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Depositional environments and processes in Upper Cretaceous nonmarine and marine sediments, Ocean Point dinosaur locality, North Slope, Alaska

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Abstract

A 178-m-thick stratigraphic section exposed along the lower Colville River in northern Alaska, near Ocean Point, represents the uppermost part of a 1500 m Upper Cretaceous stratigraphic section. Strata exposed at Ocean Point are assigned to the Prince Creek and Schrader Bluff formations. Three major depositional environments are identified consisting, in ascending order, of floodplain, interdistributary-bay, and shallow-marine shelf.

Nonmarine strata, comprising the lower 140 m of this section, consist of fluvial distributaries, overbank sediments, tephra beds, organic-rich beds, and vertebrate remains. Tephras yield isotopic ages between 68 and 72.9 Ma, generally consistent with paleontologic ages of late Campanian–Maastrichtian determined from dinosaur remains, pollen, foraminifers, and ostracodes.

Meandering low-energy rivers on a low-gradient, low-relief floodplain carried a suspended-sediment load. The rivers formed multistoried channel deposits (channels to 10 m deep) as well as solitary channel deposits (channels 2–5 m deep). Extensive overbank deposits resulting from episodic flooding formed fining-upward strata on the floodplain. The fining-upward strata are interbedded with tephra and beds of organic-rich sediment. Vertical-accretion deposits containing abundant roots indicate a sheet flood origin for many beds. Vertebrate and nonmarine invertebrate fossils along with plant debris were locally concentrated in the floodplain sediment. Deciduous conifers as well as abundant wetland plants, such as ferns, horsetails, and mosses, covered the coastal plain. Dinosaur skeletal remains have been found concentrated in floodplain sediments in organic-rich bone beds and as isolated bones in fluvial channel deposits in at least nine separate horizons within a 100-m-thick interval. Arenaceous foraminifers in some organic-rich beds and shallow fluvial distributaries indicate a lower coastal plain environment with marginal marine (bay) influence.

Marginal marine strata representing interdistributary bay deposits overlie the nonmarine beds and comprise about 15 m of section. Extensive vegetated sand flats, shoals, and shallow channels overlain by shallow bay deposits (less than 7 m deep), containing storm-generated strata characterize the marginal marine beds. Abundant bioturbation and roots characterize the stratigraphic lowest bay deposits; bioturbated sediment, pelecypods, barnacles, and benthic microfossils are found in the overlying bay storm deposits. The sediments abruptly change upward from hummocky cross-stratified bay deposits to a muddy marsh deposit containing shallow organic-rich channels to prograding nonmarine to marginal marine beds.

Transgressive, abundantly fossiliferous shallow-marine strata more than 13 m thick comprise the uppermost exposures at Ocean Point. The marine beds overlie nonmarine and bay strata and represent an environment dominated episodically by storms. The age of the marginal marine and marine beds is late Maastrichtian based on pollen.

Keywords: Cretaceous; Northern Alaska; Depositional environments; Dinosaur occurrences; Prince Creek Formation; Schrader Bluff Formation

1. Introduction

Strata exposed in low bluffs along the lower Colville River near Ocean Point, Alaska, at about 70° North latitude contain one of North America's northernmost occurrences of dinosaur skeletal remains. This dinosaur

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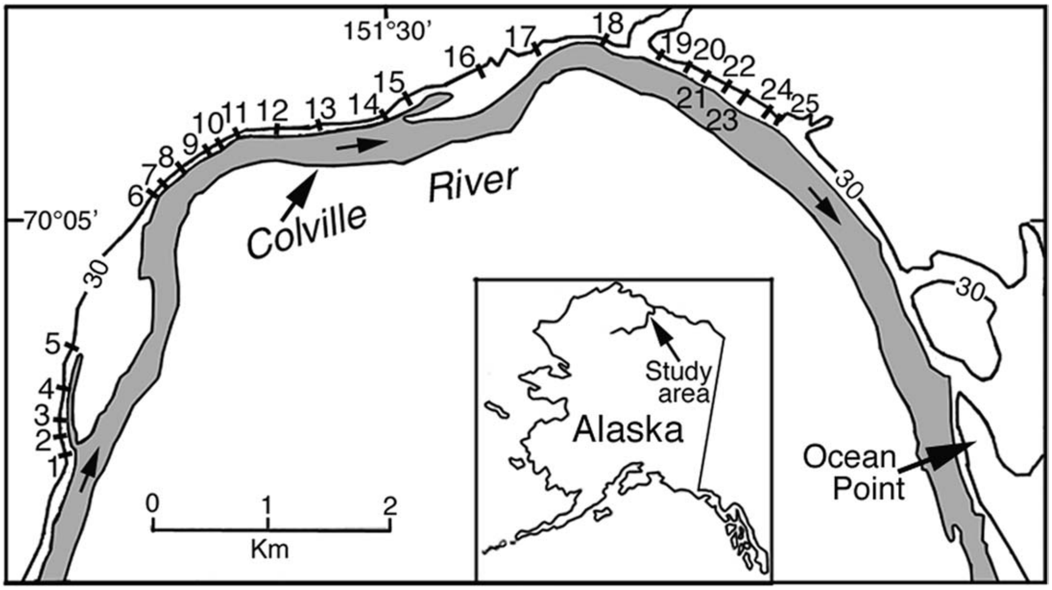

Fig. 1. Study area and locations of measured sections of the Prince Creek and Schrader Bluff formations along the Colville River near Ocean Point, North Slope, Alaska. The arrows indicate current flow direction in the Colville River. Contour in meters.

occurrence is significant in that it shows these reptiles existed at high-latitudes, 83–85° North, based on continental reconstruction of northern Alaska in the latest Cretaceous (Ziegler et al., 1983; Lawver et al., 2002). The dinosaurs lived in a coastal plain deltaic environment in a cool-temperature climate regime, 2–8 °C, with little seasonal climate variations (Spicer, 1987; Parrish & Spicer, 1988; Spicer & Parrish, 1990a). If the dinosaurs overwintered, they were subject to long periods of darkness with probable short periods of freezing (Parrish et al., 1987; Clemens, 1992a; Waller & Marincovich, 1992). The main questions posed by this dinosaur occurrence are, did they overwinter and were they possibly endothermic (Clemens & Nelms, 1993), or did the dinosaurs migrate south with the retreating sunlight (Parrish et al., 1987; Currie, 1989)?

The strata record nonmarine, bay, and marine environments. Identification of depositional elements allows reconstruction of paleoenvironments and major sedimentological processes in these high-latitude northern regions where deltaic progradation into the ancestral Arctic Ocean dominated the sedimentological history. This report identifies the stratigraphic setting, facies associations, sedimentary processes, and depositional environments that existed during the latest Cretaceous in these northern latitudes.

The field investigations conducted in 1986, with subsequent visits in 1987 and 1992, measured, described, and collected samples from 25 stratigraphic sections (Fig. 1). Work included analyzing vertical and lateral changes within the bedded sequences, and laterally tracing and correlating strata between the measured sections. The lithology, sedimentary structures, paleocurrent trends, fossils, mineralogy, and texture are identified within each depositional sequence. The sediment texture was analyzed using standard techniques (Folk, 1974).

2. Geologic setting

The study area is located on the Arctic Coastal Plain physiographic province along the lower Colville River approximately 45 km south of the Beaufort Sea. In the study area along the western and northern sides of the Colville River, 30-m-high bluffs contain excellent and laterally extensive exposures. The exposed sediments consist of well-bedded, consolidated sand, silt, clay, tephra, and organic-rich silt. Extensive river erosion and slumping of the bluff frequently modify the exposures so that the exact outcrops described and illustrated here are most likely no longer present.

In the lower Colville River region an angular unconformity separates the sands and silts of the Colville Group from the overlying Pliocene/Pleistocene sands and gravels of the Gubik Formation (Black, 1964). The Gubik Formation is flat-lying while the Colville Group dips gently at 3 degrees or less to the northeast. The beds studied include a 178-m-thick stratigraphic section, of which approximately 150 m is exposed (Phillips, 1988). Four high-angle faults of unknown but probably small (<30 m) displacement are identified in the study area: two are exposed, and two are covered but suggested by abrupt lateral changes in lithology and bed thickness.

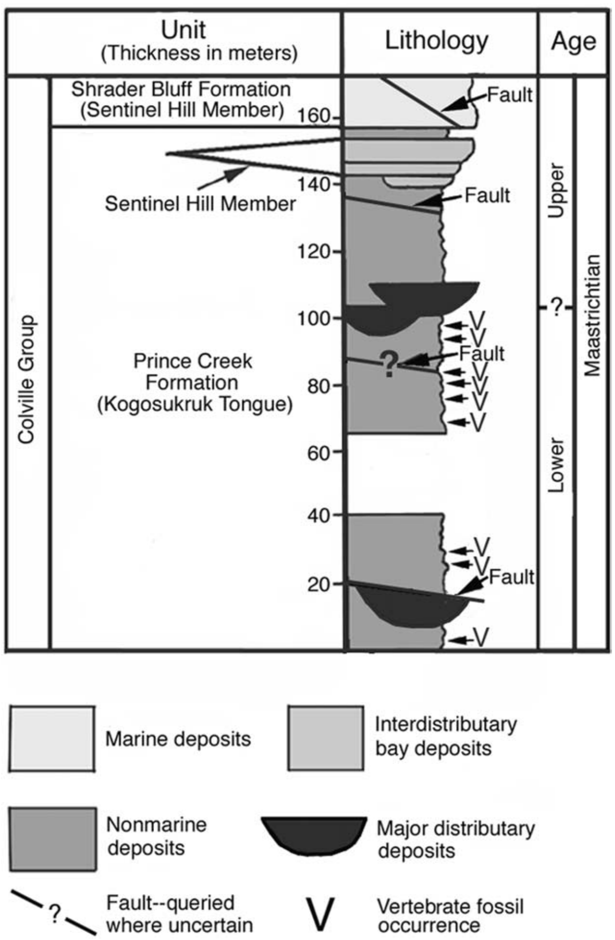

Fig. 2. Composite stratigraphic section, 178 m thick, of the study area along the lower Colville River, Alaska showing stratigraphic nomenclature, generalized lithology, faults, and vertebrate (dinosaur) occurrences. The approximate position of the Lower-Upper Maastrichtian boundary is from Frederiksen & McIntyre (2000).

The strata in ascending order consist of nonmarine, marginal marine, and marine beds (Fig. 2). The nonmarine beds represent the Kogosukruk Tongue of the Prince Creek Formation (Brosgé & Whittington, 1966) and now as revised represent the middle part of the Kogosukruk Tongue (Frederiksen & McIntyre, 2000). The marginal-marine and marine beds constitute part of the Sentinel Hill Member of the Schrader Bluff Formation (Macbeth & Schmidt, 1973; Marincovich et al., 1985; McDougall, 1987; Frederiksen & McIntyre, 2000).

The nonmarine strata, the lower 140 m of the stratigraphic section, are Late Cretaceous, but the overlying marine strata, the upper 38 m, based on different fossil assemblages suggest a Late Cretaceous or possibly an early Tertiary age. The age of the nonmarine strata, on the basis of vertebrate remains, has been recorded as Late Cretaceous (Clemens & Allison, 1985), Maastrichtian or possibly Campanian (Davies, 1987), and late Campanian–early Maastrichtian (Gangloff, 1992) or possibly early Maastrichtian (Clemens & Nelms, 1993). The lower 135 m of nonmarine strata are late Campanian–early Maastrichtian based on ostracodes, arenaceous foraminifers, and pollen (Brouwers et al., 1987), or late Maastrichtian (Brouwers & De Deckker, 1992; 1993) based on ostracodes. K-Ar and ^{40}Ar/ ^{39}Ar dating of tephra beds bracketing the dinosaur-bone-bearing strata in the interval from 124 to 40 m below the contact with the overlying marginal marine strata yielded dates between 68 and 71 Ma (McKee et al., 1989; Conrad et al., 1992). These ages correspond to mid- and early Maastrichtian according to Gradstein et al. (1994). A sanidine analyses yields an age of 72.9 Ma, late Campanian, for a single tephra bed in the lower stratigraphic section (J. D. Obradovich in Clemens, 1992a). Based on pollen the strata are Maastrichtian with the lower-upper Maastrichtian boundary, at 69.5 Ma, apparently placed above the major fluvial channel deposits (Frederiksen & McIntyre, 2000).

