Testing the Utility of Vertebrate Remains in Recognizing Patterns in Fluvial Deposits: An Example from the Lower Horseshoe Canyon Formation, Alberta

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Depositional cycles in fluvial successions are described here as chronostratigraphic packages of strata founded on a laterally extensive, scour-based, amalgamated channel-sand body, overlain by mudrocks, isolated channel fills, avulsion and splay complexes, and paleosols. Ten packages are described from the lower Horseshoe Canyon Formation (Campanian-Maastrichtian), one of a succession of clastic wedges filling the Alberta foreland basin in south-central Alberta. The structure of these packages is consistent with the fall-rise-fall cycle of base-level described in other studies, but the package-bounding scours and internal surfaces are discontinuous and difficult to trace in the mudrock-dominated strata. Terrestrial vertebrate fossils are preserved in relatively fossiliferous, facies-independent horizons 1 to 3 m thick that statistically correlate with the stratigraphic position of package scours and surfaces. Fossiliferous horizons formed as a result of attritional accumulation under an optimum, relatively low, regional deposition rate. Not only do these horizons aid in locating package surfaces, but they also provide insight to the interaction of the package-scale, base-level oscillation with the larger-scale fluctuation in accommodation associated with the formation of the clastic wedge. As such, fossiliferous horizons in the Horseshoe Canyon Formation make better boundary markers than do paleosols, splays, coal seams, or even the surfaces associated with package structure. Therefore, the vertebrate fossil record may supply a means of stratigraphically evaluating sections in other locations in which typical sedimentological and architectural cues for surfaces are absent.

INTRODUCTION

Facies and structural elements in fluvial successions regularly are described in terms of a subtle, repeating pattern of fining-upward packages. The typical package structure includes basal, laterally extensive scour-bottomed sandstone sheets or amalgamated sandstone bodies, overlain by sheets of mudrock encasing lenses of sand, in turn overlain by coal, laminated mudrocks, or paleosols. Whereas older studies of fluvial deposits report these patterns as details of facies architecture, recent research interprets fining-upward packages as indicators of cyclic base-level change (Table 1; for a complete review, see Blum and Törnqvist, 2000). Distinctive contacts recurring in successive packages, especially the erosional scour present under most sandstones, have been interpreted as important surfaces in both allostratigraphic (Bhattacharya, 1989; Cant, 1998) and sequence stratigraphic (Shanley and McCabe, 1991; Aitken and Flint, 1995; Kamola and Van Wagoner, 1995) frameworks. In each case, these results are based on sedimentologic evidence alone. In fluvial strata, cross-cutting relationships, lateral facies transitions, pinch-outs, reworking, bioturbation, and stacking of similar facies can obscure or destroy such boundaries. Any additional information potentially useful for tracing stratigraphically important contacts or surfaces should be exploited. In marine stratigraphy, invertebrate fossil evidence has been used to locate surfaces (Kidwell, 1986, 1988a,b, 1989; Banerjee and Kidwell, 1991; Brett, 1995, 1998; Holland, 1995; Tew and Mancini, 1995). Many fluvial successions with repeating packages also include fossil remains, particularly those of large terrestrial animals such as dinosaurs and mammals. Taphonomy is the focus of many studies in which stratigraphic packages are described (Wood, 1985; Behrensmeyer, 1987; Wood et al., 1988; Davies-Vollum and Wing, 1998). A recent inquiry into vertebrate fossils in the Two Medicine Formation (Rogers and Kidwell, 2000) found no correlation between third-order sequence boundaries and fossil distribution. To date, terrestrial fossil occurrences essentially have been neglected as potential indicators of higher-order (fourth- or fifth-order) stratigraphic surfaces and patterns of stratigraphic cyclicity in fluvial successions.

The present work focuses on exposures of the lower Horseshoe Canyon Formation (HCF) of south-central Alberta, a succession of latest Campanian to earliest Maastrichtian fluvial strata. The first goal of this study is to describe repeating cycles of facies and structures in the lower HCF from sedimentologic information. The second goal is to describe the distribution of vertebrate fossils in the lower HCF. The distribution of fossils is tested for correspondence both with the stratigraphic data and with the cycles in fluvial deposition, with particular attention to the potential usefulness of fossils as markers for important stratigraphic surfaces. The interpreted depositional history from the stratigraphic and fossil record then is compared to other documented stratigraphies.

HORSESHOE CANYON FORMATION

The Horseshoe Canyon Formation (HCF) consists of estuarine and fluvial sandstones, mudrocks, and coal, part

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TABLE 1—Examples of the studies describing fining-upward rhythms in fluvial strata. One third of these references describe such rhythms in the context of a stratigraphic framework (sequence stratigraphy or allostratigraphy), and fewer acknowledge the presence of terrestrial fossils.

Region	References	Age	Depositional environment	Applied stratigraphy	Term for base	Dominant facies	Paleosol	Splay	Coal	Bone
Breathitt Gp, KY	Aitken and Flint, 1994, 1995	Carboniferous	shoreface to lower floodplain	sequence stratigraphy	scour	mud > sand	yes	?yes	yes, few	no
Monogahela-Dunkard Gps, WV	Ghosh, 1987	Pennsylvanian/Permian	lower to upper floodplain	facies architecture	undefined	mud ≫ sand	yes	yes	no	no
Salt Wash Mbr, Morrison Fm, UT	Robinson & McCabe, 1998	Jurassic	upper to central floodplain	facies architecture	scour	sand > mud	no	?no	no	no
Mannville Gp, AB	Cant, 1998	early Cretaceous	upper to central floodplain	allostratigraphy	unconformity	cgl/sand < mud	no	no	yes	no
northeast NM?	Holbrook & White, 1998	early Cretaceous	upper to central floodplain	facies architecture	?scour	sand = mud	no	yes	no	no
Dunvegan Fm, AB	Bhattacharya, 1989	late Cretaceous	estuary	allostratigraphy	scour	sand ≫ mud	no	no	no	no
Book Cliffs, UT	Van Wagoner, 1995; Kamola & Van Wagoner, 1995; Olsen et al., 1995	late Cretaceous	lagoon to lower floodplain	sequence stratigraphy	unconformity	sand > mud	yes	?no	yes	no
Straight Cliffs, UT	Shanley & McCabe, 1991, 1993, 1995; Shanley et al., 1992	late Cretaceous	shoreface to central floodplain	sequence stratigraphy	unconformity	sand ≫ mud	no	yes	yes	yes, few
Judith River Fm, AB	Wood, 1985; Wood et al., 1988	late Cretaceous	central floodplain	facies architecture	?scour	sand ≫ mud	no	no	no	yes
Horseshoe Canyon Fm, AB	Rahmani, 1988; Ainsworth & Walker, 1994; this study	late Cretaceous	shoreface to upper floodplain	sequence stratigraphy	unconformity	mud > sand	yes	yes	yes	yes
Wilcox Gp, TX	Breyer, 1997	?Paleogene	estuary to lower floodplain	sequence stratigraphy	unconformity	sand = mud	yes, few	no	yes	no
Willwood Fm, WY	Davies-Vollum & Wing, 1998	Eocene	upper floodplain	facies architecture	scour	sand > mud	yes	no	no	yes
Siwaliks, Pakistan	Badgley, 1986; Behrensmeyer, 1987; Willis & Behrensmeyer, 1994	Miocene	central floodplain	facies architecture	scour	sand = mud	yes	yes	no	yes
Ebro Basin, Spain	Nichols & Hirst, 1998	Miocene	alluvial fan	facies architecture	scour	mud > sand	no	no	no	no
Mississippi River, MS	Aslan and Autin, 1998, 1999	Holocene	lower to central floodplain	facies architecture	?scour	sand = mud	yes, few	yes	no	no
Okavango Basin, S Af, Neuquen Basin, Argentina	Legarreta & Uliana, 1998	Holocene	alluvial fan	facies architecture	scour	sand > mud	yes	no	no	no

of a succession of clastic wedges shed into the Cretaceous Interior Seaway from a thrust belt to the west (Cant and Stockmal, 1989; Jerzykiewicz and Norris, 1993; Hamblin, 1998a; Fig. 1). The HCF lies over the marginal-marine Bearpaw Formation and is underlain by the Whitemud, Battle, and Scollard formations, collectively forming the Edmonton Group (Allan, 1922; Allan and Sanderson, 1945; Ower, 1960; Shepheard and Hills, 1970; Irish, 1970; Nurkowski, 1980; Hamblin, 1998a). The informally named Drumheller Marine Tongue (DMT) records a mi-

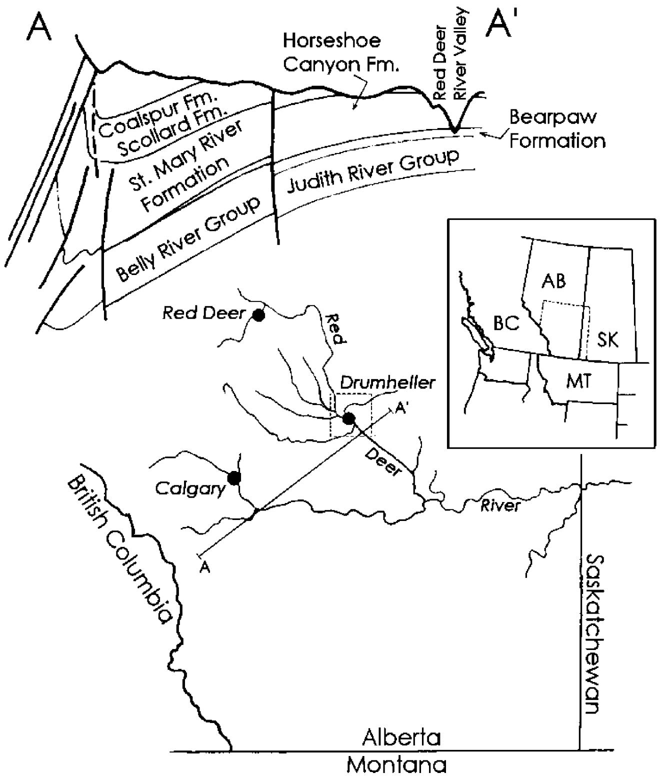

FIGURE 1—General geology of the Alberta Foreland Basin in southern Alberta. The structural cross-section A-A' is generalized from Jerzykiewicz and Norris (1993). An enlargement of the field area near Drumheller, Alberta, is shown in Figure 2.

