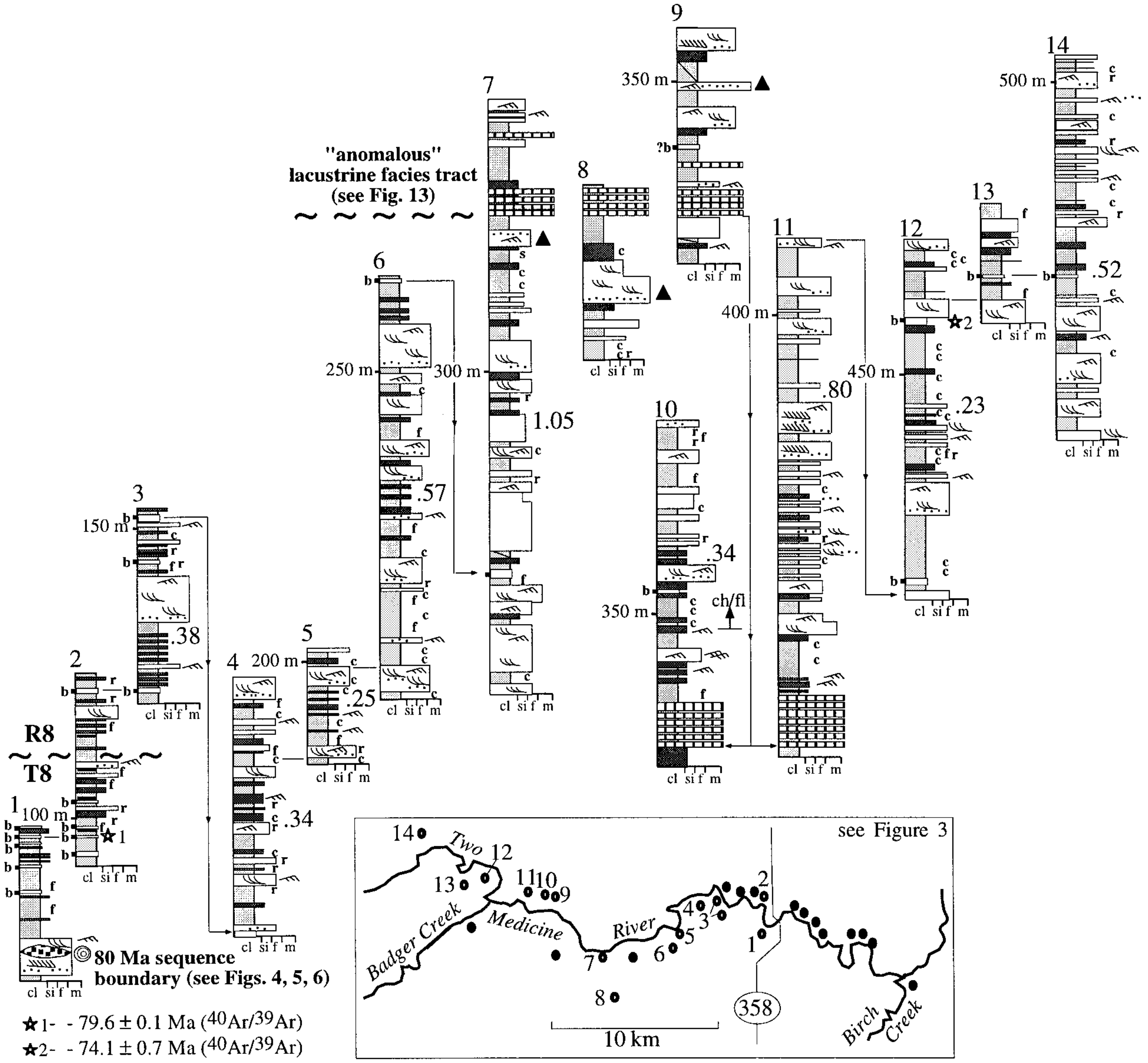

FIG. 12.—Measured sections extending from the 80 Ma sequence boundary to the top of accessible exposures in the Two Medicine Formation type area (see inset map for locations) illustrate the unique nature of the lacustrine carbonate facies tract that crops out ~ 330 m above the base of the Two Medicine section. This lacustrine facies tract is tentatively correlated with the T9 discontinuity in the Judith River record. Channel/floodplain ratios (calculated as in Figure 11) are posted to the right of sections. A general trend toward increasing channel density and channel body thickness is apparent in R8-equivalent alluvial facies up to the base of the lacustrine interval. Channel density generally diminishes above the lacustrine interval in what are interpreted as T9-equivalent facies. Radioisotopic ages are from Rogers et al. (1993). Use key in Figure 4.

Medicine sequence boundary is defined by subtle (but nevertheless persistent) evidence for fluvial incision, widespread oxidation, and an increase in grain size within the fluvial system (Fig. 5). There is not an immediately apparent dislocation of facies, and recognition hinges upon careful comparison with surrounding fluvial facies.

The throughgoing discontinuity in the nonmarine Judith River record (Figs. 8, 9) does not conform to conventional definitions of a sequence boundary, and it apparently did not form in response to a fall in relative sea level. Nowhere on or immediately beneath the discontinuity is there evidence of anomalous fluvial incision or prolonged paleosol development, and thus there is no indication of a base-level fall or of an appreciable decrease in rates of sediment accumulation prior to or during generation of the discontinuity. This discontinuity instead appears to record an abrupt increase in the rate of generation of accommodation within the Montana portion of the Western Interior foreland basin. Facies above the discontinuity indicate a regional rise in relative sea level and increased rates of aggradation on the floodplain, and within the type area of the Judith River Formation the discontinuity correlates with the base of a backstepping composite sequence set (Fig. 8). It is provisionally interpreted as the nonmarine equivalent of a third-order transgressive surface coincident with the updip correlative conformity.

Transgressive and Highstand Depositional Systems

In the Two Medicine outcrop belt, shoreface strata are exposed only at the base of the section and in a few patchy exposures above the 80 Ma

