

ARTICLES

Associations of Vertebrate Skeletal Concentrations and Discontinuity Surfaces in Terrestrial and Shallow Marine Records: A Test in the Cretaceous of Montana

Raymond R. Rogers and Susan M. Kidwell¹

*Department of Geology, Macalester College, 1600 Grand Avenue, St. Paul, Minnesota 55105, U.S.A.
(e-mail: rogers@macalester.edu)*

ABSTRACT

Although lags of bones and teeth are commonly cited criteria for marine unconformities, the consistency of the association of vertebrate fossils and discontinuity surfaces, as well as the taphonomic (postmortem) controls on this relationship, are poorly understood. A field test across fluvial, paralic, and shallow marine facies in the Campanian Two Medicine and Judith River formations of Montana indicates that the distribution of vertebrate skeletal concentrations is poorly correlated with the inferred durations of erosional and omission hiatuses. Instead, vertebrate concentrations associated with discontinuities of all durations tend to be patchy and closely track the abundance of fossil material in underlying and lateral facies. Based on the analysis of 83 measured sections, we found first that erosional bases of channels and minor scours within channels yield vertebrate lags; tidally influenced fluvial deposits are more productive than are "upland" fluvial deposits. Second, erosional shoreface ravinements and their correlative transgressive marine flooding surfaces (fourth-order sequence boundaries) have well-developed vertebrate lags only along segments that cut across older shoreface deposits. Third, a nonerosional, widely traceable discontinuity, which is interpreted as the nonmarine extension of a 75.4-Ma third-order transgressive surface, is completely lacking in vertebrate concentrations. Despite being unfossiliferous itself, this discontinuity does mark a regional change in the richness of the vertebrate fossil record, with overlying beds characterized by a much greater abundance of skeletal material. Fourth, a laterally extensive set of erosional surfaces, embedded within multistory fluvial sandstone sheets, is the nonmarine extension of an 80-Ma third-order sequence boundary in the marine basin and lacks vertebrate concentrations. The strong dependence of vertebrate lag development on preexisting local sources of skeletal material rather than on the magnitude of the erosional vacuity or the duration of the hiatus contrasts with skeletal concentrations of invertebrates in marine successions, where exhumation is generally much less important than the production of new elements during the hiatus. These findings provide a guide to prospecting productive fossil horizons in terrestrial records and underscore fundamental differences in the ways in which bioclastic material accumulates in terrestrial and shallow marine settings, the qualities of paleobiologic data derived from such concentrations, and the relative reliabilities of skeletal material as cues to stratigraphically significant discontinuities.

Introduction

Lags of bones and teeth are classic criteria for recognizing marine unconformities (e.g., Krumbein 1942), but little attention has been focused either on determining how systematic this relationship is in marine or terrestrial settings or on the relation-

ship between vertebrate fossils and discontinuity surfaces in general. For example, although vertebrate hardparts should be durable to the rigors of reworking, not all unconformities are mantled by such debris and, conversely, not all vertebrate concentrations mark significant hiatuses. How consistently are widespread erosional unconformities accompanied by relative concentrations of vertebrate skeletal material? Does the taphonomic signature (postmortem features) of these concentrations differ significantly from those associated with ero-

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¹Department of Geophysical Sciences, University of Chicago, 5734 South Ellis Avenue, Chicago, Illinois 60637, U.S.A.; e-mail: skidwell@midway.uchicago.edu.

sional and omissional hiatuses of shorter duration and extent? In general, how strong an influence do patterns of physical sedimentation—both across facies tracts and through stratigraphic cycles—exert on the distribution and taphonomy of vertebrate fossils?

Empirical data from the marine stratigraphic record demonstrate a strong association between benthic macroinvertebrate concentrations and discontinuity surfaces of many types, as well as congruence between taphonomic attributes and the inferred duration of the associated hiatus (Kidwell 1991, 1993*a*, 1993*b*; Brett and Baird 1993; Brett 1995; Garcia and Dromart 1997; Naish and Kamp 1997; Abbott 1998; Gillespie et al. 1998; Kondo et al. 1998). It is thus reasonable to suspect that physical patterns of sedimentation, specifically lateral and temporal variation in erosion, sedimentary omission, and deposition, might exert a similarly strong influence on the distribution and quality of vertebrate fossil assemblages in both marine and terrestrial systems. Aepler and Reif (1971), Reif (1982), and Kidwell (1989) have published brief stratigraphic characterizations of some marine bone beds, and Behrensmeyer (1987, 1988) and Rogers (1993) have described how terrestrial bone assemblages vary with subsidence-related shifts in alluvial architecture. Still, the distribution and quality of vertebrate fossil assemblages in relation to physical patterns of sedimentation remain poorly understood.

Here we present the results of a field test across a transect of fluvial, paralic, and nearshore marine environments in the Campanian Two Medicine and Judith River formations of Montana. The focus is on links between relative concentrations of skeletal debris and the discontinuity surfaces essential to sequence analysis. This record is especially advantageous both because it is richly fossiliferous, thus giving maximum likelihood of finding associations, and because an independent evaluation of discontinuity surfaces and their potential for sequence stratigraphic analysis has already been completed (Rogers 1994, 1998).

Expected Patterns in the Distribution of Vertebrate Fossils

In terms of the concentration and preservation of vertebrate or invertebrate hardparts, intervals of nondeposition and erosion are double-edged swords (Kidwell 1986). On the positive side, nondepositional hiatuses create conditions of low sedimentary dilution for the "rain" of skeletal material produced by contemporaneous vertebrate populations

and, thus, should foster relative concentrations of vertebrate material by purely passive means (e.g., along a soil surface during an interval of slow landscape aggradation). The longer the period of these conditions, the greater the absolute quantity of hardparts supplied and, thus, the richer or laterally more continuous the ultimate skeletal concentration may be. Erosion (negative net sedimentation) augments the effect by preferentially removing sedimentary matrix, leaving behind a true hydraulic lag of larger and denser skeletal material exhumed from previous deposits. Theoretically, the more deeply erosion cuts into older strata, the greater the volume of previously deposited vertebrate material that can be intersected and concentrated into lag form.

On the negative side, conditions of low or zero net sedimentation increase the period that any cohort of skeletal material is subject to destructive postmortem processes operating at or near the depositional interface. In terrestrial systems, these processes include trampling, scavenging, weathering (UV exposure, oxidation, fungal and other microbial attack, freeze-thaw), detrimental soil processes, and exhumation-burial cycles (e.g., via bedform migration within channels; Behrensmeyer 1991). Erosional downcutting during the hiatus may simply aggravate already difficult conditions for preservation. Erosion could potentially increase the local supply of hardparts to the discontinuity surface through exhumation, but any cohort of skeletal material will probably undergo a larger number of reworking events than it would during purely aggradational conditions. Moreover, erosion itself represents an additional agent of skeletal breakdown and transport out of the local system, and exhumed skeletal material may be less durable rather than equally or more durable than newly produced hardparts, so that exhumation has little net positive effect on hardpart supply. It is thus possible that taphonomic processes may be more severe during hiatuses (or at least during long hiatuses or during erosional rather than purely omissional hiatuses) than during "background" times, so that any advantages of lowered dilution and/or input of exhumed hardparts may be outweighed by taphonomic culling.

If newly produced hardparts are relatively durable under prevailing climatic and edaphic conditions, then skeletal material from local mortality may accrue to appreciable quantities during phases of nondeposition or very slow net sedimentation (e.g., on stable soil surfaces or in laterally accreting channel belts held at grade). The ultimate assemblage that mantles the discontinuity would be time

averaged to a greater or lesser degree, depending on the duration of the hiatus, but would date to the period of the hiatus itself (i.e., be a true hiatal concentration, *sensu* Kidwell 1991). Local pockets might preserve census assemblages (e.g., mass mortalities from drowning or other ecologically brief mortality events), but in general the material will be time averaged. The longer the hiatus, the greater the opportunity for ecologically heterogeneous assemblages (i.e., the mixing of noncontemporaneous communities or community states rather than simply the mixing of generations from single communities).

An alternative scenario, which is not mutually exclusive with the first, is that the bulk of skeletal material is exhumed from underlying and lateral facies during incision, planation, or both. Exhumed material might already be in a prefossilized state (permineralized), which would presumably increase its durability. Skeletal material would be entirely older than the hiatal surface. The more severe the downcutting, the greater the age differential between material in the lag and the hiatus that concentrated it, and the lower the relevance of its taxonomic composition to paleoenvironmental conditions during the hiatus. Taphonomic artifacts of exhumation might include abrasion and rounding (although this modification feature is not diagnostic), polish (A. K. Behrensmeyer, pers. comm.), angular as opposed to spiral breakage patterns (Morlan 1984), and environmentally mixed assemblages. Sedimentological features consistent with exhumation include stratigraphic evidence of incision and exotic sedimentary matrices adhering to exhumed skeletal debris.

The ultimate nature of the vertebrate fossil record, and in particular the association of vertebrate skeletal material with discontinuity surfaces, depends on the relative importance of these two contradictory aspects of low to negative sedimentation—low dilution and the exhumation of additional supply on the one side and prolonged exposure and perhaps elevated rates of hardpart destruction on the other. The accumulation of bones and teeth in nonmarine conditions may follow several different scenarios, depending on the relative importance of hardpart sources (hiatal production vs. exhumed debris) and the durabilities of hardparts.

Stratigraphic and Taphonomic Framework

The Campanian Two Medicine and Judith River formations are widely exposed across much of northwestern and north-central Montana and are

characterized by the intertonguing of marine and nonmarine strata at several scales, ranging from decimeter-scale transgressive-regressive cycles to third-order depositional sequences (Rogers 1998; fig. 1). The ~545-m-thick Two Medicine Formation accumulated during two major cycles of the Western Interior Seaway (R7-T8 and R8-T9 of Kauffman 1977) and comprises the proximal alluvial facies of two eastward-thinning clastic tongues. It consists predominantly of pedogenically modified gray and gray-green silty claystone and siltstone with widely spaced beds of fine- to medium-grained sandstone. At least 19 discrete bentonite beds are intercalated in the type area of the Two Medicine Formation (Rogers et al. 1993). The ~180-m-thick Judith River Formation comprises the distal reaches of a single eastward-thinning clastic tongue of alluvial, coastal plain and shallow marine sediments that accumulated during regression of the Claggett Sea (R8) and subsequent transgression of the Bearpaw Sea (T9). It is a heterolithic composite of gray and tan silty claystones, siltstones, and fine- to medium-grained sandstones of fluvial, tidal, and shallow marine origin, with subordinate beds of dark gray to black lignite and tan to orange ironstone. Several bentonite beds are also intercalated within the Judith River section in the type area (Rogers 1995; Rogers and Swisher 1996). The Judith River Formation correlates to the west across the erosional Sweetgrass arch with nonmarine deposits of the middle and upper Two Medicine Formation and is bounded above and below by marine shales of the Bearpaw and Claggett formations (fig. 1).

