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2. SEDIMENTOLOGICAL BACKGROUND*

Emlyn H. Koster and Philip J. Currie
Tyrrell Museum of Palaeontology
Drumheller, Alberta, Canada

In the Park area, the Red Deer River valley originated during deglaciation as a deep, jointed-aligned spillway system through near-horizontal Upper Cretaceous strata. Except where the bedrock surface is cut by buried valleys, the capping veneer of Pleistocene deposits rarely exceeds 3 m. Subsequent erosion of the spillway walls has led to the modern terrain along Deadlodge Canyon - the largest tract of badlands in Western Canada.

This major geomorphic feature provides excellent exposure of the upper 60-100 m of the Judith River Formation (McLean, 1971, 1977). It represents a coastal plain succession richly fossiliferous with vertebrates (Table 1; Dodson, 1983). East of 472500mE (Fig. 1) above 735-740 m a.s.l., the basal 25 m of the overlying marine Bearpaw Formation also crops out. This sequence of concretionary fissile shales contains the ammonites Placenticeras meeki and Hoploscaphites, the ornate bivalve Cymella montanensis, as well as shark teeth, fish scales, mosasaur and plesiosaur remains. The Judith River-Bearpaw boundary represents a continental-marine transition separating the last two cycles of foreland sedimentation along the Western Interior. The actual transition is conspicuously marked by a coaly argillaceous zone, 5-15 m thick, that locally includes several metres of herringbone cross-laminated, greenish sandstone containing the trace fossils Ophiomorpha nodosa, O. bornensis and bored oyster valves. According to Dodson (1970, 1971), deposition occurred in both high- and low-sinuosity alluvial systems, with possible evidence for tidal influence. An estuarine setting is considered to provide the best explanation for the array of sedimentary and taphonomic features in this coastal plain succession. The NNE-trending Sweetgrass Arch underlies the park area (Dodson, 1970; Beland and Russell, 1978), but its role during Campanian sedimentation and subsidence is uncertain.

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TABLE 1 -- List of fossil faunal groups from park-area outcrop of the Judith River Formation. Current numbers of species are included.

SUBAERIAL	FRESHWATER
Herbivorous Dinosaurs	Mesoreptiles
Hadrosaurs - 8	Turtles - 11
Ceratopsians - 7	Crocodiles - 4
Pachycephalosaurids - 4	Champsosaurs - 1
Ankylosaurs - 2	Fish - 14
Thescelosaurids - 1	Salamanders - 7
Carnivorous Dinosaurs	Frogs - 3
Dromaeosaurids - 4	Molluscs - 4
Tyrannosaurids - 3	
Ornithomimids - 3	
Dromaeosaurids - 3	
Caenagnathids - 2	
Elmisaurids - 1	MARINE
Troodontids - 1	Fish - 2
Mammals - 20	Plesiosaurs - 1
Lizards - 11	?Unreworked plankton
Flying Reptiles - 2	
Birds - 1	

PALAEOGEOGRAPHIC SETTING

The aggrading coastal plain supported a rich vertebrate/fauna (Table 1) and was well-vegetated under a warm, equable climate with seasonally variable precipitation (Koster, 1984). Perennial drainage from newly uplifted parts of the Cordillera flowed across the foreland basin to the encroaching shoreline of the Western Interior Seaway. In theory, the combined effect of tidal circulation (Parrish et al., 1984) and a rising base-level would have rendered the lower reaches of the low-gradient drainage susceptible to an estuarine influence.

FACIES ASSEMBLAGES

Vertebrate-bearing 'coarse members', commonly 4-6 m thick, form most of the exposed Judith River strata. These variable channel deposits occur between a three-dimensional complex of vertically-accreted, inter-channel 'fine members' (Fig. 2). Dodson (1971) found that palaeochannel units comprised about 70% of his measured sequences, although Park-wide the vertical ratio between coarse/fine members varies between 0.4 and 2.9. Higher ratios apply to the central and eastern areas and reflect the common occurrence of multi-storey channel units.