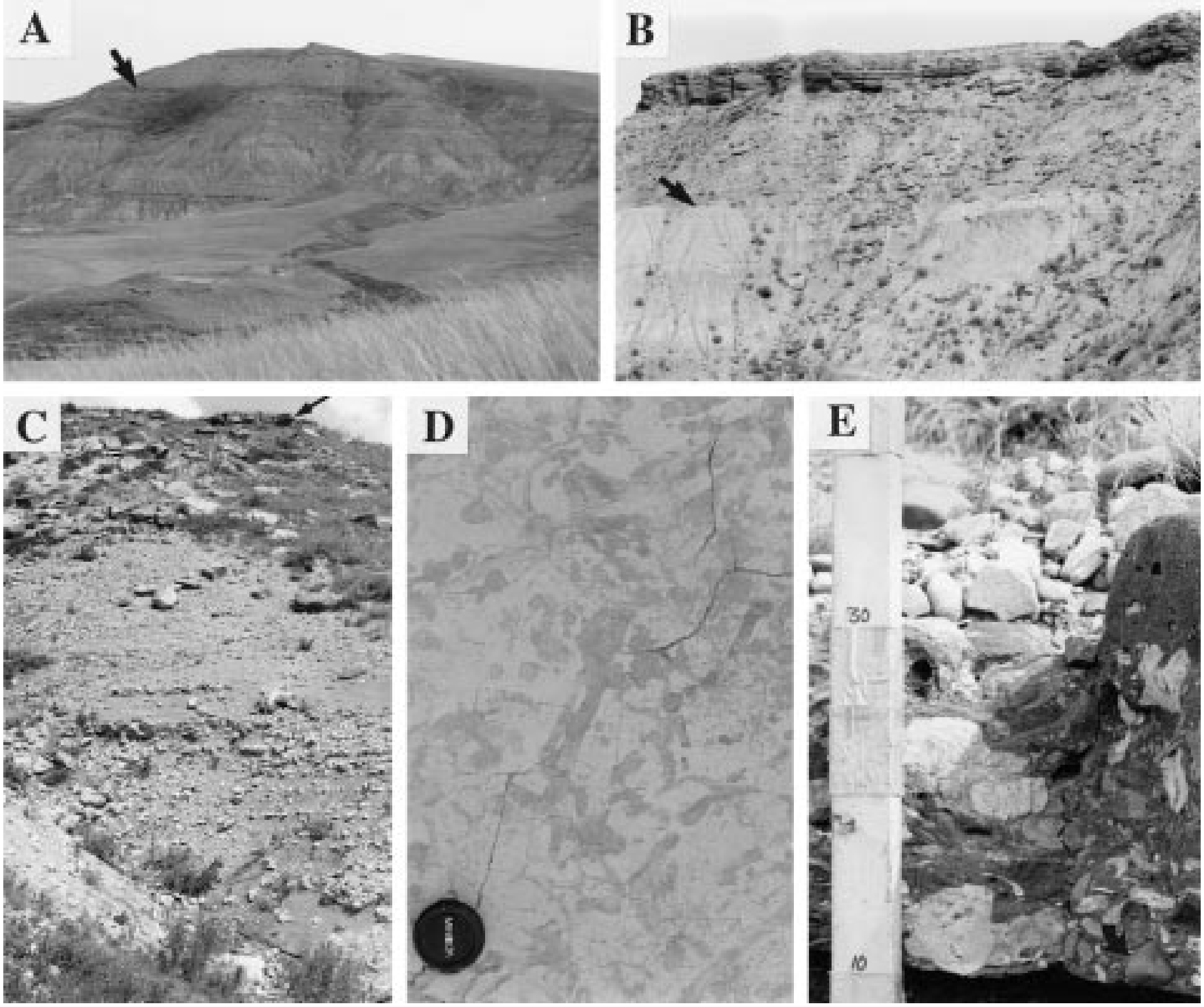

FIG. 13.—Outcrop photographs of lacustrine facies in Two Medicine Formation type area (see Fig. 3). **A)** Arrow points to base of lacustrine interval. **B)** Close-up view of lacustrine succession. Thin-bedded lacustrine carbonates pass upsection into silty and sandy lacustrine facies (caprock). Arrow points to base of lacustrine interval. **C)** Close-up view of bedded carbonate (small arrow near center points to hammer). The carbonate facies consists of micrite with scattered quartz grains and clay granules. Upper arrow points to extraformational clast-bearing sheet illustrated in photograph E. **D)** Bedding-plane view of intense bioturbation in capping siliciclastic lake facies. **E)** A coarse-grained polymictic sandstone sheet that preserves extraformational quartzite clasts (arrow), carbonate rip-ups, and *Unio* fragments crops out near top of the lacustrine interval on the north side of the Two Medicine River. A fluvial sandstone with a basal lag of claystone pebbles and scattered extraformational pebbles crops out immediately beneath the lacustrine interval on the south side of the river. Sandstone beds yielding extraformational clasts are enriched in volcanic detritus.

sequence boundary. As a consequence, it is impossible to directly link the alluvial architecture of the Two Medicine record with contemporaneous shallow-marine facies, and thus to test their relationship with conventional depositional sequences or systems tracts. Such a test is possible, however, within the Judith River type area, where shoreface strata are well exposed, especially above the T9 transgressive surface (Fig. 8). Three backstepping shoreface sequences crop out above the basal transgressive surface, and the systems tracts and sequence boundaries that define these fourth-order sequences can be projected westward into nonmarine Judith River strata. Of these surfaces, only the basal transgressive surface can be traced confidently into the fully alluvial record (see above). The other surfaces are marked in marine strata by abrupt facies dislocations and shoreface erosion, and their intervening transgressive and highstand systems tracts pass westward into heterolithic coastal-plain facies that show no clear evidence of cyclicity or throughgoing erosion, flooding, or omission surfaces.