Two major stratigraphic discontinuities subdivide the largely nonmarine Two Medicine–Judith River record into regressive and transgressive depositional systems (fig. 1). The lower of these two discontinuities, SB1, consists of a laterally extensive set of amalgamating erosional surfaces embedded within multistory fluvial sandstone sheets and is considered to be the nonmarine (upstream) extension of a type 1 sequence boundary (Rogers 1994, 1998). It correlates with a regionally traceable marine disconformity embedded within the more distal Eagle Formation (Hanson and Little 1989) and other marine units and formed in response to a dramatic fall in relative sea level that occurred in the Western Interior Basin at approximately 80 Ma (DeGraw 1975; Shurr and Reiskind 1984; Van Wagoner et al. 1990). Shallow marine and paralic strata immediately overlying the SB1 sequence boundary accumulated during the subsequent transgression of the Claggett Sea (T8). These facies preserve a set of at least nine bentonite horizons that correlate stratigraphically and radioisotopically with the ma-

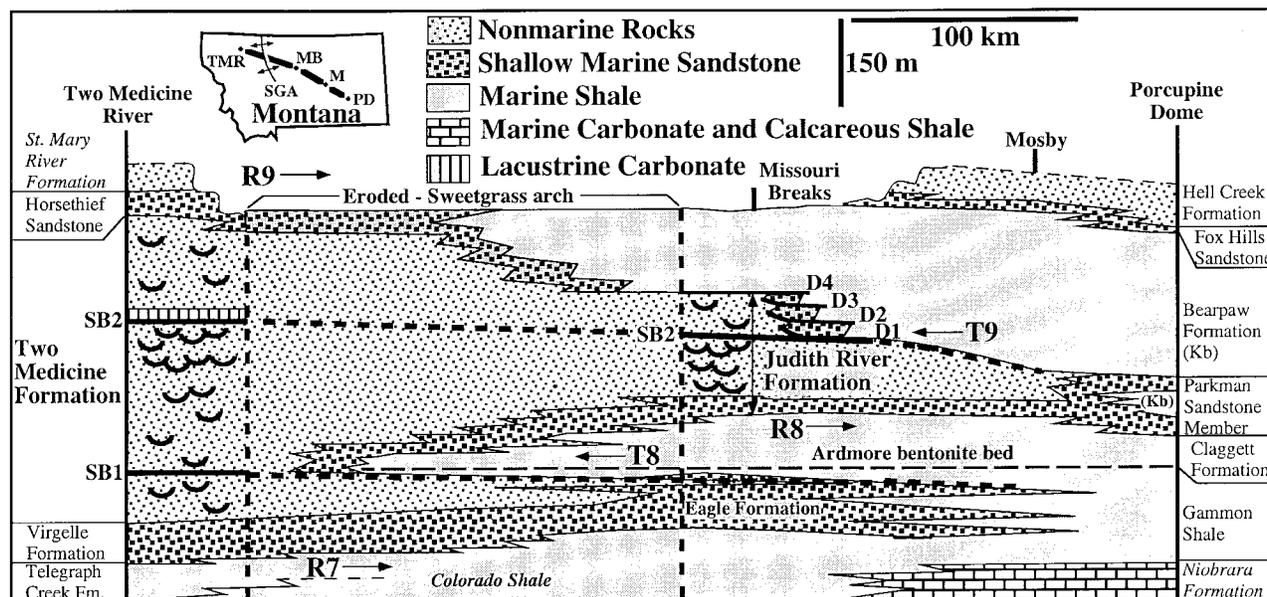


Figure 1. Schematic cross section of the Two Medicine–Judith River study interval restored across the Sweetgrass arch (SGA). Discontinuities referred to in the text (SB1, SB2, D1, D2, D3, D4) are indicated, as are the major third-order transgressive and regressive cycles of the Western Interior Seaway (Kauffman 1977). Changes in the density and stacking of fluvial channel sandstones across the study interval are schematically portrayed by the spacing of U-shaped channel symbols. All units, aside from those italicized, are included within the Montana Group. Modified from Gill and Cobban (1973).

rine Ardmore bentonite bed. Radioisotopic dating of two bentonites and a crystal tuff from this interval has yielded dates of 79.6 ± 0.1 Ma, 79.8 ± 0.1 Ma, and 80.0 ± 0.1 Ma, respectively (Rogers et al. 1993). The shift from transgressive (T8) to regressive (R8) phases in the Two Medicine record is interpreted to coincide with an observed shift to facies more typical of inland fluvial and floodplain settings. During the early stages of R8, the alluvial record of the Two Medicine Formation is dominated by fine-grained interchannel facies. The channel/floodplain ratio increases upsection within the nonmarine equivalent of the highstand depositional system, and concurrent with this increase in sandstone abundance is a shift to more amalgamated sheet geometries (fig. 1). The late highstand depositional system in the more distal Judith River Formation shows a comparable record of facies architecture, with the alluvial record dominated by relatively thick sandstone bodies with sheet geometries signifying a decrease in the rate of addition of accommodation (Rogers 1998).

The upper discontinuity, SB2, is a nonerosional, widely traceable discontinuity that is marked by the abrupt appearance of lacustrine-carbonate de-

posits in upland areas (Two Medicine) and by a sharp and regionally traceable decrease in channel density in the coastal plain (Judith River). It rests only a few meters beneath a bentonite bed dated at 75.4 Ma in the Judith River Formation type area (Rogers and Swisher 1996) and is interpreted to correlate with the widespread addition of accommodation that coincided with the turnaround from the Claggett regression (R8) to the Bearpaw transgression (T9) in the marine basin (fig. 1). In the eastern part of the Judith River Formation type area (fig. 1; Missouri Breaks), SB2 converges with a shoreface ravinement (D1 surface) at the base of three backstepping fourth-order sequences that accumulated during the Bearpaw transgression. Bounding surfaces of these fourth-order sequences (D1–D4 in fig. 1) are defined by facies juxtapositions indicative of abrupt deepening (flooding surfaces): the lower few meters of each sequence comprises a deepening-up interval, which is why these packages are not categorized as parasequences (Rogers 1995). Where shoreface facies are superimposed immediately on these flooding surfaces, there is clear evidence for erosion. Post-Cretaceous erosion over the Sweetgrass arch hinders our tracking of compara-

ble fourth-order (or higher order) transgressive-regressive cycles and their bounding surfaces to the west in strata above the D4 surface, although their presence would be predicted.

Both the Two Medicine and Judith River formations are richly fossiliferous and contain a variety of skeletal concentrations set in a background of dispersed skeletal material (Rogers 1993, 1995). These concentrations include dinosaur nests and nesting horizons (Horner and Makela 1979; Horner 1982, 1994), dinosaur bone beds dominated by large elements (Hooker 1987; Rogers 1990, 1995; Fiorillo 1991; Varricchio 1995), and diverse vertebrate microfossil localities (microsites) of both terrestrial and marine origin (Sahni 1972; Case 1978; Carrano et al. 1995; Rogers 1995). The vertebrate microsites, which typically consist of small physicochemically resistant elements such as teeth, scales, scutes, and compact bones (phalanges, vertebrae), are particularly abundant. Loosely to densely packed freshwater and marine shell beds crop out in the study interval as well (Stanton and Hatcher 1905; Sahni 1972; S. M. Kidwell and R. R. Rogers, unpub. data).

One of the interesting taphonomic features of the study interval is that vertebrate skeletal debris and invertebrate shell material commonly co-occur in both terrestrial and marine concentrations, contrary to the segregated patterns that are usually described from the fossil record. Another interesting taphonomic aspect is the gradient in the quality of vertebrate skeletal occurrences relative to proximal (Two Medicine) and distal (Judith River) positions in the clastic wedge. The proximal record is dominated by high-resolution assemblages that show minimal evidence of time averaging, such as mono- or paucispecific dinosaur bone beds and nest sites, whereas the distal record is dominated by vertebrate microsites with high probable levels of time averaging (Rogers 1993). Still another large-scale taphonomic pattern in the study interval is variation in the abundance of vertebrate skeletal material relative to third-order regressive-transgressive cycles. The vast majority of vertebrate skeletal material in the Two Medicine and Judith River formations occurs in the transgressive record, particularly in the nonmarine facies equivalents of the T9 marine cycle (Rogers 1995).

Taphonomic Signatures of Discontinuity Surfaces

To test for relationships between taphonomic signature and sedimentary hiatuses, stratigraphic surfaces need to be ranked for hiatal length, using independent physical stratigraphic criteria. In marine

records, Kidwell (1993b) ranked surfaces (from shortest to longest) as (1) bedding planes and bed-set boundaries; (2) parasequence boundaries (flooding surfaces; the stratigraphically lowest flooding surface within the transgressive systems tract is the transgressive surface *sensu stricto*); (3) transgressive ravinements (landward segment of flooding surface that includes an erosional vacuity created by migration of the shoreface); (4) midsequence starved intervals (omissional "surface of maximum transgression" or "maximum flooding surface"; this is the master downlap surface within the depositional cycle); and (5) sequence boundaries marked by subaerial erosion (third order). Composites of the surfaces are possible, for example, transgressive ravinements that converge with sequence boundaries over part of their extent. This ranking assumes a general correspondence between the lateral extent of the physical discontinuity surface and the temporal duration of the hiatus (at least in settings of relatively broad diastrophism) and reflects the hierarchical reasoning of Campbell (1967) and the sequence stratigraphic terminology of others (e.g., Van Wagoner et al. 1990; Mitchum and Van Wagoner 1991).

Hierarchical classifications of alluvial records have focused on sedimentary units rather than on the surfaces that separate them (e.g., Miall 1991, 1996), and the emphasis has largely been on finer-scale depositional units. To fill out the scale up to third-order sequences, we have used the same reasoning for channel-stacking and alluvial architecture as others (e.g., Allen 1978; Bridge and Leeder 1979; Shanley and McCabe 1991, 1994; Posamentier and Allen 1993; Wright and Marriott 1993; Gibling and Bird 1994; Miall 1996). A comparable but not precisely equivalent ranking of discontinuities for nonmarine foreland basins based on observations in the Campanian of Montana (Rogers 1994, 1998) would be (1) bedding plane and bed-set boundaries; (2) erosional bases and internal scours of single or multistory channels and paleosols developed locally within single overbank units; (3) fluvial erosion surfaces, bypass (transport) surfaces, and omission surfaces (including paleosols) that are more laterally extensive amalgamations within an alluvial succession or that lie between tracts with appreciable facies offset; (4) regionally extensive discontinuities or narrow stratigraphic intervals in which alluvial architecture (primarily channel type and spacing) indicates an abrupt increase in accommodation within the foreland basin, with a possible concurrent landward (toward uplifted source area) shift in facies, analogous to turnaround from low-stand to transgressive systems tracts in the marine

Table 1. Taphonomic Signatures of Discontinuity Surfaces in the Two Medicine and Judith River Formations

Stratigraphic discontinuities	Vertebrate	Invertebrate	Plant
Basal and internal scours of “upland” fluvial channels ($n = 114$; erosional; claystone, and caliche intraclasts)	Concentrations of skeletal debris generally rare, ~2.5% of channels surveyed preserve lag concentrations of skeletal debris, mixed faunal composition, variable preservational quality, mostly dense compact elements, some polished bone pebbles	<i>Unio</i> present but not common, preservational quality varies from shell hash to intact disarticulated and articulated valves, rotated out of life position	Rare carbonaceous wood fragments and phyto-debris, rare silicified wood
Basal and internal scours of tidally influenced fluvial channels ($n = 47$; erosional; claystone, and ironstone intraclasts)	Concentrations of skeletal debris relatively common, ~9% of channels surveyed preserve lag concentrations of skeletal debris, mixed faunal composition, variable preservational quality, mostly dense compact elements, abundant polished bone pebbles	<i>Unio</i> relatively common, abundant shell debris, disarticulated and articulated valves, typically rotated out of life position	Abundant carbonaceous wood fragments and phytodebris, rare silicified wood
Marine flooding surfaces (D1, D2, D3, D4): Shoreface on paralic ($n = 19$; erosional; claystone intraclasts)	Very rare bone pebbles, fragmented and abraded, poor preservational quality	3–35-cm-thick shell beds, oyster-dominated (<i>Gyrostrea</i>) with rare <i>Corbicula</i> and <i>Goniobasis</i> , pinch and swell laterally, widely scattered oyster valves, rare <i>Unio</i> fragments, leached debris, material varies from intact valves to fragments, disarticulated, oxidized	Coaly stringers, coaly rip-ups
Shoreface on shoreface ($n = 11$; erosional; burrow rip-ups, reworked concretions, chert pebbles, ironstone intraclasts)	Widely scattered bones and teeth interspersed with localized concentrations of shark teeth, fish bones, marine reptile bones, rare bones and teeth of terrestrial taxa (mammals, dinosaurs), high degree of fragmentation and abrasion, rounding	Rare fragmentary shell debris, white chalky preservation, partial and complete valves, rare gastropod steinkerns	None observed

