Middle Turonian dinosaur paleoenvironments in the Upper Cretaceous Kaskapau Formation, northeast British Columbia

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Abstract: The Kaskapau Formation is a mudstone-dominated wedge up to 950 m thick that spans late Cenomanian to middle Turonian time. The formation has a prominent wedge geometry and was deposited in the foredeep of the Western Canada Foreland Basin. In outcrop in northeast British Columbia, nearshore sandstones are locally well developed and include rare wedges of nonmarine strata. On Quality Creek, near Tumbler Ridge, 11 m of nonmarine strata contain abundant dinosaur tracks and the first in situ dinosaur bone reported from British Columbia. This site, at a paleolatitude of about 67°N, preserves a rare glimpse of Turonian terrestrial environments during global eustatic highstand. Three main dinosaur habitats are recognized: strandplain and beach-ridge; freshwater lake; and brackish lagoon. Back-beach sandstone has a relief of about 2.5 m, interpreted as beach ridges; sandy coals containing abundant dinosaur tracks represent inter-ridge slough deposits. Overlying lake deposits comprising laminated muds with freshwater molluscs grade up into rooted muddy siltstone and locally, dinoturbated sandstone. Lake deposits are capped by lagoonal mudstone with abundant brackish-water molluscs, locally including a dinosaur-trampled oyster bioherm. The upper parts of sandy lagoonal deltas are pervasively dinoturbated. Sandstone filling a tidal channel contains logs, oyster shells, and bones of dinosaurs, turtles, and crocodiles, as well as fish scales. The lagoonal succession is erosively overlain by offshore sandy mudstones. Various lines of evidence suggest that the mean annual temperature at this sea-level location was about 14 °C, with a cold-month mean no less than 5.5 °C. The high-latitude location implies a significant period of winter darkness, and correspondingly diminished plant productivity.

Résumé : La Formation de Kaskapau a la forme d'un prisme prononcé et elle est dominée par un mudstone atteignant une épaisseur de 950 m; elle s'étend du Cénomanien tardif au Turonien moyen. La formation a été déposée dans l'avant-fosse du bassin d'avant-pays de l'Ouest canadien. Dans des affleurements du nord-est de la Colombie-Britannique, les grès littoraux sont bien développés et comprennent de rares prismes de strates non marines. Au ruisseau Quality, à proximité de Tumbler Ridge, 11 m de strates non marines présentent de nombreuses traces de dinosaures et le premier os de dinosaure in situ rapporté en Colombie-Britannique. Ce site, à une paléoaltitude d'environ 67 ºN, nous donne un rare aperçu des environnements terrestres au Turonien durant le haut niveau eustatique global. Trois grands habitats de dinosaures sont reconnus : une plage plane avec un cordon littoral, un lac d'eau douce et une lagune saumâtre. Le grès d'arrière-plage a un relief d'environ 2,5 m et il aurait formé des cordons littoraux; des charbons sablonneux contenant de nombreuses traces de dinosaures représentent des dépôts vaseux entre les crêtes. Des dépôts lacustres sus-jacents comprenant des boues laminées avec des mollusques d'eau douce évoluent en des siltstones boueux contenant des racines et, par endroits, des grès perturbés par les dinosaures. Les dépôts lacustres sont recouverts de mudstones de lagunes comportant de nombreux mollusques d'eau saumâtre ainsi qu'un bioherme d'huîtres piétiné par les dinosaures. Les parties supérieures des deltas lagunaires sablonneux sont profondément perturbées par les dinosaures. Le grès remplissant un chenal de marée contient des bûches, des coquillages d'huîtres et des ossements de dinosaures, de tortues et de crocodiles ainsi que des écailles de poisson. Des mudstones sableux recouvrent la succession lagunaire au-dessus d'une discordance d'érosion. Selon divers éléments probants, la température moyenne annuelle, à cet emplacement, au niveau de mer aurait été d'environ 14 ºC et la moyenne des mois froids n'était pas inférieure à 5,5 ºC. L'emplacement de haute latitude implique une période importante de noirceur hivernale et une diminution correspondante de productivité des plantes.

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Introduction

Some of the highest sea levels of the Mesozoic are recorded by rocks of early Late Cretaceous age, with a globally recognizable eustatic peak in the early Turonian (e.g., Kauffman and Caldwell 1993; Hay et al. 1993), currently estimated to have been about 70 m above present (Van Sickel et al. 2004). This highstand has been attributed to a major increase in the length of oceanic spreading ridges coupled with the rise of a mantle plume beneath the Pacific Ocean (Kominz 1984; Harrison 1990; Larsen 1991). Static loading of the western margin of North America by the Rocky Mountain orogen resulted in the formation of a highly elongate foreland basin which underwent several kilometres of flexural subsidence during the Cretaceous (e.g., Price 1973; DeCelles 2004). Tectonically induced subsidence, coupled to a lesser extent with eustatic rise, resulted in the flooding of the interior of western North America and the formation of the Western Interior Seaway, which reached its greatest extent in the early Turonian (Fig. 1A). A consequence of these transgressive events is that marine rocks dominate the sedimentary record of the early Late Cretaceous, and particularly the early to middle Turonian (Wolfe and Kirkland 1998). Attendant upon the scarcity of Turonian terrestrial deposits is a correspondingly sparse record of terrestrial vertebrate body and trace fossils.

The middle Turonian site described here (Fig. 1B) has yielded the first significant accumulation of dinosaur skeletal material in British Columbia, and also abundant dinosaur tracks, and provides the oldest formal record of dinosaur remains in western Canada (McCrea 2003: McCrea and Buckley 2004). Crocodile and turtle material is also present. The site was located at a paleolatitude of about 67°N (interpolated from paleogeographic maps of Irving et al. 1993), and therefore must have experienced almost total darkness at mid-winter. Although the inferred paleolatitude implies a significant period of winter darkness, considerable debate surrounds the issue of temperature, especially winter minimum means. Some studies (e.g., Sellwood et al. 1994), based on isotopic data, suggest a mean annual temperature of about 10 °C at about 67°N, whereas a Turonian–Coniacian champsosaur–turtle fauna from a paleolatitude of about 72°N on Axel Heiberg island (Tarduno et al. 1998) has been interpreted as evidence of a mean annual temperature of about 14 °C and a coldest month mean temperature of no less than about 5.5 °C (Markwick 1998). The new material described here provides evidence of co-existing dinosaurs, crocodiles, and turtles inhabiting a variety of freshwater and brackish-water habitats on the seaward margin of the coastal plain, close to the Turonian Arctic Circle.

The Kaskapau Formation

In northern Alberta and adjacent British Columbia, rocks deposited during the late Cenomanian – late Turonian Greenhorn Cycle are assigned to the overall transgressive Kaskapau and overall regressive Cardium formations (Stott 1967; Fig. 2). The Kaskapau Formation is a wedge-shaped sedimentary unit that thins from about 950 m in the west to <50 m in the east over 250 km. The wedge geometry indicates deposition during a phase of rapid flexural subsidence spanning about 3.5–4.5 million years (e.g., Jordan and Flemings 1991; Kreitner 2002; Kreitner and Plint 2006; Varban 2004; Varban and Plint 2005). The high accommodation rate in the west resulted in sand and gravel being trapped close to the orogenic front (e.g., Heller et al. 1988), and only mud, silt and very fine sand were transported offshore by southeast-directed storm-driven flows (Hay et al. 2003; Varban and Plint 2005; Fig. 2). Although the Kaskapau Formation is volumetrically dominated by thinly bedded offshore marine siltstone and mudstone, nearshore and terrestrial deposits are present in the Foothills of British Columbia between Tumbler Ridge and Chetwynd and are also exposed to the east along the Peace River valley in Alberta (Plint 2000; Kreitner 2002; Varban and Plint 2005; Kreitner and Plint 2006). In the lower (late Cenomanian) portion of the Kaskapau Formation, these marginal marine deposits consist of upward-shoaling successions typically 3–15 m thick that represent shallow-water, wave-influenced deltas that prograded towards the east and southeast (Kreitner 2002; Kreitner and Plint 2006). The upper (early to middle Turonian) portion of the Kaskapau Formation is dominated by offshore siltstone and mudstone except in the British Columbia Foothills where fine-grained rocks pass laterally westward over about 20 km into stacked shoreface sandstones.

The Turonian portion of the Kaskapau Formation cropping out in the British Columbia Foothills was subdivided by Varban and Plint (2005), into five major transgressive–regressive packages, termed *units*, each of which included a more muddy transgressive marine package at the base, overlain by a succession of stacked shoreface sandstone bodies that prograded no more than 20–40 km to the east (Fig. 2). Units I–III contain insignificant volumes of nonmarine deposits. In contrast, units IV and V include packages of nonmarine strata up to 40 m thick that accumulated on the coastal plain during the early phase of each relative sea-level rise; each nonmarine unit is erosively overlain by offshore marine facies.

Units IV and V of the Kaskapau Formation are well exposed in Quality Creek, 4 km northeast of Tumbler Ridge (Fig. 1B). Reconnaissance study of this exposure by McCrea in 2003 revealed a nonmarine succession that contained numerous dinosaur tracks (McCrea 2003). A lenticular sandstone at the top of the succession yielded terrestrial vertebrate fossils including ribs, vertebrae, limb elements, teeth, and osteoderms from a variety of dinosaur groups (McCrea 2003; McCrea and Buckley 2004). This study was undertaken to provide a detailed paleoenvironmental context for the vertebrate trace and body fossils (Rylaarsdam 2004).

Kaskapau Formation stratigraphy and facies in Quality Creek

Marine strata at the top of Kaskapau unit IV and nonmarine strata at the base of unit V (Fig. 2) are exposed in Quality Creek from immediately above Lower Quality Falls, southward for about 900 m (Fig. 3, inset map). Eight stratigraphic sections were measured, and semi-continuous exposure allowed various marker horizons to be traced along the creek, helping to confirm correlations between sections.

Fig. 1. (A) Paleogeographic map of North America in the early Turonian and location of the study site. Paleo-shorelines modified slightly from Williams and Stelck (1975) and Kauffman (1984); Paleo-latitude from Irving et al. (1993). (B) Detailed map of study area in northeastern British Columbia showing principal towns, rivers, roads (numbered), and location of Quality Creek study site.