Fine Members

Intervals of inter-channel sediments (Figs. 2 and 6) have conformable bases, erosional tops and mostly consist of bentonitic olive-gray mudstones. Thicknesses locally reach 18 m in western outcrops, although eastward where 'coarse members' are commonly multi-storeyed 2-6 m is more typical. Trenching generally reveals a massive structure to the mudstones with conformable or pedogenic changes between levels of different texture, color, carbon content degree of rooting and abundance of macrofloral debris. However, x-ray radiographs reveal convolute laminations, possible gas escape structures, and bioturbation probably due to animal trampling. Mudstones are rich in palynomorphs although the known macroflora is limited mostly to water-worn and split logs, and vertebrate remains are extremely rare (Dodson, 1971). Present-day weathering is responsible for surfical concentratious of gypsum crystals that commonly lie strewn over sulfur-rich intervals.

Relatively thick 'fine members' are locally interrupted by horizons of ironstone concretions, splay sands locally capped by diverse ichnofauna, unionid-bearing, iron-cemented sandstones or volcanic ash layers.

Coarse Members

End-Member Facies

Variability in palaeochannel units (Fig. 2) resolves into a mixture of two end-member facies assemblages representing extremes in the channel-fill processes. These are inclined heterolithic stratification (IHS) due to low-energy, rhythmic accretion of point bars in meandering reaches (Fig. 3A and B), and cross-stratified sand (CSS) sequences due to high-energy, episodic aggradation in wider, non-migratory reaches (Fig. 3C and D).

IHS units have an average dip of 7° and a bimodal pattern of vectors indicating a slightly translational meander geometry on an ESE palaeoslope (Fig.4A). 'Heterolithic' refers to sand-mud couplets on a dm-scale, in which the relative abundance of traction-deposited layers varies from 15-90%. Above a planar erosional base, an overall upward-fining trend is common. Couplets typically consist of a slightly scoured base to a very fine-grained sand with ripple cross-lamination (vector mean of 094°), and an upper conformable unit of brown or olive-gray bentonitic mudstone. Successive couplets are either parallel with uniform dip, or may occur as large discordant packages bounded by higher-order erosional surfaces. Horizontal partings are commonly smothered with plant remains, but their degree of preferred orientation and carbonization is variable. Other conspicuous features of some IHS sequences are repeated development of ledge-forming ironstones and syn-depositional deformation of upper levels into ball-and-pillow structures. In mud-dominant