Table 1. (Continued)

Stratigraphic discontinuities	Vertebrate	Invertebrate	Plant
Offshore on paralic ($n = 12$; no obvious erosion)	None observed	Rare shell beds, up to 20 cm thick, dense packing, predominantly oysters (<i>Gyrostrea</i>) with rare <i>Corbicula</i> and <i>Goniobasis</i> , variable preservational quality, intact and fragmentary valves	Coaly rip-ups
Offshore on shoreface ($n = 4$; no obvious erosion; ironstone and claystone pebbles)	None observed	Rare aragonitic shell fragments	None observed
Offshore on offshore ($n = 2$; no obvious erosion)	None observed	None observed	None observed
75.4-Ma transgressive surface (SB2; no obvious erosion):			
Proximal	None observed	None observed	None observed
Distal	None observed	None observed	None observed
80-Ma sequence boundary (SB1; erosional, abundant claystone and siltstone intraclasts):			
Proximal	Rare bone fragments, isolated elements	Rare gastropod steinkerns	Carbonaceous plant debris, logs
Distal	No data	No data	Carbonaceous plant debris, logs

Note. Observations are based on the analysis of 83 measured sections (Rogers 1995, 1998). Surfaces are ranked by inferred duration of hiatus. The n values reported in the stub column reflect the number of observations for a given type of discontinuity or facies juxtaposition (in the case of flooding surfaces).

realm (but not necessarily timed with such a change); (5) regionally extensive discontinuities or narrow stratigraphic intervals in which alluvial architecture indicates a shift to decreasing accommodation, analogous to turnaround from transgressive to highstand systems tract in the marine realm; and (6) regionally extensive erosion surfaces, either planed or incised, analogous to third-order sequence boundaries.

Several different types of stratigraphic discontinuities in the Two Medicine–Judith River record are described in table 1, with emphasis on facies associations and taphonomic characteristics. In this report, a vertebrate skeletal concentration (bone bed or vertebrate microsite) is defined as a deposit preserving at least 5% bones and/or teeth per unit volume (*sensu* Behrensmeyer 1999), with at least two or more individuals represented.

Minor Discontinuities Associated with Fluvial Channels. Channel sandstones within the Two Medicine and Judith River formations can be characterized as being either an “upland” type with purely fluvial characteristics or a “tidally influenced” type (table 1). Tidal indicators include inclined heterolithic stratification, carbon drapes on fore- and toesets (in some instances distinctly paired), and the presence of brackish and marine taxa (e.g., *Teredolites*, marine reptiles, sharks). Channel sandstones are interstratified with a variety of floodplain facies, including crevasse-splay deposits, diversely fossiliferous floodbasin pond/lake deposits (dissociated plant, mollusk, fish, aquatic vertebrate, and lesser quantities of terrestrial dinosaur and mammal material), coastal swamp deposits (lignite and coal beds), and sporadic bentonite beds and ironstone beds (see Rogers 1995 for more detailed facies descriptions). These floodplain facies show abundant evidence of pedogenesis.

Fluvial channels in both the Two Medicine and Judith River formations contain a multitude of minor scours and nondepositional bedding-plane-scale hiatal surfaces, in addition to the more significant erosional surfaces that define channel bases and individual stories (fig. 2). Skeletal debris is found on all of these types of surfaces throughout the Two Medicine–Judith River study interval but is more common in tidally influenced channels. Using our database of 83 measured sections, we found that, of the 114 “upland” channels surveyed (most of these were in the Two Medicine Formation), only ~2.5% yield appreciable concentrations of vertebrate skeletal elements. Tidally influenced fluvial deposits (most of these are in the Judith River Formation) are considerably more productive, with

~9% of the 47 channels surveyed yielding concentrated lags of vertebrate debris (table 1).

Lags of vertebrate debris from both “upland” and “tidal” channel types tend to be taxonomically diverse assemblages of elements, such as teeth, which are thoroughly dissociated and physico-chemically resistant, e.g., dinosaur, crocodile, champsosaur, mammal teeth; turtle shells; crocodile scutes; gar scales; and assorted small dense bones and bone fragments. The degree of fragmentation, abrasion, and weathering can vary widely. For example, fragile vertebrae with intact lateral processes are occasionally found in association with thoroughly rounded and highly polished bone pebbles. Carbonaceous plant debris and silicified wood, unionid and pisidiid bivalves, small high-spired gastropods, and rounded claystone and siderite pebbles are commonly found in association with fluvial concentrations of vertebrate debris (fig. 2).

Shoreface Ravinelements and Marine Flooding Surfaces. Four discontinuities, referred to here as D1, D2, D3, and D4, are surfaces of conspicuous deepening that cut through paralic and shallow marine facies of the Judith River Formation and mark the bases of small-scale (20–40 m thick), fourth-order transgressive-regressive cycles along the distal edge of the nonmarine clastic wedge (figs. 1, 3). Each of these discontinuities is a composite surface comprising both a fourth-order sequence boundary and its transgressive surface, which merges landward with a concave erosional ravinelement surface. This ravinelement marks the maximum incursion of the marine shoreface in that cycle. None of the fourth-order cycles can be distinguished among the paralic strata landward of the points where the ravinelement detaches from the sequence boundary *sensu stricto*. Coals are lenticular and unreliable as a means of cycle definition and tracking in this particular record. The surfaces we define as D1–D4 thus diverge from sequence boundaries in their proximal segments and are locally diachronous but, throughout their extent, record omission and some amount of shoreface erosion associated with marine flooding and thus have similar origins. We studied outcrop exposures of skeletal material across these surfaces and found that biogenic debris is present in low quantities in virtually all outcrops but that well-developed vertebrate lags are present only along segments that cut across older shoreface deposits.

The D1 discontinuity, which coincides over part of its extent with the 75.4-Ma discontinuity, is easily identified in well logs but is poorly exposed along the Missouri River. In the few localities where we could examine it, the surface juxtaposes

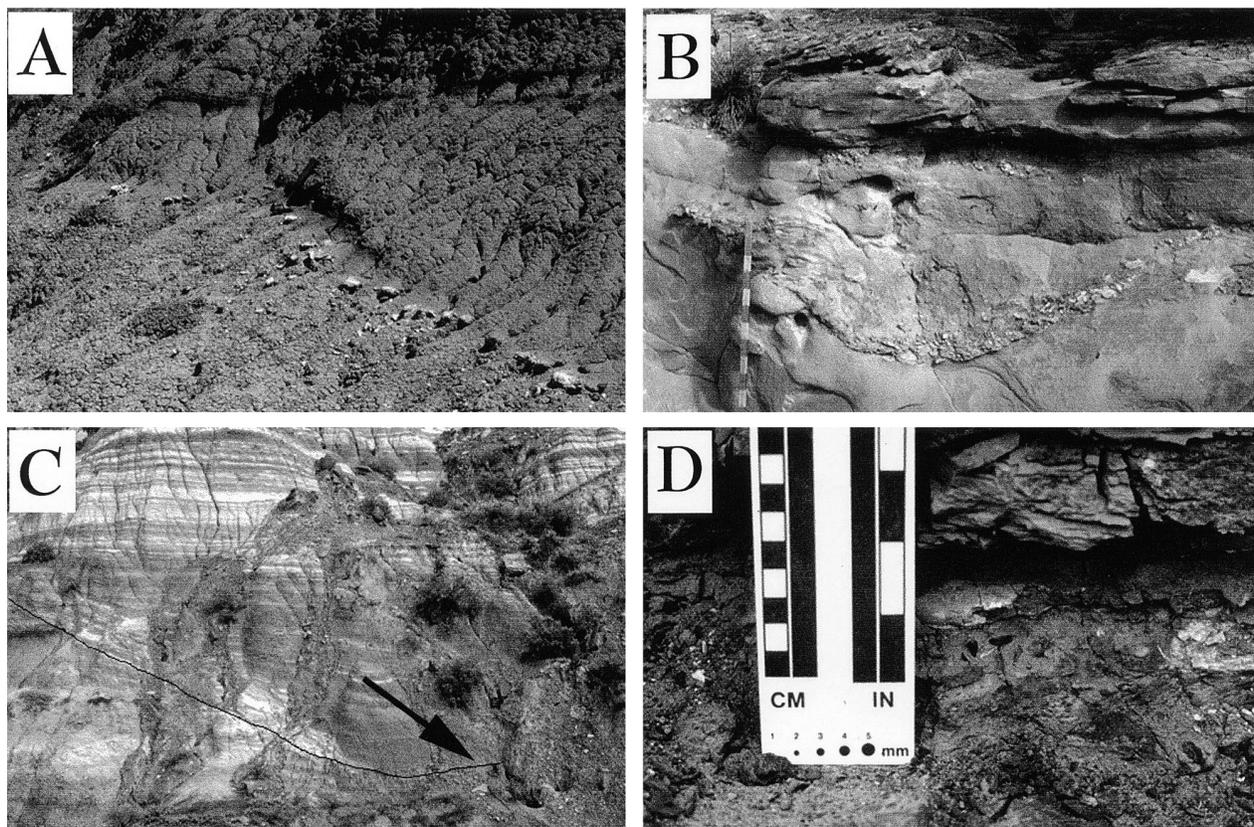


Figure 2. Outcrop photographs of fossiliferous fluvial channel deposits. *A*, Lag of *Unio* shell debris and bone draping basal disconformity of a tidally influenced channel (hammer is 30 cm long). *B*, Internal scour surface mantled by an intraclast lag of claystone and ironstone pebbles and disseminated vertebrate elements. *C*, View of tidally influenced channel deposit characterized by well-developed inclined heterolithic stratification and several meters of erosional relief. Channels in the study interval that show evidence of tidal influence are more likely to preserve lags of vertebrate skeletal material than are their “upland” counterparts. This presumably reflects the fossiliferous nature of surrounding source facies in coastal settings, which are reworked during downcutting or lateral migration of channels to produce lag concentrations. Arrow points to basal lag concentration illustrated in *D*. *D*, Basal lag includes disarticulated *Unio* valves interspersed with carbonaceous debris and compact vertebrate elements (teeth, scales, phalanges, vertebrae), some of which exhibit polish.

shoreface strata on lignite, coal, or, more rarely, carbonaceous claystone. Dispersed coaly rip-ups mantle the surface along with widely scattered shells and shell fragments (predominantly oyster valves). Based on admittedly scant exposures, there is no appreciable vertebrate material associated with this surface (table 1).

The well-exposed D2 and D3 discontinuity surfaces have been traced for several tens of square kilometers in eastern portions of the Judith River Formation type area (figs. 3, 4). Along the seaward segment of the D2 surface, offshore clay shales of the Bearpaw Formation rest on paralic beds of lignite or coal. With this facies association, the surface

is relatively unfossiliferous, although scattered coal rip-ups and very rare isolated shell fragments are present (table 1). Along western (more onshore) segments of the D2 surface, where sandy shoreface strata rest on paralic facies, bioclastic debris is dispersed but more frequently encountered. Bioclasts include highly abraded and weathered bone pebbles (presumably dinosaur); isolated, weathered, and typically fragmentary valves of the freshwater clam *Unio*; and small to large rip-ups of lignite. Thin stringers of chalky shell hash crop out locally a few centimeters above the D2 surface.