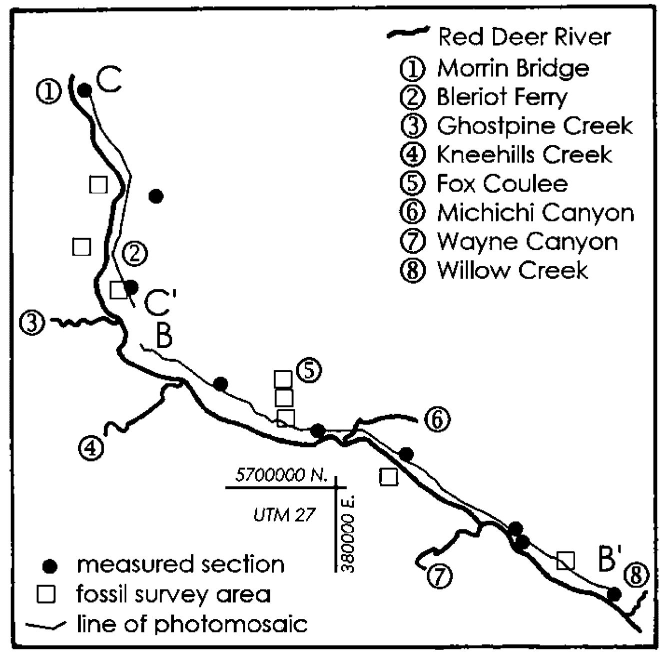

FIGURE 2—Field area around Drumheller, Alberta. Nine measured sections (dots) and eight fossil survey areas (squares) lie along two transects (B-B′, C-C′) on the eastern valley wall.

nor transgressive episode (Langston, 1959b; Russell and Chamney, 1967), recently correlated to the Campanian/Maastrichtian boundary (Lerbekmo, pers. commun., 2000), that divides the HCF into upper and lower successions of subequal thickness (Nurkowski and Rahmani, 1984). Up to 165 m of the lower HCF and the overlying 30 m of the DMT represent approximately 2 myr of relatively continuous deposition, and constitute a cycle of aggradation and progradation of a clastic wedge, ending with the final incursion and retreat of the Bearpaw Sea into south-central Alberta (Catuneanu and Sweet, 1999). Exposures of this interval were studied in a 35-km transect along the Red Deer River Valley around Drumheller, Alberta (Fig. 2).

The upper Bearpaw and basal Horseshoe Canyon formations previously have been described in terms of repeating shoaling- and fining-upward packages, partitioned by discontinuities interpreted as incisions and flooding surfaces (Waheed, 1983; Rahmani, 1988; Ainsworth, 1994; Ainsworth and Walker, 1994; Eberth, 1995). Extension of these surfaces into the updip fluvial succession has not been attempted because the surfaces are obscured by the absence of marine ichnofossils and by lateral lithofacies variation. Coal seams used as informal stratigraphic markers in the HCF (Gibson, 1977; Nurkowski and Rahmani, 1984; McCabe et al., 1989; Hamblin, 1998a,b) have been numbered as Coal Seam 0 above the Bearpaw/HCF contact to Coal Seam 10 within the DMT. However, coal seams are more numerous in the HCF than this scheme suggests, in many places pinching out or splitting (Figs. 3 and 4). Multiple coal seams, occurring in intervals averaging 10 m in thickness and separated by relatively organic-poor intervals of 30 m or more, are more reliable as gross stratigraphic markers than are individual discontinuous seams (Straight and Eberth, 1998).

The Red Deer River dissects the lower HCF to expose dip sections on steep valley walls and strike sections in the tributary coulees, allowing the examination of stratigraphy and facies distribution in three dimensions. Shallow dip ($<2°$ to the north-northwest) and limited distortion allow study of each surface and package laterally over tens of kilometers. Prior stratigraphic work in the transitional deposits at the base of the Horseshoe Canyon/Bearpaw Formation contact (Rahmani, 1988, 1989; Ainsworth, 1991, 1994; Eberth, 1995, 1996) offers the opportunity to correlate fluvial chronostratigraphic markers with a framework of marine-margin chronostratigraphic surfaces. Finally, vertebrate fossils in the HCF are plentiful, rapidly exposed by erosion, and have not been subjected to prolonged organized collecting, permitting a relatively unbiased measurement of fossil abundance, density, facies relationship, and taphonomy.

STRATIGRAPHIC METHODS

Nine stratigraphic sections were measured using conventional field techniques on the eastern Red Deer River Valley wall between Hoodoos Provincial Park (17 km southeast of Drumheller) and Starland Municipal Park (22 km north-northwest of Drumheller). Data for these measured sections are available as part of the online repository (Appendix). In addition, 35 photographic mosaics cover over 50 km of outcrop. A composite mosaic (Figs. 3

FIGURE 3—Stratigraphic architecture of the 29-kilometer-long B-B′ dip transect of the northeastern wall of the Red Deer River Valley. Ticks refer to vertical sections on 26 photographic mosaics at which the relative position of visible contacts were measured. Vertical lines mark the positions of measured sections. Numbers in circles refer to landmarks similarly labeled in Figure 2; numbers without circles refer to coal seams, modified from Gibson (1977). Shading indicates sandstone facies. Vertical scale is approximate.

and 4) was assembled from these data to show the architecture of the exposures of the lower HCF and DMT.

FACIES ASSOCIATIONS

Coarse sediments constitute slightly less than half the sediments throughout the HCF and range from very fine to medium mature litharenitic sandstone, usually white, tan, or yellow. Siltstone is typically gray or green-gray, whereas claystone although uncommon in the HCF is generally black, brown, or tan. Mudrocks contain variable proportions of swelling clays, disseminated plant fragments, and amber. Roots, preserved as black carbonaceous films and as red-brown iron oxide casts, are common in some mudrocks. Sub-bituminous coal and lignite form laterally extensive seams averaging 45 cm in thickness and commonly incorporate compressed, partly silicified wood fragments. Siderite nodules, many surrounding bone or silicified wood, form clusters or stringers and range in size from paper-thin sheets to nodules 60 cm in diameter. These sediments are organized into 17 facies in the HCF (Table 2; Fig. 5) and are arranged into facies associations based on common juxtapositions seen in the field: (1) plane-bedded to crossbedded sandstone bodies, (2) terrace-forming sheet sandstone bodies, (3) mud-draped crossbedded sandstone bodies, (4) sandstone-mud-

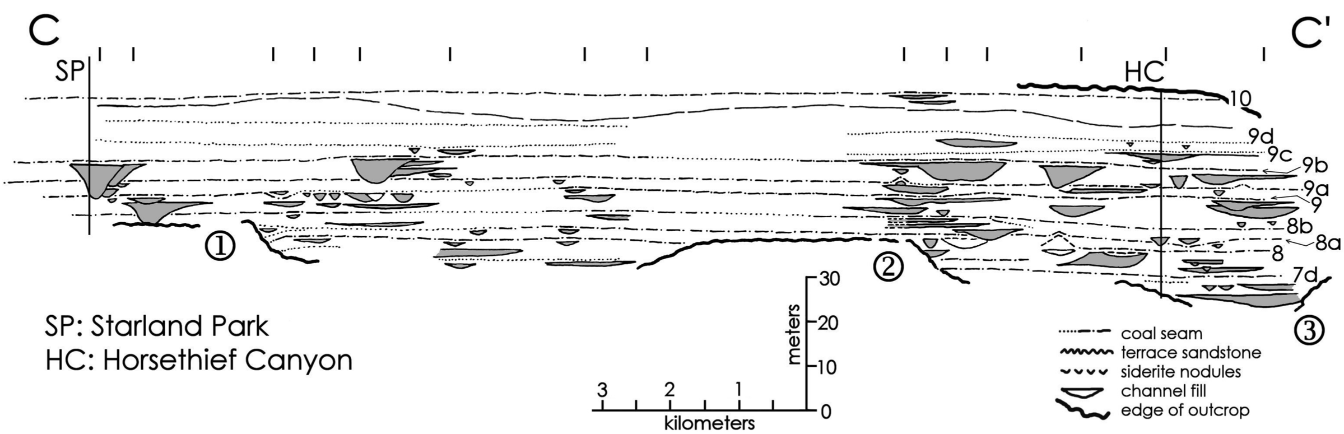

FIGURE 4—Stratigraphic architecture of the 14-kilometer-long C-C′ oblique transect of the eastern wall of the Red Deer River Valley. Ticks refer to vertical sections on 9 photographic mosaics at which the relative position of visible contacts were measured. Vertical lines mark the positions of measured sections. Numbers in circles refer to landmarks similarly labeled in Figure 2; numbers without circles refer to coal seams, modified from Gibson (1977). Shading indicates sandstone facies. Long-dashed line below coal seam 10 indicates a visible change in color of deposits from red-brown to green-gray. Vertical scale is approximate.

TABLE 2—Facies of the lower Horseshoe Canyon Formation, including the Drumheller Marine Tongue, following the nomenclature of Miall (1978, 1992).

Code	Facies description	Association	Interpretation
C	Blocky subbituminous coal interbedded with black fissile mud, lignite lamina, partly silicified/coalified wood, *in situ* stumps, amber, bone, and sulfur coatings.	5	Peat swamp, probably brackish estuarine where sulfur is present.
Fa	Blocky to moderately fissile, pale to dark gray silty mud, with roots and plant fragments, amber, bone, slickensides, and bentonite.	5, 6	Seasonally saturated floodplain, possibly marshland.
Fe	Massive dark brown mud, granular parting, sparse plant fragments.	5	Saturated floodplain, possibly as an overbank flood.
Ff	Poorly fissile, carbonate-cemented pink or red-brown mud/silt, decimeter-thick erosion-resistant sheets or thicker lenticular bodies with sparse hash, oxide-cast plant fragments, roots, slickensides, and amber.	5	Paleosol leaching horizon.
Fg	Green or gray-green silty mud, interlaminated or mottled with very fine sand or silt in contorted enclaves or thin ripple-laminated seams, swelling clay, plant fragments, fragmentary bone and small teeth.	6	Trampled splays on dry floodplain.
Fo	Blocky red-brown or tan, massive or sparsely laminated with very fine sand or silt, with oxide-cast roots, abundant siderite nodules, and rare bone.	6	Dry floodplain.
Gb	Large blocks of tilted strata, attenuated in downstream direction.	3	Bank collapse blocks.
Gl	Lag of reworked siderite clasts, wood, bone, and mudstone intraclasts.	1, 2, 3	Lag accumulated by winnowing in channel.
Sb	Medium/fine sand with nearly horizontal bedding, occasionally interbedded with laminated mud, with burrows, coal fragments, sulfur, gypsum, and glauconite.	4	Washover fan.
Se	Horizontal or gently undulating laminae of fine/very fine sand and pale green/gray silty mud bedded in couplets; gypsum, shell debris; subtle scour beneath each sand.	4	Tide- or event-dominated middle estuary, possibly near turbidity maximum.
Sf	Fine/very fine sand in laterally extensive decimeter-thick sheets with climbing ripples, with complete to patchy carbonate cementation, burrows, and roots.	2	Splay fringe
Sl	Medium/fine sand with inclined plane beds, interbedded or draped with mud and/or hash lamination, fining and increasing mud content upward, with reworked siderite pebbles and bone on bedding surfaces.	1, 2, 3	Lateral accretion surfaces, usually from a low-sinuosity meandering channel.
Sn	Alternating horizontal laminae of fine/very fine sand and tan or gray mud; amber, plant hash and fragments, wood, bone, nodules, and rooting.	5, 6	Floodplain deposition of alternating splays and levees
So	Carbonate-cemented very fine sand/silt with breccia of complete and partial brackish-water bivalves.	4	Oyster bank debris, possibly from washover.
Sp	Medium/fine sand with planar crossbeds, reworked siderite pebbles on bedding surfaces.	2, 3	Migrating sand bars and bedforms in an active channel.
Sr	Fine/very fine sand, fining upward with ripple lamination and small trough crossbeds, commonly as winged lens-shaped bodies or sheets, with coal rip-up clasts, hash, bone, and wood on an irregular basal scour.	1, 2	Splay channel/chute fill.
St	Medium/fine sand with trough crossbedding, siderite lags, and hash lamination on bedding surfaces; in layers or in fining upward stacks; wood and bone fragments.	1, 2, 3	High-energy channel-bottom fill.

stone couplet sheets, (5) organic-rich mudrocks, and (6) organic-poor mudrocks.

