Nature and origin of through-going discontinuities in nonmarine foreland basin strata, Upper Cretaceous, Montana: Implications for sequence analysis

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ABSTRACT

Two laterally traceable discontinuities (Montana, United States) that vary in character and origin provide a means of subdividing fully nonmarine strata into genetic packages that are likely related to changes in relative sea level. Both discontinuities are situated >100 km inland of contemporaneous shorelines, and both are characterized by features that render them distinguishable from other surfaces in the alluvial record (e.g., pervasive oxidation, persistent and unusually thick lags, extraformational clasts). The lower discontinuity probably formed due to a fall in eustatic sea level and appears analogous to a marine sequence boundary. The upper discontinuity probably formed due to a tectonically induced increase in the rate of base-level rise and lacks characteristic features of a sequence boundary.

INTRODUCTION

Sequence stratigraphic analysis (in the sense of Posamentier et al., 1988; Van Wagoner et al., 1988, 1990) hinges upon the recognition of sequence-bounding unconformities (and correlative conformities) that develop in response to relative falls in sea level. In ideal cases, sequence analysis of marine and marginal marine records may yield high-resolution intra- and interbasinal correlations. Dividing the nonmarine record into genetic packages via sequence analysis is complicated, however, due in large part to the unresolved response of fluvial systems to fluctuating sea level. Changes in relative sea level may have dramatic effects in marine basins and in the general vicinity of shorelines, but how far upstream will a sea-level signal propagate and what will its inland expression be? Moreover, will through-going discontinuities in alluvial strata (regardless of origin) have features that distinguish them from other erosional and nondepositional surfaces of only local extent and significance? Questions along these lines have spurred several recent conceptual papers that focus on sequence stratigraphy in nonmarine depositional systems (Miall, 1991; Schumm, 1993; Wescott, 1993; Wright and Marriott, 1993; Shanley and McCabe, 1994). These papers underscore the difficulties of applying a stratigraphic model developed primarily for shelf and slope facies on passive margins to the fluvial record, and they stress the inherent complexity of fluvial depositional systems. This paper summarizes results of an empirical, outcrop-based investigation of two stratigraphic discontinuities located well inland of contemporaneous shorelines.

THROUGH-GOING DISCONTINUITIES IN THE TWO MEDICINE INTERVAL

The Campanian Two Medicine Formation of northwestern Montana comprises the proximal alluvial facies of two eastward-thinning clastic tongues in the Western Interior foreland basin. Nonmarine and nearshore marine equivalents within central Montana include the Eagle and Judith River Formations, which thin eastward into the fully marine Claggett and Bearpaw shales. Post-Cretaceous erosion over the Sweetgrass arch (Lorenz, 1982) has isolated the Two Medicine Formation from correlative deposits in central and eastern Montana (Figs. 1 and 2). The stratigraphic context of the two through-going discontinuities found in the Two Medicine record suggests that they probably mark the turnaround from regressive to transgressive phases within each wedge (Fig. 2).

The lower discontinuity crops out 75–80 m above the base of the Two Medicine Formation in the type area (Two Medicine River), capping a succession of nonmarine claystones, siltstones, and fine- to medium-grained sandstones (Fig. 3). The sheet sandstones that host the lower discontinuity are dominated by medium- to large-scale wedge-planar and trough cross-stratification, indicating a fluvial origin. This discontinuity can be tracked throughout the