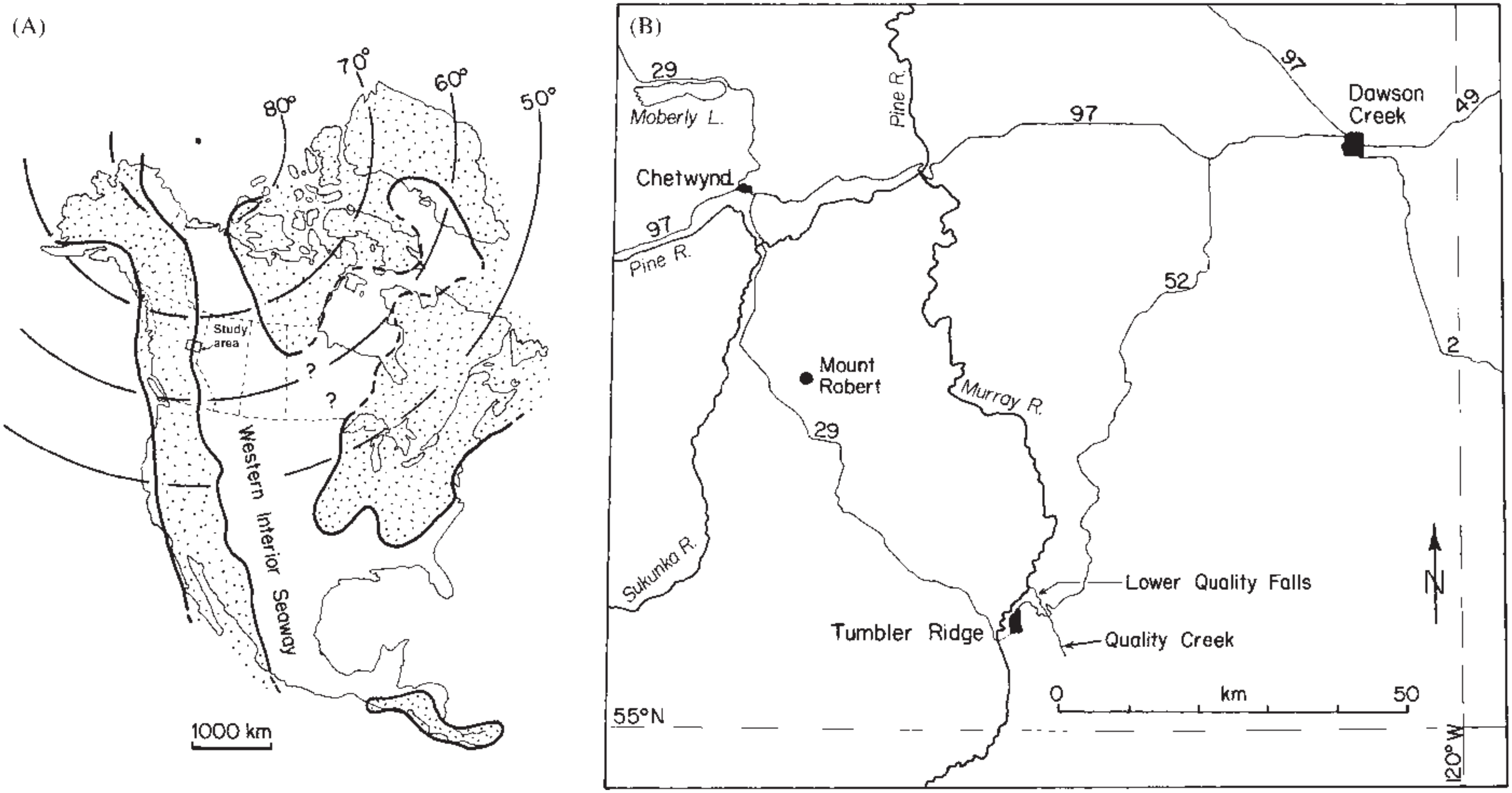


Fig. 2. Block diagram summarizing the stratigraphy of the middle and upper part of the Kaskapau Formation between Mount Robert and Tumbler Ridge (see Fig. 1B for locations). The Kaskapau Formation has a prominent wedge shape, thinning eastward towards the forebulge. Coastal sandstone and nonmarine deposits are confined to the most western part of the formation and pinch out rapidly basinward. The studied nonmarine interval lies at the base of unit V.

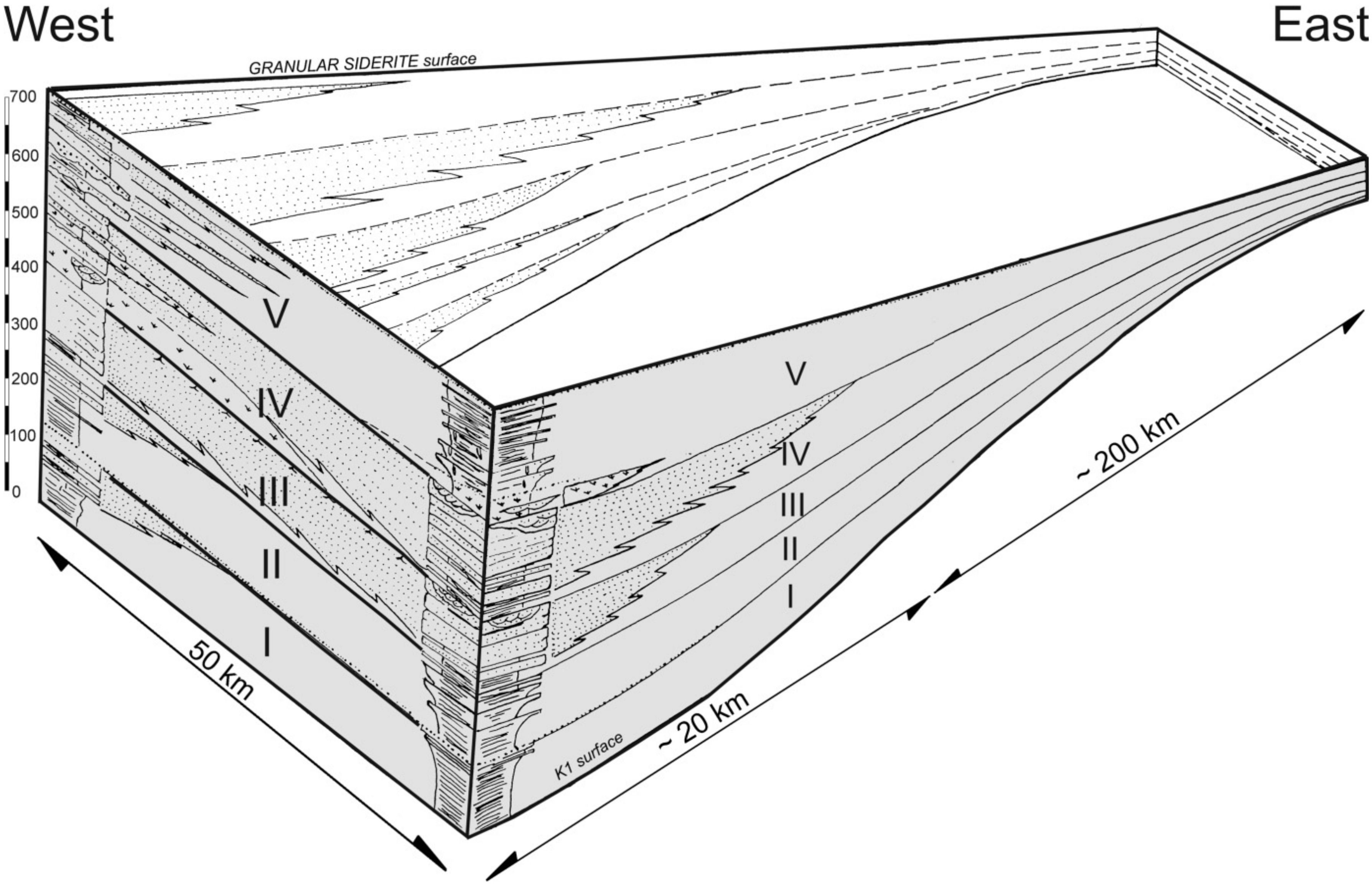


Fig. 3. Correlation of eight stratigraphic sections in Quality Creek. Relative position of sections is shown in the inset map. See text for full discussion of facies and environmental interpretations.