Plane-Bedded to Crossbedded Sandstone Bodies

Medium-grained litharenitic sandstone deposits appear as a sheet or complex stack of sheets and lenses throughout the lower HCF. Individual lenses are from 1 to 3 m thick, in many cases with tapering wing-like lateral extensions of the flat upper margin extending the cross-section to >100 m in width. Each unit generally fines upward and lies on a sharp, erosional boundary across which grain size abruptly increases. Isolated sandstone bodies incised into underlying mudstone facies are typically strongly convex-up.

Individual beds in this assemblage average 1 m in thickness, and are distinguished by their shape and internal structure (Fig. 5A). The sharp basal contact is overlain by trough-crossbeds (St) and a sparse assortment of gravel-sized fragments of reworked nodules, fossilized wood, and bone (Gl). Thicker sandstone bodies also may feature planar crossbeds (Sp) and sheet-like bodies display low-angle inclined surfaces (Sl), usually covered with a thin veneer of mud and/or coalified plant fragments. Ripple-lamination in small sandstone channel fills (Sr) occurs at some upper, abrupt gradational contacts of sandstone bodies

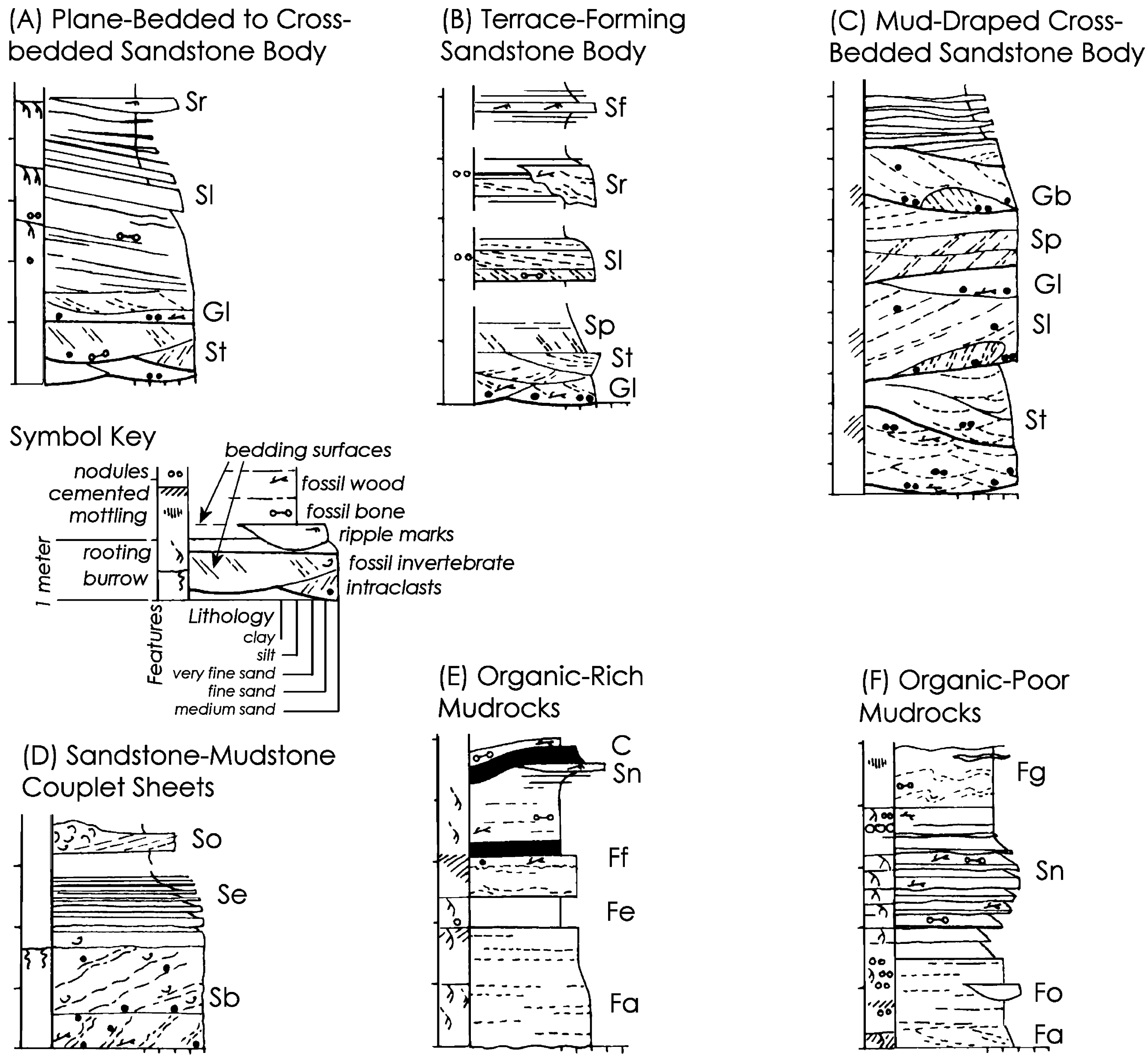

FIGURE 5—Typical arrangement of facies within the six facies associations of the HCF. Each image is a composite of several field examples. Facies nomenclature from Table 2.

with overlying mudrocks. Bedding surfaces usually are obscure, most often revealed in the presence of erosion-resistant nodules, stringers, or thin sheets of siderite and patchy calcite cement.

This association, also described from the HCF by others (Pagani, 1985; Rahmani, 1988, 1989), represents a fluvial channel in a low-sinuosity fluvial system. The fining-upward bedding and the inclined surfaces imply the presence of laterally migrating point bars, but these are not numerous in the HCF sandstone bodies. Channel amalgamation, crosscutting bedding surfaces, basal trough crossbedding, and fossiliferous lags at the base of the association suggest channel incision occurred during relatively high-energy flow. The waning-flow progression of bedforms, the abrupt decline in grain size below the upper contact, and the muddy intercalations at the upper contact are interpreted to signal abrupt abandonment of channels followed by prolonged infilling by fine clastic material.

Terrace-Forming Sandstone Bodies

Broad, radially thinning sheets of medium sandstone make excellent visual markers around Drumheller, forming benches traceable up to 4 km along the exposure. The resistant nature of these benches, exposed in three dimensions by the dissection of the strata by coulees and the valley wall flanking the Red Deer River, demonstrates that each of these units has a laterally extensive, flat-based lenticular shape, up to 2 m thick at its thickest and distally splitting into two or more sandstone sheets intercalated with mudrocks.

The thickest portions of each sheet (Fig. 5B) feature two or more 0.5-m-thick tabular units of trough crossbeds (St) or planar crossbeds (Sp), with bedding surfaces marked in places by gravel-sized fragments of wood, bone, reworked nodules, and rounded mudstone clasts (Gl). Laterally, each sheet pinches and the crossbedded facies grades into thin tabular beds of low-angle plane beds (Sl) intercalated with less common ripple-laminated channel lenses with erosional concave-up bases in places strewn with gravel-sized fragments of wood and bone (Sr). Distally these facies are displaced by beds <10 cm thick of ripple-laminated very fine sandstone or siltstone (Sf).

This association is interpreted as a crevasse-splay or avulsion complex, with the thickest area of the sheet representing filled channels closest to the crevasse. The lateral variation in lithology and internal architecture in splays and avulsions have been described by studies of ancient and modern examples (Ghosh, 1987; Smith et al., 1989; Törnqvist, 1993). The relatively coarse material, crossbedding, and small channels of the thicker portions of these terrace-forming sandstones suggest rapidly modified anastomosing flow. The absence of evidence indicating bioturbation or pedogenesis indicates that this facies was deposited and buried quickly, in keeping with the rapid aggradation associated with modern avulsions (Smith et al., 1989; Nanson and Knighton, 1996).

Mud-Draped Crossbedded Sandstone Bodies

Broad belts of litharenitic sandstone >100 m wide and up to 15 m deep fill concave-up erosional incisions into the laminated mudstone of the upper Bearpaw Formation. Erosional bases of smaller lens-shaped bodies, each >10 m wide and 1–4 m thick, stack atop one another and internally subdivide the belt. Each of these lens-shaped sandstone bodies is partitioned internally by low-angle planar bedding surfaces, which pinch out against or are truncated by the small-scale scours. Sediments of this association grade upward and downdip into mudrocks.

Sandstone dominates the association, with individual beds fining upward (Fig. 5C). Bedding surfaces are present but obscure, particularly in the basal half of the fill. Basal beds feature large-scale trough-crossbeds (St) and tilted blocks up to 4 m long of laminated strata (Gb) with an apron of coarse debris, including chunks of the block, reworked nodules, rip-up clasts, and *Teredolites*-bored logs on one side. Similar but more sparse lags (Gl) reveal a few internal bedding surfaces. Tabular sheets of planar crossbeds (Sp) overlie the trough-crossbedded facies in places. The upper half of each belt features thin inclined beds of fine sandstone draped with brown mudstone and/or plant hash (Sl), a facies representing about half the fill of each body. The transition to overlying mudrocks is gradational but relatively abrupt. Siderite cements *Ophiomorpha* burrow-fills and other ichnofossils near some upper contacts, and calcite-cemented sandstone reveals bedding surfaces.

This association has been described in previous work as representing a tidally influenced upper and middle estuarine channel (Rahmani and Hills, 1982; Rahmani, 1988, 1989; Bhattacharya, 1989; Ainsworth, 1991, 1994; Eberth, 1995, 1996). The fining-upward trend, the abundant trough crossbedding, bank-collapse blocks with attendant wedges of debris attenuated downstream, and crosscutting erosional scours at several scales indicate incised channel deposition (Rahmani, 1989). The mud drapes vary cyclically in thickness and are doubled in places, characteristic of tidally influenced slack-water deposition (Rahmani, 1989; Ainsworth, 1994). The alternating sandstone-mudstone bedding also is known as inclined heterolithic stratification (IHS) and is characteristic of migrating sandstone bars in an estuarine channel (Wood et al., 1988; Facies E of Rahmani, 1989; Eberth, 1995).