The D3 flooding surface is also overlain by increasingly shallower water facies to the west. The

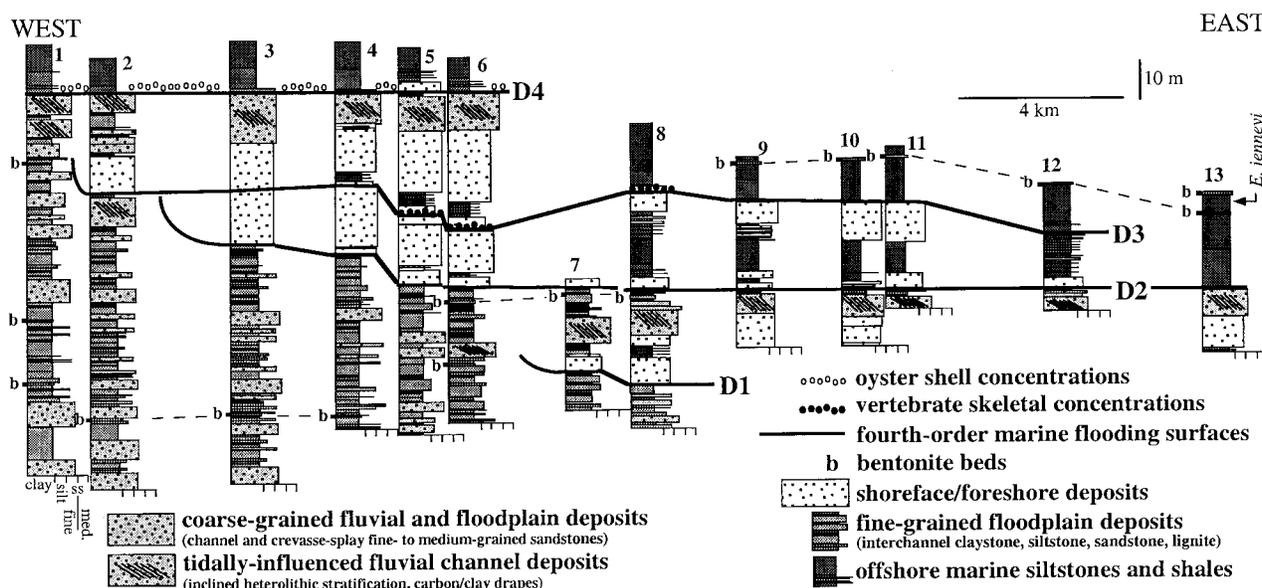


Figure 3. Dip-parallel cross section in eastern portion of Judith River Formation type area showing the four discontinuity surfaces (*D1*, *D2*, *D3*, *D4*) that bound three fourth-order transgressive-regressive cycles. Each discontinuity is a composite surface comprising both a fourth-order sequence boundary and its transgressive surface, which merges landward with a concave, erosional ravinement surface. Biogenic debris is present in low quantities in virtually all outcrops of these surfaces, but well-developed vertebrate lags are present only along segments of the *D3* surface that cut across older shoreface deposits (note considerable erosional relief where the shoreface is juxtaposed). The *D3* discontinuity is in general extremely fossiliferous with regard to vertebrate skeletal hardparts; fossil debris is strewn as a thin pavement where the *D3* surface is planar, and rich concentrations occur within local erosional scours.

D3 surface is extremely fossiliferous and is richest where shoreface strata cut across older shoreface deposits (figs. 3, 4). In these segments, fossil debris is strewn as a thin pavement where the *D3* surface is planar; however, rich concentrations occur within small erosional scours (0.5–2 m; fig. 4). These lags are 1–5-cm thick on average, and in some localities, two discrete lag stringers spaced 10–15-cm apart are present. Wet-sieving of matrix from a single scour can yield thousands of shark teeth and fish elements, along with marine reptiles, rare terrestrial vertebrates, siderite and chert pebbles, and reworked cemented burrow-fills (primarily simple tubes; see Case 1978 for a description of selachian fossils from the *D3* surface in the vicinity of Suction Creek).

The skeletal composition of *D3* lags is overwhelmingly dominated by vertebrates: molluscan shell debris is minor, and there are no recorded plant occurrences. Vertebrate debris exhibits variable states of preservation, including rare elements in pristine condition, but is dominated by taxonomically unidentifiable bone pebbles. Most elements exhibit some degree of surficial degradation, with rounding and abrasion most common. The

composition of bioclasts varies from onshore to offshore, probably due to the variable bioclast content of underlying facies that were reworked during erosive transgression of the shoreface (cf. Fischer 1961; Swift 1968; Liu and Gastaldo 1992). In the vicinity of sections 4–6 in figure 3, vertebrate debris overwhelmingly dominates bioclasts, both in lags and in isolated occurrences; concentrations of this type can also be traced for ~17 km along depositional strike (N-S) from the Missouri River outcrops shown in figure 4. Approximately 5 km to the east, in the vicinity of section 8, the *D3* lag contains far less vertebrate debris but does contain a diverse array of cemented burrow-fills (shallow-marine *Thalassinoides* and *Rosselia*, among others) along with rare small nautiloids.

The widely exposed *D4* surface is a transgressive overstep that can be traced throughout most of the Judith River Formation type area (Rogers 1995). This surface is extremely fossiliferous, as recognized since Stanton and Hatcher's (1905) original report on the Judith River Formation. It is characterized by extensive oyster-dominated shell beds rather than by vertebrate-dominated lags (fig. 4). Across most of its outcrop belt, the *D4* surface is

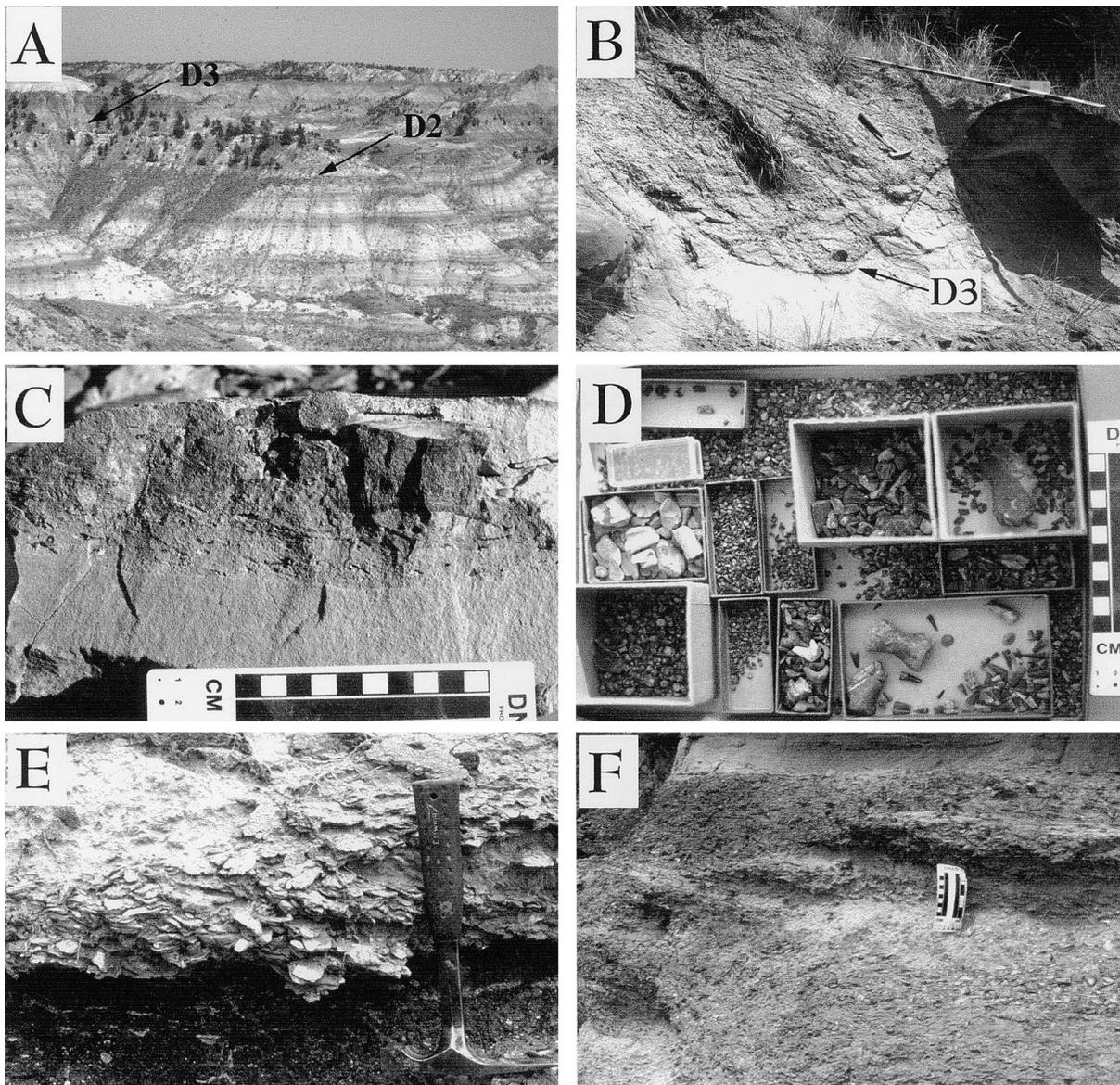


Figure 4. *A*, View of D2 and D3 discontinuity surfaces along Woodhawk Creek drainage, on the right bank of the Missouri River, in the Judith River Formation type area. Shoreface strata (marked by trees) are sharply juxtaposed over coastal plain strata. The D3 discontinuity is embedded within shoreface strata, and the D3 arrow points to the approximate position in figure 4B–4D. Based on regional thickness data, the position of D1 would be approximately at the base of the exposures. *B*, Local scour marking the D3 erosional discontinuity. This erosional surface has been cut between two large ironstone concretions that were already indurated on the Campanian sea floor when transgression ensued. The base of the scour preserves a concentration of shark teeth, marine reptile and fish bones (the large bone immediately adjacent to the D3 arrow is a plesiosaur limb element), rare shell debris, and cemented burrow casts. *C*, Close-up of the D3 discontinuity. In the absence of skeletal debris, this sand-on-sand surface would be virtually impossible to identify. The presence of a skeletal lag makes it possible to track this surface over an area of approximately 100 km² in the Judith River Formation type area. *D*, Representative sample of vertebrate debris screen washed from the D3 locality figured in figure 4B. Wet-sieving of matrix from a single scour can yield thousands of shark teeth and fish elements, along with marine reptiles, rare terrestrial vertebrates, siderite and chert pebbles, and reworked cemented burrow fills (primarily simple tubes). *E*, Outcrop view of the D4 surface. At this particular locality, a ~20-cm-thick oyster-dominated shell bed is sharply juxtaposed on an underlying bed of lignite. *F*, View of a tidally reworked oyster coquina exposed along the rim of Knox Coulee in the western portion of the Judith River Formation type area. Comparable beds, which accumulated in tidal channels and reach 3 m thick, presumably supplied oyster shell debris to the D4 surface through the process of shoreface erosion.