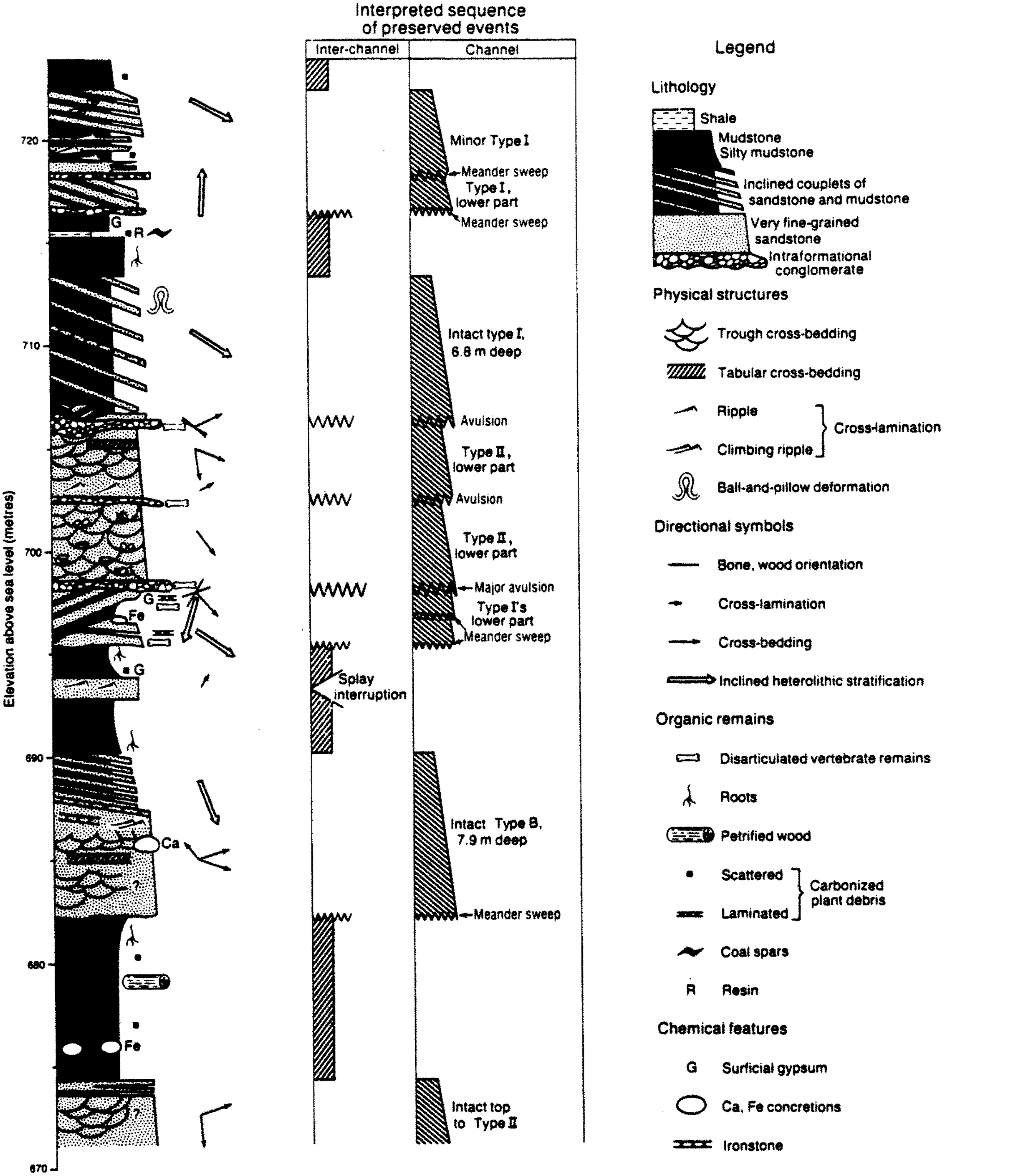

Figure 2. - A 52 m section from 684550mE, 5621430mN outside the south east limit to the park showing the typical alternation of channel (single-and multi-storey) and inter-channel facies.