The age of the strata overlying the nonmarine beds, the marginal marine and marine beds varies depending on the fossil groups analyzed. On the basis of mollusks the marine strata have been assigned a late Maastrichtian or early Paleocene age (Waller & Marincovich, 1992), or post-Danian Paleocene–early Eocene (Thanetian–Ypresian) based on mollusks and ostracodes (Marincovich, 1993; Marincovich et al., 1985, 1990). An early Paleocene (Danian) age based on ostracodes is indicated for the marginal marine and marine strata (Brouwers & De Deckker, 1992; 1993). On the basis of benthic foraminifers, the age of the marine strata is considered Campanian (Macbeth & Schmidt, 1973) or early Maastrichtian (McDougall, 1987). On the basis of palynomorphs, the beds are Maastrichtian (Frederiksen et al., 1986, 1988; Frederiksen & Schindler, 1987; Frederiksen, 1991), and early late Maastrichtian (Frederiksen & McIntyre, 2000).

In summary, the nonmarine strata containing dinosaur remains apparently range from late Campanian to early Maastrichtian based on pollen, vertebrates, and isotopic dating of tephras. The marginal marine and marine strata contain fossil assemblages whose ages are widely divergent, ranging from Campanian to early Eocene. Mollusks and ostracodes indicate late Maastrichtian–early Eocene ages, while foraminifers and pollen suggest Campanian–early late Maastrichtian.

However, the preponderance of pollen evidence suggests a Maastrichtian age for the upper marginal marine and marine strata. Well-preserved Paleocene pollen assemblages are identified from the lower Colville River and sites east of the Colville River (Frederiksen et al., 1988). The Paleocene floras do not show up at Ocean Point. If the upper marine strata at Ocean Point were a mixture of Maastrichtian and Paleocene sediment, the pollen assemblages should contain both

Cretaceous and Paleocene fossils. No evidence of a mixed age flora is observed in the upper strata (Tom Ager, pers. comm. 2002). The approximate position of the Cretaceous-Tertiary boundary is placed north of the Ocean Point outcrops (Frederiksen et al., 1988). Following Frederiksen & McIntyre (2000), an early late Maastrichtian age will be used for the upper marine sequence.

3. Depositional facies and interpretation

The strata of the Colville Group can be divided in ascending order into three major facies consisting of: (1) nonmarine strata containing fluvial distributaries, overbank sediments, tephra beds, organic-rich beds, and vertebrate remains; (2) marginal marine strata containing extensive vegetated sand flats, channels, and storm-generated strata; and (3) a transgressive storm-dominated marine sequence (Fig. 3a–c).

3.1. Nonmarine facies

Nonmarine strata, which comprise the lower 140 m of the stratigraphic section, contain major and minor fluvial distributaries, extensive overbank strata, and tephra beds. Toward the top of the stratigraphic interval, the nonmarine sediments interfinger with bioturbated interdistributary and storm-dominated bay deposits.

Major distributary deposits. Three sand-filled and one mud-filled channel form the major fluvial distributaries identified in the nonmarine section. All but one of these, a sand-filled channel, occurs in a multistoried channel system (Fig. 3a, b). Exposures of the channel deposits consist of a transverse cut across the solitary channel and an oblique cut nearly parallel to the channel axis of the multistoried channel system. The individual channel-fill sequence ranges in thickness from 6.5 to 10 m.

The channels are incised into floodplain sediments. The base of each channel is a concave erosional surface with low relief. Thin (less than 10-cm-thick) discontinuous lag deposits overlie the erosional surface. The lag deposits consist of mud rip-up clasts, large carbonized wood fragments up to 20 cm thick, comminuted plant debris, rare solitary dinosaur bones, and detrital carbonate concretions. Strata overlying the lag deposits exhibit large-scale 2- and 3-dimensional cross-beds (classification of Ashley, 1992). The upper contacts of the channel deposits are gradational with overlying floodplain strata.

The channel deposits contain the coarsest sediment in the nonmarine facies fining upward from medium-grain sand to very fine silty sand to very fine sandy silt (classification of Folk, 1974). The sand volume, likewise, decreases vertically from a maximum of 68 per cent near the base of the channel deposits to a minimum of 23 per cent near the top (Fig. 4). The sand fraction consists of angular to subrounded quartz, muscovite, organic fragments, and abundant lithic grains of mica schist.

Cross-beds within two of the sandy channel deposits change vertically from large- to small-scale 2- and 3-D bedforms (Fig. 3a, b). The lowest channel in the multistoried system contains only small-scale cross-beds and planar laminations. Within the thickest channel deposit, the sediment above the basal lag contains large-scale 3-D cross-beds in sets up to 1.5 m thick with some beds deformed. Mud rip-up clasts usually separate the cross-beds. Overlying the 3-D cross-beds are sets of large-scale 2-D cross-beds, up to 74 cm thick, which also decrease in thickness vertically; some sets contain wood fragments, abundant plant debris, thin mud beds, burrows, and mud rip-up clasts (Fig. 5). Planar laminations occur at the top of the 2-D cross-beds.

The uppermost part of the channel, which reflects the lowest energy conditions, forms a tabular to wedge-shaped deposit up to 2.7 m thick. It contains small-scale organic-rich 2- and 3-D cross-beds interbedded with planar silt laminations. The strata containing the small-scale cross-beds dip at low angles (4 degrees or less). A small U-shaped channel, 1.5 m deep, cuts through the upper part of this sequence in one exposure. Abundant vertical root structures extend downward 2–6 m below the top of the channel deposits. Beds of olive to gray mud gradationally overlie the channel strata. Thinly laminated to structureless blue to gray mud, 8.5 m thick, and marked by a basal erosional surface, represents a mud-filled abandoned channel (Fig. 3b, section 10).

Interpretation. The large-scale cross-beds within the lower parts of the channels are interpreted as vertical-accretion deposits that formed from 2- and 3-D bedforms migrating within the channel. Fluctuating flow velocities within the channel resulted in the formation of different bedform types. The inclined strata containing small-scale cross-beds overlying the large-scale bedforms represent migration of lateral-accretion surfaces of point bars or lateral bars within the channel. The upper parts of these bars were extensively vegetated, as indicated by the abundant root structures. The mud-filled channel deposit may have resulted from river avulsion, possibly by neck cutoff of a meander bend.

Evidence for the fluvial meanders includes: (1) abandoned mud-filled channel plugs, good indicators of sinuous rivers (Walker & Cant, 1984); (2) fining-upward sediment texture and the upward decrease in the size of sedimentary structures (Allen, 1965; Rust, 1978; Galloway, 1985), and (3) multistoried channels. Caution is needed, however, in inferring the geometry of a few channel deposits (Bridge, 1985); especially when outcrops are essentially two-dimensional, as they are in the study area.

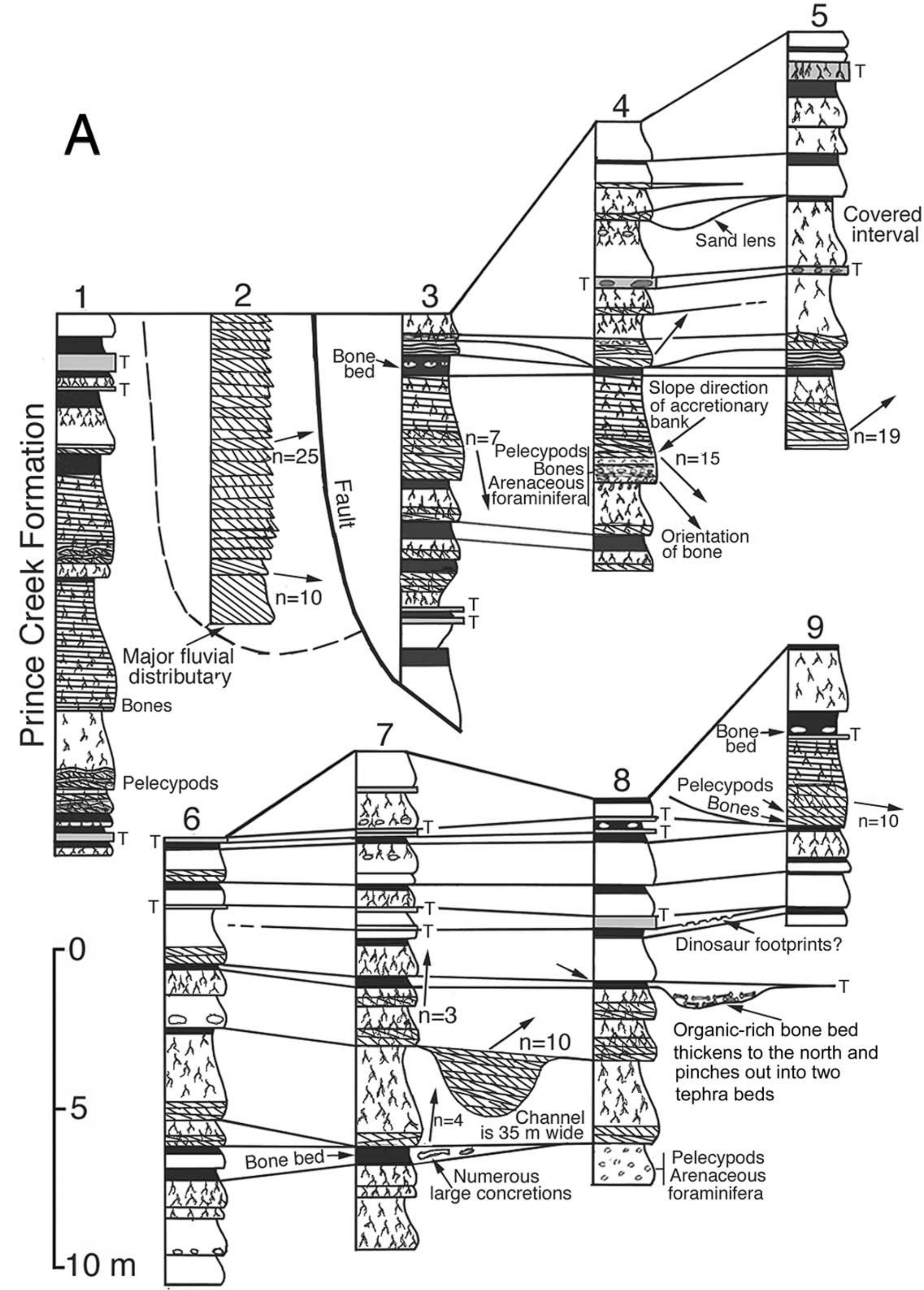

Fig. 3. A, measured sections 1–9, floodplain deposits. B (see over page), measured sections 10–19, floodplain to interdistributary bay deposits. C (see over page), measured sections 20–25, interdistributary bay and marine deposits. See Fig. 1 for locations of sections.

The fine sediment fraction was transported within these channels mainly as a suspended load, and therefore the rivers represent a suspended-load fluvial system using the classification of Schumm (1968). The sand fraction was transported in lower-flow-regime bedforms with locally fluctuating velocities that produced different