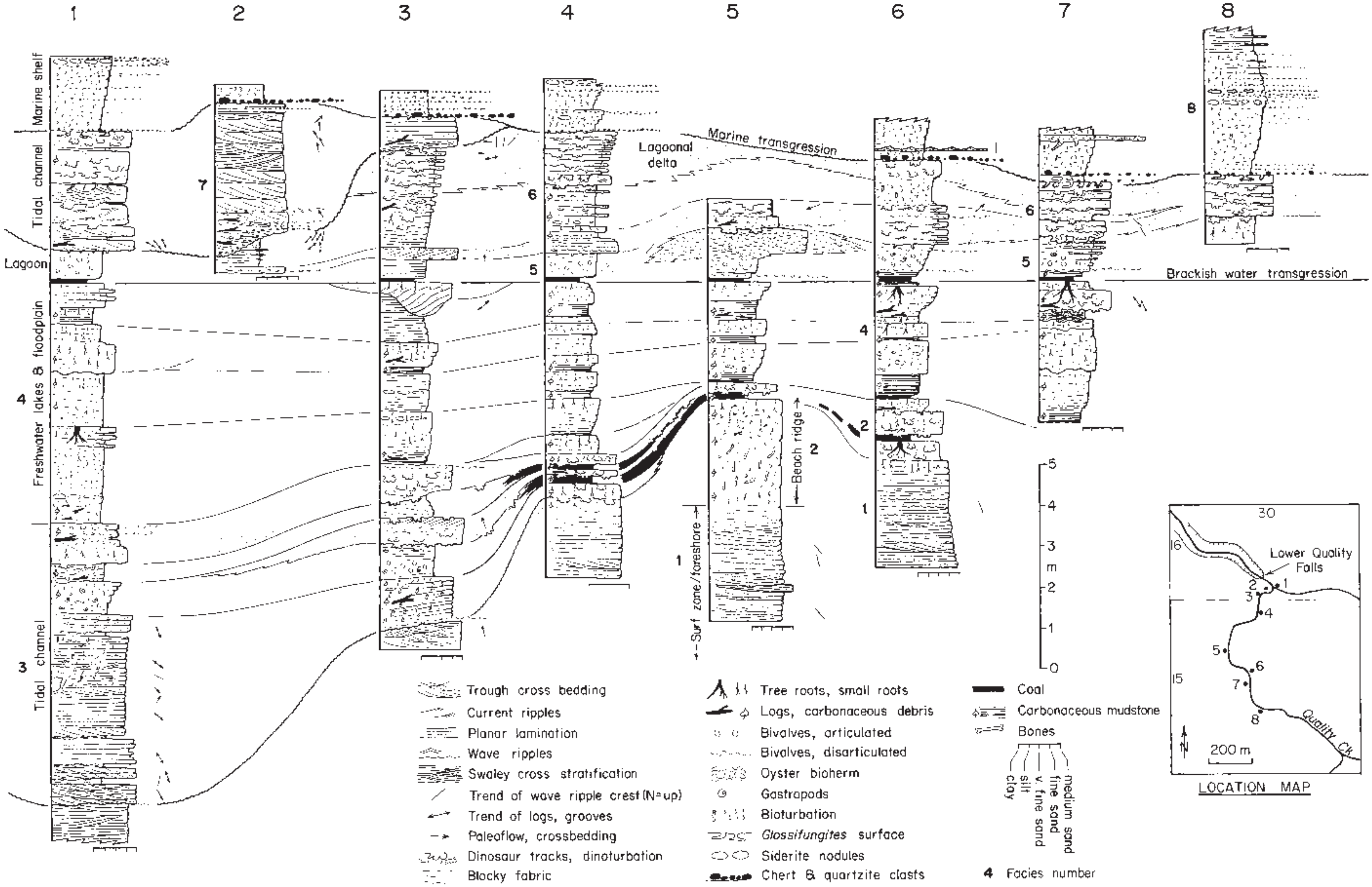


Fig. 4. Shoreface sandstone at the top of the Wartenbe sandstone (which forms the lip of Lower Quality Falls), overlain at "S" by 10 m of nonmarine strata. "R" marks marine ravinement surface that defines the top of the nonmarine section; the immediately underlying sandstone is a channel-fill containing dinosaur bones. Photograph immediately downstream from Lower Quality Falls (See inset map in Fig. 3 for location).

Sedimentary facies

Sedimentary facies can be broadly divided into regressive strandplain, transgressive freshwater, transgressive brackish-water, and transgressive marine facies, in ascending order. The vertical succession and lateral relationships of facies in the eight measured sections are summarized in Fig. 3.

Regressive strandplain facies

Facies 1: shoreface and beach

The lowest part of the section comprises the upper part of the Wartenbe sandstone, which consists of about 100 m of stacked shoreface sandstones (Varban and Plint 2005; Fig. 4). At the base of the studied section in Quality Creek, swaley cross-stratified fine sandstone grades up into about 3 m of trough cross-bedded, wave-rippled, and planar-laminated fine sandstone. This succession is readily interpreted in terms of a wave-dominated shoreface, grading up into dunes migrating in the ridge and runnel system of the surf zone. Planar lamination represents foreshore deposits (Walker and Plint 1992).

Facies 2: beach ridge and slough

Planar-laminated beach sandstone grades up into pervasively rooted, structureless very fine sandstone that varies laterally from 0.2 to 2.5 m thick over about 200 m. The structureless, rooted sandstone is onlapped from both north and south by decimetre-scale interbeds of carbonaceous sandstone and sandy coal (Fig. 5). Each carbonaceous sandstone is intensely rooted, contains abundant logs of wood and is pervasively dinoturbated (i.e., dinosaur trampled; Lockley 1991); identifiable tracks can be attributed to large ornithopods. Abundant sand-filled dinosaur under-tracks penetrate the interstratified sandy coals. The thin dinoturbated sandstones can be traced northward from site 4 to site 3, where they form cross-bedded sandstones interstratified with brackish-water mudstones in the upper part of a tidal channel fill (see later in the text; Fig. 3). Sandy coals grade laterally into brackish-water mudstone within the channel-fill.

The structureless, rooted sandstone is interpreted as a beach ridge deposit. The ridge is inferred to have had a topography of up to 2.5 m, based on the change in thickness of the bioturbated sandstone and the onlap relationship of the overlying beds (Fig. 3). The topography can not be attributed to differential compaction because the lithology is sandstone throughout the exposure, and the onlap of mudstone units against the sandstone indicates a contemporaneous, pre-burial topography. The interstratified sandy coals are interpreted as marsh or swamp deposits that accumulated in sloughs between beach ridges and are comparable to slough deposits on the modern Nayarit strandplain (Curray and Moore 1964; Curray et al. 1967). The laterally interfingering relationship among the sandstones, coals, and brackish mudstones suggests that the sandstones were deposited by floods, which washed sand into peat mires adjoining a tidal channel. The flood-lain sandstones were subsequently homogenized by roots and dinosaur trampling. Intense dinoturbation indicates that this area of coastal marshes and tidal channels was populated by dinosaurs, some of which are identifiable as large ornithopods. Differential compaction of the peat during burial resulted in the apparent draping of the sandstone beds over the beach-ridge topography.

Fig. 5. Flaggy-bedded sandstone in lower part of photograph is a beach deposit, overlain by interbedded rooted sandstone and sandy coal interpreted to represent slough deposits between beach ridges (site 5, Fig. 3). The top of the coal is deeply impressed by sandstone-filled dinosaur tracks (outlined by white line). Hammer is 33 cm long.

Facies 3: tidal channel

The beach, beach ridge, and slough deposits are locally cut out by an erosive-based, lenticular heterolithic unit up to 6.5 m thick that pinches out over ~120 m. At its thickest point (site 1, Figs. 3, 6), the unit is dominated by up to 4.5 m of trough cross-bedded medium- to fine-grained sandstone with a mean paleoflow of 140°N. Cross-bedded sandstone grades up into 1–2 m of thinly bedded, current and wave-rippled fine sandstone with abundant millimetre-scale carbonaceous and mud interlaminae (Fig. 6A). Upward and laterally, the sediment becomes muddier and intensely bioturbated. Trace fossils include *Asterosoma, Chondrites* (commonly reburrowing *Asterosoma*), *Helminthopsis, Palaeophycus heberti, Palaeophycus tubularis, Phycosiphon, Planolites, Thalassinoides* (locally reburrowed with *Phycosiphon*), possible *Ophiomorpha irregulaire*, possible *Rosselia*, and *Teichichnus* (J. MacEachern, personal communication, 2005). In addition, the sediment contains *Teredo*-bored logs (Fig. 7A), abundant fine plant debris, and rare cones (Fig. 6B). The uppermost part of the unit consist of interbeds of fine sandstone and rooted and bioturbated mudstone, inclined at about 5° to the ENE (Fig. 8). Oysters, corbulids, and *Brachydontes* are present locally at the top of the succession, and abundant dinosaur tracks are present on the basal and top surfaces of the sandstone beds (Fig. 8).

The overall lenticular geometry, abundance of cross-bedding, upward decrease in the scale of sedimentary structures with flow apparently transverse to the dip of the accretion surfaces suggests deposition on a point bar. Abundant logs and finer plant debris indicate a forested hinterland. The abundance of mud and carbonaceous drapes and presence of *Teredolites*, *Brachydontes*, corbulids, oysters, and a marine ichnofauna in the upper part of the unit suggest both tidal influence (Nio and Yang 1991) and increasing marine salinity within the channel (Bromley et al. 1984; Brewster-Wingard 2001). The two thin cross-bedded sandstone beds in the upper part of the fill probably represent flood events; these sandstones extend well beyond the margin of the channel to interfinger with marsh deposits of facies 2. The overall interpretation is of a sinuous tidally influenced channel, possibly a minor deltaic distributary, transecting the beach ridges on the strandplain. Dinosaurs walked on, and possibly waded across, the upper part of the point bar. The facies and faunal succession suggest progressive abandonment of the channel, which resulted in fresh to brackish water gradually being replaced by tidally influenced seawater. Figure 9 summarizes the interpreted paleoenvironments on the regressive strandplain.

Transgressive freshwater facies

Facies 4: freshwater lake deposits

Tidal channel, shoreface, and beach ridge deposits are blanketed by up to 6 m of dominantly muddy strata. The rocks are typically organized into packages 0.5–2 m thick, each of which grades up from laminated dark grey silty clay into muddy siltstone. Individual packages can be traced throughout the study area (i.e., for >900 m). The laminated silty clays are highly carbonaceous, lack roots and dinoturbation, and locally contain logs and well-preserved leaves. A very small (3–4 mm) species of “river limpet,” possibly *Acroloxus* (cf. Hanley and Flores 1987), was found in one locality. Muddy siltstone is typically blocky, structureless, pale grey-green to orange-brown and contains abundant roots, some of which are up to 5 cm in diameter and >50 cm long and probably represent trees (Fig. 7B). Siderite concretions are locally common. At sites 6 and 7 (Fig. 3), muddy siltstone grades laterally into fine sandstone that shows evidence of intense dinoturbation. At site 3 (Fig. 3), a sharp-based lenticular sandstone body up to 1 m thick and about 20 m wide cuts into laminated silty mudstone. The top of this facies unit is defined by a coal bed up to 20 cm thick that can be

Fig. 6. (A) Thinly bedded, fine-grained bioturbated sandstone and carbonaceous mudstone in the middle part of the channel-fill illustrated in Fig. 8; (B) Conifer cone in bioturbated muddy sandstone, coin is 25 mm in diameter. Photographs A and B are located in Fig. 8.