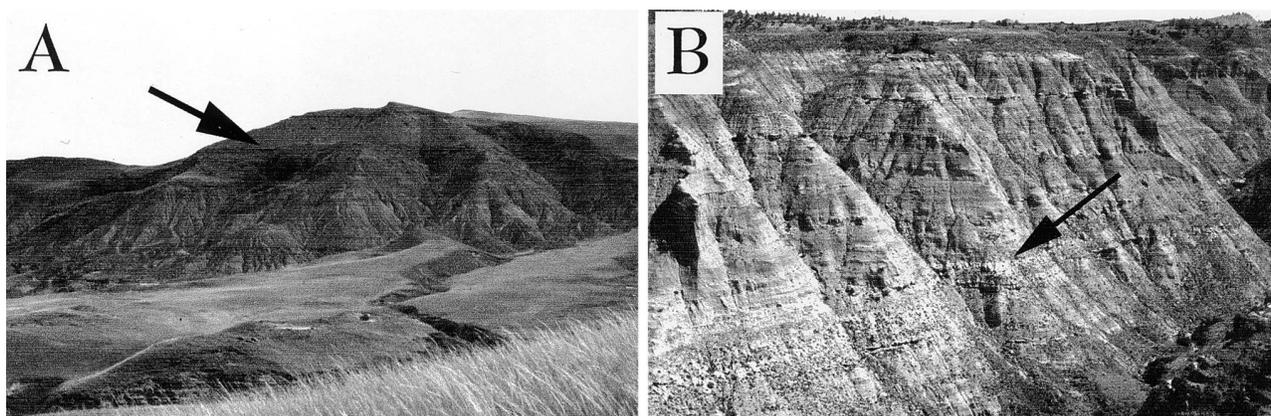


Figure 5. SB2 discontinuity. *A*, Arrow points to base of abrupt facies juxtaposition in Two Medicine Formation separating underlying fluvial facies from overlying lacustrine carbonate facies. *B*, Arrow indicates position in Judith River Formation of abrupt shift from a sandstone-dominated alluvial record to a mudstone-dominated alluvial record. No biogenic debris of any sort has been found in direct association with this discontinuity, although the relative abundance of vertebrate skeletal debris (dinosaur nest sites, bone beds, vertebrate microsites) above and below this surface does change dramatically in both the Two Medicine Formation and the Judith River Formation.

embedded between lignite or low-grade coal and several overlying meters of massive to swaley-bedded sandstone, commonly containing the shallow-marine trace fossil *Ophiomorpha*. This sandstone passes rapidly upward into dark shales of the Bearpaw Formation. Pavements or densely packed beds (up to 50 cm thick) of disarticulated and fragmental oyster shells (*Gyrostrea subtrigonalis* [Evans and Shumard]; genus according to Malchus 1990) occur at the lignite-sandstone contact in most outcrops. Subordinate taxa at the D4 surface include similarly euryhaline corbulid and anomiid bivalves and the gastropod *Goniobasis*. The oyster-dominated shell bedforms a tabular but not perfectly continuous body that can be traced eastward from the erosional limit of the stratigraphic interval for more than 40 km. On the east (downdip, distal edge), it thins to a single-valve pavement, which disappears entirely at a point roughly coincident with the pinchout of paralic facies in the underlying Judith River Formation.

Locally, thin pavements of disarticulated oysters (and more rarely *Anomia*) occur within the underlying lignite. Such pavements may have been the source of some shell debris concentrated in the D4 lag, but the lignites are clearly very difficult to erode. The shells within the lignites are probably allochthonous material transported into the coastal swamps during storms rather than populations that grew in situ. Much of the oyster material in the D4 lag is probably also allochthonous and, in this in-

stance, was exhumed and redistributed seaward through the process of shoreface erosion from autochthonous oyster banks in tidal environments whose sedimentary record has been otherwise destroyed by transgressive ravinement. Such a complex of small in situ oyster banks and tidally reworked oyster coquinas are preserved in close association with the D4 flooding surface along the western rim of Knox Coulee, in the western portion of the Judith River Formation type area (fig. 4).

Nonerosional SB2 Discontinuity (Nonmarine Extension of 75.4-Ma Third-Order Transgressive Surface). The SB2 discontinuity marks an abrupt change in facies and channel-stacking patterns in both upland and coastal plain portions of the Two Medicine–Judith River clastic wedge and is interpreted to correlate with the turnaround from regression to transgression in the marine basin (fig. 1; Rogers 1994, 1998). In the Two Medicine Formation type area, the SB2 surface juxtaposes anomalous lacustrine carbonate facies on fluvial channel and floodplain facies (fig. 5) and also coincides with an increase in volcanic detritus and the appearance of extrabasinal metamorphic pebbles. In the more distal Judith River Formation, the SB2 surface marks an abrupt shift from sand- to mud-dominated alluvial facies that can be traced in outcrop and in geophysical logs throughout north-central Montana and southern Alberta (fig. 5). The discontinuity itself shows no physical evidence of erosion, despite its striking appearance when viewed at a

distance. The nature of the facies change indicates an increase in accommodation, coinciding with the onset of Bearpaw transgression (T9) in the marine basin to the east. Thus, we refer to the SB2 discontinuity as the nonmarine (upstream) expression of that 75.4-Ma transgressive surface. The only documented erosion along this transgressive surface is in the easternmost part of the study area, where SB2 locally merges with the fully marine D1 ravinement. It may well be that there is virtually no hiatus of any type—erosional or omission—associated with the SB2 discontinuity along its nonmarine extent. The discontinuity lies in an appropriate position to be a sequence boundary, but applying the operational definitions of Van Wagoner et al. (1990), Christie-Blick and Driscoll (1995), and Van Wagoner (1995), among others, we avoid that terminology in the absence of clear evidence for a fall in baselevel (erosional downcutting or beveling). Instead, SB2 could be referred to as a type 2 unconformity (with minor subaerial exposure) or the updip correlative conformity of a sequence boundary (cf. Rogers 1998).

Facies on both sides of the SB2 discontinuity in both the Two Medicine and Judith River formations contain moderately to extremely abundant vertebrate and invertebrate fossils (Rogers 1995). However, we have nowhere found a direct association of skeletal material, of any quantity or quality, with the discontinuity (table 1). The only taphonomically notable aspect of the SB2 discontinuity is the dramatic increase in the abundance of bone concentrations in facies above the contact (see below). These concentrations include dinosaur nest sites, bone beds, and vertebrate microfossil localities, as well as scour-associated fluvial concentrations as described above (Rogers 1995, 1998; Rogers and Eberth 1996).

Erosional SB1 Discontinuity (Nonmarine Extension of 80-Ma Third-Order Sequence Boundary). The SB1 discontinuity is a laterally extensive set of erosional surfaces embedded within multistory fluvial sandstone sheets low within the Two Medicine Formation (figs. 1, 6). This major through-going discontinuity is interpreted as the nonmarine extension of the 80-Ma third-order sequence boundary (Rogers 1994, 1998). It can be traced in nearly continuous outcrop for tens of kilometers along the Two Medicine River and Cut Bank Creek and is tentatively correlated with a major erosional surface embedded within Hanson and Little's (1989) "sequence 4" of the marine Eagle Formation. In the Two Medicine type area, the discontinuity is contained within a 10–15-m-thick interval of intercutting fluvial scours and channels and is charac-

terized by a thick (up to 1.3 m) and laterally persistent intraclast lag facies, pervasive and unusually intense oxidation, and a temporary shift from fine- to medium/coarse-grained sandstone (fig. 6). The lag consists of rounded to angular pebbles and blocks of intraformational claystone and siltstone in a matrix of coarse-grained oxidized sandstone. Vertebrate and invertebrate skeletal debris is exceptionally rare (table 1) and is in poor condition (e.g., bone pebbles, gastropod steinkerns). In contrast, plant material is both abundant and well preserved. Large carbonized logs and log impressions are common (fig. 6), as is finer phyto-debris. This is similar to the more distal Eagle Formation, where large oriented logs and angular sandstone blocks are reported to rest on a regionally traceable marine disconformity (Hanson and Little 1989).

Facies surrounding the SB1 discontinuity in the Two Medicine Formation are not particularly fossiliferous. Underlying beds preserve scattered carbonaceous material and root traces, and silicified logs crop out locally. The first appreciable concentrations of bones and shells crop out above the discontinuity in beds that accumulated in a lower coastal plain setting contemporaneous with the Claggett transgression (Rogers 1995, 1998).

Additional Taphonomic Observations. The taphonomic condition of vertebrate skeletal material associated with discontinuity surfaces varies relatively little across the study interval. Disarticulated and dissociated vertebrate elements consistently exhibit evidence for physical abrasion and progressive faceting, regardless of whether they are in a marine or terrestrial setting. Moreover, there is an apparent size sorting of skeletal debris in both settings, with long axes of vertebrate elements derived from a wide array of taxa, ranging from 1 to 20 mm on average, with relatively few outliers (see fig. 4). Important taphonomic distinctions exist as well. Polish is occasionally developed on faceted skeletal debris recovered from fluvial channels but has not been found in the marine record. This taphonomic attribute may have important implications for the origins of skeletal lags. In addition, there is a tendency for vertebrate material in fluvial channels of the Two Medicine Formation to be more indurated (less friable) than counterparts in tidally influenced channels of the Judith River Formation. This variation in induration may relate to the differing geochemical environments of the channel facies themselves (e.g., there is more organic debris in the tidal beds, and presumably there was saltwater influence as well). Alternatively, it may reflect a different taphonomic history for the