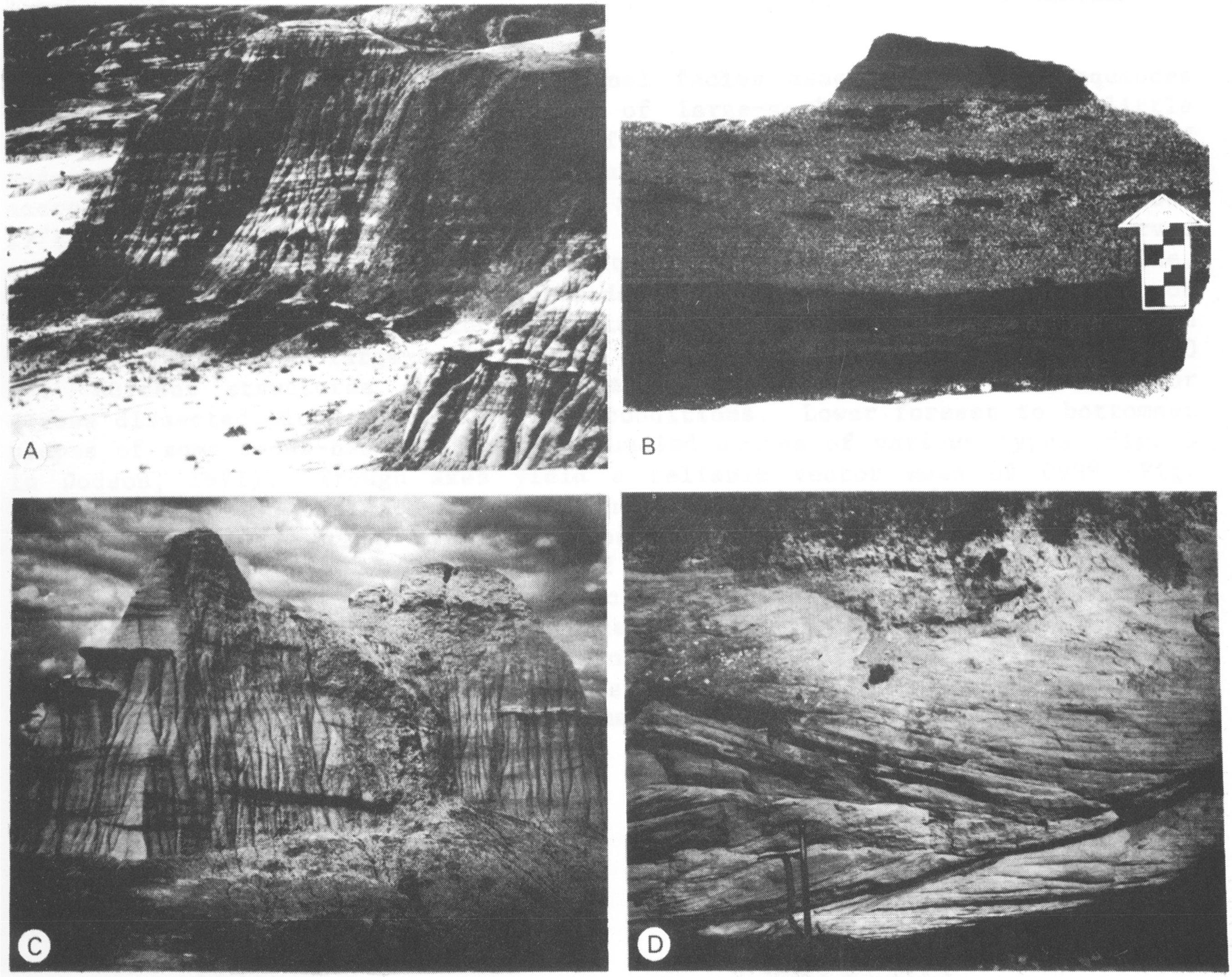

Figure 3. - A) 6.3 m thick IHS unit with basal elevation of ca. 670 m a.s.l. at 656550mE, 5622140mE (person at lower left). Above a flat erosional base on inter-channel mudstone, the unit accreted at between 5-10° towards 159-201°. B) Close-up of one couplet in A with details as described in text. C) Lower-to-middle part (ca. 4.8 m) of a CSS-dominated unit at the southeast corner of the Centrosaurus bonebed. Trough cross-beds, with bottom sets commonly outlined by drapes of plant-rich mud or haematite stain, characterize the sequence above an uneven, erosional base. This prominent landmark known locally as the 'Citadel' has a summit elevation of 684 m a.s.l. D) A well-cemented, creek-bed outcrop at 641500mE. 5622010mN, elevation 647 m a.s.l., showing part of a coset of trough cross-beds with a local east-northeast flow into the face (pick is 80 cm long).

couplets, ripple bedforms are extensively mud-draped giving rise to flaser or wavy bedding. Upper mud layers to couplets, some of which contain evenly-spaced silt laminae, yield a well-preserved, abundant assemblage of palynomorphs as well as occasional damaged specimens of dinoflagellates and acritarchs. Trace fossils are rare, and mostly limited to Skolithos and escape structures.

At the other extreme of palaeochannel facies assemblages, CSS sequences are characterized by extensive cosets of large-scale cross-bedding, little vertical organization, frequent signs of reactivation, minimal occurrence of mud-size sediment (apart from intraclasts) and no direct sign of lateral accretion. Vertebrate remains abound in these 'clean sandstones' (Dodson, 1971), particularly at lower levels. In order of abundance, preserved structures include trough cross-bed sets up to 1.5 m deep and 19 m wide, smaller cosets of planar cross-beds, thin intervals of ripple or climbing-ripple cross-laminations, tabular units of horizontal lamination and rare single sets of large-scale planar cross-beds over areas approaching 150 m^2. Current structures are best examined in concretionary intervals, or across dissected slopes with low light conditions. Lower foreset to bottomset slopes of some cross-bed sets contain bundled drapes of various types (fig. 5 in Dodson, 1971). Trough axes yield a reliable vector mean of 099^{o} (Fig. 4B) -- a direction that bisects the meander migration pattern deduced from IHS units (Fig. 4A). Other types of cross-beds show greater spread about a similar mean direction. The low-relief bases of single-storey CSS sequences is commonly strewn with mudstones intraclasts, abraded skeletal fragments and, occasionally, articulated remains. Once aggradation was underway, relief of the sand bed varied from scour holes in front of bedform crests up to 1.8 m deep to relatively flat reactivation surfaces. Intact upper boundaries to cross-bed sets occasionally bear unornamented tube-like burrows.