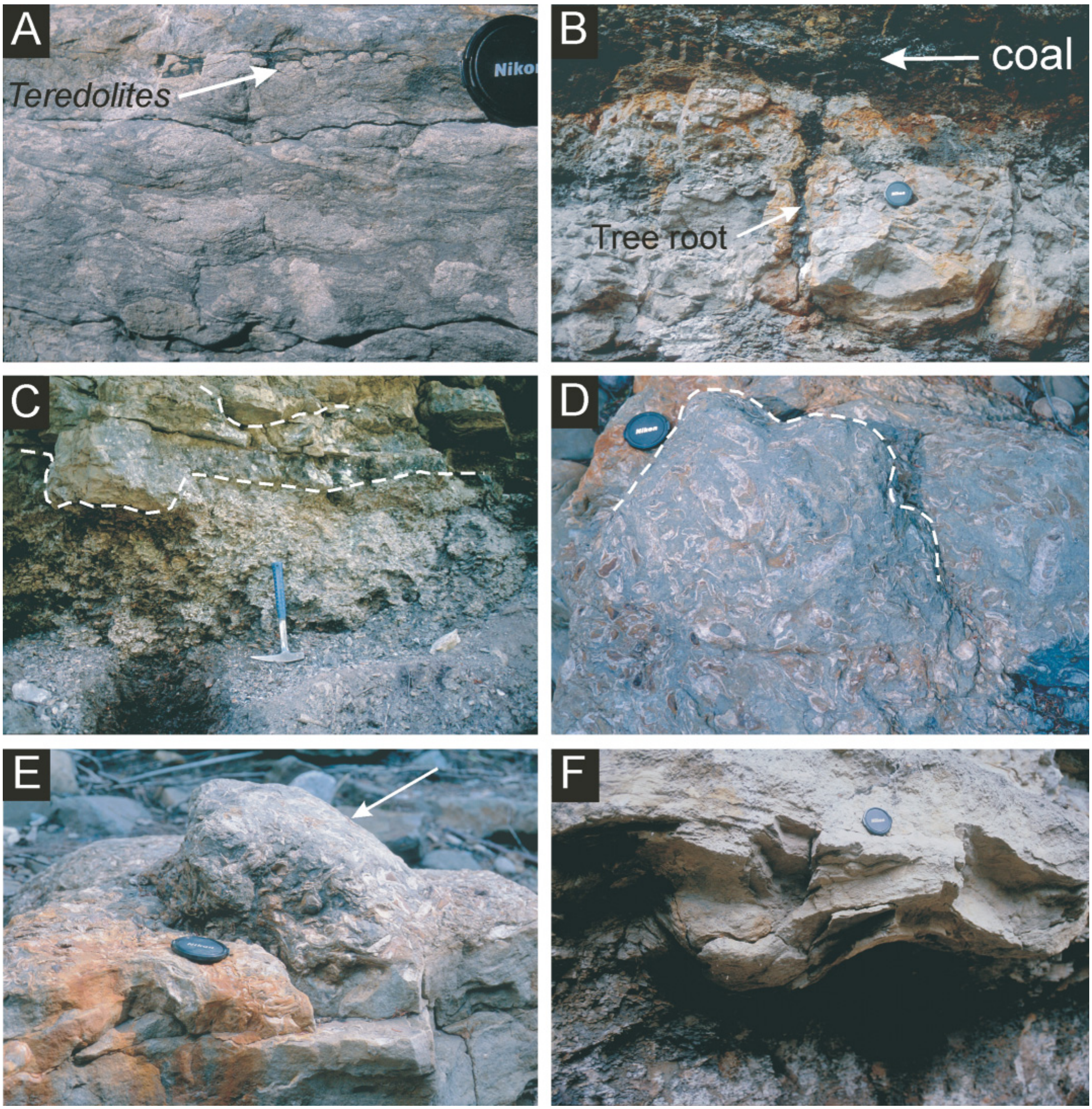
traced throughout the study area and is used as a stratigraphic datum in Fig. 3.

Laminated carbonaceous silty clay was probably deposited in the central parts of shallow freshwater lakes, as indicated by the pulmonate gastropod ?*Acroloxus*. Abundant organic input and poor circulation resulted in dysaerobic conditions, leading to preservation of organic matter. In Alaska, Spicer et al. (1992) interpreted similar accumulations of well-preserved leaves in lacustrine deposits to record rapid shedding of deciduous leaves in response to seasonal low light and cold weather. Under such conditions of low temperature and abundant organic supply, aerobic bacteria were unable to degrade the plant material, resulting in high-quality preservation. The lack of roots in facies 4 suggests that the water was sufficiently deep, perhaps about 2 m, that colonization by bottom-rooted plants was inhibited. The lack of dinoturbation may indicate that the water was also too deep for wading, or simply that lacking vegetation, these areas presented no attraction to feeding dinosaurs. The upward gradation from laminated silty clay into coarser, rooted muddy siltstone suggests shallowing and colonization by plants, including trees. The blocky to structureless fabric of the muddy siltstone is suggestive of pedogenic processes, possibly involving wetting and drying cycles (McCarthy and Plint 1999), and this interpretation is supported by the paler and warmer colours (grey, orange, brown) suggestive of somewhat better drained conditions and partial oxidation of organic matter. Pervasive dinoturbation is also likely to have contributed to the loss of primary stratification. The local presence of highly dinoturbated sandstone (site 7 in Fig. 3) suggests deposition close to a river channel, possibly on a levee or crevasse splay. The isolated, lenticular sandstone at site 3 is probably the fill of a crevasse channel.

The overall impression is of shallow (probably <2 m) lakes, several kilometres in extent, the margins of which were heavily vegetated. Mainly suspended sediment was supplied by sluggish rivers flowing from the west and southwest. This low-energy environment permitted rivers to construct elongate deltas, and observed stratigraphic continuity suggests that deltas extended for several kilometres. Figure 10 portrays a summary of the various freshwater environments. Correlation to well logs to the east shows that the marine shoreline lay beyond a series of beach ridges extending as much as 10 km to the east. These low topographic barriers, together with the high inflow of river water maintained freshwater conditions at the Quality Creek locality.

The stacking of upward-shallowing lake-fill successions suggests repeated changes in the accommodation to supply ratio leading to lake flooding and filling cycles. These cycles might be related to changes in the rate of tectonic subsidence. The general absence of coal from this facies suggests that the rate of clastic sedimentation was too high to permit the accumulation of peat. Repeated emergence may also have led to oxidation and destruction of surface organic accumulations.

Fig. 7. (A) Sandstone filling *Teredolites* in wood enclosed within intensely burrowed muddy sandstone near the top of the tidal channel-fill. Located in Fig. 8. (B) Large tree root in highly dinoturbated silty fine sandstone at the top of the nonmarine succession at site 7 (Fig. 3). The coal bed above the root marks the boundary between freshwater and overlying brackish-water deposits. (C) Oyster bioherm at site 5 (Fig. 3), in which the density of attached oysters increases upward. The bioherm is abruptly overlain by dinoturbated fine sandstone, and a large sandstone-filled ornithopod track (outlined) is impressed into the top of the bioherm. Additional dinosaur tracks are visible above. Hammer is 33 cm long. (D) Plan view of sandstone cast of ornithopod track from the top surface of the oyster bioherm at site 5, shown in Fig. 7C. (E) side view of the same ornithopod track cast; arrow indicates sole of foot. (F) Intense dinoturbation, attributed to ornithopods, at the base of a lagoonal delta sandstone, 1.2 m below the ravinement surface at site 7 (Fig. 3). Lens cap in A, B, D–F is 63 mm in diameter.



However, the widespread development of coal at the top of the lacustrine succession suggests a major drop in the local rate of clastic supply, perhaps attributable to base-level rise and drowning of the coastal plain. The rise in the water table initially favoured widespread accumulation of peat, but continued deepening led to incursion of saline water, indicated

Fig. 8. Drawing of the main components of the interpreted tidal channel fill exposed between sites 1 and 3 (see Fig. 3). The position of photographs in Figs. 6 and 7A are indicated. Note dinosaur tracks on both top and base of two thin sandstone beds within the upper part of the channel-fill, and brackish-water bivalves (*Brachydontes*, *Ostrea*) in the intervening mudstone. The channel cuts down through laminated and cross-bedded sandstone representing foreshore and surf zones, to rest on swaley cross-stratified sandstone representative of the middle shoreface. See Fig. 3 for legend to symbols.

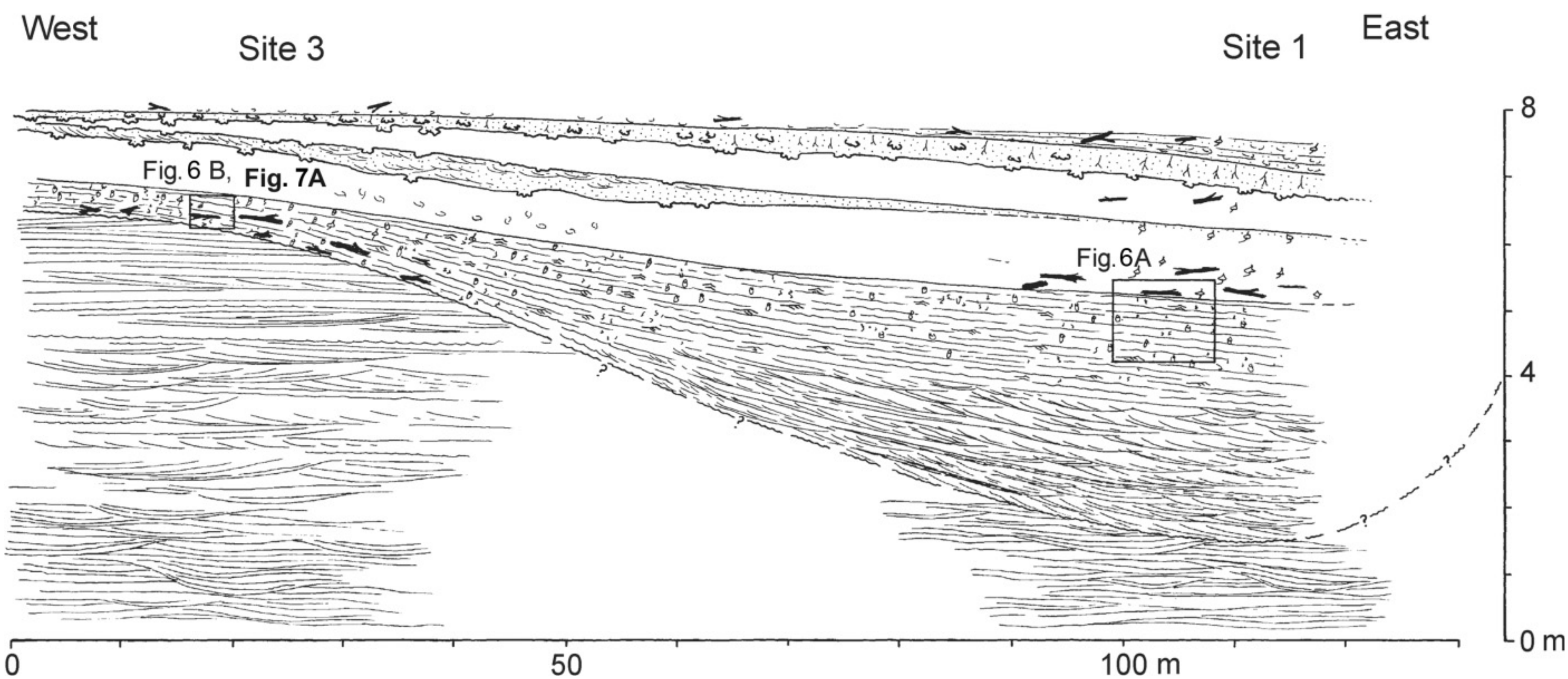


Fig. 9. Cartoon illustrating interpreted progradational strandplain paleoenvironments. Beach ridges are interpreted to have been 1–2.5 m high and partly wooded; inter-ridge sloughs were freshwater and accumulated peaty sediments that were intensely dinoturbated.