Despite these limitations, the Two Medicine and Judith River alluvial deposits provide valuable ground truth for conceptual models of alluvial sequence stratigraphy (Schumm 1993; Wescott 1993; Wright and Marriott 1993). For example, Wright and Marriott (1993) predicted that fluvial architecture would change through a third-order base-level fall and subsequent rise because of changing rates of generation of accommodation. During the highstand phase, a slowdown in the generation of accommodation results in channels combing their floodplain (by way of lateral accretion) and reworking fine-grained facies. If stream gradients increase and erosion intensifies during highstand, rivers may shift to a braided pattern because of increased sediment load. Regardless of the exact nature of the channel facies, the record of alluvial highstand deposition would be characterized by increased density of channel deposits (high channel/floodplain ratio) and well developed (although possibly rarely preserved) paleosols. In contrast, accommodation is created during the transgressive phase of the third-order cycle, and fluvial systems respond by shifting to vertical accretion. The potential for sediment storage on the floodplain is enhanced, and accord-

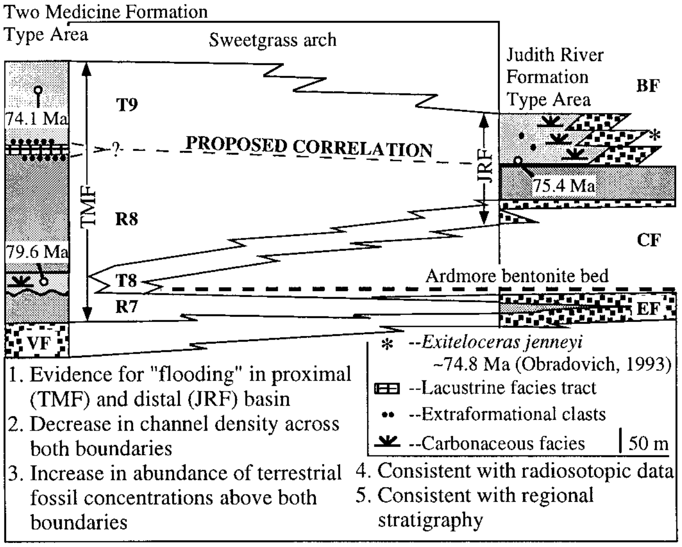

FIG. 14.—Proposed correlation between lacustrine carbonate facies tract in the Two Medicine Formation type area and the throughgoing discontinuity that separates R8- and T9-equivalent alluvial facies in the Judith River Formation type area. The Ardmore bentonite bed is used as a datum. $^{40}Ar/^{39}Ar$ ages are from Rogers et al. (1993) and Rogers and Swisher (1996). VF = Virgelle Formation, EF = Eagle Formation, CF = Claggett Formation, BF = Bearpaw Formation.

ingly channel/floodplain ratio is diminished. In general, paleosols of the transgressive depositional system will be somewhat less mature than their highstand counterparts, and they might also be hydromorphic. Channel facies might show sheet or ribbon geometries, depending on the rate of addition of accommodation.

The conceptual model of Wright and Marriott (1993) is largely consistent with the alluvial record of the third-order R8–T9 cycle. Approximately 230 m of Two Medicine strata apparently accumulated during R8, and these alluvial facies are interpreted as the highstand depositional system. During the early stages of R8, the alluvial record is dominated by fine-grained interchannel facies. Channel sandstones that accumulated during this early highstand phase are characterized by both sheet and ribbon geometries, and intercalated paleosols are weakly developed. Channel/floodplain ratio increases upsection within the highstand depositional system (Fig. 12); concurrent with this increase in the relative density of sandstone facies is a shift to more amalgamated sheet geometries. Paleosols also show an increase in maturity and caliche content upsection, with striking but localized evidence for pedogenesis and caliche development in late highstand facies that crop out beneath the lacustrine interval. The late highstand depositional system of the Judith River Formation shows comparable facies architecture, with the alluvial record dominated by relatively thick sandstone bodies with sheet geometries (Figs. 9, 10, 11). The shift to transgressive depositional systems with the onset of T9 is marked in both the Two Medicine and Judith River records by a significant drop in channel/floodplain ratio (Figs. 11, 12). In addition, evidence of color banding and caliche development in fine-grained facies decreases at the base of the transgressive depositional system in the Two Medicine record, and there is widespread evidence for a shift to hydromorphic floodplain conditions in the Judith River Formation. The hydromorphic nature of the Judith River transgressive depositional system is attributed to both rising base level and close proximity to the western shoreline of the Western Interior Seaway.