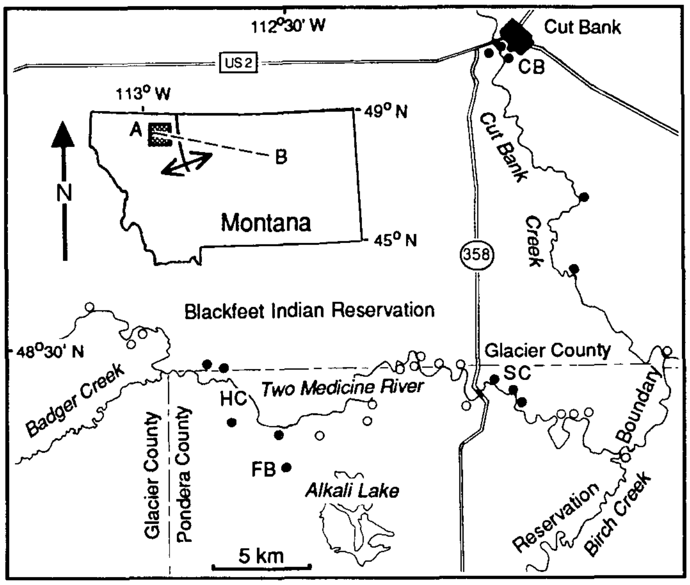

Figure 1. Two Medicine study area. Inset map of Montana shows position of Sweetgrass arch relative to study area and location of cross section A-B (Fig. 2). Open and solid circles denote measured sections in study area. Solid circles east of Route 358 represent sections intersecting lower discontinuity; solid circles west of Route 358 represent sections intersecting upper discontinuity. Stratigraphic sections illustrated in Figure 3: HC—Hagan's Crossing (composite); FB—Flag Butte; SC—Shield's Crossing (composite); CB—Cut Bank (composite).

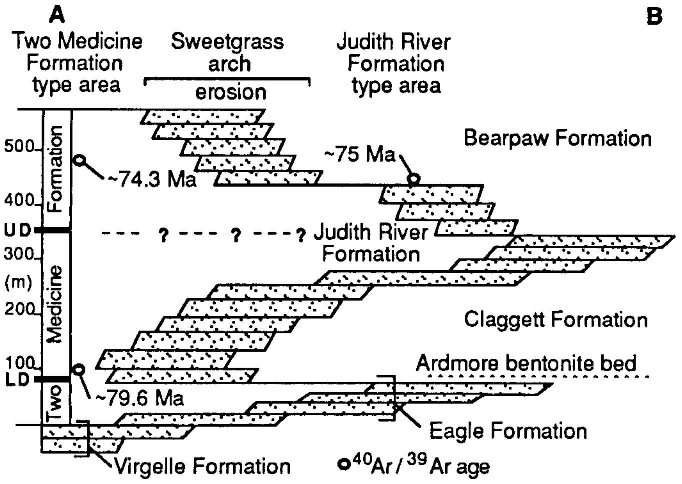

Figure 2. Schematic cross section of Two Medicine interval (see Fig. 1 for location). Nonmarine rocks are present to west of shallow-marine deposits (dot pattern), marine shales are present to east. Stratigraphic context of lower (LD) and upper (UD) discontinuities suggests that they probably mark turnaround from regressive to transgressive phases within each clastic wedge. Relative proportions of transgressive and regressive deposits are based upon ammonite zonation and strandline reconstructions of Gill and Cobban (1973) and ^{40}Ar/^{39}Ar ages from Rogers et al. (1993) and Rogers and C. C. Swisher (unpublished).

available outcrop belt, ~20 km along depositional strike and 5 km along depositional dip (Fig. 1). It varies in character along strike, ranging from a single erosive surface on the Two Medicine River and Cut Bank Creek to a 19-m-thick disconformable interval comprising several closely spaced erosive surfaces in a sandstone body exposed near Cut Bank (Fig. 3).

Although internal scour surfaces are present in sandstones throughout the Two Medicine Formation, the lower discontinuity is distinguished from all others by (1) several metres of erosional relief (up to 5 m); (2) a thick (up to 1 m) and relatively persistent lag of rounded green and gray clay pebbles, large subrounded to angular bank-collapse blocks, carbonized trees and plant fragments, and scattered fossil bone debris (other erosion surfaces are typified by thin [≤0.15 m], localized lags of small clay and caliche pebbles); and (3) pervasive oxidation, with lag deposits and immediately overlying and underlying sedimentary units 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-grained sandstone is developed locally across the lower discontinuity.

This lower discontinuity is overlain by ~30 m of carbonaceous claystones, siltstones, and lignites that contain a low-diversity, brackish-water molluscan fauna (the bivalves *Corbula* and *Corbicula*, a small whelk, and a naticid gastropod) along the Two Medicine River. Near Cut Bank, the lower discontinuity is overlain by shoreface sandstones characterized by swaley bedding, the marine trace fossils *Cylindrichnus* and *Terebellina*, and localized lags of oyster debris and flattened siderite pebbles (Fig. 3). These paralic and shallow-marine facies are interpreted as a transgressive systems tract. Up to seven thin bentonite beds are intercalated within this transgressive systems tract, one of which yielded an ^{40}Ar/^{39}Ar age of 79.6 ± 0.1 Ma (Rogers et al., 1993). This zone of bentonites probably correlates with the Ardmore bentonite (Spivey, 1940), a regionally extensive marker horizon consisting of several bentonite beds that crops out near the base of the Claggett Formation within the *Baculites obtusus* ammonite zone (Gill and Cobban, 1973), which has been K-Ar dated at 79.3 ± 0.8 Ma (Obradovich, 1988).