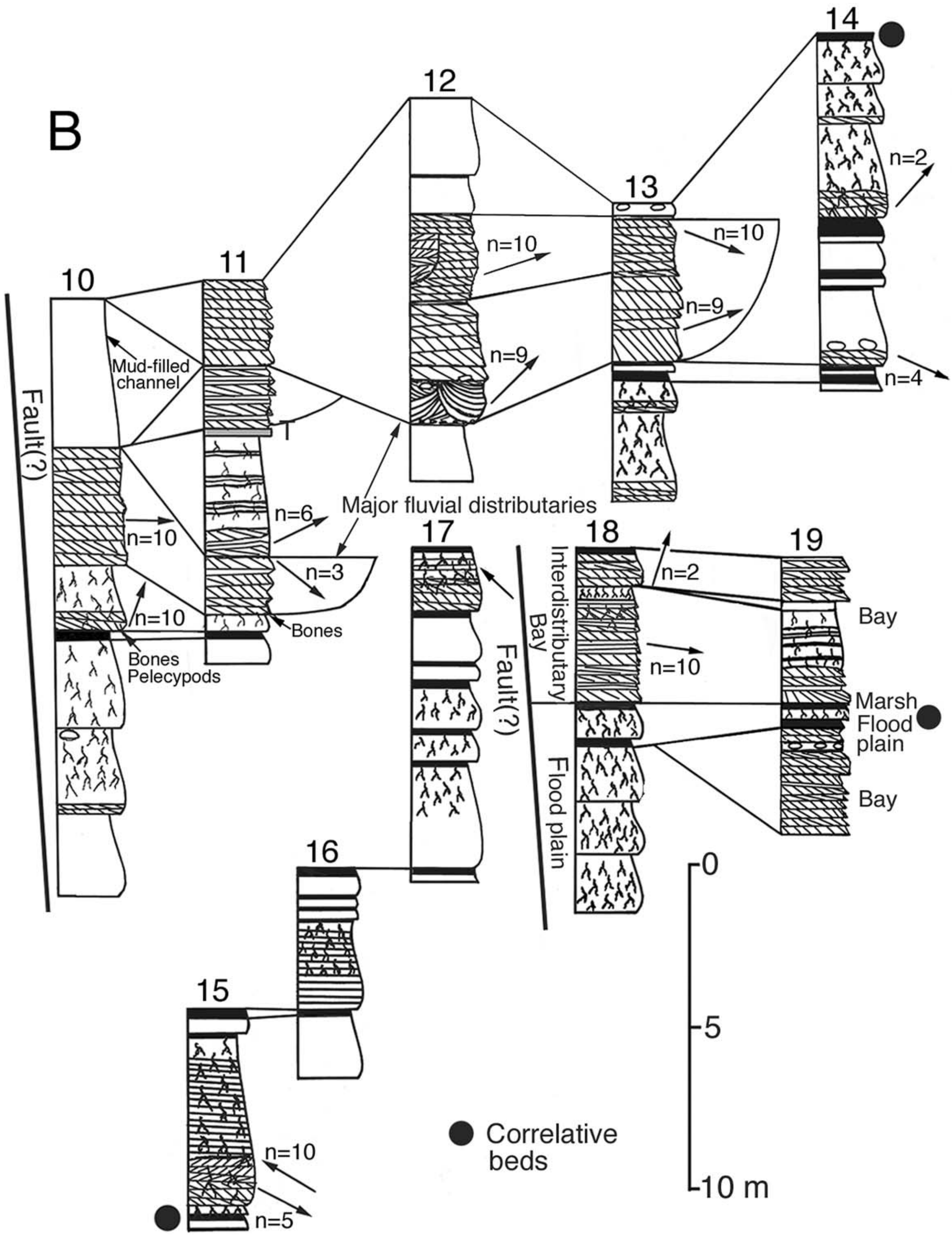

Fig. 3B

bedform types. The river banks and bars were extensively vegetated. The paleocurrent data record an easterly-directed trend for the fluvial channels (Fig. 4). The fluvial channels meandered eastward across the coastal plain transporting the coarsest available sediment (medium-grain sand); the rivers were at least 10 m deep and 500–600 m wide (width determined by the method of Leeder, 1973), approximately the same dimensions as the present-day Colville River in this region.

Minor-distributary deposits. Minor-distributary-stream deposits consist of tabular channel-fill strata

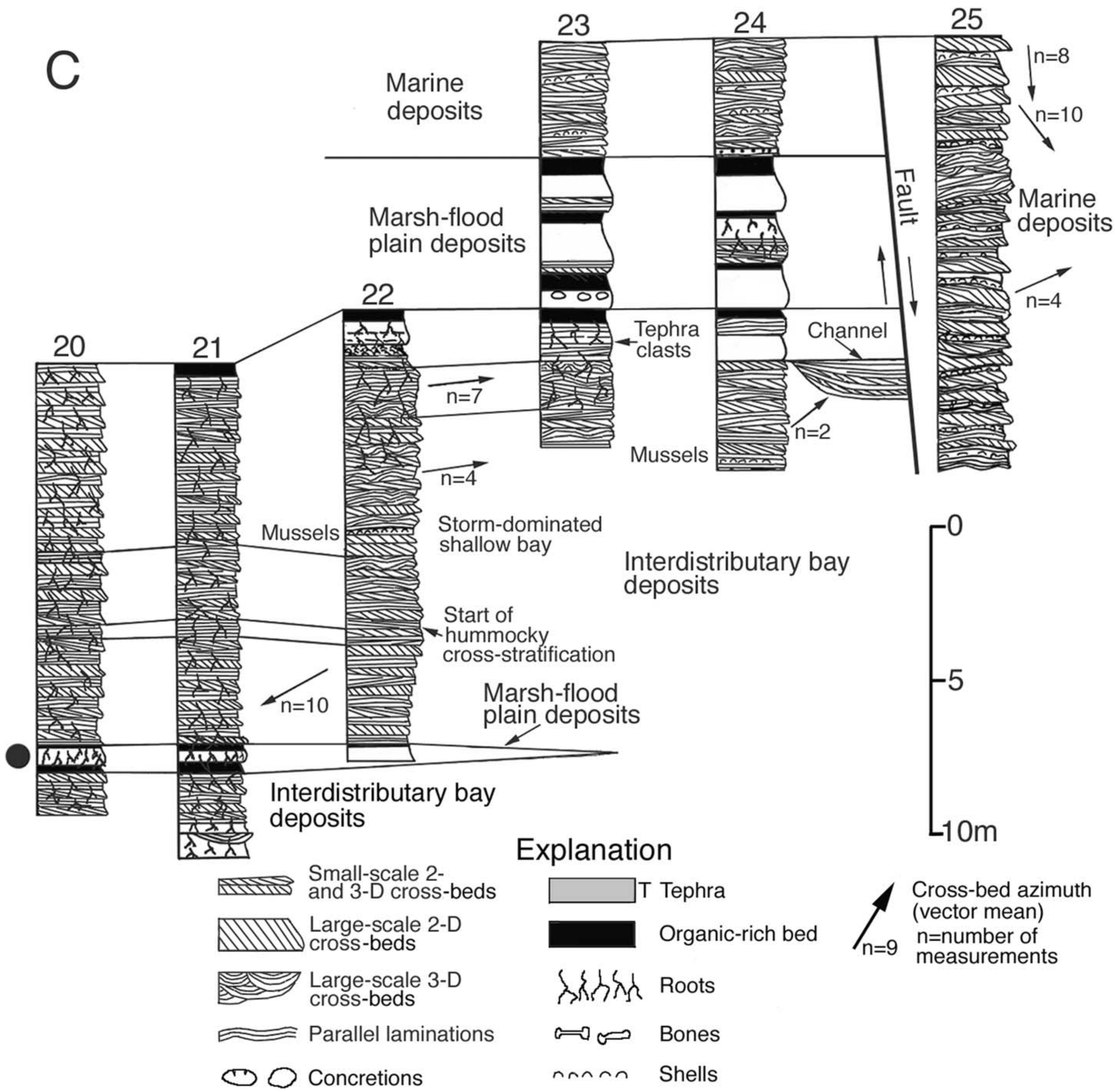

Fig. 3C

having a sharp erosional base and a lower coarse member of gently inclined sandy mud grading upward to a fine member of silt and clay. Some channel-fill deposits contain only structureless mud. These deposits range in thickness from 2.7 to 5.5 m, averaging 3.4 m.

The base of each channel is formed by a flat or gently undulating erosional surface, with minor local relief, cut into fine-grained floodplain deposits. Lag deposits on the erosional surface are rare but can contain finely comminuted plant material, carbonized wood, mud rip-up clasts, rare to abundant freshwater invertebrates, vertebrate skeletal remains, and, in two channel deposits, arenaceous foraminifers. Burrows containing large pelecypods are found within and extending beneath some channel-lag deposits into the underlying depositional unit (Fig. 6).

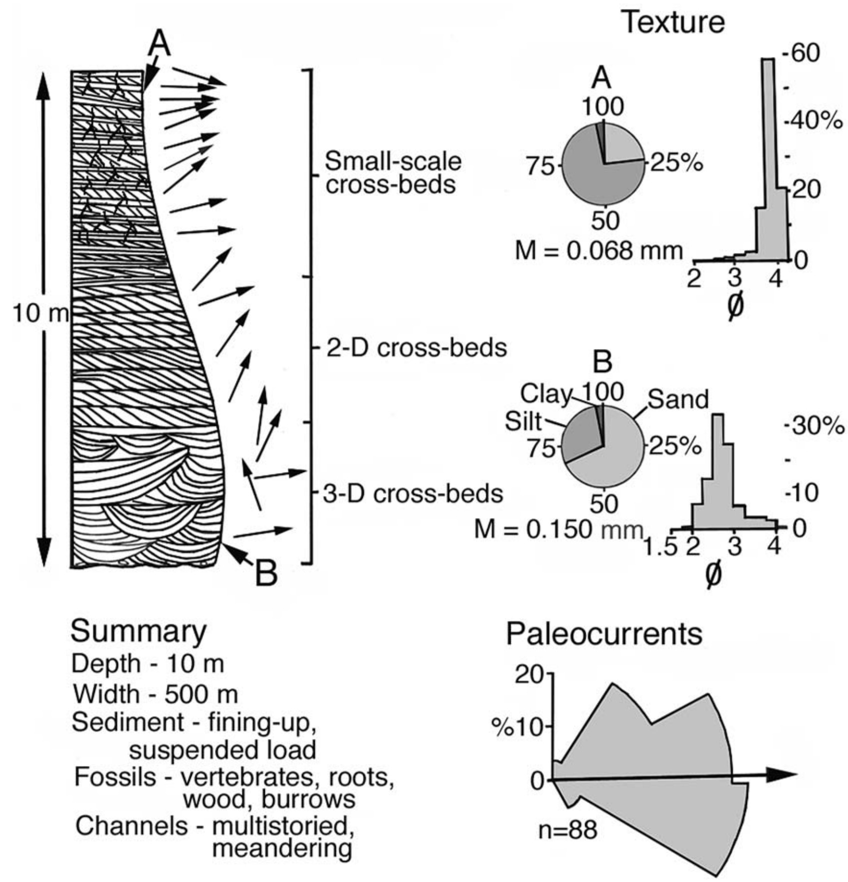

Fig. 4. Summary of sedimentologic features of major fluvial distributary deposits in the Prince Creek Formation, lower Colville River region, Alaska. Letters adjacent to vertical section indicate locations of samples for textural analysis. Paleocurrent data from large- and small-scale cross-beds.

The basal coarse member of the fining-upward cycle consists of very fine sand to sandy mud. Small-scale 2- and 3-D cross-beds in sets ranging from 1 to 3 cm thick or parallel and undulatory laminations interbedded with small-scale cross-beds comprise the sedimentary structures. Sediment in this member is classified as sandy mud with the sand fraction decreasing and the silt and clay fraction increasing upward (Fig. 7). The sand volume, up to 26 per cent by weight, consists of angular to subangular quartz, muscovite, lithic grains, pyrite, organic fragments, and volcanic glass shards. Within some deposits, glass shards form more than 90 per cent of the sand-sized fraction.

The coarse member grades vertically into the fine member. Olive to gray-brown silt and clay locally containing pyrite, mottled patches of vivianite, jarosite, carbonate concretions (of both decimeter and millimeter size), glass shards, and abundant vertical roots constitute the fine member.

Sets of epsilon cross-beds (Allen, 1963) dipping at angles of up to 7 degrees, composed of small-scale cross-beds alternating with laminated silt, fill some of the channel deposits. The dip of the small-scale cross-beds is normal to the dip of the epsilon strata. The inclined epsilon strata grade up-dip into structureless silt and clay containing abundant roots (Figs. 6 and 7). Vertical carbonaceous rhizomes of the plant *Equisetites* (horsetails; Brouwers et al., 1987; Parrish & Spicer, 1988; Spicer & Parrish, 1990b) and aquatic plants are common throughout the nonmarine section especially in the channel deposits. Paleocurrent data exhibit an irregular pattern with a dominant current trend to the northeast (Fig. 7).

Overlying the root-bearing strata and constituting the uppermost parts of the fine member are horizontal beds, rarely laminated, of black to dark-brown organic-rich silt containing varying concentrations of comminuted plant material and carbonate concretions.