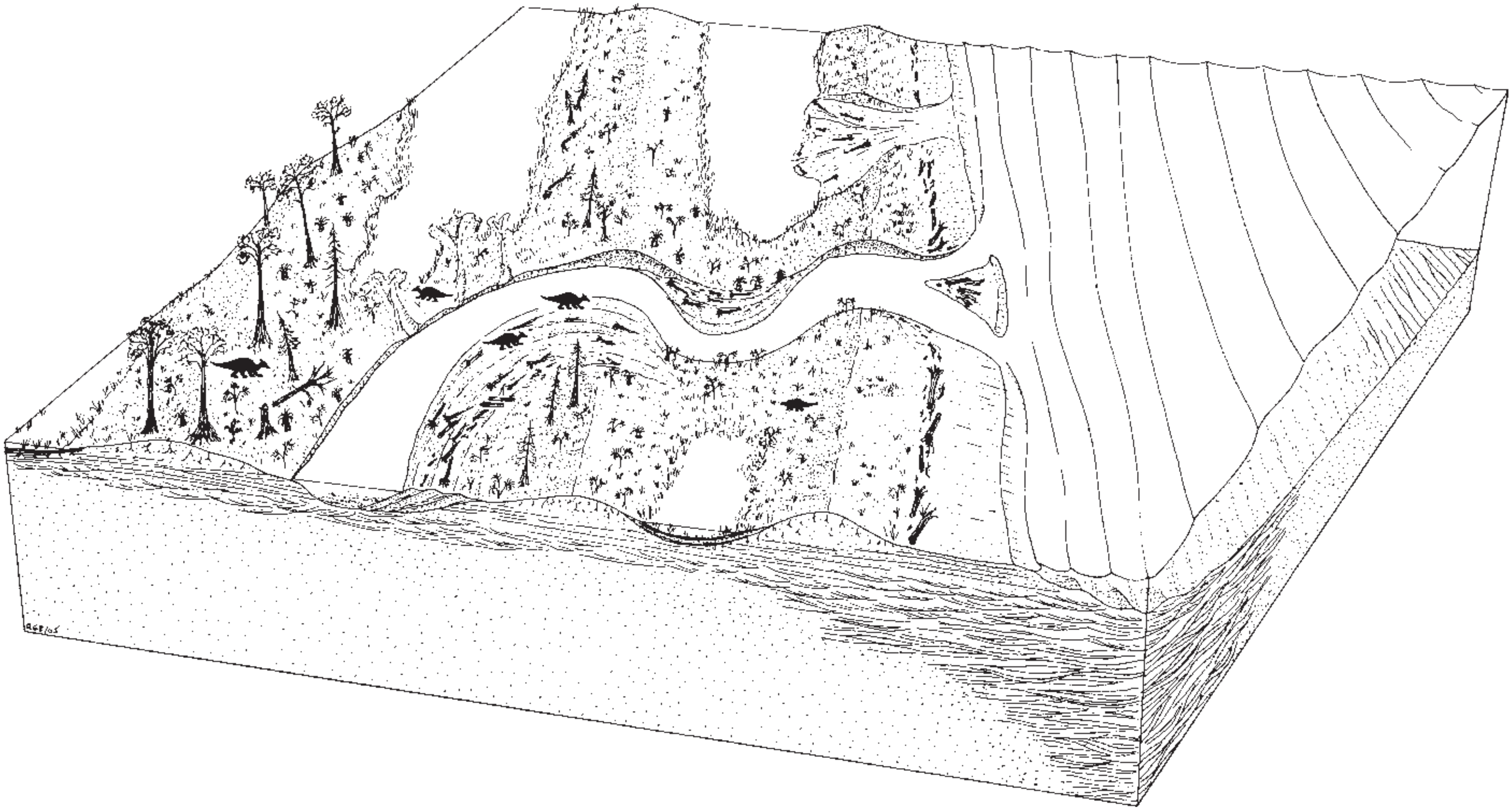
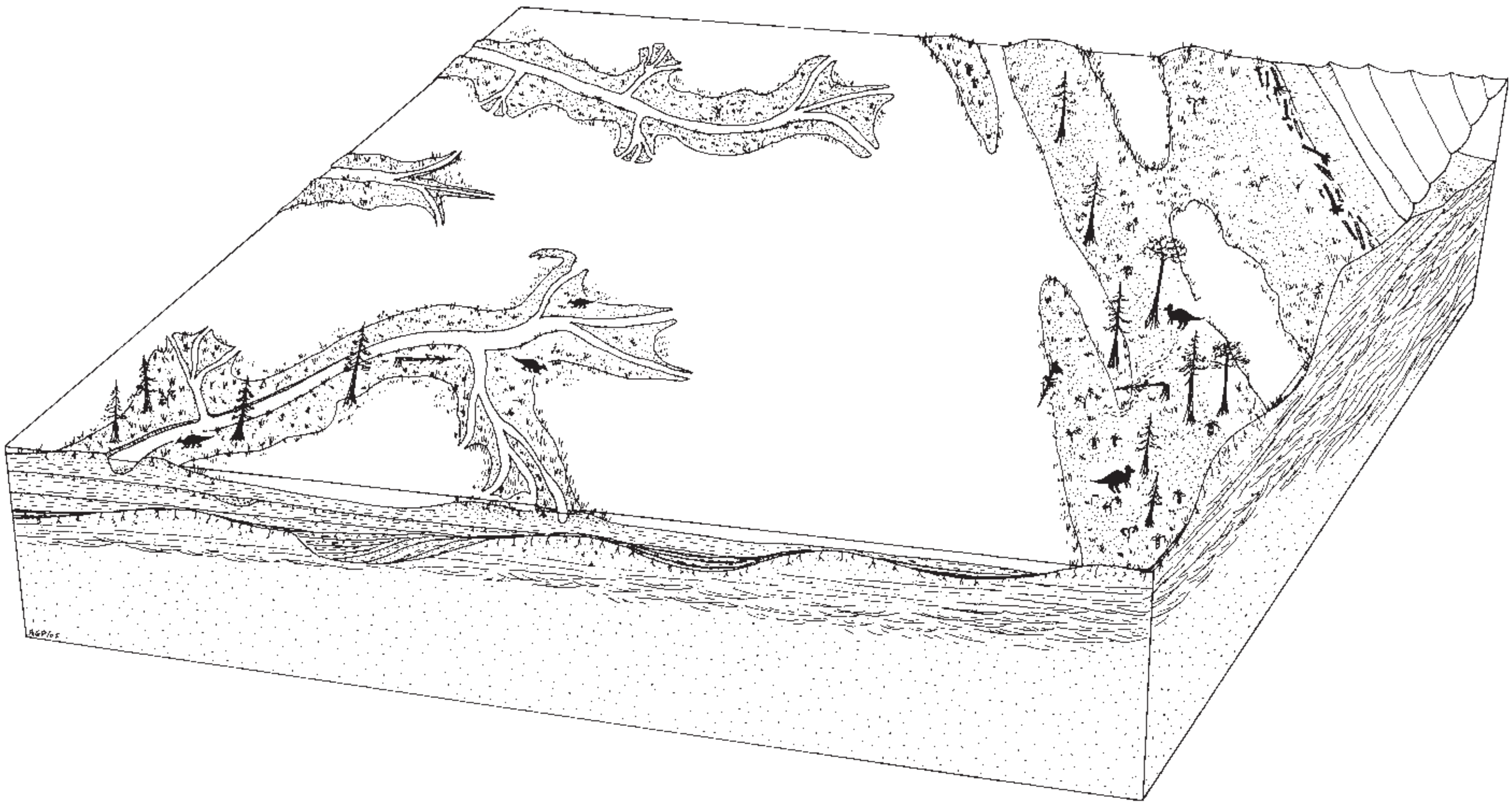


Fig. 10. Cartoon illustrating interpreted freshwater lake and lake-delta environments that developed when the strandplain underwent gradual back-tilting towards the southwest. Lake margin and lake delta sediments are heavily rooted, pedogenically modified, and dinoturbated, whereas central lake sediments are laminated and carbonaceous. Lakes are interpreted to have been 1–2 m deep.



by brackish-water molluscs above the coal and the resulting demise of the peat mire.

Transgressive brackish-water deposits

Freshwater lake deposits are abruptly overlain by up to 4 m of silty mudstone and sandstone that contain a brackish-water fauna and evidence of tidal processes. Three main facies can be distinguished.

Facies 5: brackish lagoon

The widespread coal bed capping the freshwater lake deposits is overlain by up to 60 cm of laminated to bioturbated mudstone, which contains abundant brackish-water molluscs, including oysters, corbulids, and *Brachydontes*. At site 5 (Fig. 3), oysters become progressively more abundant upward, forming an in situ bioherm up to 80 cm thick (Fig. 7C). The upper surface of this oyster bioherm bears ornithopod footprints impressed to a depth of up to 10 cm and filled with oyster-rich sandstone (Figs. 7D, 7E).

This mudstone facies suggests low energy conditions, and the molluscan assemblage indicates brackish water of variable salinity, suggestive of deposition in a quiet lagoon probably no more than 1–4 m deep. In favourable locations, oysters congregated to build reefs that became sufficiently shallow that dinosaurs could walk across their surface.