The upper discontinuity, which crops out ~270 m above the lower discontinuity, shows no clear evidence of erosional truncation but is marked instead by an abrupt shift from fluvial and flood-plain facies to lacustrine carbonate facies (Fig. 3). Deposits below the upper discontinuity consist of trough cross-bedded and ripple-laminated fluvial sandstones and paleosols characterized by small root traces (2–4 mm in diameter), red and purple hues, slickensides, and abundant caliche. At the top of this interval at Flag Butte (see Fig. 1) is a green, fine- to coarse-grained fluvial sandstone with a basal lag of clay and caliche pebbles, bone debris, and extraformational metamorphic clasts (Fig. 3). Another polymictic deposit of rounded clay, carbonate, sandstone, and bone pebbles caps a sandstone immediately beneath the upper discontinuity on the south side of the Two Medicine River, ~1 km north of Flag Butte. A conglomeratic lag containing quartzite pebbles is also present in a thin, coarse-grained sandstone sheet near the top of the lacustrine carbonate interval on the north side of the Two Medicine River, ~6 km north of Flag Butte. These lags preserve the only known concentrations of extraformational clasts in the Two Medicine type area (personal observation; Lorenz, 1981), and the sandstone bodies hosting the lags are anomalously coarse grained for Two Medicine deposits.

The ~15-m-thick carbonate-rich interval that overlies the upper discontinuity can be traced laterally throughout available exposure in badlands of the Two Medicine River drainage (Fig. 1), and like the associated extraformational clasts is unique within the ~560 m Two Medicine section exposed in the type area. The lower two-thirds of this deposit, which is interpreted as a shallow ephemeral lake, consists of gray, thin-bedded carbonate intercalated with darker gray and gray-green noncarbonate shale. The carbonate facies consists of micrite with small subvertical root traces, scattered quartz grains and clay granules, and rare calcite vugs and chert blebs or stringers. Siliciclastic lacustrine facies compose the upper one-third of the deposit, where interbedded siltstone and very fine grained sandstone beds characterized by burrow traces and ripple stratification cap the interval. The upper discontinuity also marks a change in the sandstone/mudstone ratio of fluvial facies, from ~0.65 below the upper discontinuity to ~0.33 above the lacustrine interval (personal observation; Lorenz, 1981).

EUSTATIC VS. TECTONIC ORIGINS

Theoretical models (e.g., Jordan and Flemings, 1991) postulate that eustatic sea-level falls are unlikely to produce subaerial unconformities (sequence boundaries?) in proximal regions of a foreland basin, where thrust-driven subsidence is greatest. Such surfaces are considered more likely to develop in more distal reaches, associated with the peripheral bulge. Tectonically produced surfaces are also possible in a foreland basin, but unconformities of tectonic origin should be out of phase; i.e., proximal unconformities formed during periods of tectonic quiescence and distal unconformities formed during episodes of tectonic loading and peripheral bulge reactivation. Models suggest that differentiating eustatic and tectonic signals requires good independent control on chronostratigraphy and independent evidence of tectonic uplift and sedimentation.

Physical stratigraphic and geochronometric evidence indicate that the lower discontinuity correlates with a widespread unconformity developed in distal parts of the Western Interior basin. This unconformity is embedded within marine deposits of the Niobrara and Pierre Formations and is overlain by the Ardmore bentonite (DeGraw, 1975; Shurr and Reiskind, 1984; Weimer, 1984; Van Wagoner et al., 1990). Incised drainages mark the unconformity in North Dakota, South Dakota, and Nebraska (DeGraw, 1975; Shurr and Reiskind, 1984). A regional (western interior) or possibly global fall in sea level at approximately 80 Ma has been proposed as the probable cause of subaerial exposure and regional truncation (Shurr and Reiskind, 1984; Van Wagoner et al., 1990). Given that the lower