Megafossils within these fluvial cycles are rare to abundant and include both invertebrates and vertebrates. The invertebrate fossils consist of freshwater pelecypods (up to 11 cm in diameter) and gastropods, both found within the basal coarse-grained member of four stream deposits. The pelecypods are found as paired valves in growth position and as isolated valves (Fig. 6b). Scattered vertebrate skeletal remains (dinosaur and fish), which are a common feature of fluvial fining-upward cycles (Allen, 1965), are also associated with the

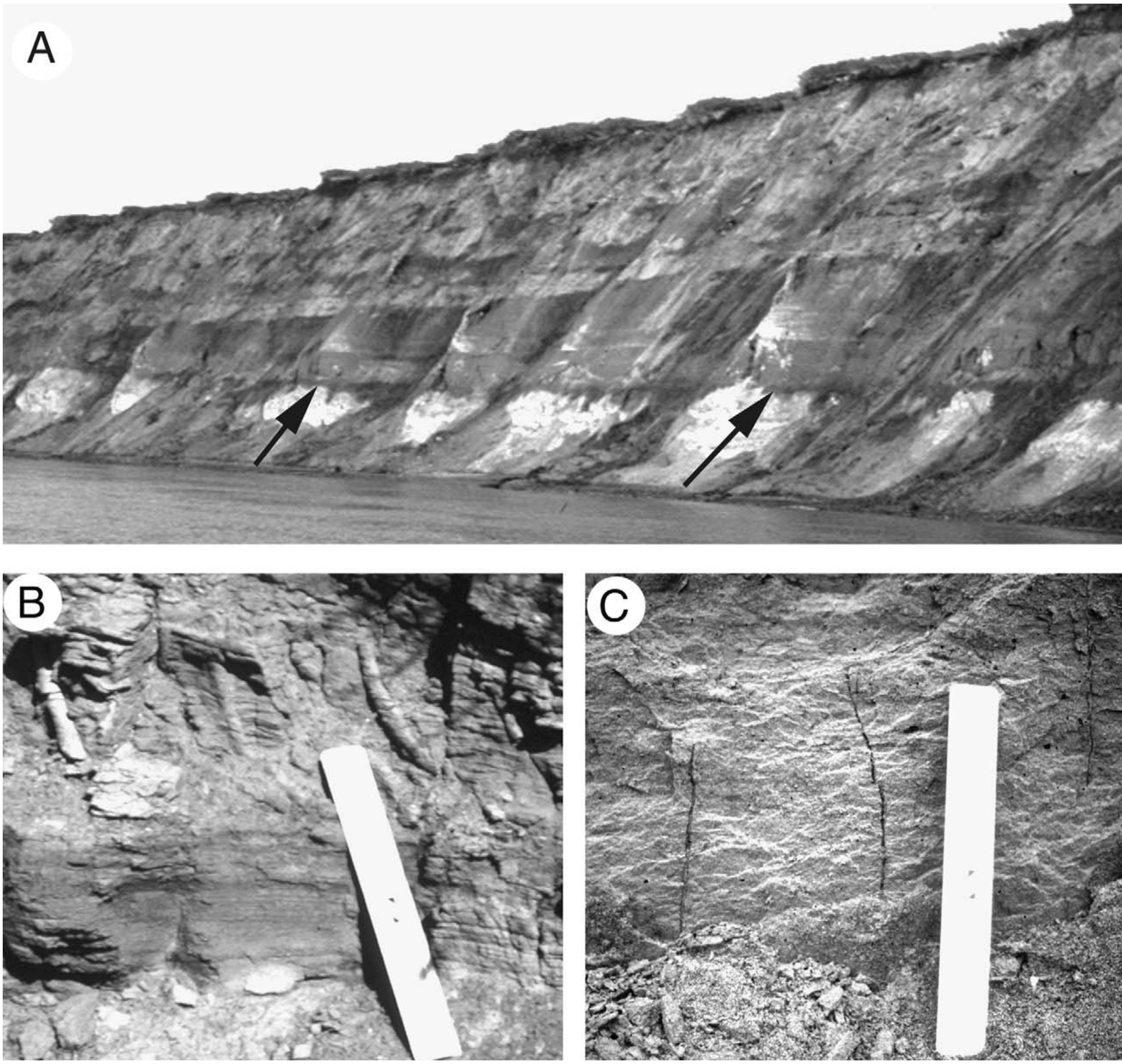

Fig. 5. Fluvial deposits exposed in the bluffs of the lower Colville River, Alaska. A, fluvial channel deposit between sections 12 and 13, Fig. 3. The arrows indicate the base of the channel. B, burrows in laminated and cross-bedded sand in fluvial deposit, section 2, Fig. 3. C, vertical roots in fine sand near top of fluvial deposits, section 13, Fig. 3. Scale is 22 cm long.

invertebrate fossils in the basal lag deposits of the streams. Even more abundant dinosaur remains (bone beds) are found in organic-rich strata at the top of two stream deposits.

Interpretation. The fining-upward fluvial cycles, as indicated by the abundant epsilon cross-strata, represent fluvial point-bar/accretionary-bank deposits (Allen, 1965) or benches (Taylor & Woodyer, 1978; Nanson & Page, 1983). These grade upward into vertical-accretion deposits of the floodplain. Shallow (2–5 m deep) streams are indicated by the thickness of the epsilon strata. Channel width, as determined from the assumption that width of epsilon strata equals two-thirds bankfull width (Allen, 1965), was from 25 to 70 m. Current velocities within the streams were low, as indicated by small-scale cross-beds that formed by lower-flow-regime current ripples. In addition, the presence of abundant roots indicates that plants were growing on the banks and within some of the shallow channels (*Equisetites* could apparently live in water to depths of 1 m, according to Kennedy, 1978). Plants growing within the channels would have restricted the current flow. The fine sediment (up to 98 per cent silt and clay at the top of the channel and 92 per cent at the base of the channel) transported within these streams was carried as a suspended load. The streams are classified as suspended-load streams (Schumm, 1968).

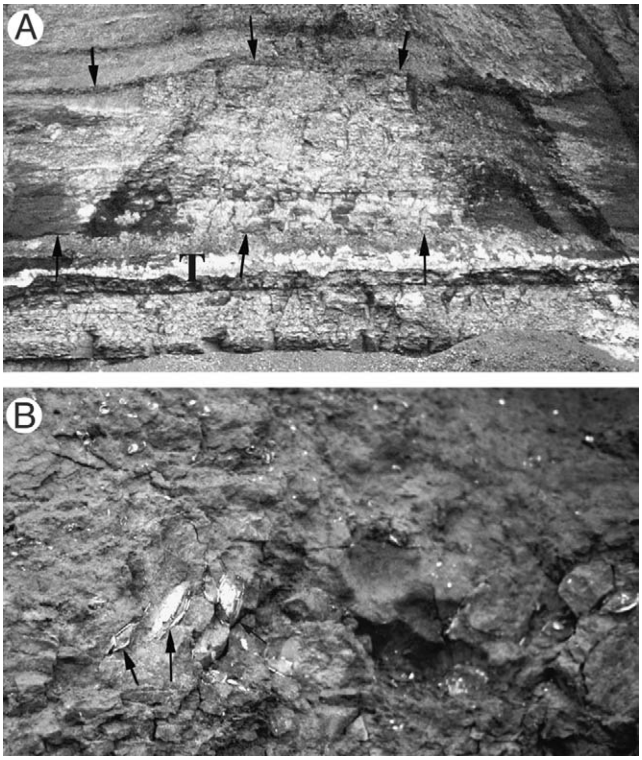

Fig. 6. Colville River bluff containing fluvial deposits. A, fining-upward minor distributary deposit 445 cm thick, bounded by arrows, showing well-developed, gently inclined, accretionary bank strata. The white bed beneath the channel is a tephra bed (T). B, pelecypods in growth position and pelecypod and gastropod fragments in base of minor fluvial distributary deposit near section 5, Fig. 3.

The deposits containing epsilon cross-beds are interpreted as streams laterally meandering on a low-gradient coastal plain. Evidence for meandering is limited primarily to sediment texture. Streams with high suspended loads tend to be more sinuous than streams with low suspended loads (Schumm & Kahn, 1972; Collinson, 1978).

Overbank deposits. Overbank floodplain deposits, which are interbedded with the river and stream-channel strata, are the most abundant deposits of the nonmarine facies, constituting 60 per cent of the beds. Interbedded fining-upward beds containing a sharp erosional base, rare coarsening-upward strata, laminated silt and sand, structureless silt and clay, and black to dark brown organic-rich silt comprise the deposits (Fig. 8). The overbank deposits contain fine sediment (silt and clay) forming laterally continuous fining-upward tabular to lens-shaped beds ranging from 17 to 161 cm in thickness.

The sand fraction in the basal part of the floodplain fining-upward strata constitutes less than 6 per cent of the total sediment. The sand composition is similar to that of the stream deposits in that it consists of angular to subrounded quartz, muscovite, lithic grains, pyrite, and glass shards. As in the distributary-stream deposits, these fining-upward cycles contain mottled patches of vivianite, jarosite, scattered carbonate concretions, and abundant roots. In 69 per cent of the floodplain strata, the upper part of the depositional unit ends in beds of rooted dark brown to black organic-rich silt and clay.

Paleocurrents, based on small-scale cross-beds within the basal part of the fining-upward strata (Fig. 9), exhibit a north to northeast trend ranging from 45 to 90 degrees from the trend of the major fluvial distributaries (Fig. 4).

Interpretation. The most abundant depositional environments recognized in the overbank deposits include crevasse splays and overbank sheetfloods (Fig. 9). Strata attributed to crevasse splays range in thickness from 39 to 161 cm. Like the fluvial deposits, these strata generally fine upward from very fine sand to silt and clay. The deposits usually have a sharp erosional base. Where erosion has occurred, broad V-shaped to narrow U-shaped channels are present. A sand-filled channel less than 35 m wide and containing small-scale cross-beds, cuts 1.6 m into the underlying overbank deposit. This channel depth represents the maximum scour observed in a channel interpreted to be a crevasse (between sections 7 and 8; Fig. 3a). Small-scale cross-beds (formed by climbing current ripples), planar and undulatory laminated sand and silt, and thin organic laminations are the typical sedimentary structures in the crevasse channels.

Other deposits attributed to crevasse splays include lens-shaped sand bodies, with a maximum thickness of 80 cm, that have a scoured base and contain small-scale cross-beds and planar-to-undulatory laminations (Fig. 8). These sand bodies grade upward and pinch out laterally into silt and clay. Thin coarsening-up strata, found in only two beds, represent crevasse-splay progradation on the floodplain. Beds of structureless silt and clay, ranging from 35 to 142 cm thick, represent the distal part of the crevasse-splay deposits, where the fine sediment settled from suspension in shallow ponds or marshes (as reported from other deposits by Elliott, 1974, and Woodyer et al., 1979). Where limited erosion has occurred during flooding, load casts and flame structures composed of organic debris intrude the overlying sediment. The deformational structures represent load structures formed where the sediment was rapidly deposited on water-saturated sediment or in organic-rich marshes or ponds.

Rare alternating thin beds of laminated silt and clay may represent levee deposits. These strata are similar to those found in ancient and modern levee deposits (Coleman, 1969; Singh, 1972; Fielding, 1984). Apparently, levees were not well developed on this floodplain, unless levee accumulations were not recognized owing to the very fine sediment size and probable destruction of sedimentary structures by extensive root development. Where levees are not well developed, overbank flooding may spread out from the channel

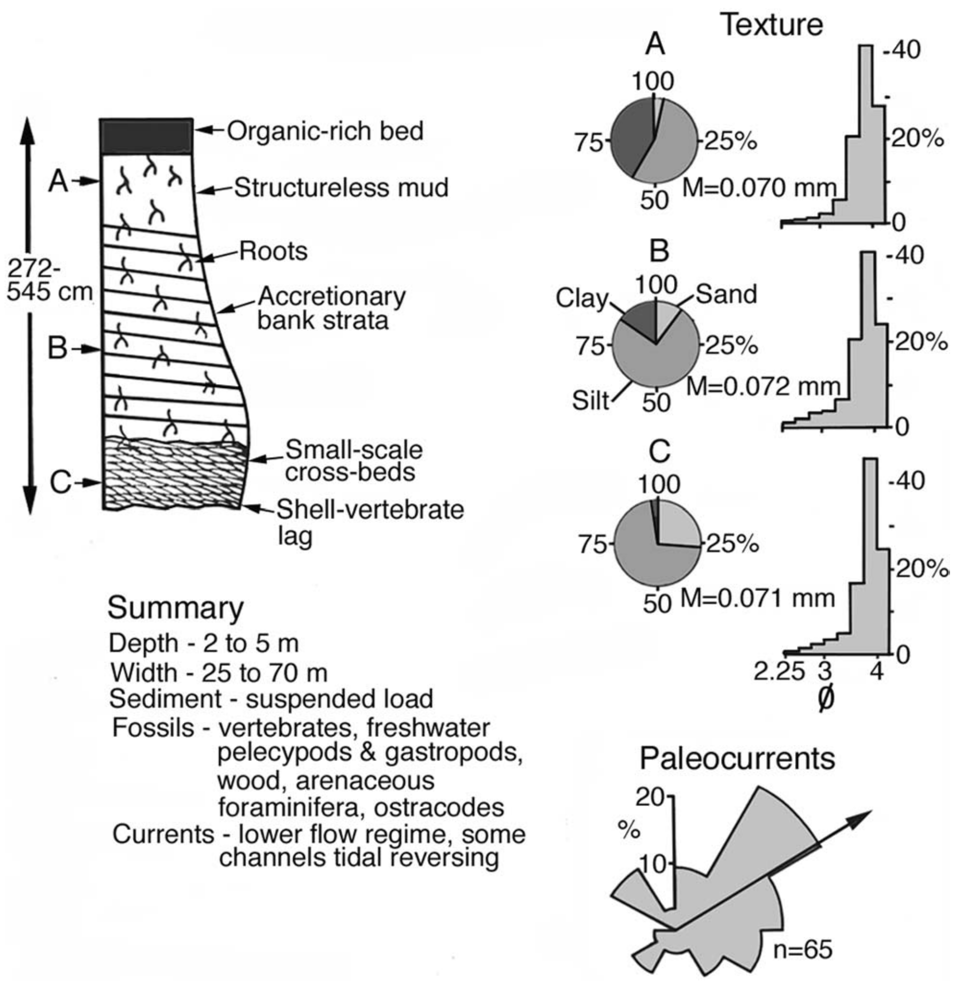

Fig. 7. Summary of sedimentologic features of minor fluvial distributary deposits in the Prince Creek Formation, lower Colville River region, Alaska. Letters adjacent to vertical section indicate locations of samples for textural analysis. Paleocurrent data from small-scale cross-beds.

mainly as sheetflow, depositing very fine sand and silt (Stear, 1983). The fine cohesive sediment, abundant organic-rich beds, and extensive vegetation on the floodplain surface would have limited erosion. Overbank sheetflow would then characterize the flood periods. Extensive overbank flooding may have formed many of the vertically stacked mud beds on this floodplain.