Facies 6: lagoonal delta

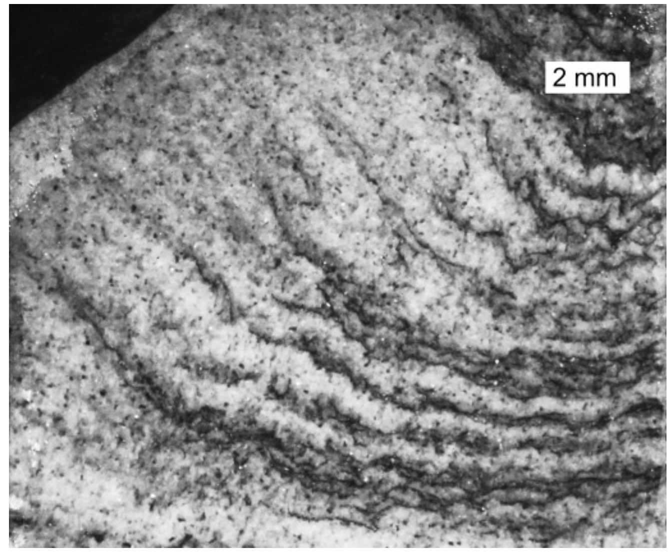
Lagoonal mudstone grades upward into centimetre-scale interbeds of very fine- to fine-grained, wave and current-rippled sandstone interstratified with muddy siltstone. Rippled beds commonly show submillimetre-scale drapes of organic matter separating cross-laminae (Fig. 11); drapes are organized in alternating thick–thin packages. Two sandier-upward successions can be recognized in most sections (Fig. 3). At some sites, sandstone rests abruptly on siltstone, and in all sections, bedding is highly deformed by dinoturbation (Fig. 7F). Roots are generally rare to absent.

The gradational relationship with the lagoonal mudstone below suggests that the rippled sandstone and siltstone successions represent small deltas that prograded into the lagoon from the south and southwest. The stratigraphic thickness of these lagoonal deltas suggests deposition in water between 1 and 4 m deep. The more sandstone-dominated portions were probably deposited closer to distributary channels, whereas more thinly bedded, silty successions were more distal to channels. Towards the south, the two sandier-upward successions gradually merge, with the intervening siltstone pinching out by site 8 (Fig. 3). This relationship suggests two stacked delta successions, both building from the south. The organic drapes on ripple cross-laminae are interpreted as tidal bundles (Visser 1980) and suggest a significant tidal effect within the deltaic distributary channels. Although the rippled sandstones are pervasively dinoturbated, suggestive of shallow to emergent conditions, roots are rare. Given the abundance of roots in comparable deltaic successions in the lacustrine deposits below, this is surprising, and might reflect inhibition of plants by a salt water influence.

Facies 7: distributary channel

At sites 1, 2, and 3, the uppermost part of the brackish-water succession consists of up to 3.8 m of fine- to medium-grained sandstone, which forms a lenticular body that pinches

Fig. 11. Thin section micrograph of current-rippled sandstone from a lagoonal delta, 1.5 m below ravinement surface at site 6 (Fig. 3), showing alternating laminae of fine sandstone and carbonaceous debris, interpreted as tidal bundles. Note alternating thick–thin bundle pairs, suggestive of a semi-diurnal tidal rhythm.



out over about 130 m towards the west (Fig. 3). The base of the sandstone is highly erosive and is ornamented with groove casts. Combined paleocurrent evidence indicates flow broadly towards the north. The sandstone is dominated by decimetre-scale trough cross-bedding (Fig. 12), although at site 1, ripple cross-lamination and massive sandstone are common, and towards the margin of the sandbody at site 3, planar lamination dominates. At site 1, millimetre- to centimetre-scale mud laminae separate decimetre-scale packages of rippled sandstone. In the lower 1.5 m of the sandstone, coarser material, including sideritized mudstone intraclasts, disarticulated oyster shells, and large logs are present. None of the logs show evidence of *Teredolites*. A fallen block of this sandstone has yielded an assemblage of vertebrate fossils, including dinosaur material (McCrea and Buckley 2004); this material is described in more detail later in the text. Bones tend to be concentrated around logs and appear to be a lag deposit, comparable to other examples from western Canada (Eberth and McCrea 2001; Tanke 2004). Dinosaur tracks are common throughout the sandstone at site 1, and one example revealed skin impressions and slide marks of the lateral portion of an outer digit of a theropod preserved as an impression in a mud lamina (Fig. 13).

The relatively coarse grain size, lenticular geometry, and abundance of current-generated ripples and cross-bedding suggest deposition in a channel. Although paired tidal bundles were not observed, the common occurrence of mud drapes suggests some tidal influence (Nio and Yang 1991), and the presence of oysters may also indicate connection to a saline water body (although they could have been reworked from immediately underlying deposits). Abundant logs indicate a forested hinterland and significant floods to erode and transport the wood. The presence of tracks throughout much of the thickness of the channel-fill suggests that dinosaurs walked across the channel on numerous occasions. The presence of tracks only 50 cm above the basal surface suggests that either

Fig. 12. Cross-bedded sandstone forming a channel fill, capped by a ravinement surface "R" and pebble–cobble lag at site 2 (Fig. 3). Fallen blocks of this channel-filling sandstone have yielded dinosaur and other vertebrate bones.

Fig. 13. Detail of a theropod heel impression 1 m below the top of the channel-filling sandstone at the top of site 1 (Fig. 3). The impression was made in a thin mud lamina separating sandy layers, and preserves the skin texture of the heel. Scale is in centimetres.

dinosaurs waded through the water, or, perhaps more likely, walked on the dry river bed when water level in the channel was low, either at low tide or during low river flows. Evidence from other track sites suggests that most dinosaurs avoided crossing deep water (Lockley 1989), although Currie (1995) interpreted an ornithopod trackway as the product of an animal wading, and possibly swimming across a waterbody with a current. Paleoenvironments interpreted from the lagoonal association are summarized in Fig. 14.

Transgressive marine deposits

Facies 8: ravinement lag and offshore deposits

The top surface of the lagoonal succession is defined by a gently undulating erosion surface penetrated by abundant mud-filled *Rhizocorallium*. The erosion surface is mantled with an extra-basinal lag consisting mostly of chert pebbles up to a few centimetres in diameter, but also including 10–15 cm quartzite cobbles and a single 36 cm boulder of quartzite (Fig. 12). Some of the quartzite clasts are encrusted by inarticulate disciniscid and lingulate brachiopods, bryozoa, serpulid worms, ?solitary corals, and attached foraminifera (Plint et al. in press). The gravel lag is immediately overlain by a highly bioturbated sandy mudstone containing inoceramid bivalve fragments. The mudstone also contains dispersed chert granules that locally are concentrated into thin beds, sometimes wave rippled, and which upwardly become more abundant through about 3 m of section (Fig. 3, site 8).

Fig. 14. Cartoon summarizing lagoonal and transgressive barrier paleoenvironments. Continued tectonic tilting down to the southwest resulted in transgression of a barrier island and development of a lagoon in place of freshwater lakes. The molluscan fauna indicates brackish water, and mud drapes in lagoonal deltas suggest significant tidal exchange with the open sea. Continued relative sea-level rise resulted in transgression of the study site by a barrier island and formation of a pebble-veneered ravinement surface at the top of the shoreface.

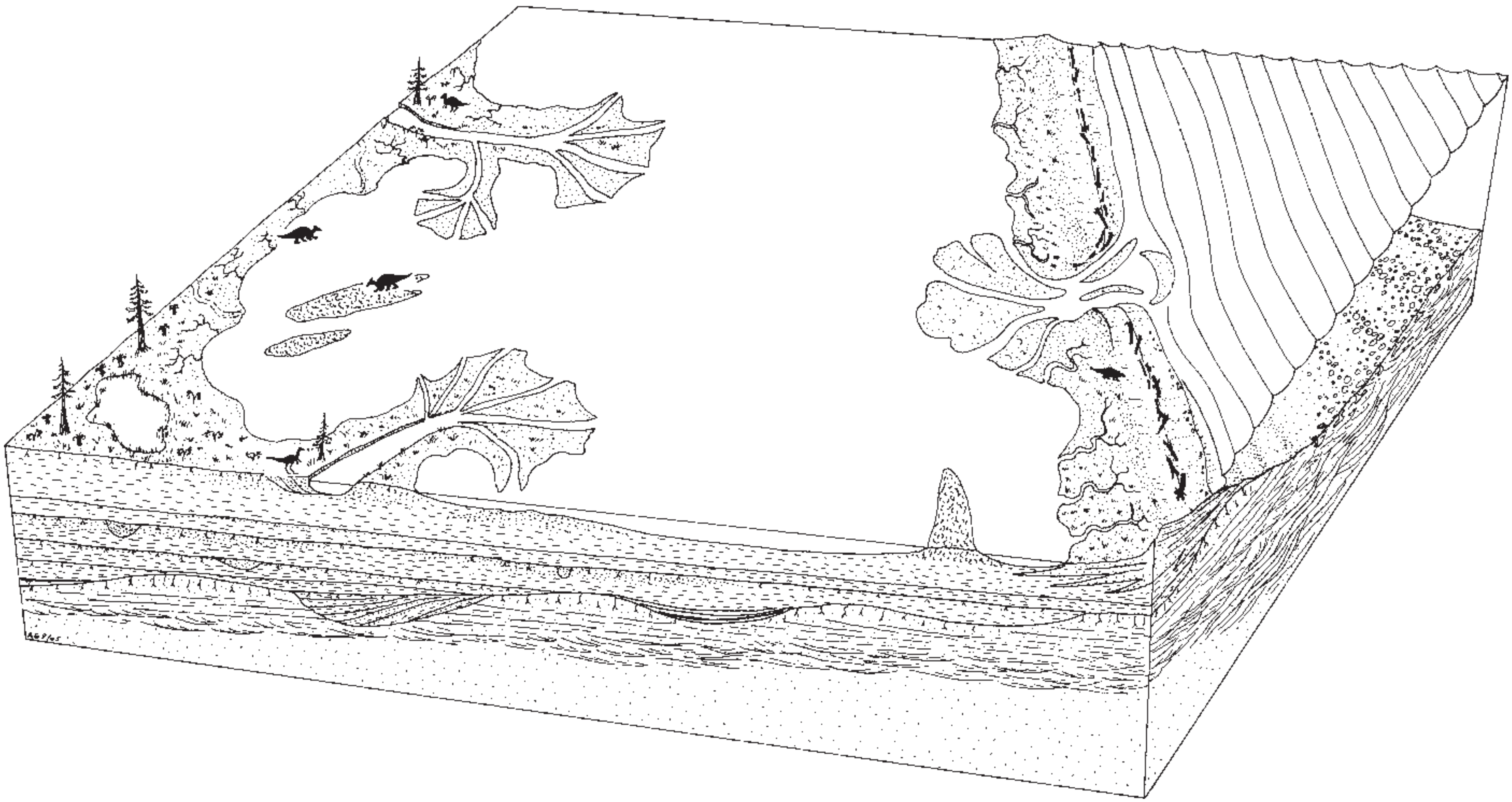
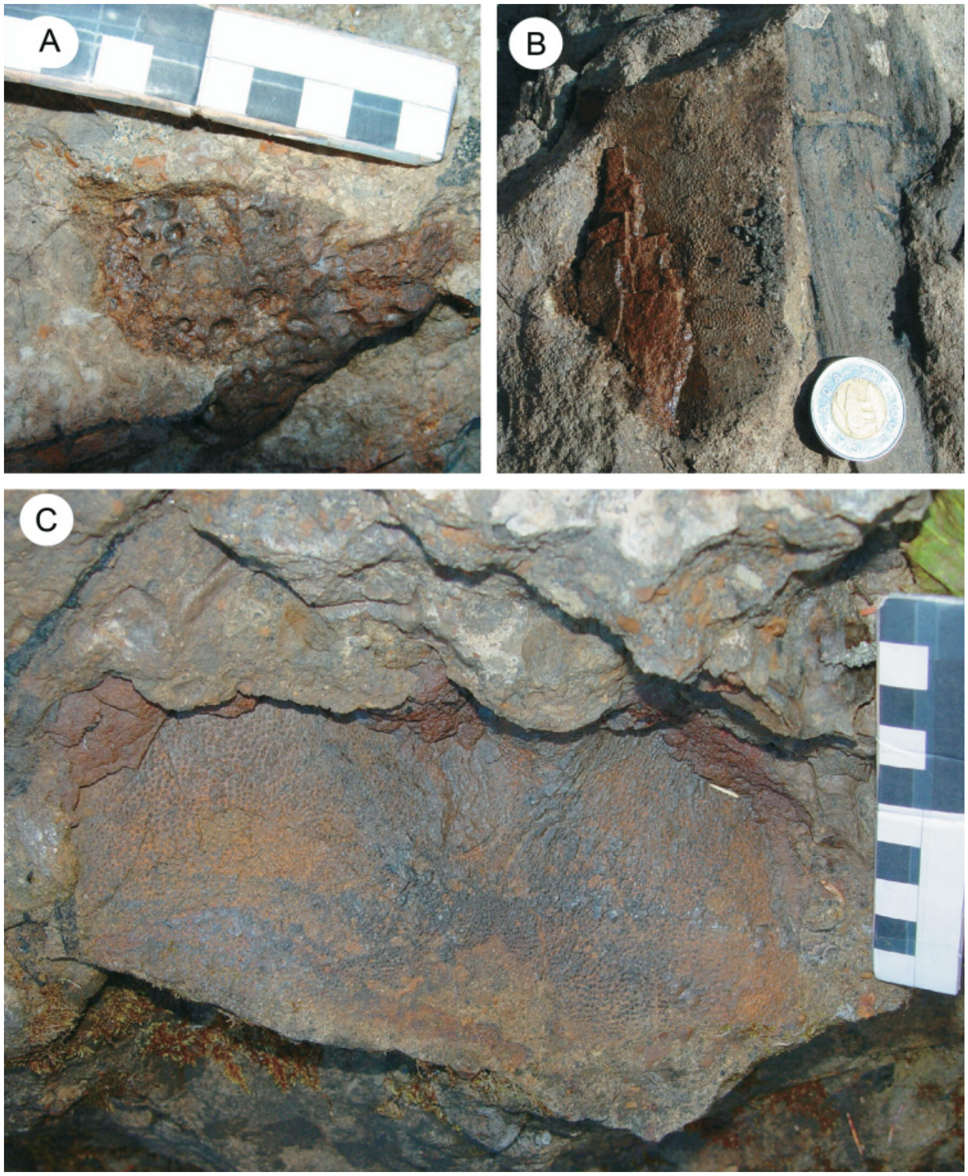