Sandstone-Mudstone Couplet Sheets

This facies association consists of >1-m-thick sheets with sharp, relatively flat, non-erosive contacts. Between Coal Seams 0 and 1, this facies grades laterally over several kilometers into a crossbedded sandstone body with mud drapes (facies association described above) at the base of the HCF. It also forms most of the Drumheller Marine Tongue interval surrounding Coal Seam 10.

Paired flat or gently undulating laminae of very fine sandstone and pale green or gray silty mudstone (Se) form stacks of couplets characteristic of this association (Fig. 5D). Sandstone laminae are generally the thicker of the pair, are ripple-laminated, and rest on an irregular but sharp base. Thick mudstone laminae feature amber, freshwater bivalve fragments, bone fragments, and teeth. In a few places, the flat bedding is interrupted by irregular clusters of jumbled, broken *Ostrea* and *Crassostrea* in calcite-cemented siltstone (So). Below Coal Seam 1, this facies is bioturbated extensively (*Diplocraterion*, *Ophiomorpha*, *Macaronichnus*) and overlies a plane-crossbedded sandstone with coal clasts, sulfur minerals, and glauconite (Sb).

This association represents a filled lagoon in an estuary. The sandstone-mudstone couplets record washover events or storms interrupting otherwise calm deposition in a back-barrier lagoon. Just above Coal Seam 1 near Willow Creek, this facies also preserves undulating bedding and reworked coalified fragments that suggest storm-driven oscillatory flow in the estuary. The types of bioturbation seen there and presence of glauconite also imply shallow marine conditions. In strata of the Drumheller Marine Tongue, this facies does not include undulatory bedding, reworking, or bioturbation, and couplets are generally thinner and feature a greater component of mud, reflecting a less active back-barrier lagoon. The presence of both brackish and freshwater invertebrate and terrestrial vertebrate fossils in DMT mudrocks suggest that these facies may record the limit of marine influence in the lagoon (Haglund, 2001) or that storm runoff periodically flushed fragmentary terrestrial vertebrate remains into a lagoon.

Organic-Rich Mudrocks

Carbonaceous mudrocks occur within many of the sandy associations, but four intervals of the lower HCF are dominated by these facies, each a virtually uninterrupted, flat, thickly bedded sheet 10–15 m thick. These intervals include several coal seams (informally termed a “swarm” by Straight and Eberth, 1998), are separated from similar swarms by up to 30 m of sandy facies, and are generally lighter in color and contain less coal than the next oldest swarm. Photomosaic images document few crosscutting relationships in this association, although coal seams do split in places.

Seams of blocky bituminous coal (C) include lignite, partly silicified wood fragments, stumps, amber, bentonite, and, below Coal Seam 2.0, sulfur minerals (Fig. 5E). In swarms, several 0.1-m-thick coal seams are interbedded with blocky pale gray and laminated fissile black shaly mudstone (Fa). Plant fragments, black root traces, slickensides, and amber increase in abundance proportionally with darkening color, whereas bone is rare. Coal seams in many places lie on a thin, cemented pink mudstone (Ff) featuring slickensides, amber, root traces, and wood fragments; coals at the top of each swarm also underlie this facies. In a few exposures, coal seams appear to arch over 20-m-wide lenses of thinly bedded silty mudstone and sandstone couplets (Sn); the same facies appears as laterally extensive sheets between carbonaceous seams in strata just below the DMT. A massive dark brown claystone with a granular parting (Fe) frequently overlies the coal seams in the middle and upper portion of each swarm. Isolated lenses of sandstone <1 m thick are encased in mudrocks between some of the coal seams.

This association is interpreted as sediments deposited in a saturated floodplain backswamp. The sulfur minerals, stumps, and woodgrounds of the coals lowest in section (Seams 0, 1, and 2 of Gibson, 1977) represent wetlands under marine influence. Thinner blocky coals represent freshwater abandoned-channel swamps. Thin coals containing amber and wood fragments may have been deposited on swampy, rapidly accreting, low-gradient floodplains (Nanson and Knighton, 1996), preserved by the thinly bedded mud/sand couplets representing floodplain levees. Slickensides in the pale mudstone facies indicate seasonal drying of swampland, preventing peat accumulation (Retallack, 1990; Aslan and Autin, 1998, 1999). The slickensides, cementation, and rooting in the cemented horizons above and below the coal seams indicate periods of pedogenesis. The brown granular facies may represent freshwater marsh deposits (Retallack, 1990) or those of distal splays or avulsions (Törnqvist, 1993).

Organic-Poor Mudrocks

Although the mudrock content of lower HCF strata remains relatively constant (mean 55%) through the section, thin intervals dominated by this association occur more frequently toward the top, at the expense of more organic-rich mudrocks, which dominate or exclusively comprise fine-grained intervals toward the base of the section. The fine-grained facies of the organic-poor association also are found as minor components of intervals dominated by the more coarse-grained associations described above. In the field, organic-poor mudrock facies appear to grade laterally over >100 m into one another, but photomosaic images show that unit relationships and shapes are highly variable. Contacts between units of this association range from simple horizontal stratification to irregular and intensely crosscut; units vary in form from laterally tapering, flat sheets to broad, shallow mud-filled scours with irregularly truncated upper margins. Numerous small channel fills and larger stacked channel complexes incise into or even through this convoluted bedding scheme.

Orange, red-brown, or tan silty mudstone with thick sandy laminae (Fo) includes oxide-cast root traces, siderite nodules, and slickensides (Fig. 5F). Similar blocky green-gray mudstone with distorted enclaves of siltstone (Fg) includes bright green traces of hydrophilic clay, mica flakes, root traces, and tiny bone fragments. Gray carbonaceous mudstone with sparse coaly particles (Fa) appears as 0.1-m-thick discontinuous seams. Silicified wood, sparse amber, and oxide-casts of roots and leaves occur in couplets of green-gray or tan very fine sandstone and silty mudstone (Sn). Clusters and strings of siderite nodules are not limited to bedding planes, in places crossing distinct contacts. In some places, polygonal networks of vein-like siderite concretions appear in patches on exposed bedding planes.

This association is interpreted as a seasonally dry, inland floodplain with slow deposition relative to facies of the organic-rich association. The sandier facies represent broad, low-angle levees and splay lobes, pedogenically developed and churned into underlying sediments by rooting, reworking, repeated wetting and desiccation, and possibly dinosaur trampling. Mudstone-filled channels may represent abandoned channels (Rahmani, 1988), and the alternating horizontally bedded sandstone and mudstone represent intercalating levee and thin distal splay deposits as described by Ghosh (1987). Blocky peds, nearly homogenous grain size, clay illuviation, and oxide casts of roots in the fine-grained facies imply advanced pedogenesis relative to other paleosols in the HCF.

PALEONTOLOGICAL AND STATISTICAL METHODS

Eight areas in the lower HCF (Fig. 2) were chosen for surveys of exposed fossil remains. Each area covers at least 250,000 m^2 and was selected for minimal slumping, minimal vegetative cover, and low slope with few slope breaks to provide good overall exposure without over-emphasizing the tops of resistant units. Surveys were conducted in areas with limited recent collecting. For each site (herein a square meter containing one or more fossil remains) encountered during the survey, position was recorded geographically by GPS and stratigraphically in relation to at least two stratigraphic markers including coal seams and terraces. For each of the 527 sites recorded in the lower HCF, position, facies, and proximity to adjacent sites were tabulated for statistical studies (Appendix).

Three statistical analyses were applied to facies and fossil distribution data from this study to determine if the stratigraphic distribution of fossil sites is dependent upon the stratigraphic arrangement of facies, facies association, and/or lithostratigraphic surfaces. The first analysis is a comparison between facies data from measured sections and facies data from the fossil surveys, treating the entire lower HCF as a single unit. To test the stratigraphic dispersion of fossil sites for dependence upon (1) facies distribution and (2) lithostratigraphic surface distribution (described below), however, facies and fossil data were binned into 4-meter-thick intervals. Incremental binning of the data was applied to avoid the *a priori* assumption of stratigraphic patterns in one or both data sets. Interval thickness was chosen to minimize ties in rank among stratigraphic position data while retaining the non-random dis-

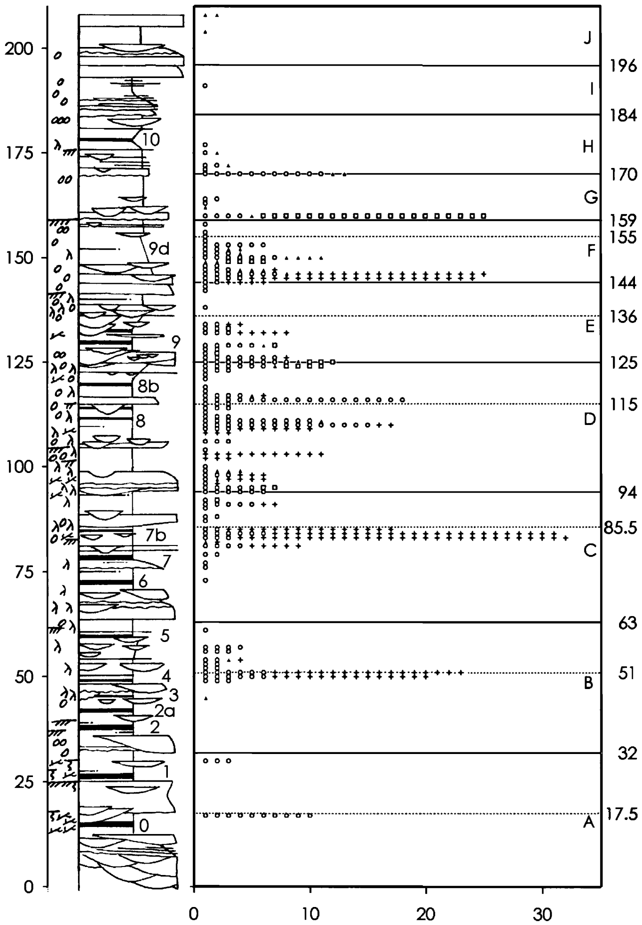

FIGURE 6—Composite section and distribution of vertebrate fossil sites in the lower HCF. Key to symbols and format as in Figure 5. Numbers right of section refer to coal seams, modified from Gibson (1977). Basal scours (solid horizontal lines in plot) and internal surfaces (dotted horizontal lines) partition the section into ten packages (letters A-J), based on facies relationships in measured sections. Stratigraphic position of fossil sites to nearest meter is based on fossil survey data. Circles represent solitary sites; triangles, microsites; crosses, sparse bonebed sites; squares, packed bonebed sites.

tribution of facies and fossil sites evident in the sections and fossil stratigraphy (Fig. 6). Three non-parametric statistical tests were used for the analyses: the Spearman rank order correlation and chi-squared two-sample tests for their ability to handle the ordinal fossil count, and the Kolmogorov-Smirnov test for its additional comparison of sample dispersion. Each group of independent data also was compared to at least ten synthetic, randomly-generated fossil distributions to determine if the real fossil site data correlated better than a random stratigraphic dispersion of fossils.