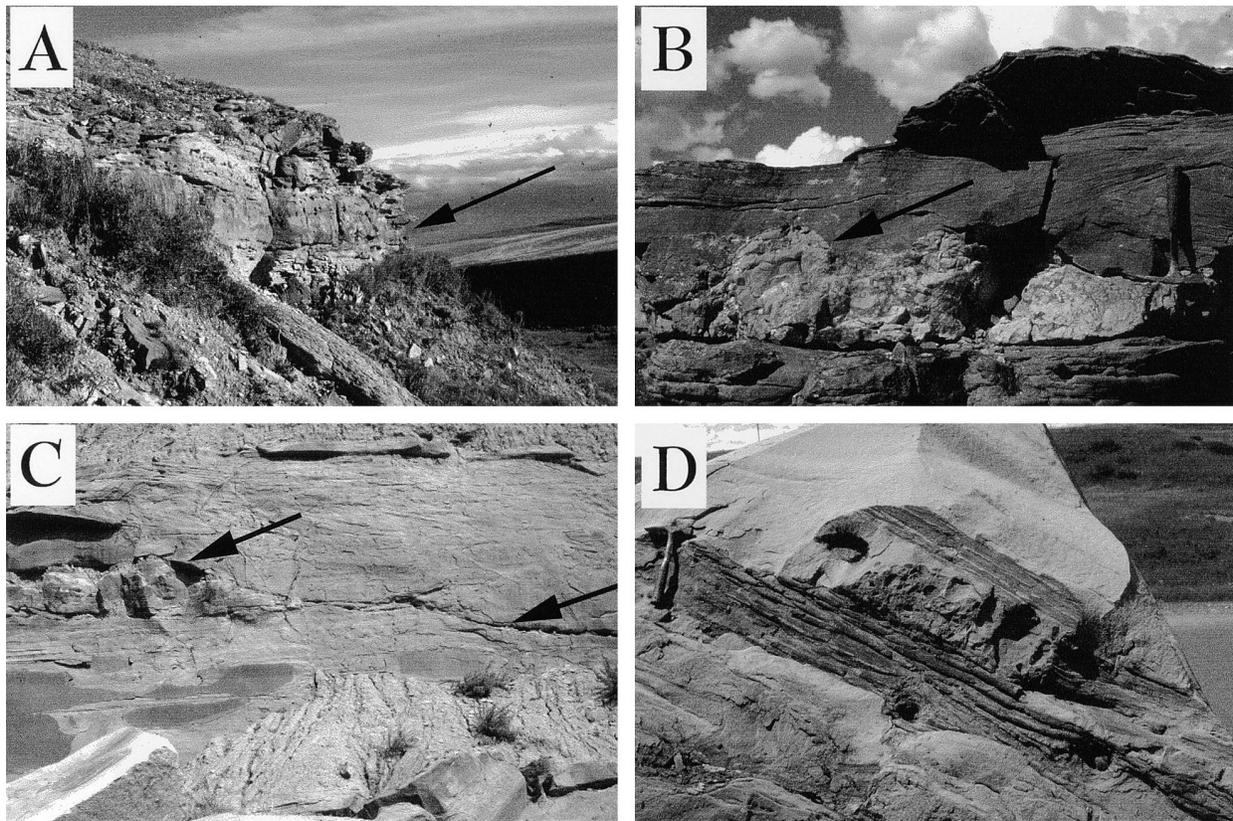


Figure 6. Outcrop views of SB1 discontinuity (80-Ma sequence boundary) in the Two Medicine Formation. *A*, View of the unconformity along the Two Medicine River showing the pervasive oxidation that characterizes facies immediately surrounding the discontinuity. *B*, Close-up view of oxidized lag that marks the SB1 discontinuity. Arrow points to rounded bank-collapse block. The intraclast lag marking the discontinuity locally exceeds 1 m thick. *C*, Arrows point to downcutting erosional surface in fluvial sandstone sheet along the Two Medicine River. Here, the surface exhibits up to 5 m of erosional relief. *D*, The only biogenic material commonly associated with the SB1 discontinuity consists of plant debris, most notably large carbonized trees.

bioclasts altogether, with channels in one locale or the other perhaps downcutting and/or eroding laterally and incorporating skeletal material from surrounding floodplain beds.

Origins of Vertebrate Skeletal Concentrations: Role of Preexisting Sources

Vertebrate skeletal material does occur in association with discontinuity surfaces within the Two Medicine–Judith River record, but there is no clear correlation between the abundance of material and the inferred duration of the actual hiatus, nor is the taxonomic diversity or taphonomic condition of bioclasts correlated with the type of discontinuity. The most significant discontinuities—the clearly erosional SB1 set of surfaces and the less clearly

hiatal but widespread SB2 discontinuity—are virtually barren of skeletal debris. In contrast, many hiatal surfaces of lesser extent and duration, ranging from marine flooding surfaces down to scours within individual fluvial channels, are mantled by rich skeletal concentrations. This indicates that these vertebrate skeletal concentrations are not simply accumulations of elements generated by death during the hiatus—that is, they were not produced solely by attritional input from communities that lived contemporaneously with the formation of the discontinuity surface (Behrensmeier and Chapman 1993). Instead, all vertebrate concentrations in the Two Medicine–Judith River record are patchy in their distribution, and even dispersed skeletal material varies in abundance along discontinuity surfaces. This variation closely tracks the

abundance of vertebrate material in underlying and laterally disposed facies, providing evidence that this material was supplied primarily through erosional reworking. By this, we are not referring to the continuous reworking of bedload that proceeds during the life of a single channel but to the exhumation of material from older strata in cut banks or during incision. Once remobilized, this exhumed material could be rapidly reburied or, alternatively, admixed with newly produced hardparts, generating time averaged and ecologically mixed fossil assemblages.

For example, the D3 flooding surface in the marine portion of the Judith River record demonstrably truncates several meters of underlying shoreface strata along the discontinuities most fossiliferous segment (figs. 3, 4), and the shark teeth, fish and marine reptile bones, and scattered chert pebbles that mantle the surface can also be found, albeit more widely dispersed, in underlying beds. Additional evidence for exhumation consists of reworked steinkerns of burrows (indurated casts), which are found in abundance on the D3 surface and are of the shoreface ichnogenera commonly found in underlying beds. Their concentrated occurrence on the surface is strong evidence of local erosional exhumation without significant lateral transport. Finally, the taphonomy of the skeletal debris concentrated on the D3 surface is consistent with physical reworking, in that the majority of the vertebrate elements exhibit evidence of breakage and/or abrasion (e.g., more than 70% of fish vertebrae show evidence of abrasion and rounding).

Evidence for the exhumation of skeletal debris is also apparent in the terrestrial portion of the study interval, where the recurrent skeletal lags that mantle fluvial erosion surfaces closely track the abundance of skeletal debris in surrounding floodplain facies. Fossil preservation in the floodplain environment ranges from isolated skeletal elements to concentrated dinosaur bone beds and vertebrate microsites. Sedimentologic and taphonomic data indicate that floodplain microsites formed via the attritional mortality of predominantly aquatic taxa in coastal plain ponds where, over time, physicochemically resistant elements such as teeth, scales, scutes, and small dense bones accumulated to fossiliferous levels. Floodplain microsites are particularly abundant above the SB2 discontinuity, with nine of the 13 localities that can be placed with confidence relative to SB2 intercalated in overlying strata. Channel-hosted microsite assemblages are also most abundant above

SB2, with 11 of 13 localities situated above the discontinuity (table 2).

The positive correlation in the stratigraphic distribution of floodplain- and channel-hosted microsite localities in the Judith River Formation is not a simple coincidence, and we have found evidence that suggests that Judith River channel assemblages include material reworked from preexisting floodplain microsites. The intersection of a fossiliferous channel deposit (site UC-8302; Rogers 1995) with an underlying floodplain microsite (site UC-8302A; Rogers 1995) in the Judith River Formation type area provides a good example (fig. 7). The 45-cm-thick floodplain microsite (UC-8302A) is a massive clay-rich siltstone containing turtle, crocodile, fish, and dinosaur debris interspersed with pisidiid bivalves, small thin-shelled gastropods, fragmentary *Unio* debris, and carbonaceous stringers. The overlying channel deposit is characterized by low-angle inclined sets of massive to faintly cross-stratified fine-grained sandstone. Thin carbon and clay partings drape most set boundaries and some foresets; small- to medium-scale trough cross-bedding, ripple lamination, and rare climbing ripples are present near the top of this tidally influenced fluvial deposit. The skeletal lag in the basal 20 cm of this unit (UC-8302) crops out immediately above UC-8302A and contains a comparable assemblage of vertebrate elements in association with abundant fragmentary shells of channel sand-dwelling *Unio* bivalves and floodplain-derived smaller invertebrates (mud-dwelling pisidiid bivalves and gastropods), ironstone and claystone pebbles, and coal stringers. The UC-8302 assemblage crops out immediately above an erosional scour developed on the underlying UC-8302A stratum (fig. 7a), and this association is interpreted to reflect the erosional exhumation and reworking of a preexisting source bed, with subsequent generation of a fossiliferous fluvial lag deposit.

Locality UC-8349 (Rogers 1995) provides a second example of a fossiliferous channel deposit consistent with the reworking of a preexisting fossil-rich bed (fig. 7). This ancient channel deposit consists of 3.2 m of fine-grained sandstone with medium- to large-scale trough cross-bedding and localized planar bedding. A lag of vertebrate skeletal debris crops out along the basal contact, and several more lag stringers mantle internal scour surfaces that mark set boundaries. The skeletal debris amassed on these surfaces consists of teeth (dinosaur, champsosaur, crocodile, mammal), fish scales, crocodile and turtle scutes, and small dense bones (vertebrae, phalanges). Quality varies from

Table 2. Stratigraphy of 55 Vertebrate Skeletal Concentrations in the Terrestrial Two Medicine–Judith River Record Relative to the SB2 Discontinuity and Third-Order Transgressive–Regressive (T-R) Cycles of the Western Interior Seaway^a

Locality	General site categories	Microsite type ^b	T vs. R
Two Medicine Formation:			
TM-055	Hadrosaur-dominated bonebed	...	R
TM-067	Hadrosaur-dominated bonebed	...	R
TM-041	Hadrosaur-dominated bonebed	...	T
TM-019	Hadrosaur-dominated bonebed	...	T
TM-023	Ceratopsian-dominated bonebed	...	T
TM-046	Ceratopsian-dominated bonebed	...	T
GM-1 ^c	Ceratopsian-dominated bonebed	...	T
TM-068	Multitaxic dinosaur bonebed	...	T
TM-066	Dinosaur nest site	...	T
TM-018	Dinosaur nest site	...	T
TM-068A	Dinosaur nest site	...	T
TM-097	Dinosaur nest site	...	T
TM-052	Dinosaur nest site	...	T
TM-038	Dinosaur nest site	...	T
TM-061	Dinosaur nest site	...	T
TM-088	Vertebrate microsite	a	T
TM-141	Vertebrate microsite	a	T
TM-020	Vertebrate microsite	a	T
TM-053 ^d	Vertebrate microsite	a	T
Judith River Formation:			
UC-92J	Hadrosaur-dominated bonebed	...	T
UC-939	Multitaxic dinosaur bonebed	...	T
JR-142	Dinosaur nest site	...	T
JR-122	Dinosaur nest site	...	T
UC-9312	Vertebrate microsite	a	R
UC-932	Vertebrate microsite	a	R
UC-934 ^d	Vertebrate microsite	a	R
UC-935 ^d	Vertebrate microsite	a	R
UC-929 ^d	Vertebrate microsite	b	R
UC-8325 ^d	Vertebrate microsite	a	R
UC-9314 ^d	Vertebrate microsite	a	T
UC-9311	Vertebrate microsite	a	T
UC-9313	Vertebrate microsite	a	T
UC-8326 ^d	Vertebrate microsite	a	T
UC-914 ^d	Vertebrate microsite	a	T
UC-8302A ^d	Vertebrate microsite	a	T
UC-8322B ^d	Vertebrate microsite	a	T
UC-8303 ^d	Vertebrate microsite	a	T
CBH ^{d,e}	Vertebrate microsite	a	T
UC-938	Vertebrate microsite	b	T
UC-937 ^d	Vertebrate microsite	b	T
UC-9210 ^d	Vertebrate microsite	b	T
JR-142A ^d	Vertebrate microsite	b	T
UC-9110 ^d	Vertebrate microsite	b	T
UC-8322A ^d	Vertebrate microsite	b	T
UC-941 ^d	Vertebrate microsite	b	T
UC-915 ^d	Vertebrate microsite	b	T
UC-917 ^d	Vertebrate microsite	b	T
UC-919 ^d	Vertebrate microsite	b	T
UC-8302 ^d	Vertebrate microsite	b	T
UC-8315 ^d	Vertebrate microsite	a	?
UC-9310 ^d	Vertebrate microsite	a	?
UC-931 ^d	Vertebrate microsite	a	?
UC-936 ^d	Vertebrate microsite	a	?
UC-913 ^d	Vertebrate microsite	b	?
UC-8439 ^d	Vertebrate microsite	b	?

Note. TM and JR indicate Museum of the Rockies (Bozeman, Mont.) localities. UC designations were used by Rogers (1995) to distinguish among sites in the field.

^a Rogers 1995, 1998.

^b a = Floodplain microsite, subaqueous (pond/lake) settings ; b = channel-hosted microsite.

^c *Brachyceratops* bonebed of Gilmore 1917.

^d Sample available at Macalester College (St. Paul, Minn.).

^e Clambank Hollow site of Sahni 1972.