In contrast, Wright and Marriott's (1993) general predictions of highstand architecture do not readily conform with the alluvial record of the older R7 in the Two Medicine Formation. Contrary to their model, sandstone-body density does not increase upsection during the highstand phase (see Fig. 4). Instead, the Two Medicine record shows a general upsection trend toward decreasing sandstone-body thickness and channel/floodplain ratio beneath the 80 Ma sequence boundary. This stratal architecture is presumably a physiographic artifact that reflects shifting position on the stream profile, with deposits of large distributary channels/river mouths dominating the early highstand record. This result does not necessarily speak to the control of accommodation on alluvial architecture.

EUSTASY AND TECTONICS IN THE CAMPANIAN OF MONTANA

Early Campanian Eustasy?

A regional (Western Interior, see Heller et al. 1993) or possibly global fall in sea level at approximately 80 Ma has been proposed as the probable cause of the subaerial exposure and regional truncation associated with the 80 Ma sequence boundary (DeGraw 1975; Shurr and Reiskind 1984; Van Wagoner et al. 1990). This interpretation is certainly consistent with large-scale depositional patterns within the Western Interior Basin. For example, the Eagle Formation of Montana prograded to its maximum seaward extent in the late early Campanian, with the regressive maximum falling within the zone of *Baculites* sp. (weak flanking ribs) (Gill and Cobban 1973). A contemporaneous record of shoreline progradation is present in the basin approximately 1500 km to the south, with the Point Lookout Sandstone of northern New Mexico and southern Colorado reaching its maximum seaward extent within the same ammonite range zone (Molenaar 1983). Independent support for a potential eustatic component in the generation of the 80 Ma sequence boundary comes from studies of coeval passive margins. Olsson (1991) recognized an ~ 80 Ma unconformity in the Campanian Woodbury Formation of New Jersey that presumably reflects a eustatic fall. There is also evidence for early Campanian regression in parts of western Europe (Hancock 1975; Hart 1980a, 1980b) and Israel (Flexer et al. 1986).

The sedimentology of the 80 Ma Two Medicine sequence boundary is also consistent with a eustatic scenario. The throughgoing fluvial disconformity is marked by anomalous erosion and oxidation indicative of a fall in base level, but displays no evidence for tectonic rejuvenation of the Cordilleran fold-and-thrust belt (e.g., a change in provenance and/or influx of extraformational clasts; see below). A fall in base level/sea level alone can account for the sedimentological changes associated with the disconformity.

Late Campanian Tectonic Subsidence

During the late Campanian, shorelines shifted ~ 350 km to the east, and the Claggett Sea receded (Gill and Cobban 1973). Subsequently, in the latest Campanian (~ 75.4 Ma; Rogers and Swisher 1996), accommodation was added to the basin in sufficient volume to reverse the direction of strandplain migration and prompt the westward backstepping of high-frequency shoreface sequences. Onset of the Bearpaw transgression (T9) has traditionally been attributed to a pulse of tectonic subsidence (Gill and Cobban 1973; McLean and Jerzykiewicz 1978), and the late Campanian in general is considered to have been a time of active tectonism in the fold-and thrust belt of southern Alberta and northern Montana (Stockmal and Beaumont 1987; Cant and Stockmal 1989; Eberth and Hamblin 1993; Kauffman and Caldwell 1993; McMechan and Thompson 1993).