Most of the fossils were left undisturbed during the survey, although a few specimens were collected for geochemical and mineralogical analysis. For each of 19 powdered bone samples from the lower HCF, a diffraction pattern from 5° to 65° 2θ was collected on a Rigaku D/Max-B X-ray diffractor to test for diagenetic alteration of fossil remains (Appendix).

DISTRIBUTION OF VERTEBRATE REMAINS

In the lower 90 m of the study section, fossil sites are clustered within 1-to-4-m-thick fossiliferous horizons (Fig. 6), with the intervening strata virtually devoid of fossils. In the upper half of the section, similar fossiliferous horizons are thinner, and the intervening strata contain some sites. Strata of the DMT are impoverished in fossil remains, with a few thin horizons bearing the majority of sites. Within each fossiliferous horizon, sites occur in up to four types of spatial arrangements. Solitary fossils separated by at least 20 m from any other remains account for 50% of lower HCF sites. Several sites at the same stratigraphic level in the same geographic area are termed bonebeds and appear in two forms in the lower HCF. Sparse bonebeds have 1–2 fossils per site, with sites separated by up to 5 m, but this low fossil density often covers more than 100 m^2. Sparse bonebeds account for 37% of the sites documented in the lower HCF. A packed bonebed can cover up to 20 m^2, with each site holding several bones lying in contact, immediately adjacent to one or more sites. Packed bonebeds occur in four horizons within the surveyed areas, but together cover almost 40 m^2, accounting for 7% of the documented sites. The remaining 6% come from microsites, accumulations of tiny fragmentary remains of small freshwater vertebrates and weathered teeth of dinosaurs and mammals (Brinkman, 1990). An individual microsite may cover 10 m^2 but also can occur as a patchwork of smaller sites in similar facies along a stratigraphic horizon. The dominance of solitary and sparse-bonebed sites indicates attritional accumulation as the mode in the lower HCF.

Fossils in the lower HCF are preserved as pale blue, purple, tan, brown, or glassy black bones and bone fragments up to 150 cm in longest dimension. Results of X-ray diffraction (Appendix) indicate that fossils throughout the lower HCF are preserved as carbonate hydroxyapatite, consistent with fossilization in fluvial sediments and with minimal diagenetic change (Lucas and Prévôt, 1991; Person et al., 1995), even where specimens preserved in coal appear corroded. Facies data from the fossil surveys correlate closely with bulk facies distribution from the lower HCF stratigraphic sections (Table 3). Mudrock facies and coal contain 66% of lower HCF sites, and facies characteristic of floodplain environments (mudrocks, coal, and splay sediments) contain 85% of the sites (Table 4). Most of the

TABLE 3—Distribution of facies in raw section data and from fossil sites. Facies listed in Table 2 not included here collectively comprise less than 10% of the lower HCF and contain less than 1% of HCF fossil sites. Results of correlation between facies distributions are significant; $r = 0.789$, two-tailed, 0.01 level of significance, $n = 15$.

Distribution of facies . . .	Fa	Fe	Ff	Fg	Fo	C	Sl	Sn	Sr	St
. . . from fossil sites	19%	6%	10%	8%	13%	10%	10%	7%	12%	5%
. . . in raw section data	30%	6%	2%	7%	7%	7%	12%	7%	7%	6%

TABLE 4—Distribution of sites and site arrangements within different facies associations in the lower HCF. The other two facies associations preserve no fossil remains.

	(1) Plane-bedded, cross-bedded sandstone body	(2) Terrace-forming sandstone body	(5) Organic-rich mudrocks	(6) Organic-poor mudrocks
Total Sites	88	50	228	161
Solitary	52	28	112	69
Packed Bone-bed	15	3	0	20
Sparse Bone-bed	15	16	107	9
Microsite	6	3	9	16

bone in channel facies occur alone, usually on bedding surfaces with reworked mud clasts, reworked siderite clasts, and wood fragments. However, within each fossiliferous horizon, sites occur in a broad mix of facies, associated with lateral facies change. Non-fossiliferous intervals incorporate the same or greater thickness of facies in which fossils elsewhere in the section are preserved in abundance. Thus, the stratigraphic arrangement of facies and fossils is not consistent.

To test the hypothesis that the stratigraphic arrangement of fossils is independent of facies arrangement, facies data from the measured sections and fossil sites were subdivided into 4-m-thick intervals and compared statistically (Table 5). The stratigraphic distribution of fossil sites was compared to the percentage of each facies at the 0.05 level of significance for each test. All Spearman rank order correlation tests rejected the hypothesis (no relationship), except for facies Fo, which was significantly related at the 0.01 level; the other statistical tests of distribution were rejected. Statistical tests on ten synthetic fossil distribution models also rejected relationships for each facies most of the time, although the Spearman rank order correlation test detected a relationship once for each of five of the facies (Table 5). Similar tests comparing the distribution of facies associations to that of fossil sites also generally rejected a relationship. In essence, fossil sites are distributed randomly through the facies of the lower HCF. Therefore, the stratigraphic pattern in fossil distribution (Fig. 6) is related to some characteristic of ecology, burial, or preservation other than lithology.

STACKING PATTERNS IN FACIES ASSOCIATIONS

A typical stacking pattern in the arrangement of facies associations of the lower HCF is herein termed a *package,* a fining-upward, laterally continuous interval of strata bounded by erosional surfaces. The package pattern repeats ten times through the lower HCF section, although some packages are incomplete. These ten packages are designated informally here as “A” at the base of the lower HCF to “J” in the DMT (Fig. 6). Based on measured sections, field observations, and outcrop photographs of the ten packages in the lower HCF, a typical 30-m-thick package consists of eight intervals defined by their facies association (Fig. 7).

Interval a (Facies Association 1)

The irregular scour under a broad sandstone sheet is the basal contact for the typical package. Overlying the scour is a sandstone channel fill capped by lateral accretion surfaces that alternate upward with thin beds of mudstone. Locally, channels filled with fine sandstone incise the top of this sheet and in places are stacked several deep.

Interval b (Facies Association 5)

A relatively thick interval of organic-rich mudrocks includes as many as four coal seams, progressively thinner and more woody upward in section. Sandy channel fills encased in the mudrocks are up to a meter thick and are commonly lens-shaped, although some are sheet-like and up to 100 meters wide.

Interval c (Facies Associations 5 and 2)

An interval of gray mudrocks encases small channel lenses and less common crevasse-splay sheets with narrow stacked channel fills on top. The channels are 0.5 m thick and up to 25 m wide, whereas the splays extend over 100 m

TABLE 5—Statistical comparison of relationship between the stratigraphic dispersion of facies against the stratigraphic dispersion of fossil sites. Each statistical test of the fossil survey data (*no* indicates no relationship at the level of significance for the test) is contrasted with similar tests against ten synthetic, random fossil site distributions (listing is the number of tests resulting in a significant relationship).

	Individual facies										Facies associations			
	Fa	Fe	Ff	Fg	Fo	C	Sl	Sn	Sr	St	(1)	(2)	(5)	(6)
Spearman rank														
survey, 0.01 level	no	no	no	no	yes	no	no	no	no	no	no	no	no	no
survey, 0.05 level	yes	no	no	no	yes	no	yes	no	no	no	no	no	yes	no
random, 0.05 level	1	1	0	0	0	1	0	0	0	1	0	0	0	1
Kolmogorov-Smirnov														
survey, 0.05 level	no	no	no	no	no	no	no	no	no	no	no	no	no	no
random, 0.05 level	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Chi-squared 2-sample														
survey, 0.05 level	no	no	no	no	no	no	no	no	no	no	no	no	no	no
random, 0.05 level	0	0	0	0	0	0	0	0	0	0	0	0	0	0

laterally with sharp flat bases that locally incise underlying strata. Coal seams are thin and shaly, but root casts and siderite concretions are more abundant upsection.

Interval d (Facies Associations 6 and 2)

Pale gray or tan mudrocks intercalate with coaly carbonaceous shale and thin tabular splays and finer-grained, more irregular silty levee couplets. Individual beds are usually less than 10 cm thick, laterally discontinuous over 10 m, heavily rooted, and contain common siderite concretions.

Interval e (Facies Association 2)

Point-bar sandstone beds 2 m thick extend laterally over 100 m, incised in places by small sandy channel fills. A sparse veneer of plant fragments, leaves, and reworked siderite concretions marks the presence of lateral accretion surfaces, which otherwise usually are distorted or not preserved.

Interval f (Facies Association 6)

One or two thin carbonaceous mudstone beds intercalate with shallow crosscutting lenses of clay- rich, mottled green or tan siltstone and mudstone with common root casts.

Interval g (Facies Associations 1 and 2)

Stacked splays and small channel fills intercalate with sheets of sandy levee couplets. Bedding surfaces are hard to detect in most places, but where seen are nearly flat, slightly inclined, or contorted. The scour at the base of the overlying package irregularly incises these sediments.

Variations

In the field, many packages differ from the archetype (Fig. 7) in some details. The basal interval of the lowermost package (A, Fig. 6) differs in that an estuary fill complex (Facies Association 3) overlies the basal scour and a washover fan and tidal flat deposit (Association 4) overlies the internal surface at Willow Creek. An extremely large channel complex overlies the same internal surface just southeast of Aerial, AB (Fig. 3). The four uppermost packages in the study (packages G, H, I, and J, the top 70 meters of the section, Fig. 6) are part of the Drumheller Marine Tongue and feature washovers and tidal flats (Association 4) instead of channels and organic-rich mudrocks. In terms of thickness, the packages of the lower HCF fall into three groups: (1) packages A-D are each ~31 m thick, matching the typical package; (2) packages E-G successively decrease in thickness; and (3) packages H-J are each ~12 m thick (Fig. 6). The organic-rich lower intervals are compressed, and splays and stacks of levee couplets are common in the thinner packages.