Breaching of major riverbanks during flood periods results in the formation of crevasse channels in the proximal areas and crevasse splays in the distal regions. Whereas some floodplains display both vertical and lateral accretion of sediment (Lattman, 1960; Bridge, 1984, 1985; Fielding, 1986), on others vertical accretion is the dominant process (Elliott, 1974; Woodyer et al., 1979; Smith & Smith, 1980; Nanson, 1986). Aslan & Autin (1998, 1999) have shown that sediments can accumulate continuously rather than during infrequent floods on the Mississippi floodplain and suggests that is a common mechanism for vertical accretion.

Successive, episodic flood events and resulting vertical accretion of sediment dominated the depositional history of this Cretaceous floodplain. The thin sheet-like and lens-shaped fining-up sand bodies may represent either distal parts of crevasse channels where the water was spreading out (splaying) on the floodplain (Graham, 1983; Stear, 1983) or may represent sheet-flood deposits. The thick, structureless, sheet-like tabular silt and clay beds represent the most distal deposits, where the sediment was deposited on a low relief floodplain. Vertical accretion was the dominant process recorded within these floodplain deposits. The presence of dark, organic-rich beds at the top of the fining-up depositional cycles indicates that the flood events were episodic. Plant material had sufficient time to accumulate on the floodplain and in marshes and ponds before the next flood event.

Organic-rich sediment. At the top of the fining-upward cycles are organic-rich beds up to 89 cm thick that vary in thickness laterally. These beds are composed of laterally continuous organic-rich black to dark-brown mottled silt and clay containing up to 6.8 per cent organic carbon (Brouwers et al., 1987). The beds contain

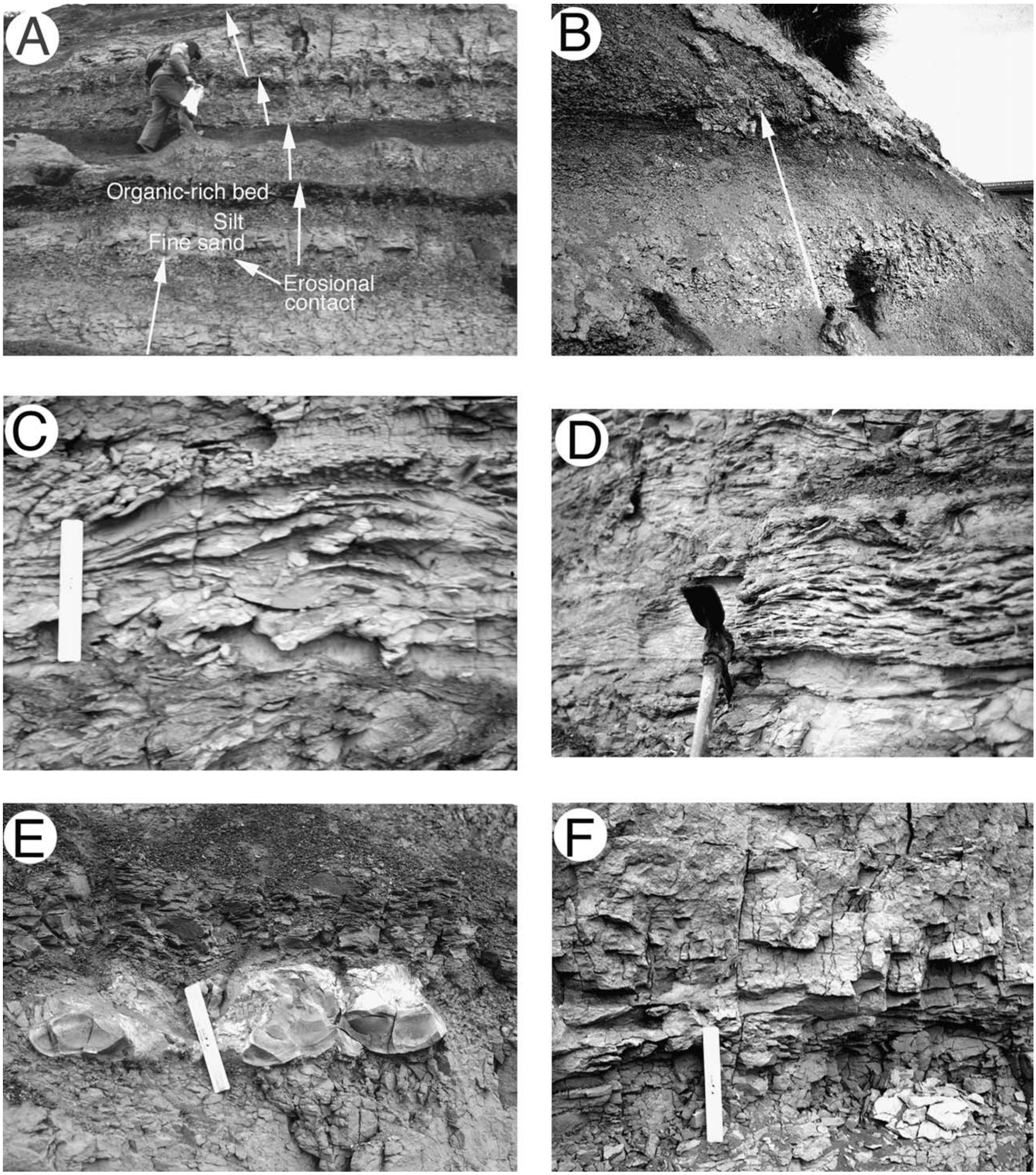

Fig. 8. Colville River bluff containing floodplain deposits. A, fining-up cycles consisting of fine sand grading upward to silt containing roots, with an organic-rich bed (dark) at the top of the depositional unit. B, fining-upward cycle. C, undulating laminated sand at base of fining-upward cycle. D, planar laminations and small-scale cross-beds at base of fining-upward cycle. E, top of the fining-upward cycle containing an organic-rich bed (dark) with large carbonate concentrations at base of bed. F, abundant vertical roots in fining-upward cycle. Scale is 22 cm long.

jarosite, pyrite, varying concentrations of comminuted plant debris, including abundant conifer needles that sometimes have a preferred orientation, and in some beds rare to abundant vertebrate remains. Some strata contain parallel laminations, but most lack internal bedding. Scattered elongate and irregular-shaped carbonate concretions, up to 5 m long and 50 cm thick, are locally common in these beds (Fig. 8e).

The abundant organic-rich strata and the presence of pyrite indicate a reducing environment, which is favored where the ground-water table is high (Buurman, 1980; Ugolini & Edwards, 1983) and oxidation is inhibited.

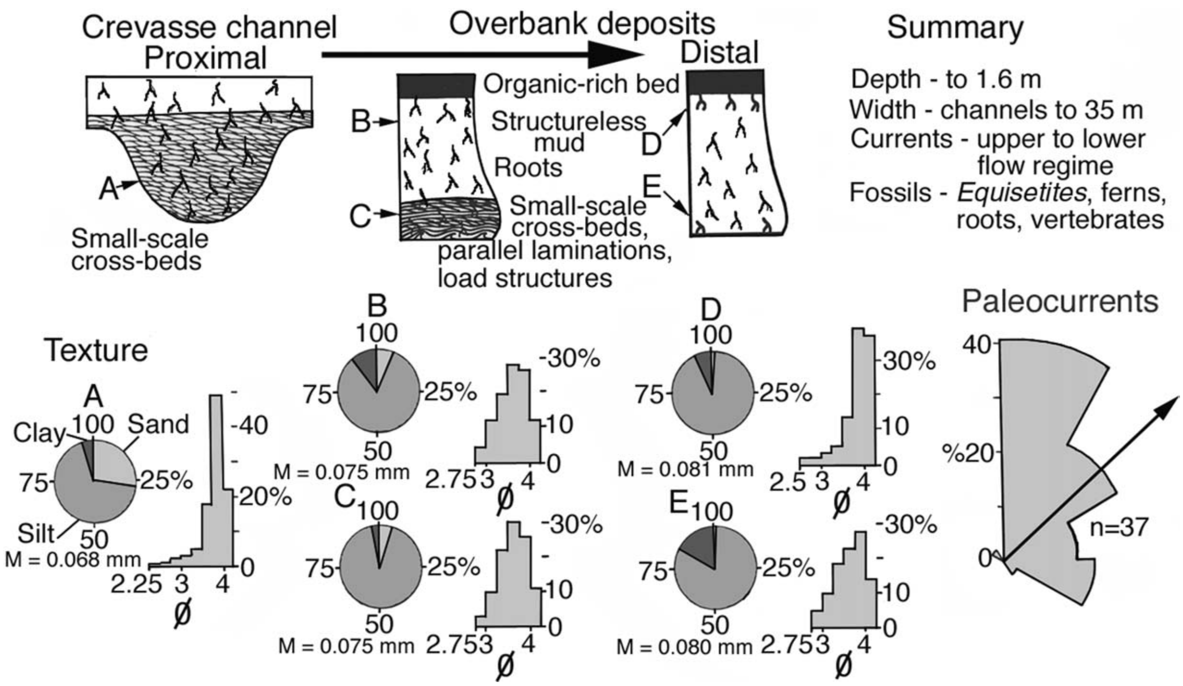

Fig. 9. Summary of sedimentologic features of floodplain deposits in the Prince Creek Formation, lower Colville River region, Alaska. Letters adjacent to sections indicate locations of samples for textural analysis (below). Paleocurrent data from small-scale cross-beds.

Poor drainage also favors the preservation of organic material (Aslan & Autin, 1998). Development of soil structures is severely limited below the water table (Retallack, 1986). However, oxidization and possible formation of immature paleosols is indicated in beds where jarosite has formed (Buurman, 1980) and where color mottling occurs (Retallack, 1986). Both of these conditions are common in some of these organic-rich floodplain strata. Likewise, the carbonate concretions within some organic-rich beds may be of pedogenic origin; they may have formed during early diagenesis (Freytel, 1973; McBride, 1974) at or above the water table (consistent with other evidence that a shallow water table existed on the floodplain), or they may have formed where decomposing organic material raised the pH and promoted local carbonate crystallization (Deegan, 1971).

The organic-rich beds were derived in part from plants that lived *in situ* on the floodplain (root structures are common to abundant) and in part from plant debris that was carried in by floods and settled from suspension within topographic low regions (Baker et al., 1983; Smith & Smith, 1980; Wright et al., 2000). Organic-rich beds are a common feature at the top of modern and ancient distributary point-bar strata (Stewart, 1983; Bridge et al., 1986; Fastovsky, 1987). Evidence of organic-rich beds that formed in place on the floodplain is provided by overlying laterally continuous tephra beds containing root structures that are bounded by organic-rich beds. In these cases, tephra was deposited on an organic-rich marsh, and a new organic-rich bed developed on top of the tephra.

Interpretation. The organic-rich beds may have multiple origins, but many represent marsh environments (reducing environment with high water table) as well as forming from plant debris swept into topographic low regions (ponds) during overbank flooding on the low relief floodplain. Immature paleosols are also observed in some of these beds. The presence of freshwater gastropods and pelecypods, along with arenaceous foraminifers, show that some organic-rich beds represent marginal marine marsh environments.