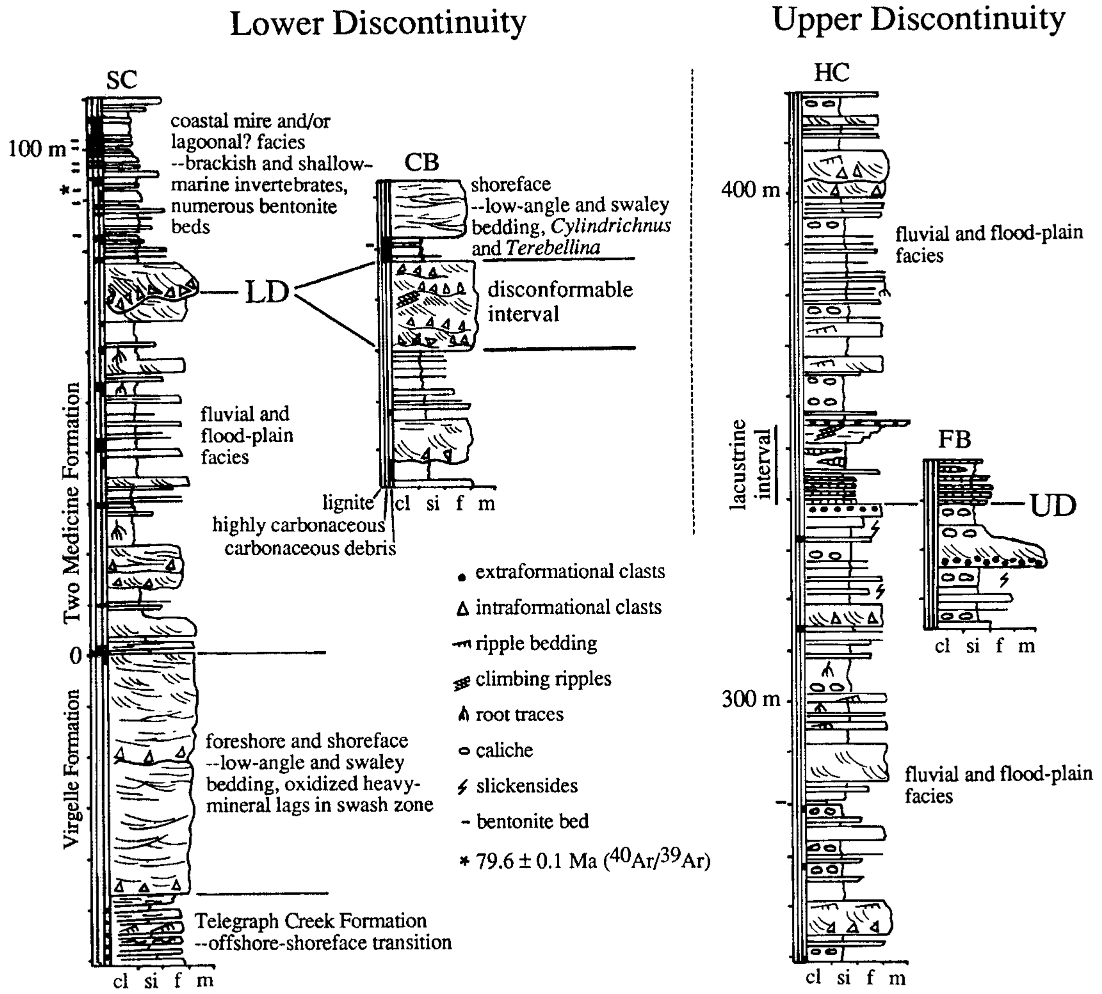

Figure 3. Graphic stratigraphic logs measured through lower and upper discontinuities (see Fig. 1 for localities). At Shield's Crossing (SC) on Two Medicine River, lower discontinuity (LD) is single erosive disconformity characterized by several metres of relief, oxidation, persistent intraclast lag, and local increase in grain size. Near town of Cut Bank (CB), LD is disconformable interval comprising several lag-draped, oxidized erosion surfaces in thick sandstone body. Paralic and/or shallow-marine facies overlie LD at both localities, indicating relative rise in base level. In vicinity of Hagan's Crossing (HC) and at Flag Butte (FB), upper discontinuity (UD) is marked by abrupt shift to lacustrine carbonate facies, change in sandstone/mudstone ratio of fluvial facies, and associated extraformational clasts. Grain size: cl—claystone; si—siltstone; f—fine sandstone; m—medium sandstone.

discontinuity probably formed approximately in phase with maximum regression, it appears that Two Medicine streams responded to this sea-level fall at least 125 km inland of contemporaneous shorelines (based on strandline reconstructions of Gill and Cobban, 1973). The response, however, was not widespread erosion and the development of incised valleys such as seen near marine shorelines, but instead a more subtle change; the broad, low-sinuosity channel deposits hosting the lower discontinuity exhibit only moderate erosional relief due to stream rejuvenation.