Two surfaces stand out in the package archetype (Fig. 7). The basal scour is laterally discontinuous, detectable under adjacent channel fills but untraceable in mudrocks between them. Because the channel fills vary slightly in thickness, the stratigraphic position of the scour varies by up to 4 m. A second surface under interval "e" divides the archetype into unequal parts and is marked by a sharp irregular contact across which grain size abruptly increases. This internal surface is distinct from the basal scour by more localized erosion and by less vertical variation in position. In the field, these surfaces occasionally are detectable using changes in facies

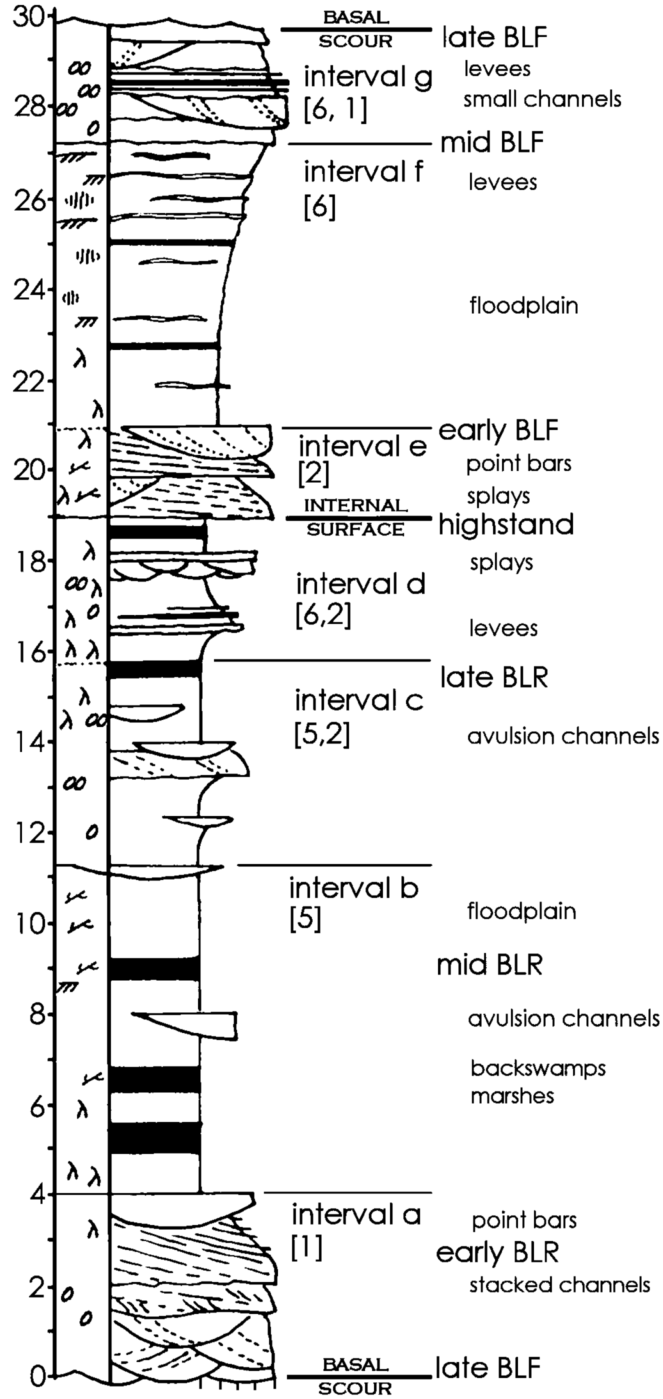

FIGURE 7—Typical package from the HCF. Key to symbols and format as in Figure 5. Intervals are marked by a vertical change in facies association. Thinner packages usually have thinner intervals b, e, f, and g; very thin packages do not preserve intervals above the internal surface, and the overlying basal scour truncates interval d. Base-level change interpretation discussed in text. BLR = base-level rise, BLF = base-level fall.

TABLE 6—Statistical comparison of relationship between the stratigraphic position of bounding surfaces (described in text) and stratigraphic position of fossiliferous horizons. Each statistical test of the fossil survey data (*yes* indicates a relationship was present at the level of significance for the test) is contrasted with similar tests against 20 synthetic, random fossiliferous horizon distributions (listing is the number of tests resulting in a significant relationship).

	Survey	In 20 random
Spearman rank order		
0.05 level	yes	0
Kolmogorov-Smirnov		
0.01 level	yes	0
0.05 level	yes	3
Chi-squared 2-sample		
0.05 level	yes	0

color and grain size. Stratigraphically below the internal surface, carbonaceous root casts are very common. Unusually large siderite nodules and nodule clusters occur up to 2 m beneath each type of surface (Fig. 6), and more prominently under the basal scour. Basal scours tend to be easier to locate in measured sections and in the field than the internal surfaces, and evidence for the internal surfaces in packages G-J is equivocal, indicating that those surfaces always may not be preserved.

FOSSIL OCCURRENCE IN PACKAGES

Packages of the lower HCF fall into three categories regarding the position of fossiliferous horizons. Packages A-D each feature a 2-to-3-m-thick horizon just under the internal surface (Fig. 6), with less productive horizons underneath. The first three packages also include thick sheets of essentially non-fossiliferous strata, whereas three minor fossiliferous horizons occur in package D in addition to the primary one associated with the internal surface. Packages E-H each feature a 1-to-2-m-thick horizon just above the basal scour (Fig. 6), with less productive auxiliary horizons immediately above. Packages I and J are essentially non-fossiliferous.

When the stratigraphic position of package surfaces (basal scours and internal surfaces) is compared to the stratigraphic position of fossiliferous horizons, the correspondence is visually striking (Fig. 6). The most productive fossiliferous horizon associated with the internal surface occurs in package C, with an almost symmetrical decline in fossil yield at internal surfaces up- (packages D and E) and down-section (packages B and A). Similarly, the most productive horizon associated with the basal scour occurs in package F, with symmetrically declining yield up- (packages G and H) and down-section (packages F and E). To test the visual correlation between horizons and surfaces, the same statistical methods applied to the facies data were used to compare the stratigraphic position of surfaces with the position of fossiliferous horizons. Horizon position was determined by marking each 4-m-thick interval with 10 or more sites (the mean number of sites for a 4-m-thick interval of the lower HCF). All three tests show significant relationship between surfaces and fossil horizons at the 0.01 level of significance (Table 6). Of twenty tests of synthetic, random horizon distributions, none detected a relationship at the 0.01 level of significance, although three were related significantly in the Kolmogorov-Smirnov test at the 0.05 level. Therefore, fossiliferous horizons are stratigraphically non-random and correlate with package surfaces, indicating that the timing and circumstances of their formation are related. The lithostratigraphic characteristics and the fossil record independently subdivide the packages of the lower HCF into the same three groups (A-D, E-G, and H-J), suggesting that the relationship is depositional and connected to larger-scale controls.

INTERPRETATION OF PACKAGE DEPOSITION

The repeating packages in the lower Horseshoe Canyon Formation are interpreted as a depositional response to a fall-rise-fall cycle in base level. During late base-level fall, low-sinuosity meandering rivers locally incised and reworked older floodplain deposits. The crosscutting scours made by the laterally migrating channels formed the irregular erosional basal surface (interval a; Fig. 7) that continued to expand until after base level began to rise again (e.g., Ghosh, 1987; Aitken and Flint, 1995; Cant, 1998; Robinson and McCabe, 1998).

During early base-level rise, accommodation increased, filling channels with coarse bedload, building laterally migrating point bars, and turning interfluves into marshes (see also Shanley and McCabe, 1994). As accommodation increased rapidly, levees grew and avulsion replaced migration as the common type of channel switching, creating stacked, amalgamated channel sandstone bodies (interval a; Fig. 7). Levees also partitioned the floodplain, temporarily starving the poorly drained interfluves of sediment supply, permitting available accommodation to fill with thick peat. At the zenith of the rate of base-level rise, accommodation reached a maximum, and river competence and gradient each reached a minimum. Avulsions and splays periodically deposited sheets of mud in interfluves (interval b), and the channel system split into a system of anastomosing distributaries (Törnqvist, 1993, describes a similar transition in the Rhine-Meuse delta during late Holocene base-level rise). The geometries of channel fills in the lower HCF packages suggest that drainage planform alternated between a Type 1b or 1c (anastomosing river system depositing mostly organic-rich mud by avulsion) and Type 3 (mixed-load laterally active anabranching rivers) *sensu* Nanson and Knighton (1996) during the deposition of each package. Owing to increasing accommodation, these narrow streams were abandoned and filled rapidly (see Smith et al., 1989; Nadon, 1994), preserved as encased channel fills. As aggradation exceeded accommodation, better-drained forest soils formed on broad levees at the expense of interfluve bogs (interval c). From waning base-level rise to highstand, accommodation decreased, and abandoned channels, avulsions, and splays left thinner, more closely packed sandy deposits between thinly bedded floodplain mudrocks (interval d; Törnqvist, 1993). Two-thirds of the typical package accumulated between the highest rate of base-level rise and immediately after highstand, following the model of Posamentier and Vail (1988).

During highstand, the anastomosing channels coalesced into fewer channels (Smith et al., 1989) and built levees of silty sand, forming the internal surface of the typical package (interval e). Avulsion ceased, and vegetated soils that developed on levees restricted lateral migration. The upward broadening and thinning of channel sandstone bodies and the upward increase in paleosol maturity in the package archetype resulted from diminishing accommodation space on the floodplain following highstand, in accordance with Wright and Marriott's (1993) model. During early base-level fall, the distributaries coalesced through channel abandonment, forming ribbon-like depressions filled with organic-rich silt and mud (interval f). A few channels gradually assumed the majority of the discharge, and rare floods or crevassing events resulted in stacks of extensive thin splays (preserved and modern examples described by Lehman, 1982; Smith and Perez-Arlucea, 1994) rather than new channels (interval g). The abandonment of the floodplain during late base-level fall resulted in long periods of pedogenesis (see Behrensmeyer, 1987; Bown and Kraus, 1993; Willis and Behrensmeyer, 1994; Behrensmeyer et al., 1995 for examples from the Siwaliks and from the Willwood Formation) between local deposition of sheets of muddy sediments from levees and distal splays (see Ghosh, 1987). Carbon dioxide from the decay of buried organic material and iron leached during soil formation mixed at the top of the water table and precipitated nodular siderite. During middle and late base-level fall, the river system reverted to a single-channel drainage that reworked uppermost floodplain sediments by lateral migration, creating the scour at the base of the next package, thereby completing the depositional cycle.

The variation of form among the ten packages in the lower HCF is interpreted as a response to the base-level rise and fall associated with the construction of the clastic wedge, occurring over a period of approximately 2 myr (Catuneanu and Sweet, 1999). The combination of this grand-scale cycle of base-level change (Fig. 8A) with ten smaller oscillations (Fig. 8B) describes a complex variation in accommodation availability through time (Fig. 8C). During later grand base-level rise and stillstand, accommodation space was produced continuously through each package-scale cycle, resulting in several full-thickness, thickly-bedded packages with more accumulation below the internal surface than above (packages A-D, Fig. 6). Coals, organic-rich mudrocks, and encased channel fills common in these packages are consistent with rapid aggradation. After grand highstand, the smaller cycle base-level fall allowed periods of zero and negative net accommodation, producing progressively thinner packages with greater erosional truncation at the tops (packages E-G). Reduced accommodation during the formation of these packages resulted in thin bedding, pedogenesis of mudrocks, and stacking of splays and levees, all characteristics of progradation and bypass. Grand base-level fall resulted in complete bypass or erosion during times of zero accommodation in each smaller-scale cycle, resulting in very little or no deposition and possibly creating a significant unconformity in the fluvial strata. During grand-cycle lowstand, the small-scale variation again controlled deposition, resulting in thin packages containing levees, paleosols, and possibly marine influence, and recording only small net accommodation increases (packages H-J).