Aside from being compatible with the inferred timing of regional Cordilleran tectonism, several sedimentological features suggest that the onset of the T9 transgressive phase probably was tectonic in origin. Widespread evidence for flooding within the basin (lacustrine in the Two Medicine uplands, marine in the Judith River lowlands) is consistent with pervasive subsidence-related generation of accommodation. The shift to predominantly fine-grained fluvial sedimentation across the T9 discontinuity is also consistent with thrust loading and basin subsidence. Increased rates of generation of accommodation would have trapped coarse-grained detritus in the most proximal reaches of the foredeep (Heller et al. 1988; Burns et al. 1997) and favored preservation of fine-grained floodplain facies as vertical aggradation rates increased (Bridge and Leeder 1979; Wright and Marriott 1993). The relatively minor but nonetheless anomalous presence of metamorphic pebbles in the Two Medicine lacustrine zone and T9-equivalent Judith River facies also suggests the possible rejuvenation of source terranes. Lastly, considerable tectonic subsidence of the foreland basin in Montana and Alberta during the late Campanian is required given the substantial thickness of the Two Medicine–Judith River clastic wedge (Ryer 1993).

CONCLUSIONS

This study provides outcrop documentation of nonmarine stratal architecture during two third-order regressive–transgressive cycles in the Western Interior Basin. The results of this study have important implications for nonmarine sequence analysis in foreland basin settings: sequence boundaries and correlative conformities can be recognized in inland settings and traced updip beyond coastal-plain facies, and examples of alluvial ‘‘transgressive’’ and ‘‘highstand’’ depositional systems (Wright and Marriott 1993) can potentially be distinguished several hundred kilometers inland.

Identification of the 80 Ma sequence boundary in Two Medicine strata provides one of the very few well-documented examples of a nonmarine sequence boundary. This sequence boundary, which is embedded within flat-based fluvial sheet sandstones, is characterized by several meters of erosional relief, an anomalously persistent and thick intraclast lag, widespread oxidation, and an increase in grain size within the fluvial system. Unlike most other examples of nonmarine sequence boundaries, it is not marked by an immediately apparent facies-tract dislocation (an abrupt basinward shift in facies), and thus recognition hinges upon comparison with surrounding fluvial facies. Generation of the sequence boundary is interpreted to reflect a negative base-level adjustment in the proximal foreland basin prompted by a regional (Western Interior) or possibly global fall in sea level. This implies that the loss of accommodation due to falling sea level temporarily outpaced any addition of accommodation in the proximal foreland basin resulting from long-term flexural subsidence. In contrast, the throughgoing discontinuity in the nonmarine Judith River record, which is not consistent with conventional definitions of a sequence boundary, is interpreted to reflect an abrupt increase in the rate of generation of accommodation within the Montana portion of the foreland basin. This widespread addition of accommodation presumably resulted from flexural subsidence of the basin due to tectonic loading (thrust-sheet emplacement?) in the orogen during the late Campanian. Regardless of origin, this regionally traceable discontinuity, like the 80 Ma sequence boundary intercalated several hundred meters below it, serves to establish a time-stratigraphic framework within the nonmarine record.

The throughgoing discontinuities described in this report effectively subdivide nonmarine strata of the lower and middle Montana Group into genetic units that reflect changes in relative sea level. Prior to sequence analysis of the study interval, only generalized correlations were available for nonmarine portions of the Montana Group. The development of a high-resolution stratigraphic framework that extends into fully nonmarine facies of the Two Medicine and Judith River formations enables the reconstruction of geologic history with considerable paleogeographic breadth: transgressive and regressive events in the marine Western Interior Seaway can now be linked to the stratigraphy of the coastal-plain lowlands (Judith River Formation) and alluvial uplands (Two Medicine Formation), and trends in alluvial architecture, nonmarine sedimentology, and even terrestrial taphonomy can now be evaluated in the context of third-order sea-level cyclicity.

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