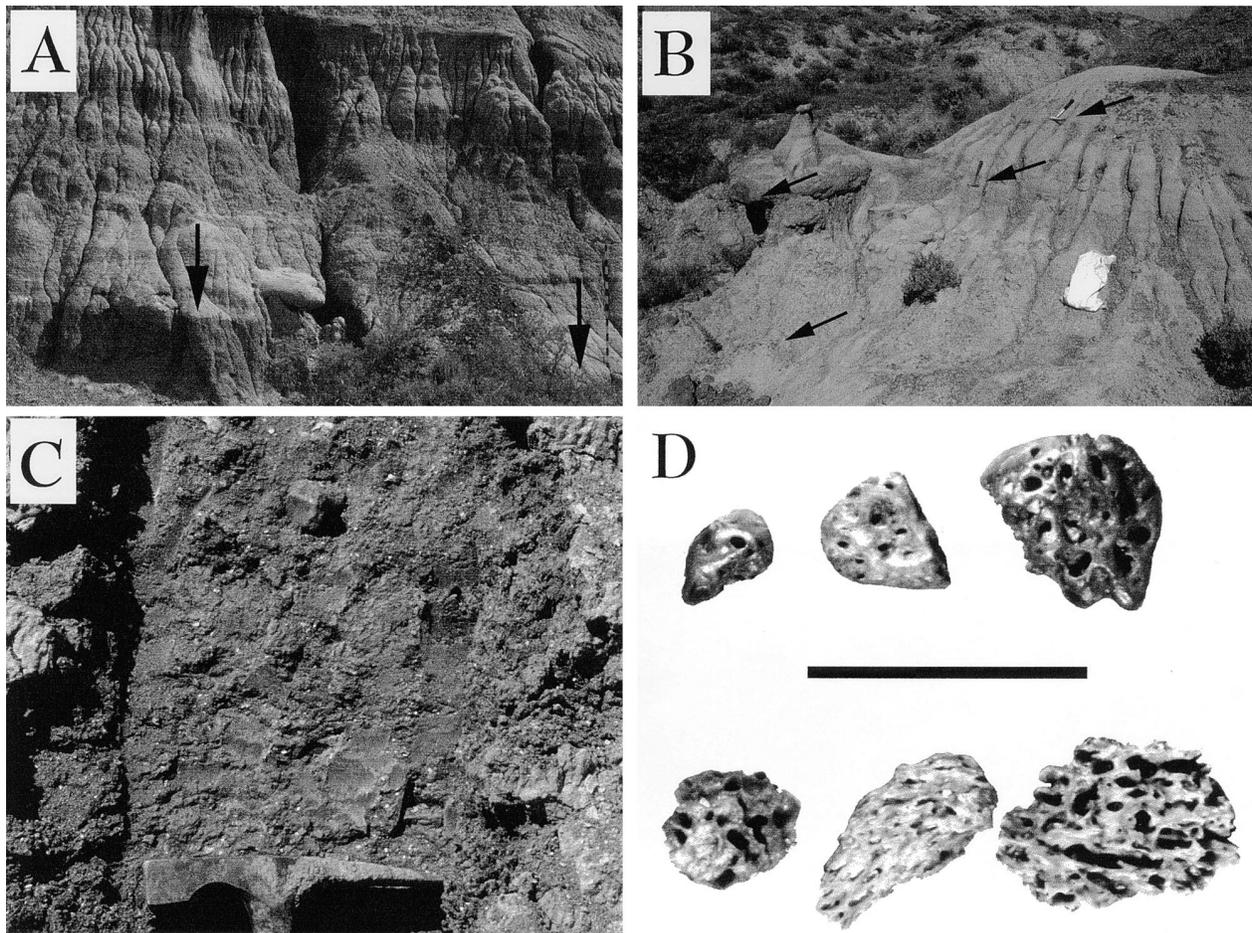


Figure 7. *A*, Channel-lag locality UC-8302. The skeletal lag in the basal 20 cm of this tidally influenced sandstone body contains vertebrate debris in association with abundant fragmentary shells of channel sand-dwelling *Unio* bivalves and floodplain-derived smaller invertebrates (mud-dwelling pisidiid bivalves and gastropods), ironstone and claystone pebbles, and coaly stringers. Arrows indicate position of lag deposit and demonstrate the downcutting of the channel to the right. The underlying 45-cm-thick source bed (UC-8302A) is a tan-to-brown massive clay-rich siltstone containing turtle, crocodile, fish, and dinosaur debris interspersed with pisidiid bivalves, small thin-shelled gastropods, fragmentary *Unio* debris, and carbonaceous stringers. *B*, View of locality UC-8349, which preserves several lag stringers of vertebrate skeletal debris on internal scour surfaces that mark set boundaries (*arrows*). The recurrence of skeletal lags in this deposit suggests that a preexisting source of skeletal debris supplied the channel as bedforms migrated and the channel filled. *C*, Close-up of typical floodplain microsite “source facies” showing scattered shell fragments (*white*) and a small dinosaur centrum (*top center*) in a matrix of massive, silty claystone. The sedimentology of these tabular beds indicates that deposition occurred in shallow floodbasin ponds or lakes. Skeletal debris presumably accumulated via attritional processes. Bioclasts typically include fragmentary and intact pisidiid bivalves, small high-spined gastropods, and disseminated vertebrate elements (teeth, scales, scutes, phalanges, vertebrae, etc.). *D*, The three polished pebbles of trabecular bone above the scale bar (=1 cm) were collected from the basal lag of a fluvial channel deposit in the Judith River Formation (UC-9301), and they presumably reflect the physical abrasion of permineralized material. The bone pebbles below the scale bar are typical of low-energy floodplain sites (see fig. 7C) and show no evidence of polish.

pristine elements to rounded and unidentifiable bone pebbles. Claystone pebbles and carbonized wood fragments, constituting rip-ups from floodplain facies, are also concentrated on basal and in-

ternal scours. The recurrent nature of skeletal lags at this particular site is interpreted to reflect the erosion of a nearby source bed that repeatedly supplied the channel with skeletal debris. Bones and

teeth were apparently delivered to the active channel from an eroding bank somewhere upstream from the present site, and skeletal material was concentrated in the scour pits of three-dimensional bedforms as they migrated downstream.

Finally, features of the lag concentrations themselves lend credence to the reworking hypothesis. First, the taxonomic makeup of channel-hosted assemblages shows a general correspondence to that of floodplain localities (Rogers et al. 1995; Carrano et al. 1995, 1997; Blob et al. 1997), with the rare exception of the marine taxa (plesiosaurs, sharks) that may be found in tidally influenced channel facies. Moreover, channel-lag assemblages contain the same basic assortment of elements as the floodplain microsites—teeth, vertebrae, phalanges, scutes, and scales—but some elements are polished (fig. 7). Polish is an enigmatic bone modification feature (Morlan 1984; Behrensmeyer et al. 1989), and its origin (or origins) is less than clear. It can presumably be imparted to permineralized (“pre-fossilized”) material on exhumation and physical abrasion (A. K. Behrensmeyer, pers. comm. 1994); in fact, an initial period of burial and diagenesis would seem to be prerequisite for abrasion to result in polishing rather than rounding alone. The presence of polished bones in the concentrations that drape fluvial scours suggests that at least a portion of the skeletal fraction was reworked in a pre-fossilized condition. Interestingly, polish is not evident on reworked skeletal material recovered from marine flooding surfaces in the study interval. Whether this indicates a more limited depth of stratigraphic incision or different fossilization dynamics in the two depositional settings, is unclear.

Comparison with Marine Invertebrate Skeletal Concentrations

The strong dependence of vertebrate lag development on preexisting local sources of skeletal material, rather than on the magnitude of the hiatus, contrasts with skeletal concentrations of invertebrates in marine successions. The marine invertebrate record includes many kinds of shell beds (relative concentrations of skeletal elements ≥ 2 mm), which are distinguished by variations in physical scale, composition, preservational state, and inferred origins (Kidwell 1991; Brett and Baird 1993; Doyle and MacDonald 1993; Fürsich and Oschmann 1993; Meldahl 1993). The majority of shell beds are (1) relatively simple event concentrations created by short, discrete, and localized events of skeletal input or reworking (e.g., storm beds, turbidites, shell-filled feeding pits, clusters of

gregarious benthos) and (2) generally larger-scale, amalgamated or accretionary composite concentrations that reflect more complex multiple-event histories of local colonization, physical and biogenic winnowing, and/or input from exotic sources (e.g., facies-scale bioclastic shoals, subtidal channel fills, washover fans; classification scheme of Kidwell 1991). Basin-scale studies have shown that these types of concentrations constitute the background pattern of skeletal accumulation in aggradational shallow marine environments and are strongly facies controlled. In terms of stratigraphic discontinuities, they are most commonly associated with bedding planes and bed-set boundaries but also mantle some parasequence-bounding flooding surfaces (Kidwell 1993*b*).

Marine records are also characterized by taphonomically more complex and “time rich” (3) hiatal concentrations, dominated by skeletal hardparts generated during stratigraphically significant hiatuses in sedimentation (e.g., sediment starvation of submarine paleohighs, distal portions of basins, and transgressive shelves; sediment bypassing of shallow-water environments at grade), and (4) lag concentrations, dominated by hardparts exhumed during stratigraphically significant erosion or corrosion of older deposits (e.g., erosional beveling during transgressive ravinement, planing, or incision during forced regression of shoreline; see classification scheme of Kidwell 1991; and see Brett and Baird 1993; Fürsich and Oschmann 1993; Kidwell 1993*b*). Hiatal concentrations, like composite concentrations, are products of multiple events of colonization and winnowing but are stratigraphically condensed (demonstrably thinner than coeval, less fossiliferous strata) and typically bear additional evidence of prolonged low net sedimentation, such as ecological condensation and admixtures of hardparts with diverse taphonomic or diagenetic histories. Lags, in contrast, are typically much thinner (limited to a few centimeters or decimeters rather than ranging up to several meters in thickness), patchy (rather than laterally extensive, tabular bodies) and composed of true hydraulic and diagenetic residua and have compositions that are ecologically, biostratigraphically, and/or taphonomically discordant with the sedimentary facies that hosts them. Many studies demonstrate that, although not all marine discontinuity surfaces are mantled by skeletal concentrations, taphonomically complex hiatal and lag concentrations are consistently associated with significant discontinuities, such as parasequence-bounding flooding surfaces, transgressive surfaces, midcycle surfaces of maximum transgression, and third- or fourth-order sequence

boundaries (references above and Brett 1995; Abbott 1998; Gillespie et al. 1998; Kondo et al. 1998).

Some marine skeletal deposits are compounds of hiatal and lag concentrations. The 1–10-m-thick shelly sands exposed on many modern continental shelves provide excellent modern analogs of the hybrid concentrations that mantle transgressive surfaces. These skeletal sands contain either a mixture of lag material exhumed during shoreface ravinement of estuarine facies (e.g., black-stained oysters) or older bedrock (e.g., shells with unusual sedimentary infills, or styles of shell replacement) and hiatal shells newly produced under open marine conditions (environmentally condensed macrobenthic and marine vertebrate debris derived from the bathymetric array of communities that migrated across the shelf during the past 20,000 yr of inundation and effective sediment starvation, verified through radiocarbon dating; Fischer 1961; Swift 1968; Swift et al. 1991; Anderson and McBride 1996; Stanley and Bernasconi 1998). Volumetrically, hiatal material exceeds lag material in such compound accumulations, both here and in the fossil record, and numerically, hiatal concentrations appear to be far more common than lags (Kidwell 1991).