Under this interpretation, the two surfaces in each

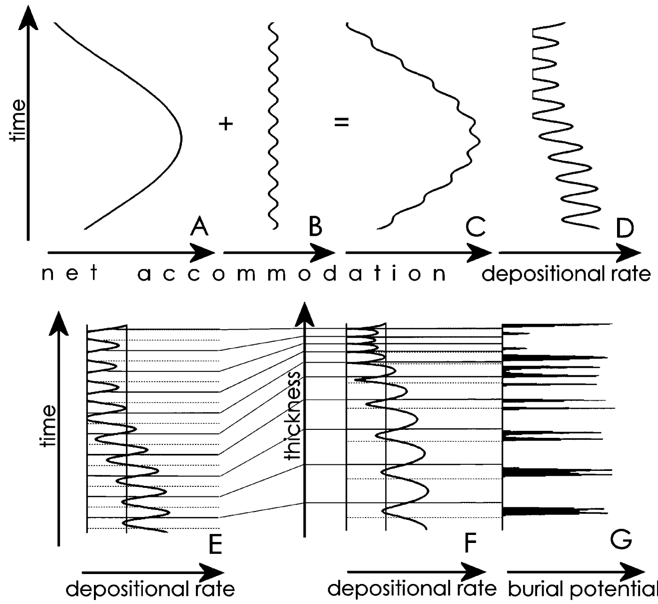

FIGURE 8—Modeling the stratigraphic distribution of fossils using only parameters of base-level variation in lower HCF. (A) Partial grand-scale cycle of variation in accommodation, probably reflecting subsidence throughout deposition of the lower HCF and DMT. (B) Ten package-scale cycles, probably resulting from climatically controlled pulses in sediment supply. (C) Sum of curves in A and B, showing complex variation of accommodation through time estimated for the lower HCF. (D, E) Relative proxy for depositional rate calculated from incremental variations in accommodation, assuming that at each time increment the available accommodation filled with sediment. The depositional rate is high between lowstand (solid horizontal line) and the following highstand (dashed horizontal line). (F) Depositional rate proxy with vertical axis reflecting preserved accommodation (accumulated thickness) instead of time. The model predicts the non-equal division of thick packages by highstand markers seen in HCF packages and has a similar three-fold hierarchy in package form (4 large packages of nearly equal thickness; 3 packages of successively diminishing thickness; and 3 thin packages without highstand markers). (G) Fossil burial potential, calculated by degree of similarity between depositional rate and an optimum rate for bone burial (vertical line through curves, E-F) for each increment of preserved accommodation. The resulting distribution and shape of peaks of fossil preservation potential are very similar to the distribution and shape of fossiliferous horizons in the lower HCF (dense isolated horizons on highstands in lower packages; thinner and weaker horizons on stillstands in middle packages; and a non-fossiliferous gap at the top). Changing any one of the parameters (cycle amplitudes and offsets, optimum burial rate, subsidence rate, etc.) in this mathematical model creates a very different distribution of fossiliferous and nonfossiliferous intervals, suggesting that terrestrial vertebrate distribution may permit a semi-quantitative discrimination of various local controls on accommodation.

package mark important changes in the rate of creation of accommodation space. The scour at the base of each package represents a surface of floodplain abandonment and incision during base-level lowstand. These surfaces incise paleosols and underlie point bar accumulations, both suggesting low accommodation availability. The internal surface in each package records base-level highstand. As no inundation occurs, this is not a true flooding surface, which does not form in floodplain deposits. Instead it marks the change from aggradation to progradation and bypass, a reduction in the rate of formation of accommodation space. This reduction creates the division of the typical package; the post-highstand deposits are thinner than pre-highstand in thick packages, and absent in thin packages.

INTERPRETATION OF FOSSIL HORIZON DEVELOPMENT

Structure, thickness, content, and stratigraphic position of fossiliferous horizons in the lower HCF packages were controlled by regional deposition rate, modified by the related interplay of the grand- and package-scale cycles in accommodation. Burial of fossils occurred during periods in which the mean regional depositional rate achieved a specific low, optimum rate for bone burial. Above this rate, individual bones were buried and preserved but highly dispersed in large volumes of sediment; below this rate, bones decomposed at the surface prior to burial or were exhumed and destroyed during periods of reworking. The density of fossil sites declines in the intervals immediately above and below fossiliferous horizons; if the site density in the fossiliferous horizon records an optimum burial rate, these less fossiliferous intervals suggest a burial rate diverging from the optimum through time.

During periods in which the grand-scale cycle of base level change boosted accommodation space when package-scale base-level rose (packages A-D, Fig. 6), potential fossils were swamped by sediment except during package highstand and fall, when mean deposition rates were least. At grand-cycle maximum, mean depositional rate was close to the optimum throughout package deposition, resulting in a scatter of sites through the package (package D) while still emphasizing depositional rate minima associated with package surfaces. Early grand-cycle fall reduced accommodation space during package-scale base-level rise and eliminated it after package-scale highstand, creating successively thinner packages without internal surfaces (packages E-G), in which the optimum depositional rate was recorded only after each package scour formed. During grand-cycle fall, accommodation space was seldom available, allowing long-term pedogenesis and possibly erosion of previously deposited fossiliferous strata. During grand-cycle recovery, accommodation space was available only during package-scale base-level rise, forming thin packages with sparse fossiliferous horizons above each basal scour (packages H-J).

A model of lower HCF deposition based on the simple curves describing accommodation availability through time (Fig. 8A-C) can be extended to test depositional rate as a control for fossil preservation. Assuming that at each time increment the available accommodation was filled, a relative proxy for depositional rate can be calculated (Fig. 8D, E). Changing the model's vertical axis from time (Fig. 8E) to preserved accommodation displays accumulated thickness in a simulation of the HCF rock record (Fig. 8F, G). The model predicts the division of the hypothetical succession into ten intervals, each bounded by lowstand markers and each split unevenly by highstand markers. If the lowstand and highstand markers in the hypothetical succession correspond to the basal scour and internal surfaces, respectively, of HCF packages, then the ten hypothetical packages in the model also have a similar three-fold hierarchy of form as the lower HCF (4 large packages of nearly equal thickness; 3 packages of successively diminishing thickness; and 3 thin packages without highstand markers; Fig. 8F). Although the model provides no prediction for actual counts of fossil sites per increment of deposition, a relative measure of the potential for bone burial can be calculated by comparing the depositional rate in each increment to an optimum bone burial rate (Fig. 8G). In increments in which the depositional rate is similar to the optimum burial rate, the likelihood of burying bone is high, whereas for increments with a dissimilar depositional rate the likelihood is low or zero. The resulting distribution and shape of peaks in fossil burial potential in the model (Fig. 8G) resemble the stratigraphic position and shape of fossiliferous horizons in the lower HCF (dense isolated horizons on highstands in lower packages; thinner and weaker horizons on stillstands in middle packages; and a non-fossiliferous gap at the top). Changing any one of the parameters (cycle amplitudes and offsets, optimum burial rate, subsidence rate, etc.) in this mathematical model creates a very different distribution of fossiliferous and nonfossiliferous intervals, suggesting that terrestrial vertebrate distribution may allow for a semi-quantitative discrimination of various local controls on accommodation. Similar, more comprehensive numerical models have predicted complex patterns of fossil distribution in marine sequences as a succession of fossiliferous horizons and nonfossiliferous intervals (Holland, 1995, 2000; Holland and Patzkowsky, 1999). The model used herein is included as part of the data repository (Appendix).

DISCUSSION: FLUVIAL PACKAGES

The typical lower HCF package described here is similar to models developed from other fluvial successions. Portions of the Kaiparowits Plateau and the Book Cliffs of Utah each have been used to design an architectural model for cyclic fluvial deposition (Shanley and McCabe, 1991, 1993, 1995; Kamola and Van Wagoner, 1995; Olsen et al., 1995). Studies of stacked paleosols in alluvial successions have produced similar results (Behrensmeyer, 1987; Bown and Kraus, 1987, 1993; Behrensmeyer et al., 1995; Currie, 1997). Theoretical interpretations of fluvial sedimentation describe repeating cycles in facies and architecture (Goodwin and Anderson, 1985; Posamentier and Vail, 1988; Galloway, 1989; Jordan and Flemings, 1991; Wright and Marriott, 1993; Martinsen et al., 1999). Both types of interpretations attribute the facies distribution and structure to variations of accommodation controlled, in turn, by three component forces: tectonic uplift and subsidence, eustasy, and climate. Of these three, subsidence appears to have played a crucial role in the relatively continuous production of accommodation space, possibly as the mechanism behind the grand-scale variation in base-level (Shanley and McCabe, 1998). The package-scale rhythms in fluvial strata occur on time-scales consistent with Milankovitch cycles and may represent direct climatic control on precipitation (Martinius, 2000) or some indirect control, such as fluctuations of sea-ice volume during the Cretaceous (Stoll and Schrag, 1996; Miller et al., 1999). Given the number of different regions, depositional environments, and time intervals in which the same general rhythm forms in fully fluvial strata, package structure appears to be independent of the individual factors controlling accommodation and base level.

A critical element in the description of accommodation-controlled repeating structure in sedimentary successions is the presence of easily detectable reference surfaces, but these lithologic boundaries are difficult to recognize in fluvial rocks. In coastal margin and marine settings, unconformities at the juxtaposition of marine and fluvial facies mark flooding and withdrawal surfaces, but these boundaries disappear inland with the absence of marine facies. For example, an extensively bioturbated surface beneath Coal Seam 1 in the basal HCF exposures near Willow Creek is associated with a drop in mean sea level (Ainsworth, 1991, 1994; Straight and Eberth, 1998) but is not traceable more than 3.2 km updip. Ideally, transgressive flooding surfaces, represented in shelf deposits as the condensed section, should correlate inland to the entire portion of the typical package beneath the internal surface rather than the surface itself. Although the basal scours under sandstone bodies create easily visible surfaces representing the base-level lowstand, these are laterally discontinuous in the lower HCF (Fig. 3) and untraceable in thick intervals of mudrocks. Best and Ashworth (1997) cautioned against the interpretation of scours as bounding surfaces where scour relief is less than five times the bankfull depth and interbasin continuity of surfaces cannot be ascertained, both of which are true in the lower HCF. Further, the scour is not truly isochronous, formed by lateral migration and/or channel avulsion over a period of relatively low accommodation (Wright and Marriott, 1993; Olsen et al., 1995).