Fig. 15. Vertebrate skeletal material recovered from channel-filling sandstone of facies 7 at site 1 (Fig. 3). (A) Partially exposed crocodilian scute. (B–C) Partial carapaces of the turtle cf. *Naomichelys* sp. Scale in A, C is in centimetres.



Bioturbated granular mudstone is overlain by a thick succession of thinly bedded mudstone, siltstone, and very fine sandstone.

The gravel layer is interpreted as a ravinement lag resting on a *Glossifungites* surface cut by wave erosion. The presence of inoceramids and pervasive bioturbation in the overlying sandy mudstones suggest deposition in a fully marine offshore setting that nevertheless received an episodic supply of granular sand, presumably as a result of storm erosion of a nearby shoreface. Overlying thin-bedded deposits are indicative of deposition in a more distal, storm-influenced offshore area (Varban 2004). The overall stratigraphic succession suggests that the underlying lagoonal deposits accumulated landward of a transgressing barrier island that was transected by tidal inlets (Fig. 14). Continued transgression resulted in the barrier migrating across the study area. Wave scour at the toe of the barrier shoreface cut the ravinement surface across the lagoonal deposits, upon which the coarsest and least mobile clasts accumulated.

Sedimentation and accommodation change

Correlation of outcrop sections to nearby well logs (Varban and Plint 2005) shows that the shoreface deposits of the Wartenbe sandstone prograded about 10 km to the east of the Quality Creek locality, beyond which the massive sandstones pass laterally into heterolithic sandstones and mudstones representing an inner shelf environment. Varban and Plint (2005), interpreted each of the five major sandstone tongues in the Kaskapau Formation (Fig. 2) to represent a period when sediment supply matched, or somewhat exceeded, local accommodation rate, leading to vertical stacking and limited progradation of shoreface sandstones. Only the upper two sandstones (Wartenbe and Mount Robert sandstones) contain significant volumes of extra-basinal conglomerate in their upper parts. This distribution was interpreted as evidence for a progressive decrease in accommodation rate, which allowed rivers to construct progressively steeper gradients across the coastal plain, eventually resulting in gravel delivery to the shoreline (Varban and Plint 2005).

The accumulation of a southwest-thickening wedge of freshwater and brackish-water deposits above the regressive Wartenbe sandstones suggests, on geometric grounds, that new accommodation was produced as a result of the back-tilting of the strandplain towards the southwest. Muddy lacustrine deposits onlap and blanket the underlying beach ridge topography and indicate exclusively freshwater conditions at this time (Fig. 10). The freshwater deposits provide abundant evidence of shallow to emergent conditions, indicating a balance between accommodation and sediment supply rates.

The last evidence of freshwater conditions is provided by a thin but widespread coal, which extends across the study area (Fig. 7B). The coal indicates a regional rise in the water table and increased groundwater stagnation, which favoured peat accumulation. An apparent decrease in the local rate of clastic supply might reflect drowning and retreat of river systems to the southwest in response to back-tilting or simply diversion of rivers around a raised mire (McCabe and Parrish 1992). It seems likely that the groundwater remained fresh during peat accumulation: in overlying strata, plant colonization appears to have been inhibited by saline water.

The peat-forming mire was eventually overwhelmed and killed by a low-energy, brackish-water transgression that led to deposition of lagoonal mudstones across the entire study area. The lagoon appears to have been slightly deeper than the freshwater lakes, and experienced modest wave and tidal action. Small deltas prograded from the south, building lobes perhaps about 1 km in extent, supplied by distributary channels on the order of 50 m wide and 5 m deep. The absence of evidence for significant wave action indicates that the lagoon was protected from the open sea by a barrier system to the east, although inlets permitted tidal exchange (Fig. 14).

A continued increase in the accommodation to supply ratio eventually resulted in transgression of a barrier from the east and the cutting of a ravinement unconformity across the study area (Fig. 14). This event might be attributed to a further increase in the rate of back-tilting of the coastal plain, but the possibility of an eustatic component of accommodation can not be eliminated. The lowest 2–3 m of the overlying marine mudstones are intensely bioturbated and granule-rich, suggesting well-oxygenated conditions not far from shore. The upward change to thinly bedded silts and muds indicates major migration of the shoreline to the southwest and deepening across the shelf.

Discussion

Turonian paleoclimate in northern British Columbia: isotopes, models, and paleosols

During the Late Cretaceous, the Canadian portion of the Western Interior Seaway lay to the north of the Tethyan–Boreal oceanic front (Fisher and Hay 2002) and was dominated by relatively cool, lower salinity Arctic water (Hay et al. 1993). Model simulations of the Western Interior Seaway (Slingerland et al. 1996) indicate an anticlockwise circulation that drew Tethyan water north along the eastern side of the seaway, balanced by a southerly flow from the Arctic Ocean. Anomalously negative oxygen isotope ratios suggest the seawater along the western margin of the seaway was further diluted by runoff from rivers draining the eastern flanks of the Cordillera (Kyser et al. 1993).

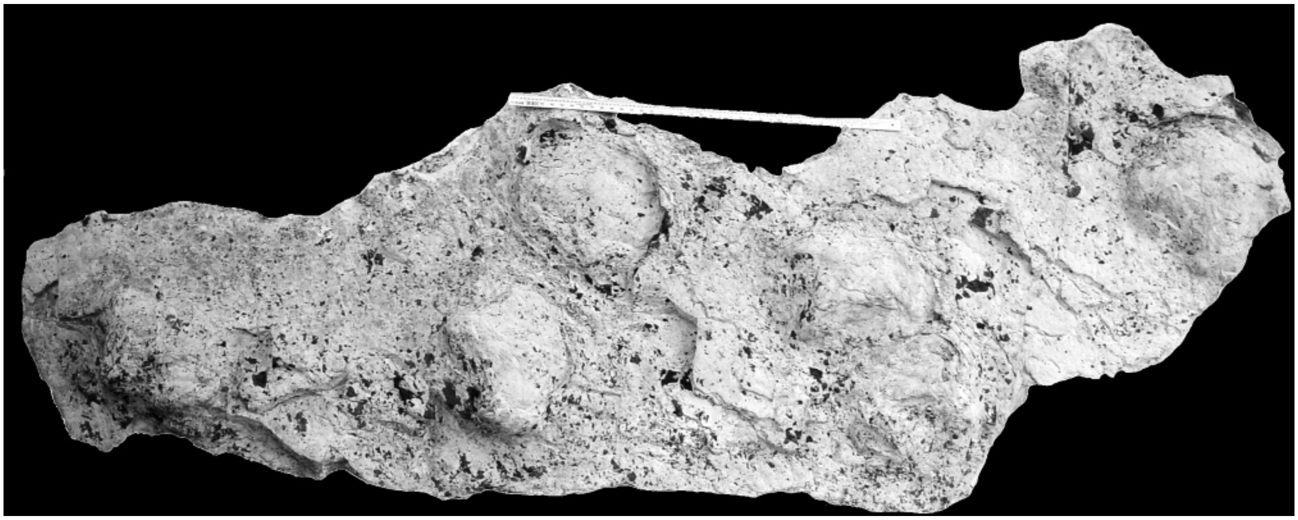
Fig. 16. Natural cast of a small tridactyl ornithopod footprint eroded from the creek bank near site 4. Scale = 10 cm.