Tephra. Interbedded with the organic-rich strata and floodplain deposits are at least 16 white to cream colored siliceous-rich tephra beds (Phillips, 1988). The tephra deposits can be laterally continuous, can pinch out, or can be interbedded with black organic-rich sediment. The maximum thickness of the tephra is 60 cm; however, to the south of the study area in stratigraphically lower beds, tephra beds are as much as 2 m thick. Internally, the tephra typically is usually structureless but some beds may contain small-scale cross-beds as well as horizontal laminations; indicating some reworking of the tephra following initial air-fall deposition (Fig. 10). Root structures are common to abundant in the tephra deposits.

Where the tephra was deposited on the floodplain surface on the organic-rich beds, it has preserved local surface relief features. In one ash bed excavated, multiple near vertical walled depressions, averaging

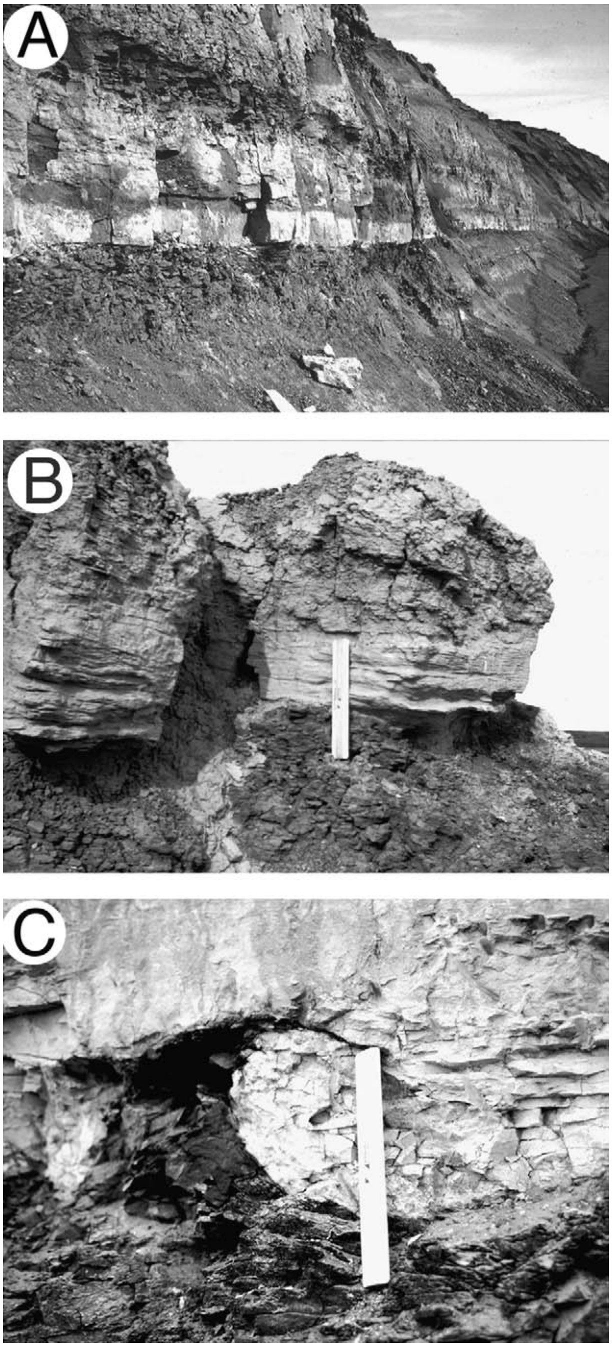

Fig. 10. Colville River bluff containing tephra deposits. A, tephra bed resting on and overlain by organic-rich silt and clay (section 8, Fig. 3). B, tephra bed containing parallel laminae and small-scale cross-beds overlying organic-rich sediment (near section 5, Fig. 3). C, load structure consisting of organic-rich sediment injected into tephra (near section 1, Fig. 3). Scale is 22 cm long.

20 cm deep and 42 cm wide and containing internal depressions, may represent tephra-filled dinosaur footprints within an organic-rich bed. These filled depressions are similar in size (40–60 cm wide, 40–50 cm length, and 10–85 cm deep), shape and appearance to late Cretaceous filled tracks attributed to hadrosaur footprints investigated by Nadon (1993).

Scattered, laterally discontinuous tephra clasts, up to 4 cm diameter, are also found in the upper 243 cm of the bay facies (sections 22 and 23), representing the stratigraphically highest tephra identified. The tephra clasts may represent an original airfall deposit that has been disrupted by bioturbation, currents or channeling, or may represent clasts of consolidated tephra eroded from a floodplain source and transported within estuary channels.

The age of the rhyolitic tephra based on K-Ar and ^{40}Ar/ ^{39}Ar dating of samples of glass from five different tephras yielded a weighted mean of all the analyses of 69.1 Ma (Conrad et al., 1992). Based on sanidine analyses from a single tephra an age of 72.9 Ma is indicated (J. D. Obradovich in Clemens, 1992a). The sanidine analysis should yield the most accurate date for these tephras and the related dinosaur occurrences.

Interpretation. The floodplain tephra deposits resulted from air-fall of ash. Wind or water may have reworked some of the tephra beds during or after deposition.

Floodplain vegetation. Fossils associated with the floodplain deposits aid in further defining the environments. Plants were abundant as indicated by the extensive root development in the floodplain strata. Vertical, closely spaced, solitary to branching rhizomes less than 4 mm wide and extending vertically over 60 cm are common within the floodplain strata. Some rhizomes contain cellular structure (Fig. 8F). The most abundant rhizome structure present in the floodplain sediments is *Equisetites* (Parrish & Spicer, 1988; Spicer & Parrish, 1990b).

A difference in plant diversity is recorded between the plant megaflora and pollen. The angiosperm component of the vegetation was principally herbaceous and is used to explain the discrepancy between the diversity of the megaflora and the palynoflora (Spicer & Parrish, 1990a). Based on plant macrofossils, the Late Cretaceous vegetation on the coastal plain was impoverished in tree species with only two deciduous conifers identified: *Parataxodium wigginsi* and a microphyllous, cupressaceous form (Parrish & Spicer, 1988). The conifer forests were apparently dominated by small trees. A low diversity angiosperm understory and a very low diversity ground cover of ferns, horsetails and aquatic plants existed in this coastal plain (Spicer, 1987; Parrish & Spicer, 1988; Spicer & Parrish, 1987, 1990a,b; Spicer & Corfield, 1992).

Based on pollen a moderately high diversity of angiosperms is indicated, which apparently formed much of the understory cover (Frederiksen, 1991; Frederiksen & McIntyre, 2000). The pollen studies also show that the vegetation covering the coastal plain was predominantly a coniferous forest with abundant ferns, mosses, and club-mosses (Frederiksen et al., 1988). Pollen of extinct plants with unknown life forms (herbs?, shrubs?) and unknown affinities if any to modern plant families are also identified in this strata (Tom Ager, pers. comm. 2002).

The fossil vegetation cover suggests that temperatures ranging from 2–8 °C mean annual temperature, with little seasonal variation, characterized the northern regions (Spicer, 1987; Parrish & Spicer, 1988; Spicer & Parrish, 1990a). The mean annual temperature decreased from 10 °C in the mid Cretaceous to 5 °C in the Late Cretaceous (Parrish et al., 1987; Spicer & Parrish, 1990b). The winters were most likely characterized by short periods of freezing as a result of the high latitude light regime with the winter dark period lasting 1.5 months (Spicer, 1987; Parrish et al., 1987; Spicer & Parrish, 1990b). In contrast, the present day Arctic winter mean annual temperature is minus 25 °C (Parrish et al. 1987). A decrease in temperature in the Late Cretaceous with temperatures dropping sharply in the Maastrichtian (based on foraminiferal records) have also been identified in the northwestern circum-Pacific by Zakharov et al. (1999).

3.2. Vertebrates

Associated with some organic-rich sediments and fluvial deposits are hadrosaurian, tyrannosaurid and troodontid remains (Clemens & Allison, 1985; Davies, 1987; Brouwers et al., 1987; Gangloff, 1992) which record in some beds multiple depositional and transport histories. Four organic-rich vertebrate-bearing beds and five channel-lag occurrences were identified (Fig. 2). Juvenile and young adult remains of the noncrested hadrosaurid *Edmontosaurus* sp. (Nelms, 1989; Clemens, 1992a) dominate the vertebrates. The ceratopsian *Pachyrhinousaurus* (Nelms, 1989; Clemens, 1992a) as well as three therapods, *Albertosaurus, Troodoon* sp. and the dromaeosaurid *Sauronitholestes* sp. (Gangloff, 1992) are also found within these beds. In addition, the channel lag deposits contain remains of the marsupial *Pediomys* as well as sharks, a sturgeon-like fish, and one or more teleost fishes (Clemens, 1992b; Clemens and Nelms, 1993; Gangloff, 1992).

The bones are found as solitary elements, or as concentrated mixtures of disarticulated and in some cases apparently articulated and vertically size-graded bones with the largest bones found at the base of the beds, indicating possible hydraulic sorting. Bones are also preserved near and within carbonate concretions, and in at least two of the bone beds are associated with tephra deposits. The bones are found in abundance within the four thickest organic-rich beds (Fig. 11).

Transportation of the bones by currents is suggested for at least two bone beds by measurement of the orientation of 'long' bones protruding from cliff exposures. Long bones within flowing water tend to be oriented either parallel or parallel and perpendicular to

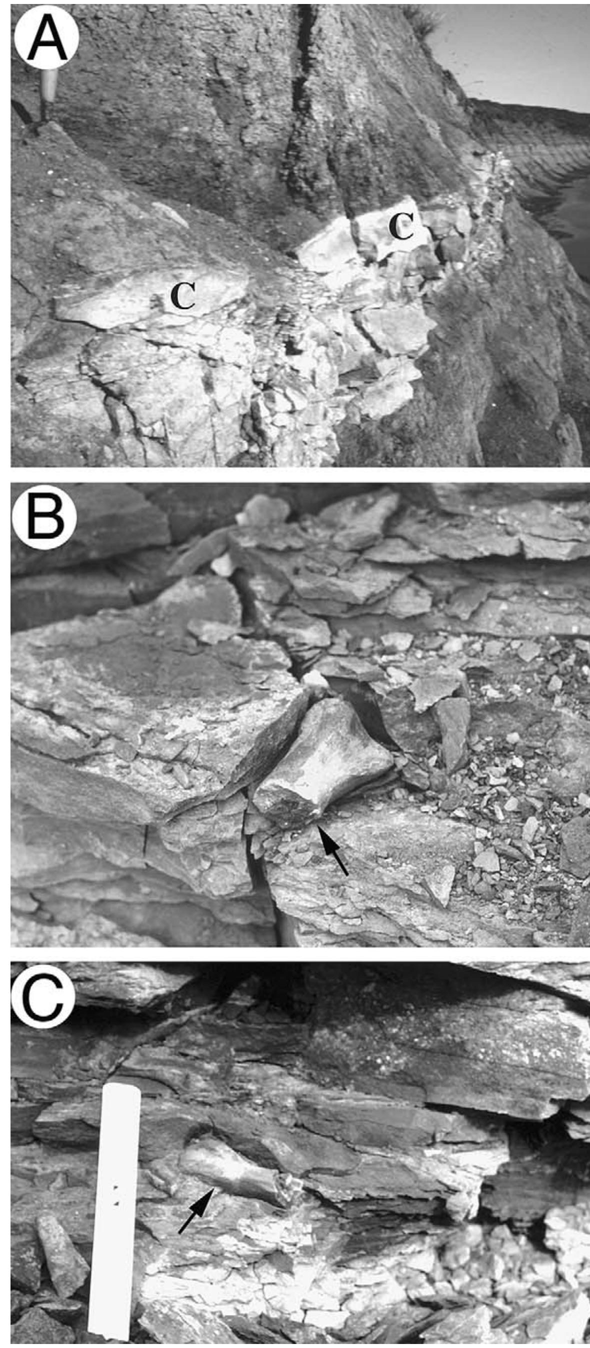

Fig. 11. Colville River bluff containing vertebrate remains. A, bone bed near top of section 3, Fig. 3 (white bed) containing concretions (C) and rare scattered bones overlying organic-rich bed. B, dinosaur bone in organic-rich bed near section 8, Fig. 3. C, dinosaur bones in organic-rich bed near section 7, Fig. 3. Scale is 22 cm long.

the current (Hanson, 1980; Bown & Kraus, 1981; Koster, 1987). A bidirectional orientation is observed for long bones in both beds (Fig. 12). A dominant northeast-southwest trend is evident with a secondary component lying southeast-northwest, nearly 90 degrees from the dominant trend. These orientations demonstrate that the long bones were lying both parallel and

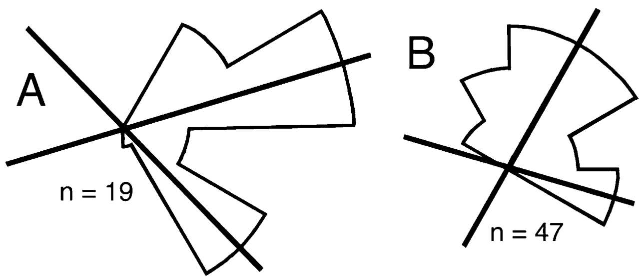

Fig. 12. Diagrams of dinosaur long-bone orientations showing a bimodal trend suggesting bones oriented both parallel and nearly perpendicular to overbank currents (Fig. 9). A, upper bone bed in section 8, Fig. 3, summarizing bone orientations measured over 25 m horizontal distance. B, lowest bone bed in sections 6 and 7, Fig. 3, summarizing bone orientations measured within a horizontal distance of 100 m.

transverse to the current. The bones in some beds initially accumulated on the floodplain but were later transported by currents during overbank flooding, swept along with organic debris and deposited in local depressions (ponds or marshes).