In the absence of clear lithological surfaces, the tops and bottoms of marker intervals might be used as reference points, but these similarly are unreliable in the lower HCF. The sandstone units and coal seams make poor markers because they are laterally discontinuous, removed by later erosion in places, and highly variable in thickness, internal construction, and content. Laterally continuous splays form terraces that resist erosion and may represent a short enough time interval to make useful markers, but all four such terraces in the 210 m of the lower HCF cluster between Coal Seams 7 and 8b, a range of about 30 m vertically. Paleosols of the lower HCF are often little more than zones of preserved rooting, and are too rare and too poorly developed to serve adequately as markers. Intense leaching zones are absent in the lower HCF. In this case, lithologic surfaces alone are not adequate to subdivide the lower HCF. Thus, package structure is described here first on the basis of repeating stacking patterns in facies associations, rather than starting with the identification of important surfaces.

In contrast to other markers, fossiliferous horizons in the lower HCF are laterally extensive, relatively continuous, and independent of facies. They can be identified easily in the field, even in intervals dominated by mudrocks or paleosols. They correlate stratigraphically to the position of the important internal surfaces and basal scours of the packages in the lower HCF. Horizon density and composition appear to provide information on variations in accommodation within packages as well as variation between packages. Hence, the terrestrial fossil record provides a powerful tool to aid in the recognition, description, and interpretation of package structure in the lower HCF, and possibly in other time-equivalent strata.

The terrestrial fossil record at other sites may reflect package structure similar to that of the lower HCF. The stratigraphic distribution of dinosaur remains in the upper 60 m of the Hell Creek Formation from Montana (Sheehan et al., 2000) is described in terms of individual animals rather than sites, but particular intervals stand out as relatively more fossiliferous horizons than the formation average. The variation in fossil yield may indicate the presence of important surfaces associated with depositional cycles. Vertebrate remains were preserved in migrating point bars in highly sinuous meandering river systems of the Dinosaur Park Formation (Wood et al., 1988; Eberth, 1990; Brinkman et al., 1998), as reworked lags in the channels of the Straight Cliffs of Utah (Shanley and McCabe, 1991, 1993, 1995; Shanley et al., 1992), in channel lags, abandoned channel fill, splays, and paleosols in the Siwalik Dhok Pathan and Nagri Formations of Pakistan (Badgley, 1986; Behrensmeyer, 1987, 1988; Willis and Behrensmeyer, 1994), and in well-developed cross-cutting soil horizons of the Eocene Willwood Formation (Bown and Kraus, 1993). All these facies are associated with low, stable, or falling accommodation. Such conditions are consistent with the formation of fossiliferous horizons during stillstands, as in the lower HCF.

Although the terrestrial vertebrate fossil record of the Campanian Two Medicine Formation is similar to that the lower HCF, there appears to be only poor correlation between stratigraphic position of two third-order sequence boundaries and the distribution of vertebrate remains (Rogers and Kidwell, 2000). The difference in correlation may have arisen because the surfaces revealed by horizons in the lower HCF are probably of fourth or higher order because they represent internal partitions of a single clastic wedge. If a third-order surface is present in the lower HCF, it would be at the base of the Drumheller Marine Tongue, the scour between packages G and H. Fossil remains are comparatively rare in package G, and package H is almost nonfossiliferous; this is consistent with the results of Rogers and Kidwell (2000). The relatively shorter duration of fourth- or higher-order depositional hiatuses may make them more compatible with taphonomic processes than the duration of third-order breaks.

DISCUSSION: HORIZON FORMATION

In the present interpretation, sedimentation rate is the dominant control on the distribution of fossil sites in the lower HCF. Vertebrate remains are effectively large (grain-size) clasts; hence, their accumulation and burial depend at least in part on accommodation availability and sediment supply. Bonebeds and fossiliferous horizons accumulated in conjunction with surfaces associated with low but nonzero accommodation and, therefore, under a low regional sedimentation rate. However, other potential controls of site distribution and preservation—ecological distribution of animals, environment, and post-depositional diagenetic pathway—must be examined as potentially important factors in the accumulation of lower HCF fossiliferous horizons.

Diagenesis after burial selectively favors or destroys accumulations based on groundwater and sediment chemistry. Fossiliferous horizons might be formed by selective, post-burial destruction of bone by some combination of pedogenic processes, groundwater dissolution, and microbial activity. However, most fossils in the lower HCF are buried in clay-rich mudrocks, generally more resistant to groundwater flow than sandy channel facies. Lower HCF strata are also entirely lacking bone casts or pseudomorphs. Mineralization from groundwater in sandy facies formed siderite nodules around bones instead of dissolving them. The abundance of siderite in lower HCF argues for high groundwater pH (Bao et al., 1998), well above levels at which bone mineral is insoluble (Lucas and Prévôt, 1991). Even where remains were deposited in peat, wherein groundwater pH approached bone solubility, HCF fossils are composed of carbonate hydroxyapatite, typical of fossilization in fluvial deposits with little alteration except recrystallization (Lucas and Prévôt, 1991; Person et al., 1995). Although diagenesis may act as a regulator of fossil preservation in some fluvial successions, it is a minor participant in the lower HCF.

Environment controls the effects of climate, precipitation, surface exposure, and topography on the spatial distribution of remains. Hence, where environmental control is dominant, the distribution of fossil sites would likely be a patchy, facies-dependent distribution, consistent with a mosaic of local microenvironments, rather than a facies-independent, even spread of remains. Given the lack of correlation between facies and sites in the lower HCF, specific microenvironments do not appear to have contributed to bone preservation. Although facies associations representing the suite of interfluve environments incorporate the majority of sites in the lower HCF, there are intervals of equal thickness and of the same associations that are essentially nonfossiliferous. Thus, environment appears to be a secondary control of fossil distribution in the lower HCF.

The ecological distribution of animals and plants controls the diversity and abundance of remains supplied to the taphonomic filter. Fossiliferous horizons might result if faunal populations on the clastic wedge were strongly variable. However, horizons formed by this control should have no particular connection to depositional surfaces unless the variations in population density were controlled indirectly by another factor that also contributed to burial, such as sedimentation rate or environment. For example, a highly populated ecotone that paralleled a coastline and moved with it during base-level changes might have buried remains only during the formation of highstand surfaces. In order to form the fossiliferous horizons preserved in the lower HCF, the terrain flanking the ecotone would have been nearly uninhabited, inconsistent with modern tetrapod population distribution. To produce the fossil record of the lower HCF, a second high-population ecotone would have had to parallel the first to manufacture horizons associated with lowstand deposits. Although unlikely, this scenario cannot be ruled out by the sedimentologic and taphonomic data presented here.

SUMMARY

A growing mass of research into terrestrial strata reveals repeating rhythms in fluvial deposits. A similar pattern was found in the tidally influenced coastal margin and fluvial sediments of the lower Horseshoe Canyon Formation, exposed in the Red Deer River Valley around Drumheller, Alberta, Canada. In this 210-m-thick clastic succession, each repetition of the package occurs as an upward-fining chronostratigraphic sheet of strata, with a basal scour-bottomed sandstone body or amalgamated channel sandstone, overlain by mudrocks encasing narrow sand-filled channels, then splays, levees, and/or paleosols. The vertical and lateral juxtaposition of facies in each of the ten packages was moderated by a fall-rise-fall cycle in base-level, consistent with interpretations of package-like rhythms of other studies. Two important stratigraphic surfaces in the typical package, the basal scour and an internal surface, correspond to the base-level highstand and lowstand, respectively. These surfaces are laterally discontinuous, hard to locate in the field, and not always preserved, limiting their usefulness in assembling a sequence-stratigraphic framework in this fluvial succession.

Terrestrial vertebrate fossil occurrence in the lower HCF, based on field surveys of surface fossil yield, is facies-independent but linked to cyclic stacking patterns in fluvial facies. Relatively high-density accumulations of fossil sites (horizons) correspond to most of the stratigraphic surfaces preserved in the ten packages in the lower HCF. Fossiliferous horizons were formed by low sedimentation rate and low accommodation associated with stillstands. Variations in the fossil density of successive horizons through the lower HCF arise from the interaction of the package-scale base-level cycle with the grand-scale cycle associated with the formation of the clastic wedge. The lowest four packages, A through D, are each ~31 m thick and feature a fossiliferous horizon on the internal (highstand) surface. Packages E through G are successively thinner, and feature fossiliferous horizons on each basal scour and numerous solitary sites throughout. Packages H, I, and J are associated with the transgressive Drumheller Marine Tongue and are nearly nonfossiliferous.

Terrestrial vertebrate fossils have received little attention as information from which to construct stratigraphic frameworks in fluvial successions, but in the lower Horseshoe Canyon Formation they not only recapitulate nearly invisible stratigraphic surfaces but also provide insight into the interplay of two scales of base-level variation. Earlier studies indicate that fossil distribution in other fluvial successions may preserve information for the construction of architectural frameworks. The fossil distributions within other fluvial successions need to be tested to assess the power and scope of the terrestrial fossil record as a tool for revealing stratigraphic frameworks.

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APPENDIX

The nine measured sections comprising the lithostratigraphic component of the project are available at SEPM's Data Repository site: http://www.ngdc.noaa.gov/mgg/sepm/archive/straight2002_01. A series of stratigraphic columns are provided in .jpg format; the symbol key and diagram legend are included with the short Wolf Coulee section (WolfKey.jpg).

The numerical model of fossil distribution used to create Figure 8 is part of the data repository. The individual graphs appear on columns AK-AS of the spreadsheet. The main diagram showing relative fossil count (x-axis) versus the accumulated thickness (y-axis) appears on columns AD-AH. All of the plots can be manipulated by changing the red values on the control panel on columns AB-AC. The *scale to thickness* value allows the accumulated thickness plots to be scaled to match any stratigraphic thickness. Frequency, position of maximum, and relative amplitude of the small- or package- scale cycle can be changed through the *# small cycles in grand,* the *y-axis offset,* and the *small amplitude* values under the SMALL header, respectively. Similarly, controls for the frequency, position of maximum, and relative amplitude of the grand-scale cycle are listed under the GRAND header. The *x-axis offset* value changes the position of the x-axis relative to the maximum amplitude of the grand scale cycle. The *subsidence rate* value controls the relative amount of accommodation created per unit time irrespective of base-level oscillations. The *optimum burial rate* value governs the theoretical depositional rate best suited for the burial of bone. Finally, the red markers on the main plot respond to the text entry and x-axis position under the MARKERS heading. The list of markers appears in column X. The default values on the spreadsheet are those used to produce Figure 8.

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