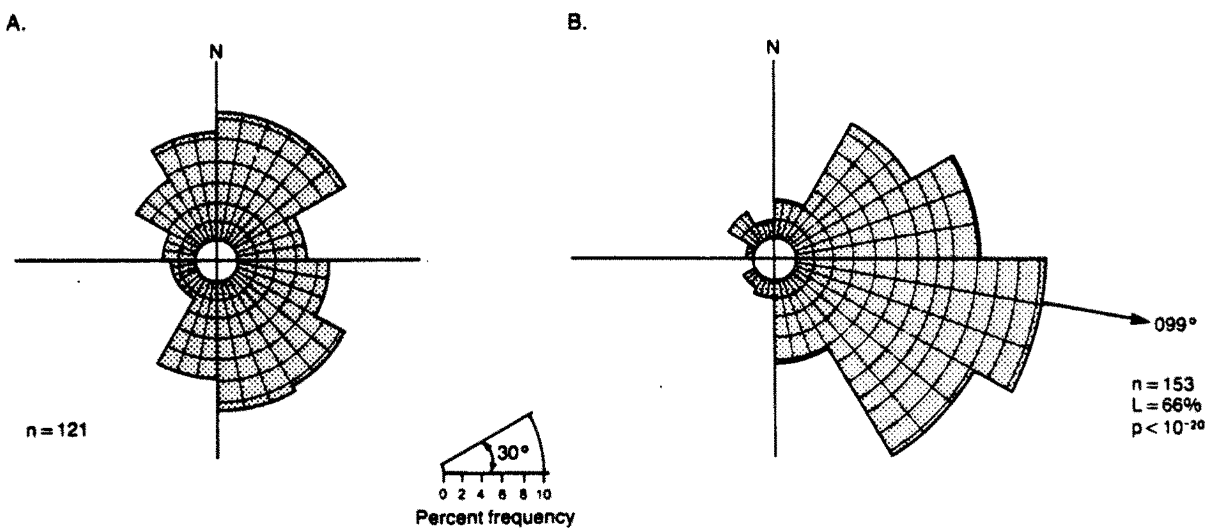

Figure 4. - Rose diagrams of lateral accretion (A) and axes of trough cross-beds (B). L and p denote the vector magnitude and the probability that the observed distribution stems from a randomly-directed population.

Form and Variability

IHS and CSS sequences, as described above, are the primary architectural elements (Miall, 1985) in a spectrum of palaeochannel sequence types. Representing a trend of increasing energy and apparently diminishing sinuosity, the spectrum consists of five main types as follows:

Type I: Composed entirely of IHS (Fig. 3A, B).

Type A: IHS above CSS, with the conformable contact between point bar and coarser thalweg facies either intercalated or relatively abrupt at 1-3 m above the base (Fig. 5A). Locally, single cosets of trough cross-beds show a landward direction of palaeoflow.

Type B: 'Streaky' occurrence of IHS at mid-upper levels in a CSS-dominated sequence (Fig. 5B).

Type C: Inclined intervals of densely-packed intraclastic breccia composed of reworked IHS and fragments of siderite concretions, alternating with CSS (Fig. 5C).

Type II: Composed entirely of CSS (Fig. 3C,D).

The above list covers observations from vertical stratigraphic sections. Complete channel sequences, when viewed in a north-south transverse orientation, either show simple or composite form. The former are infilled by one end-member vertical sequence type. In Type I, the IHS starts at a cut bank and ends at an abandoned, 35-50 m wide cross-section of the channel bend. In Type II, the CSS is contained within a broad bowl-shaped cross-section for which the total width/thickness ratio tends to increase down palaeoslope from ca. 40 to 70. In composite channel fills, the more common transitions involve I to A, I to C, B to II and C to II, indicating that the lateral accretion process was prone to various reduced forms of identity along dip.