Temperature estimates for the surface waters of the seaway during the Turonian vary. Frakes' (2002) compilation suggests, on the basis of admittedly sparse data that in the Turonian, the mean annual sea surface temperature at the latitude of our study area, at about 67°N, may have lain in the range 5–10 °C, with a corresponding mean annual land temperature of about 10 °C.

Latitudinal thermal gradients for the Cenomanian based on isotopic analyses (Sellwood et al. 1994) suggest a mean annual temperature of about 10 °C at 67°N. The modeling experiments of Kump and Slingerland (2002) indicated that at about 67°N, the temperature of the top 10 m of the water column lay in the range of 8–10 °C, and mean annual land temperature was inferred to lie in the range of 0–2 °C.

Pedological features of the middle Cenomanian Dunvegan Formation in northeast British Columbia (deposited at about 65°N) provide possible evidence of seasonally subfreezing temperatures with a mean annual temperature estimated at about 14 °C (McCarthy and Plint 1999). Paleobotanical evidence from Cenomanian strata on the North Slope of Alaska at about 75°N–80°N suggest a mean annual temperature of about 10 °C and a coldest month mean of about 0 °C (Spicer and Parrish 1990). Plint et al. (in press), considered the mechanisms by which the "outsize" quartzite cobbles and a boulder in the marine transgressive lag (facies 8, Fig. 12) were transported to the shoreline across a very low-gradient coastal plain. Although entanglement in tree roots was considered the most likely possibility, rafting by seasonal river ice could not be ruled out.

Fig. 17. Trackway of a large ornithopod preserved as a natural cast (photo taken from a replica cast). Note the inturning of the individual prints towards the midline of the trackway. Scale = 1 m.



Paleoclimatic implications of vertebrate fossils from Quality Creek

A variety of bone material has been extracted from channel-filling sandstone of facies 7 at site 1 (Fig. 3; McCrea 2003; McCrea and Buckley 2004). The majority of the material is currently unprepared and is awaiting identification. Identifiable dinosaur skeletal material includes two teeth from an unknown theropod, as well as nodosaurid ankylosaur osteoderms. Non-dinosaurian remains include turtle elements, a crocodilian scute (Fig. 15A), and two partial carapaces of the turtle genus cf. *Naomichelys* sp. (Figs. 15B, 15C), as well as fish scales. *Naomichelys* sp. occurs near or in brackish water (Eaton 1990, 1999; Eaton et al. 1999*a*, 1999*b*), but has also been recovered from sediments that have very little brackish water influence (Eaton et al. 1999*a*, 1999*b*). The presence of cf. *Naomichelys* sp. indicates that brackish-water conditions were present during deposition of the channel-filling sandstone (facies 7), corroborating the sedimentological interpretation.

Reptiles can be utilized in paleoclimatic interpretations because they have more specific tolerances to thermal extremes than do other vertebrates (Tarduno et al. 1998). Tarduno et al. (1998) used the thermal boundaries of the extant aquatic turtles *Chelydra sepentina* and *Chrysemys picta* to infer a mean annual temperature of at least 2 °C and a warm month average temperature of at least 25 °C, based on turtle remains recovered from Axel Heiberg Island. The presence of crocodilian material at this site has paleoclimatic and paleohydraulic implications. Markwick (1998) demonstrated that extant crocodilians are limited to regions that experience a mean annual temperature of no less than 14.2 °C and a coldest month temperature of >5.5 °C. Markwick (1998) also noted that the presence of standing water increased the chance of survival for crocodilians during periods of below freezing temperatures. This is consistent with the climatic interpretations for the middle Cenomanian Dunvegan Formation (McCarthy and Plint 1999) but inconsistent with isotopic analyses on Cenomanian latitudinal thermal gradients (e.g., Sellwood et al. 1994) and the models of Kump and Slingerland (2002). Tarduno et al. (1998) also inferred a thermal tolerance for champsosaurs based on the thermal tolerances of turtles and crocodilians, but to date no champsosaur remains have been recovered from the Quality Creek site.

On the basis of the various lines of evidence, it would appear that the Turonian terrestrial environments in our study area experienced a perennially humid climate with a mean annual temperature close to 14 °C, with a coldest month mean about 5.5 °C, although it is possible that winter temperatures dropped below freezing for short periods.

Depositional environments interpreted from other Turonian-age terrestrial vertebrate localities

Fox (1984) reported a humerus of *Ichthyornis* sp., a toothed, tern-like bird (Gill 1990) from a marine sandstone in the Vimy Member of the Kaskapau Formation (early Turonian), along the Smoky River at Watino, Alberta. Recent stratigraphic studies (Varban and Plint 2005; Varban, personal observation, 2005) suggest, however, that the skeletal remains may have come from the stratigraphically lower, late Cenomanian Sunkay Member of the Kaskapau or possibly the uppermost Dunvegan Formation instead of the early Turonian Vimy Member.

Although sparse, other Turonian-age terrestrial vertebrate assemblages have been reported from a variety of depositional environments. A partially disarticulated and obviously drifted carcass of a juvenile hadrosaur was reported from middle shelf to upper bathyal sediments in the Matanuska Formation (middle Turonian) in the Wrangellia composite terrane of Alaska (Pasch and May 1995, 1997, 2001). Eaton et al. (1999*a*, 1999*b*), Kirkland et al. (1998), and Parrish (1999) report dinosaur and other terrestrial vertebrate fauna from shoreface deposits with deltaic influence for the Tibbett Canyon Member (middle Turonian) of the Straight Cliffs Formation, and paludal deposits with a brackish water vertebrate fauna overlain by floodplain and lacustrine deposits from the Smokey Hollow Member (late Turonian) of the Straight Cliffs Formation. Eaton (1999) reports brackish-water conditions in the Iron Springs Formation (?Cenomanian–?Coniacian) attributable to the maximum transgression of the Greenhorn Sea.

The terrestrial vertebrate material recovered from the lower member of the Moreno Hill Formation (middle Turonian) of the Zuni Basin in New Mexico was found in fluvial and lacustrine (including coal-forming) environments (Wolfe and Kirkland 1998). Tarduno et al. (1998) report nonmarine aquatic and semiaquatic vertebrates from estuary–bay siltstone deposits on Axel Heiberg Island.

Turonian age terrestrial vertebrate material has been reported outside North America (Archibald et al. 1998). The paleoenvironment for the bone-bearing redbeds of the Valle de Angeles Group (Cenomanian to early Turonian) of central Honduras was interpreted to be a transgressive coastal succession dominated by fluvial systems and ranging from piedmont to floodplain with localized lacustrine or lagoonal or embayment environments (Horne 1994).

The Turonian record of vertebrate tracks

To date, very few reports of Turonian vertebrate tracks or trackways have been published, although significant finds of tracks and trackways have been made in northeastern British Columbia (Sampson and Currie 1996; McCrea 2003; McCrea and Buckley 2004). Isolated tracks collected from a roadcut exposure of the Cardium Formation in Alberta were then the only known tracks reported from the Turonian (Currie 1989). However, these specimens were never described and it seems they were retained as part of a private collection (P. Currie, personal communication, 2005). The only other record of possible Turonian-age tracks comes from South Korea (Paik et al. 2001). We are unaware of any other reports of Turonian tracks or trackways (although AGP has seen numerous tracks and dinoturbation in the Cardium Formation in outcrop and core, these observations have not been formally published).

The vertebrate track fauna from Quality Creek is dominated by large ornithopods, with some occurrences of possible ankylosaur tracks and a very few small to medium size ornithopod tracks (Fig. 16). The majority of identifiable tracks are preserved as natural casts that have weathered out from the banks of the creek. Well over 50 specimens have been found within the study area, both in situ and as isolated blocks. To date, only one trackway of significant length has been found. This trackway is preserved as a series of four tridactyl natural pes casts on the basal surface of a lagoonal delta sandstone at site 7 (Figs. 3, 17). The individual prints are large (~30 cm long by 30 cm wide) but are variable in size and shape. This variability is probably due to deformation caused by the weight and gait of the animal as well as the softness of the substrate. The ratio of footprint length to footprint width is almost exactly 1:1, which, together with the blunt ends and thickness, makes a large ornithopod the most likely track maker. Additional characteristics, including a wide trackway width and obviously high pace angulation indicate a large ornithopod. The average pace is ~90 cm and the average stride is 174 cm.

Conclusions

Middle Turonian strata exposed in Quality Creek, northeast British Columbia, were deposited on the western margin of the Western Interior Seaway at a paleolatitude of about 67°N. The study site represents a lower coastal plain setting that lay up to 10 km landward of the marine shoreline. A variety of nonmarine sedimentary environments are recognized, including tidal channel, beach ridge and inter-ridge slough, peat mire, freshwater lake, lacustrine delta, distributary channel, tide-influenced lagoon, oyster bioherm, and lagoonal delta. Abundant tracks provide evidence that large ornithopods, ?ankylosaurs, and small theropods inhabited all of these environments. Bone material forming a lag deposit in a distributary channel sandstone indicates the presence of ornithopods, ankylosaurs, and theropods, together with turtles of the genus *Naomichelys*, crocodiles, and fish. The paleolatitude, inferred from paleomagnetic studies, was close to the Turonian Arctic Circle. This implies a significant period of winter darkness at the study site, dormancy in angiosperms, and, presumably a more restricted winter food supply for herbivores. The presence of crocodiles suggests a coldest month mean temperature of no less than 5.5 °C and a mean annual temperature of about 14 °C. This figure is comparable to that estimated from paleobotanical and paleopedological studies, but is somewhat higher than the mean annual temperature of about 10 °C suggested by isotopic studies. This site provides both the first dinosaur bone from British Columbia and is currently the oldest record of dinosaur bone material anywhere in western Canada. Further study of the Quality Creek remains has the potential to provide a better view of the paleogeography of dinosaurs in western Canada, and of the “middle” Cretaceous immigration of Asiatic dinosaur taxa to North America.

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