Arenaceous brackish-water foraminifers (*Reophax* sp., *Textularia* sp., and *Haplophragmoides* sp.; Brouwers et al., 1987; Brouwers & De Deckker, 1993) are found in floodplain strata below the lowest bone bed (Fig. 3, section 7). The fossils occur in a dark brown organic-rich mud, which contains roots and small carbonate concretions. The high organic content within these beds suggests a probable marsh depositional environment. Brouwers et al. (1987) noted that the foraminifers represent low salinities, approaching freshwater conditions. The foraminifers may have lived within a marsh environment or may have been transported from a marginal marine setting onto the floodplain during a storm surge. The presence of brackish water foraminifers places the floodplain strata and vertebrate concentration within a marine-influenced lower coastal-plain environment.

3.3. Interdistributary bay deposits

Meandering rivers transport sediment through a delta system to a series of shallow interdistributary bays which include areas of shallow, open water that may be surrounded by marsh or levees, partially open to the sea or connected to the sea by tidal channels (Coleman et al., 1964). Interdistributary-bay environments generally are shallow and can contain fresh, brackish or normal-salinity marine water (Elliott, 1974). A variety of processes including bioturbation, tidal currents, migrating tidal channels, and storms, produce the sedimentary structures preserved within bay environments.

Bay deposits are recognized in two stratigraphic sequences separated by rooted nonmarine strata. The thickness of the lower-bay sequence is at least 4 m, the maximum thickness of strata exposed along the cliff base. The upper bay sequence is 11.4 m thick. This rests sharply on organic-rich coastal-plain marsh strata containing abundant roots. The upper bay strata grade up into prograding coastal-plain marsh beds (Fig. 13).

The bay deposits consist of very fine sandy silt to silty sand. The sand fraction is composed of rounded lithic grains of mica schist, angular to subrounded quartz grains, and abundant mica flakes. Large pieces of carbonized wood are common. Scattered siliceous tephra clasts, up to 4 cm in diameter, are found in the upper bay strata. The coarsest sediment and greatest sand content, 60 per cent, are found in large-scale cross-beds, but most of the sediment within the bay deposits is classified as sandy silt. Both fining-upward and coarsening-upward sediment textures are identified.

Sedimentary structures in the lower bay deposits consist of small-scale 2- and 3-D cross-beds, planar laminations and abundant bioturbation. Root structures are found in all outcrops. In the lower part of the upper bay deposits sedimentary structures include small-scale cross-beds, flaser beds, parallel laminations in sets as thick as 5 cm overlain by small-scale cross-beds, or laterally continuous planar to undulating organic-rich laminations. Abundant to sparse bioturbation, abundant roots (some truncated), and thin (less than 50 cm) channel-fill deposits containing inclined organic-rich laminated silt are also common (Fig. 14). These thin-bedded strata grade laterally to sets of planar laminated and small-scale cross-beds forming composite sand beds that are up to 1 m thick and are laterally continuous for over 100 m. The thick sand beds are interbedded with bioturbated silt. Laterally the sedimentary structures change abruptly to large-scale 2- and 3-D cross-beds, as much as 20 cm thick, which decrease upward in bed thickness forming a 3-m-thick sequence.

Overlying the basal bioturbated and cross-bedded strata with a sharp erosional contact is a distinctive 50-cm-thick bed composed of laminated mica- and organic-rich sand. Overlying the laminated sand is 7 m of repeated hummocky cross-stratification grading from silty sand to sandy silt in beds ranging from 16 to 25 cm thick, amalgamated hummocky stratification forming beds up to 1.5 m thick, small-scale 2- and 3-D cross-beds, and rare deformed beds (Fig. 14). Bioturbated sandy silt lies between the hummocky cross-stratified intervals. Shallow channel-fill deposits, one shell bed, and locally abundant beds containing shell fragments and an abrupt textural change to rooted mud containing organic-rich beds occur at the top of the hummocky cross-stratification. The overlying mud beds form a 5.5-m-thick deposit of nonmarine strata.

Megafossils are rare, consisting of barnacles and mussels found on the erosional surfaces of some of the hummocky cross-strata and shell beds containing scattered to concentrated mollusks at the top of the

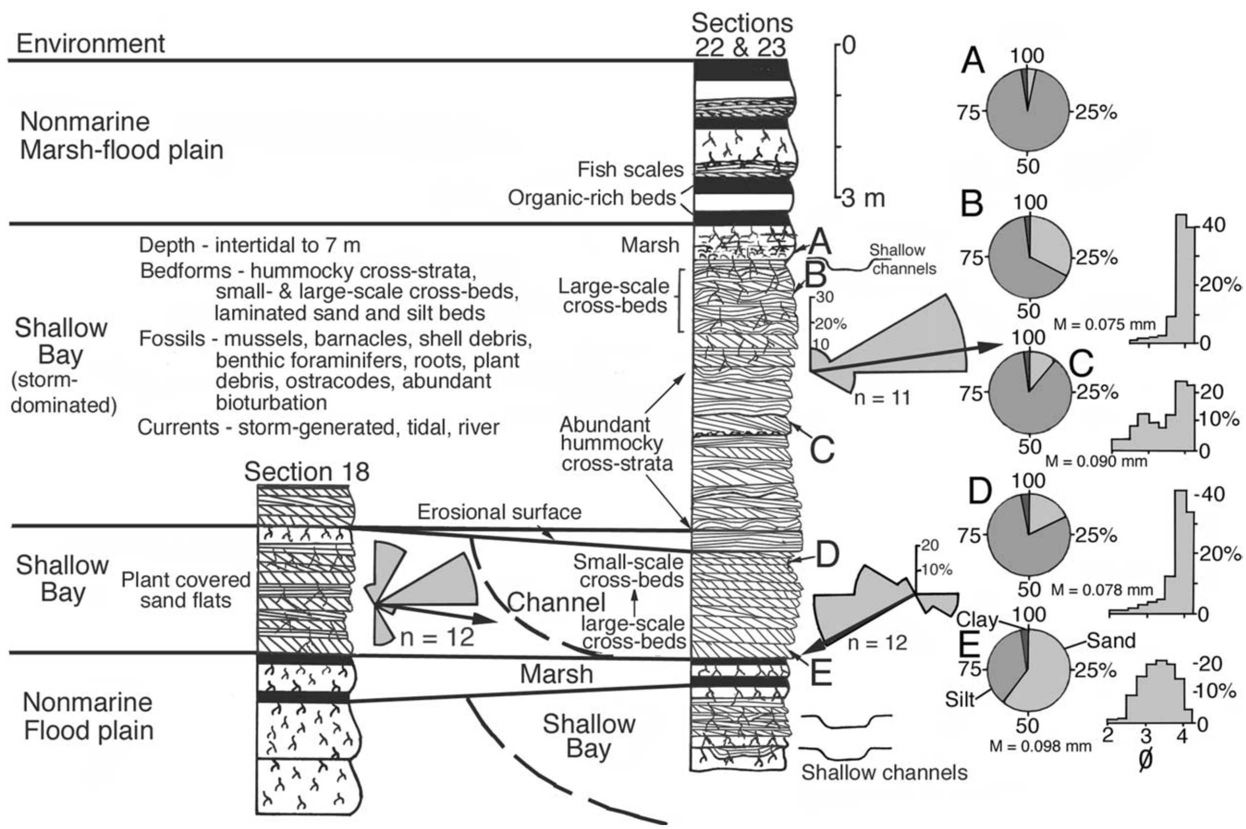

Fig. 13. Summary of sedimentologic features of distributary-bay deposits in the Schrader Bluff Formation, lower Colville River region, Alaska. Letters adjacent to sections indicate locations of samples for textural analysis (to right). Paleocurrent data from small- and large-scale cross-beds.

upper-bay deposit. Brachiopods are also reported within the bay sediments (Brouwers & De Deckker, 1993). Calcareous benthic and arenaceous foraminifers and ostracodes are associated with the hummocky cross-strata deposits. Abundant vertical roots, up to 5 mm in diameter and extending vertically 70 cm, are common throughout much of the bay deposits, including the upper part of the hummocky cross-strata (Fig. 14). *Equisetites*, which was the most abundant plant along the fringes and within the shallow parts of the bays, has also been reported from Cretaceous bay environments in England by Allen (1959) and Batten (1973, 1974). Burrows, associated with roots, are abundant in most exposures.

Paleocurrents record a bimodal opposed pattern, east-northeast-directed to southwest- to southeast-directed in the strata underlying the hummocky cross-beds. The hummocky cross-stratified beds show a unidirectional northeast-directed trend based on small-scale cross-beds on top of the hummocky strata (Fig. 13).

Interpretation. The depositional environments recorded in the lower bay deposits represent a sand flat grading upward to a prograding muddy marsh. The lower part of the upper-bay sequence represents a tidal or subtidal sand flat (small-scale cross-beds, flaser beds, truncated roots) changing laterally to a channelized shallow bay (large-scale cross-bed sets). The sand flats were vegetated, as indicated by abundant root structures. Lateral migration of bay channels formed the large-scale cross-bed sequence, which contains sedimentary structures similar to those in modern estuarine bay channels investigated by Clifton & Phillips (1980). The overlying hummocky cross-stratification (Harms et al., 1975; Walker, 1984), records the effects of storms in the shallow-bay environment. Hummocky cross-stratification has been reported from lacustrine bays at depths as shallow as 2 m (Greenwood & Mittler, 1984; Greenwood & Sherman, 1986; Duke, 1985). The maximum depth of the bay in the upper sequence would be 7 m based on the total thickness of the deposit from the first hummocky strata to the overlying prograding mud beds. The shallow bays were apparently open to the ocean, allowing storm waves direct access to the bay. Filling of the bay and coastal plain progradation then resulted in deposition of nonmarine strata over the bay sediments.