Amalgamation

Erosional surfaces below each channel episode in a multi-storey 'coarse member' (Figs. 2 and 6) represent time gaps equivalent to at least the upper part of the preceding episode, and possibly also an overbank 'fine member' that had been vertically accreted above it. Amalgamation is most conspicuous in stacked point bar sequences in which sets of IHS typically have opposing dip directions. Amalgamation between CSS-dominated episodes is more subtle because of their clearer mud-free nature, unidirectional palaeocurrent trends and apparent vertical aggradition. However, extensive lag horizons, consisting of skeletal debris, mudstone intraclasts and ironstone concretions, provide unequivocal evidence. Large abraded/aligned bone fragments and displaced blocks of bank sediment indicate shear stresses far greater than those required to entrain the enclosing sand: amalgamation was therefore associated with high-energy, degradational events.

Vertebrate Fauna

The Tyrrell Museum of Palaeontology works on four kinds of preservation. A brief overview from a sedimentological perspective of these follows as background to the details in subsequent sections. 1) Articulated skeletal remains (Sternberg, 1950: Dodson, 1983) represent the richest and most diverse dinosaur fauna anywhere. To date, more than 300 specimens have been recovered: quarry sites are assigned numbers and staked, although records are kept on all specimens encountered. After flotation in flow deeper than the animal's girth (up to 1.5 m) from an upstream mortality site, carcass remains became stranded most commonly in the basal levels of non-amalgamated CSS-dominated sequences. Skin impressions, where present, indicate that burial preceded complete decomposition of soft-parts. 2) Bonebeds are areal concentrations (10^2-$10^4 m^2$) of disarticulated skeletal remains and represent a tremendous, virtually untapped resource for palaeoecological studies. The majority contain components of numerous genera and are associated with channel-base lags, particularly in multi-storey sequences. This suggests that intermixed bone and intraclastic material were filtered out from reworked intervals in the multi-storey sequence, combined with some horizontal sorting. Although 'monogeneric' bonbeds are rare, the extensive Centrosaurus bonebed (Currie, 1982) at 465950mE, 5622350mN, is being intensively worked. This category is apparently associated with IHS-bearing sequences and may represent mass drowning. 3) 'Microsites' are important in understanding composition of the local fauna (Dodson, 1985) and constitute the primary source of information on Late Cretaceous amphibians, lizards, birds and mammals. Mostly associated with channel-base lags, they are concentrations of bones and teeth from small vertebrates as well as the teeth from dinosaurs and other larger vertebrates (Currie, 1985). Hydraulically-equivalent diameters range from coarse sand to small pebbles, and their worn surfaces and even texture suggest that multiple sorting events preceded their final burial. Modern runoff often concentrates the material of microsites even further, making it possible to collect several thousand specimens in a single day. 4) Single bones, often abraded and/or fragmentary, tend to occur at the lower levels of sand-dominated channel sequences. Long bones are typically aligned transverse to the local palaeoflow direction. Disarticulation of the parent skeleton long preceded the burial of its single bone derivatives, and generally took place far upstream of environments represented by the sequence at Dinosaur Provincial Park. Isolated bone occurrences have the potential for major significance, and in recent years have produced pterosaurs and many new species of dinosaur.

Interpretation

Four features of the coastal plain succession are considered critical to interpretation: origin of IHS, variability in palaeochannel processes, vertebrate taphonomy and the nature of 'fine members'. As used here, an estuary is the near-coastal, widening reach of a river down which alluvial processes are increasingly modified by tidal circulation and saltwater incursion (cf. Jouanneau and Latouche, 1981; Dorjes and Howard, 1975).