Thus, in the genesis of skeletal concentrations associated with significant marine discontinuity surfaces, at least those dominated by mollusks, the production of new elements during the hiatus is of equal or greater importance than the gains from erosional exhumation, and the negative aspects of hiatuses (e.g., retarded permanent burial, repeated small-scale burial-exhumation cycles, possible elevated attack from other taphonomic agents) do not outweigh the positive aspects of low sedimentary dilution. Apparently, even in sites of sediment starvation, episodes of burial and/or thin veneers of mobile sediment can protect accumulating shell material. Indeed, the progressive concentration of skeletal material during a hiatal interval may aid skeletal preservation by buffering pore waters, armoring against erosion, and stimulating further colonization by shell-producing benthos (Davies et al. 1989; Kidwell 1989).

Hiatal skeletal concentrations in the marine taphonomic sense are extremely rare in the Two Medicine–Judith River record. Paleosol-hosted assemblages would constitute hiatal concentrations of terrestrial taxa, but none of these were encountered in the study area. This is not entirely unexpected, given the harsh conditions that can accompany pedogenesis. Given the type and rate of vertebrate material supplied by local mortality in this Cretaceous example, the destructive effects of

nondepositional hiatuses on the land surface apparently outweighed the positive effects of low sedimentary dilution. Vertebrate concentrations associated with Two Medicine–Judith River overbank deposits instead consist of time averaged floodplain pond assemblages and snapshot-type assemblages generated by rapid burial of vertebrates on land surfaces (mono- or paucispecific bone beds and nest sites).

Transgressive-Regressive Differences in Taphonomy

The stratigraphy of 55 vertebrate concentrations in the Two Medicine–Judith River record was ascertained relative to the SB2 discontinuity (table 2), and despite being unfossiliferous itself, the discontinuity does mark a regional change in the richness of the vertebrate fossil record. Overlying beds, which are interpreted to have accumulated during the Bearpaw transgression (T9), are characterized by a much greater abundance of vertebrate skeletal material. In the Two Medicine Formation, 17 of 19 sites surveyed definitively occur in the transgressive record above SB2. In the Judith River Formation, 24 of the 30 sites that can be placed relative to SB2 with certainty crop out in transgressive-phase deposits (table 2).

Some potential controls on this regional taphonomic pattern can be ruled out. In particular, proximal versus distal location in the foreland basin is not a factor—upland (Two Medicine) and lowland (Judith River) facies both exhibit the regressive-transgressive contrast in preservation. Also, overall outcrop area can be ruled out as a factor because regressive-phase deposits are at least as well and perhaps better exposed than transgressive-phase deposits. However, several other explanations for this large-scale taphonomic pattern are possible, from both the supply side (rate and quality of bone input) and the removal side of the taphonomic equation.

Accessibility of Productive Facies. One possible control on the large-scale distribution of fossils is the relative richness of facies available for reworking. In the Two Medicine and Judith River formations, tidally influenced channels and floodbasin ponds are the most productive terrestrial facies, whereas shoreface deposits are the richest of the shallow marine facies. In “upland” exposures of the Two Medicine Formation, the contrast in fossil abundance across the SB2 discontinuity does not coincide with any significant change in alluvial facies, only in the channel/floodplain ratio (Rogers 1998). Fluvial and floodplain deposits of the high-stand depositional system (R8) are broadly similar

to those of the transgressive depositional system (T9). However, in the lowland coastal plain record of the Judith River Formation type area, the shift to a more fossiliferous transgressive record coincides with an increase in the abundance of tidally influenced channel and floodbasin pond deposits. The increased abundance of these two particular facies in the transgressive portion of the Judith River record clearly influences the large-scale stratigraphic pattern of fossil occurrence in the type area. Outcrops are not available to test whether the regressive record also increases in fossil content toward the paleocoastline.

Burial Rate and Likelihood of Reworking. Higher accommodation of deposition during the rising baselevel conditions of transgression should also result in higher net rates of burial of any given depositional surface—i.e., fewer burial-exhumation cycles per stratigraphic increment. Although this enhanced burial potential is probabilistic and thus would not affect every carcass or bone on an ancient landscape, it should reduce destructive cycles of exhumation and reworking within facies, as well as increase the preservation potential of facies themselves. This transgressive versus regressive reasoning is the same as used in explaining proximal-distal differences in fossil quality and abundance within the Two Medicine–Judith River record (Rogers 1993): proximal portions of the foreland basin with highest subsidence and accommodation of deposition (Two Medicine) do in fact contain more high-resolution, non-channel-lag type concentrations than in distal (Judith River) portions of the clastic wedge.

Relative burial potential for the stratigraphic intervals under scrutiny can be estimated using $^{40}\text{Ar}/^{39}\text{Ar}$ ages and thickness data (Rogers et al. 1993; Rogers 1994, 1995, 1998; Rogers and Swisher 1996). The R8 regressive depositional system yields rock accumulation rates ranging from 6 to 7 cm/1000 yr, whereas the T9 transgressive depositional system is characterized by a net rate of rock accumulation on the order of 10–11 cm/1000 yr. These values are consistent with higher net rates of skeletal burial in the transgressive record.

Differential Diagenesis. In marine transgressive-regressive cycles, carbonates within regressive phases experience more severe meteoric diagenesis than their counterparts in transgressive deposits, leading to significantly different cementation levels and grain preservation state (Heckel 1983; Braithwaite 1993). If there is a nonmarine analog to this diagenetic asymmetry, then we would also expect more favorable (less destructive) diagenesis of vertebrate skeletal material in transgressive than

in regressive phases, ignoring relative likelihoods of destruction during later diagenesis and tectonism. Phreatic diagenesis (below the water table) will presumably play a larger role in nonmarine facies deposited during transgression (baselevel rise and high accommodation) than during regression (steady or falling baselevel), where the same facies are more likely to experience near surface vadose diagenesis (above the water table).

The likelihood of bone preservation in a sediment profile is governed by several parameters, including the movement of pore waters (potential for mobilization and flushing of soluble ions), pH and Eh values, and the abundance of destructive microorganisms (Newesely 1989). In terrestrial depositional systems, destructive diagenetic processes would presumably be most severe in the vadose zone, where pore waters would be apt to circulate more quickly through the sediment profile (Tucker 1991), Eh values would presumably be higher, and microorganisms (e.g., fungi, bacteria) would be abundant and more diverse or active. Undersaturation with respect to CaCO_3 is also typical of some vadose pore fluids, especially in the upper reaches of the soil zone, and this would potentially encourage bone corrosion and dissolution. In contrast, the fully phreatic environment would be typified by more restricted movement of pore fluids (except in the immediate vicinity of the water table), lower Eh values, and probably less skeletal corrosion and leaching.

Environmental and Ecological Contrasts. The spatial mosaic of sedimentary environments on the Two Medicine–Judith River alluvial-coastal plain, which was bounded to the west by tectonic highlands and to the east by the Cretaceous Interior Seaway, would have fluctuated dramatically during major transgressive-regressive cycles. During transgression, the regional gradient would have almost certainly diminished (especially if transgression was subsidence related). This reduction in regional gradient would have presumably led to significant landward expansion of lower coastal plain environments. In fact, Eberth (1996) has estimated that tidal influence on the Judith River coastal plain of southern Alberta extended inland for more than 200 km during transgression of the Bearpaw Sea. Based on our taphonomic data and comparable observations from southern Alberta and Saskatchewan (Brinkman 1990; Eberth 1990; Eberth et al. 1990), this broad belt of coastal and paralic environments was extremely conducive to the preservation of vertebrate skeletal concentrations (predominantly vertebrate microsites and ceratopsian bone beds). This preservational bias may reflect the

productivity of aquatic and terrestrial coastal communities, the favorable geochemistry of hydro-morphic coastal environments, or both.

Although admittedly more speculative, transgression would also have potential taphonomic impacts on inland settings. During the transgressive phase, as coastal plain environments backstepped inland toward the mountain front, upland environments on the Two Medicine alluvial plain would presumably become more areally restricted. With diminishing habitat, taxa adapted for inland settings may have experienced stress due to more limited resources and perhaps heightened competition. Resource limitations in turn might have led to heightened mortality and perhaps widespread mass mortality. This prediction is consistent with the abundance of mono- and paucispecific dinosaur bone beds preserved in the transgressive depositional system of the Two Medicine Formation (Rogers 1990, 1993, 1995; Varricchio 1995). These "event" dinosaur bone beds indicate that mass mortality was a common occurrence on the Two Medicine alluvial plain during transgression of the Bearpaw Sea.

Conclusions

Based on our taphonomic analysis of the Campanian Two Medicine–Judith River record, there are clearly fundamental differences in the ways in which bioclastic material accumulates in marine and terrestrial settings, and it is also clear that vertebrate skeletal concentrations are less reliable cues to stratigraphically significant surfaces. The distribution of vertebrate skeletal material is not predictable with regard to the scale or duration of stratal discontinuities in either marine or terrestrial portions of the study interval, based on our examination of third- and fourth-order sequence boundaries, the nonmarine extension of a third-order transgressive surface, marine flooding surfaces, and localized fluvial scours. Instead, the vertebrate skeletal signatures of hiatal surfaces of all durations closely track the fossil content of underlying and lateral facies: relative concentrations of bones and teeth occur where discontinuity surfaces cut across preexisting beds with appreciable skeletal content.

The distribution of vertebrate fossils on hiatal surfaces in the Two Medicine–Judith River record is thus controlled by erosion potential and the bioclastic composition of facies that may be genetically unrelated to those of the hiatus. This result has important implications for stratigraphic analysis in nonmarine depositional systems, where the

heterolithic mix of facies would seem to preclude the widespread development of skeletal-lag-draped erosional discontinuities. The spatial patchiness of vertebrate populations in most terrestrial settings, combined with overall lower fecundity relative to most marine vertebrate and invertebrate counterparts, may actually inhibit the generation of appreciable skeletal concentrations on hiatal surfaces under any conditions, especially concentrations that are laterally persistent.

Documenting the basic patterns of fossil distribution and assessing their controls is also key to estimating the possible bias of paleobiological information and to developing more effective strategies for prospecting vertebrate occurrences. Our analysis indicates that the vast majority of vertebrate skeletal concentrations associated with discontinuity surfaces are time averaged lag-type mixtures of ecologically and, in some instances, taphonomically, disparate skeletal material. The degree of time averaging in such concentrations has been estimated to range in excess of 100,000 yr (Rogers 1993); this level of temporal mixing renders it plausible that noncontemporaneous vertebrate communities are admixed in at least some lag assemblages. Interestingly, although such lags would typically have relatively low levels of temporal acuity, they may have relatively high degrees of spatial fidelity. The direct association of lag concentrations and floodplain source beds in alluvial settings (fig. 7), coupled with evidence of lateral variation in the composition of skeletal lags on fourth-order marine flooding surfaces (presumably a function of underlying facies content), strongly suggests that little lateral transport of skeletal material occurred after exhumation.

Finally, our results reveal some broad and unexpected trends in the abundance of vertebrate fossil assemblages, both across environments and through stratigraphic cycles. Among environments in this study interval, tidally influenced channel deposits and shoreface deposits are consistently more productive than surrounding strata (table 1). At the basin scale, strata deposited during the R8-T9 third-order cycle show a striking contrast in preservation potential (table 2), with the transgressive depositional system considerably more fossiliferous than the underlying regressive depositional system, in both shallow marine and terrestrial settings. These findings highlight the control of facies on the distribution of vertebrate fossils and demonstrate the importance of this association at scales ranging from the individual deposit to the third-order cycle. The link between physical patterns of sedimentation and patterns of vertebrate fossil

distribution is unequivocal within the Two Medicine–Judith River record, and it is certainly reasonable to conclude that spatial and temporal variations in erosion, omission, and deposition might exert a similarly strong influence on the distribution and quality of vertebrate fossil assemblages in other marine and terrestrial systems.

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