In contrast, several lines of evidence suggest a tectonic component in the generation of the upper discontinuity, which is located at least 300 km inland of coeval shorelines (Gill and Cobban, 1973). Aside from being consistent with the inferred timing of regional Cordilleran tectonism (Cant and Stockmal, 1989), the upper discontinuity is associated with a unique interval of extraformational clasts in the proximal record, suggesting possible rejuvenation of source terranes in the thrust belt to the west. Furthermore, the shift to lacustrine and finer grained fluvial facies across the upper discontinuity is consistent with thrust loading and subsidence of the foreland basin according to Blair and Bilodeau (1988) and Heller et al. (1988). These studies suggest that fine-grained deposits fill a foreland basin during episodes of thrust-load emplacement except in the basin's most proximal reaches; coarser deposits are distributed across the foreland basin during a later postorogenic phase. If the upper discontinuity does record thrusting in the orogen, then it appears that the syntectonic sedimentary response was both a shift to fine-grained sedimentation (e.g., Blair and Bilodeau, 1988; Heller et al., 1988) and gravel progradation (e.g., Burbank et al., 1988). Considering the localized and thin nature of the clast-bearing deposits, it is possible that the upper discontinuity formed in proximal reaches of the foreland basin that were characterized by rapid subsidence and fine-grained sedimentation, and that were also close enough to the thrust front to receive occasional influxes of gravel. Alternatively, the upper discontinuity may record a more complex tectonic or paleoclimatic event that altered the nature of the source area or the proximal basin.

IMPLICATIONS FOR SEQUENCE ANALYSIS

In the particular case of the Two Medicine interval, direct physical linkage to established marine sequence boundaries cannot be accomplished for either the lower or the upper discontinuity because of erosion over the Sweetgrass arch (Figs. 1 and 2). Whether the lower and upper discontinuities are analogous to marine sequence boundaries remains an important consideration, however, especially in the light of recent studies questioning the feasibility of sequence stratigraphy in both nonmarine and tectonically active settings (e.g., Walker, 1990; Martinsen et al., 1993) and the current shortage of published recognition criteria for sequence-bounding surfaces or intervals developed in alluvial facies.

The lower discontinuity largely conforms to the standard definition of a sequence boundary (see Table 1), including probable origin by eustatic fall. The lower discontinuity shows evidence of subaerial exposure (oxidation), erosion, and an upsection change in facies tracts (Fig. 3) suggestive of a change in parasequence stacking

TABLE 1. COMPARISON OF LOWER AND UPPER DISCONTINUITIES WITH SEQUENCE BOUNDARY RECOGNITION CRITERIA

	LD	UD
Type 1 sequence boundary		
Subaerial exposure	Yes	No
Subaerial erosion	Yes	No
Stream rejuvenation	Yes	No
Vertical change in parasequence stacking patterns	Yes	?
Basinward shift in facies	?	?
Downward shift in coastal onlap	?	?
Onlap of overlying strata	?	?
Type 2 sequence boundary		
Subaerial exposure (minor subaerial truncation)	Yes	No
Vertical change in parasequence stacking patterns	Yes	?
Downward shift in coastal onlap	?	?
Onlap of overlying strata	?	?

Note: Criteria are those of Van Wagoner et al. (1988, 1990). Criteria relating to stratal geometry are difficult to evaluate with limited outcrop, and a change in parasequence stacking patterns is impossible to demonstrate in upland alluvial facies devoid of marine flooding surfaces. LD-lower discontinuity; UD-upper discontinuity.

pattern. The lower discontinuity is not, however, characterized by a basinward shift in facies, although this criterion may be virtually impossible to demonstrate when fluvial facies are juxtaposed in inland settings (but see Shanley and McCabe, 1991). The upper discontinuity, although also a reasonable candidate for a sequence-bounding surface because of its probable position at the end of a regressive phase (Fig. 2), deviates from the traditional definition of a sequence boundary in that it presumably reflects a regional increase in the rate of base-level rise, rather than a fall. Moreover, the upper discontinuity does not show clear evidence of subaerial erosion, prolonged hiatus, or a basinward shift in facies, although it does mark a major reorganization of depositional systems.

This study illustrates the potential for identifying and correlating through-going discontinuities in fully nonmarine foreland-basin strata and also provides insight on the stratigraphic expression of eustatically and tectonically generated discontinuities far inland of contemporaneous shorelines. The two discontinuities described here are important bounding surfaces that provide a means of subdividing the notoriously difficult nonmarine record into genetic packages that are likely related to major fluctuations in relative sea level.

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