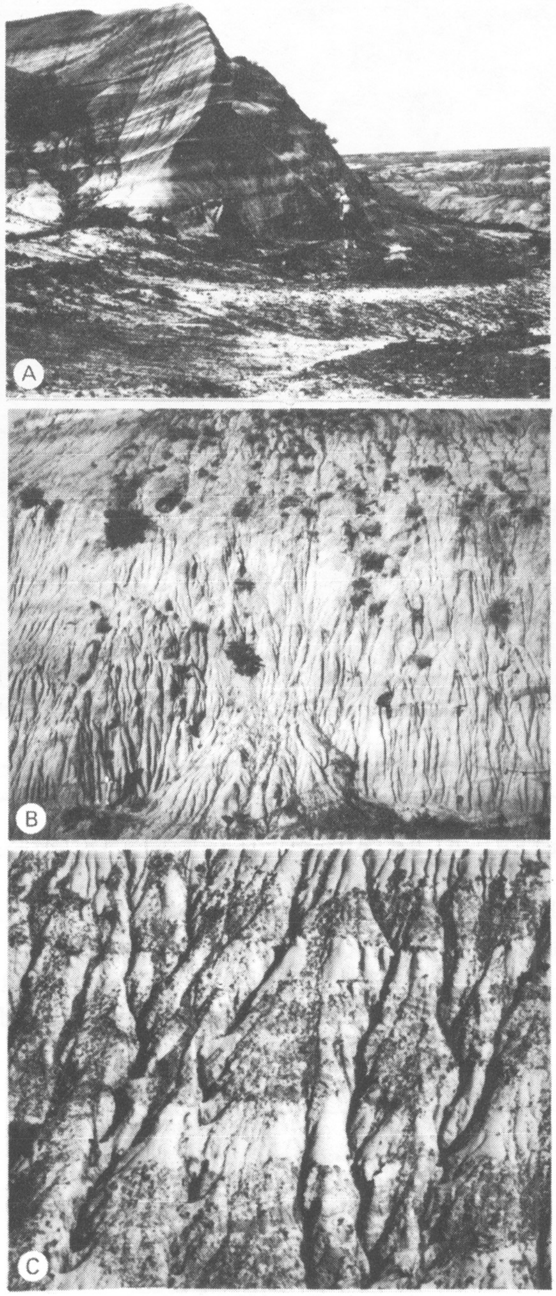

Figure 5. - Examples of the intermediate types of palaeochannel sequences as discussed in the text. Note sharp, erosional base in B, and conformable tops in A and B. A) Type A at 456000mE, 5629500mN, basal elevation 678 m a.s.l. Sequence is 9.3 m thick with lateral accretion at 11° toward 207° (person at centre). B) Type B at 459920mE, 5621350mN, basal elevation 673 m a.s.l. Sequence is 10.5 m thick with lateral accretion at 8° toward 217° (person at basal contact, lower left). C) Close-up of Type C facies at 460815mE, 5617940mN at ca. 724 m a.s.l. Mid-level of a sequence laterally-accreting to northeast, oblique to this face (view is ca. 2.5 m high).

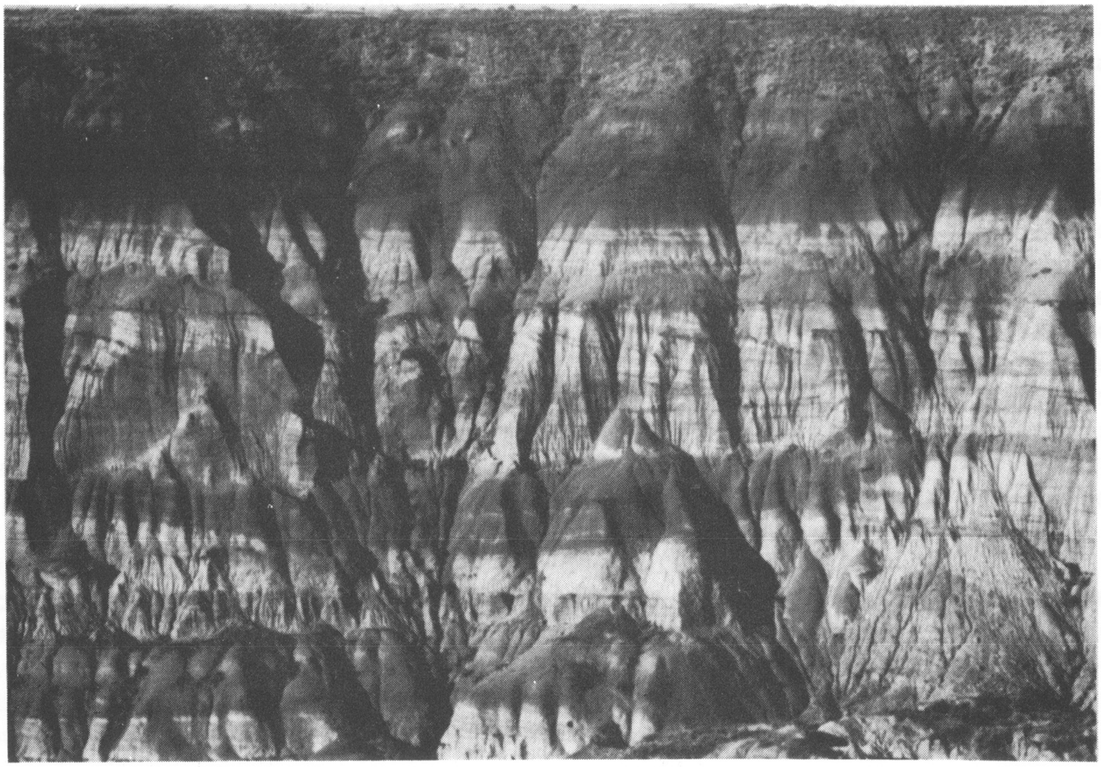

Figure 6. - The east wall of Jackson Coulee at 471475mE, 5621740mN showing a 60 m high section of multi-storey channel sequences, including an abandoned mud-filled cross-section. The uppermost, dark argillaceous unit below the Pleistocene surficial deposits represents the transition to the Bearpaw Formation: the prairie edge here is at 732 m a.s.l. and ammonite-bearing Bearpaw crops out nearby above 746 m a.s.l.

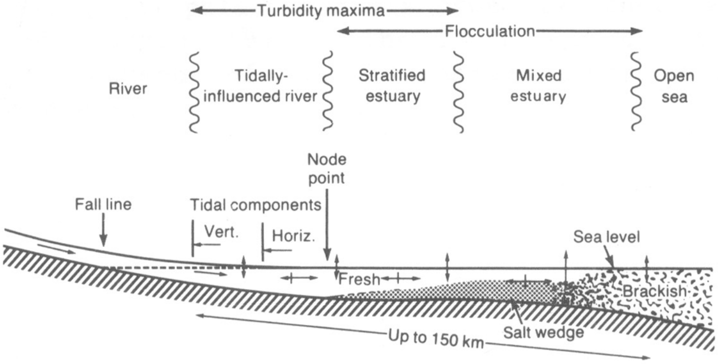

Figure 7. - Schematic, longitudinal section down an estuary showing important aspects of water circulation and dynamic series of zones, each characterized by a different balance of fresh and saltwater effects.

Commonly, a transitional series of zones exists between strictly fluvial conditions upstream of the fall line and the open sea (Fig. 7). Zonal boundaries oscillate on timescales relating to the lunar tidal cycle, seasonal river regime and periodic onshore storm surges, whereas the entire estuarine system will shift in response to transgression or regression.

Following Smith (1985), IHS is viewed here as a distinctive style of lateral accretion in tidally-influenced point bars. Sand-mud couplets relate to rhythmic additions of traction-deposited sand and fallout of suspended fines. Complete coverage of the point bar slope by undesiccated and unrooted mud drapes shows that bankfull velocity was minimal and subaerial exposure was briefly, if ever, attained. Along the upper sinuous reaches of modern estuaries, sluggish river flow alternates with slackwater, the latter induced both by rising tide and diminished slope of the water-surface: when river discharge is high there is less opportunity for backwater and mud deposition. An estuarine setting (Fig. 7) also provides a coherent framework for the variability in palaeochannel types, with Type I as the upstream end-member in the 'tidally-influenced river' zone. Type II sequences are considered to have formed within the lower estuary under fluctuating, relatively high-energy flow (cf. Lithofacies I of Terwindt, 1971). It is envisaged that Types A and B formed at intermediate locations in the 'stratified estuary' zone. Type C represents a major local change in channel process and form, whereby IHS-forming point bars were suddenly rendered unstable by extreme flow conditions.

Clearly, avulsion and amalgamation of palaeochannels both played a major role in concentrating vertebrate remains. Whereas buried carcasses indicate a short, single episode of movement from a nearby site of death, disarticulated bone fragments commonly show signs of prolonged wear. Given that fluvial transport of fossil material is effectively halted within the estuarine zone (Frey et al. 1975), only a small portion of the preserved population may have inhabited the immediately surrounding inter-channel environments (cf. Beland and Russell, 1978).

Because modern estuaries are flanked by various floral communities (e.g. Dorjes and Howard, 1975), the palaeochannels probably inherited a mixed sample of estuarine flora (cf. Jarzen, 1982). The low frequency of splay events in overbank areas is a consequence of the low-energy nature of bankfull flow in tidally-influenced channels.