The water most likely ranged from fresh and brackish to possibly marine. The presence of benthic foraminifers within the hummocky cross-stratification suggests at times nearly normal-marine conditions; however, storms may have transported the foraminifers from deeper

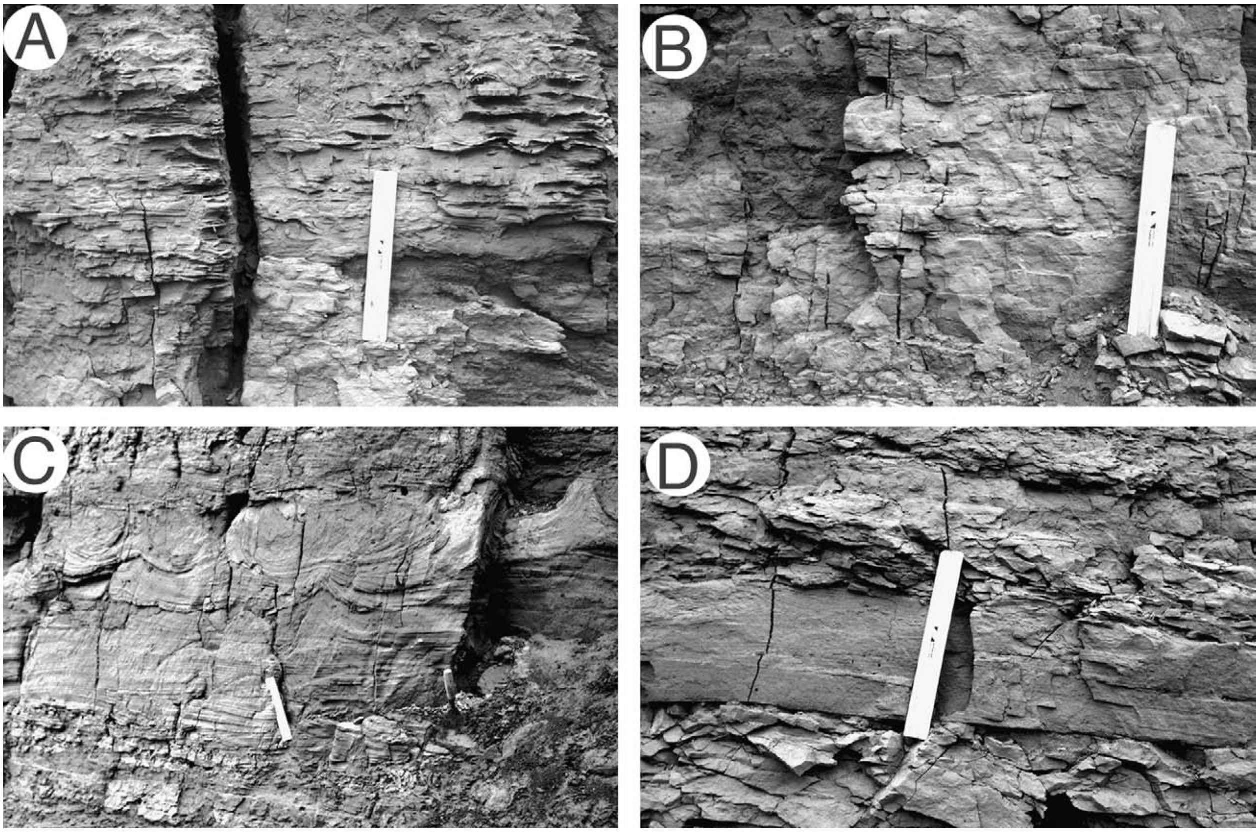

Fig. 14. Shallow distributary bay deposits in the Schrader Bluff Formation, lower Colville River region, Alaska. A, bay sand flat deposits containing flaser beds, parallel laminations, small-scale cross-beds, abundant bioturbation, and roots (sections 19–20, Fig. 3). B, abundant vertical roots in bay sand flat sediment near section 18, Fig. 3. C, amalgamated hummocky cross-strata containing deformed beds (sections 22–23, Fig. 3). D, hummocky cross-strata containing low-angle-dipping laminae changing up to small-scale cross-beds and bioturbated silt at the top of the bed (section 22, Fig. 3). Note thin black vertical root structures in all exposures. Scale is 22 cm long.

offshore areas. The occurrence of nonmarine ostracodes in the bay strata (Brouwers & De Deckker, 1993) also indicates very low salinities at times within the bay or transport of the nonmarine ostracodes from the floodplain into the bay. The lack of an abundant and diverse marine fauna, such as found in the overlying marine strata, also confirms that the bay deposits did not contain normal-salinity marine water for long periods of time.

3.4. Marine deposits

Rising sea level and a resulting marine transgression extended across the underlying floodplain and marsh strata. The flooding surface developed on top of an organic-rich marsh deposit. Marine deposits overlying the nonmarine strata represent a shallow, storm-dominated depositional sequence. An east-west-trending fault of unknown displacement separates two stratigraphic sections of marine beds (Fig. 2). On the upthrown north side of the fault, the basal marine strata form a sequence as thick as 12 m resting on black organic-rich coastal-plain silt. Scattered well-rounded, siliceous clasts and large pectens rest on or just above the nonmarine organic-rich bed. South of the fault, approximately 13 m of marine strata are exposed (Fig. 15). The beds in both stratigraphic sections are horizontal and composed of fossiliferous, interbedded parallel gray to iron-stained sand and sandy silt; individual sand beds are up to 1 m thick.

The sediment texture ranges from sand to silty sand in storm-generated beds to sandy silt in the non-storm intervals. Quartz, mica flakes, and organic material are the major components of the sand-size grains. The sand fraction, which consists of very fine sand, forms as much as 83 per cent of the sediment within some hummocky cross-strata, whereas it only forms 16 per cent in the non-storm beds (Fig. 15).

The marine deposits contain a variety of sedimentary structures consisting of interbedded planar to low-angle-dipping laminations, climbing small-scale cross-beds in sets up to 12 cm thick, 3-D cross-beds in sets up to 22 cm thick, and abundant bioturbated sand and silt beds. Cyclic hummocky cross-stratification grading upward to small-scale cross-beds and then to bioturbated silt, beds of amalgamated hummocky cross-stratification, shell

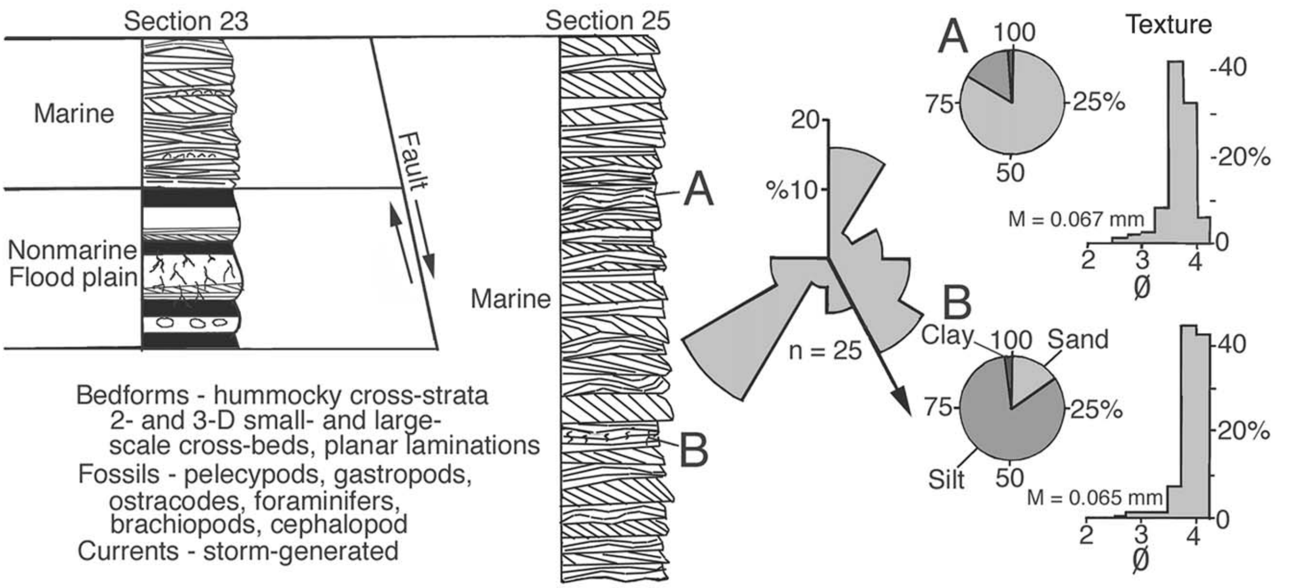

Fig. 15. Summary of sedimentologic features of marine deposits in the Schrader Bluff Formation, lower Colville River region, Alaska. Letters adjacent to vertical section indicate locations of samples for textural analysis (to right). Paleocurrent data determined from large- and small-scale cross-beds.

lags, and mud rip-up clasts form the dominant structures in this deposit (Figs. 15 and 16). The hummocky cross-strata rest with a sharp erosional contact on bioturbated silt or form amalgamated beds. The basal contact of the hummocky strata can be flat but is usually undulating and may contain shell lags or mud rip-up clasts. The texture fines upward from sand to sandy silt and the structures change from parallel and downlapping laminae on the lower bounding surface to hummocky stratification to small-scale cross-bedding to bioturbated silt. These structures usually change thickness laterally as a result of erosion. Paleocurrents obtained from both small- and large-scale cross-beds show a variable trend (Fig. 15).

Megafossils (pectens and other pelecypods, gastropods, brachiopods, echinoids, and a cephalopod) and microfossils (ostracodes and foraminifers) are abundant within the marine section (Macbeth & Schmidt, 1973; Marincovich, 1993; Marincovich et al., 1985, 1990; McDougall, 1987; Brouwers & De Deckker, 1993). The bivalves are found in growth position in the silty, bioturbated beds and as local concentrations of transported single and paired valves in hummocky cross-stratification.

Interpretation. The cyclic marine strata record initial erosion and deposition by upper plane-bed currents forming hummocky cross-stratification and with reduced-energy conditions changing to a lower-flow regime, forming small-scale cross-beds and then finally deposition from suspension (silt) along with increased bioturbation. This sequence represents a storm-dominated environment with storm-generated structures similar to hummocky cross-stratification and associated structures investigated by Harms et al. (1975), Dott & Bourgeois (1982), Walker (1984), Duke (1985).

The sandstone beds within these storm deposits become thicker (up to 1 m), contain more amalgamated sand beds, and have more 3-D cross-strata up-section, suggesting increasing-energy conditions or a possible shallowing environment. Amalgamated sandstones are interpreted as resulting from more energetic or frequent storms and/or possibly shallower depths (Dott & Bourgeois, 1982; Walker et al., 1983; Duke, 1985). An overall decrease in water depth for these same beds is indicated by foraminiferal trends investigated by Macbeth & Schmidt (1973) and McDougall (1987).

The depositional environment of this deposit is a shallow storm-dominated shelf. As storm-generated hummocky cross-stratification is believed to be preserved between fair-weather wave base and storm wave base, water depths were probably between a few to several tens of meters (Dott & Bourgeois, 1982; Walker et al., 1983).

4. Late Cretaceous environments

This study documents depositional environments and sediment characteristics of a 178-m-thick section of latest Cretaceous strata exposed in Colville River bluffs in the Ocean Point area of northern Alaska. These deposits represent the youngest Late Cretaceous strata exposed in this region, strata that total about 1500 m in thickness and comprise a relatively complete record of

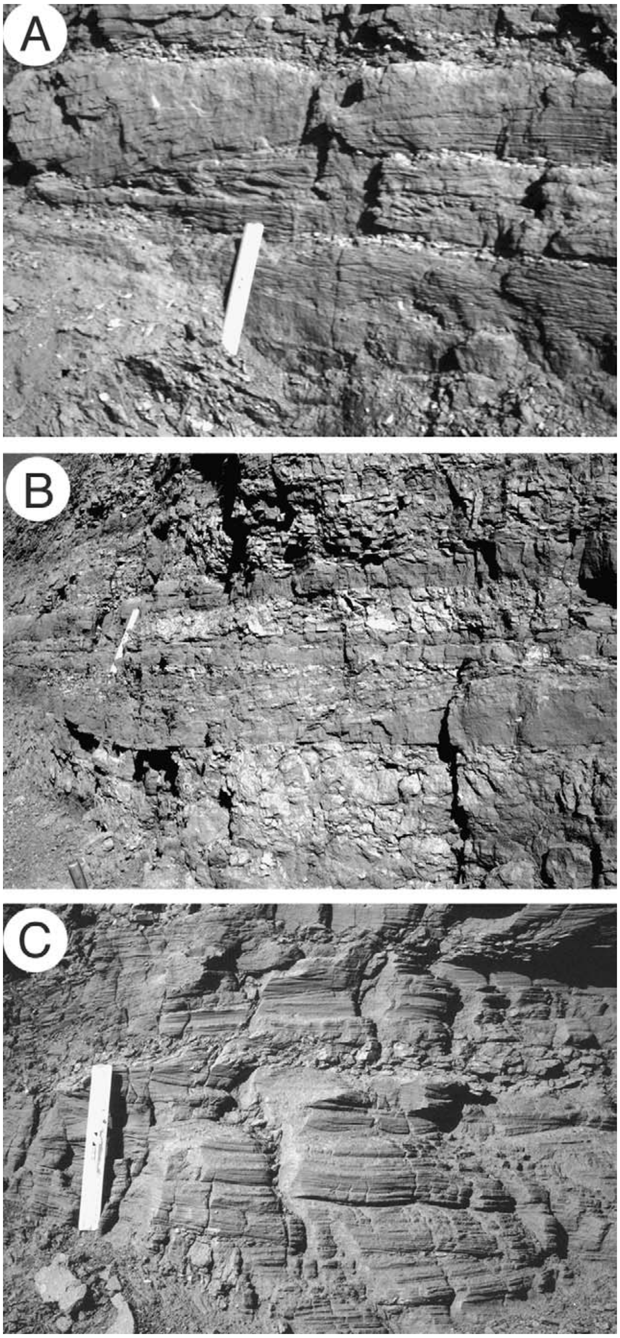

Fig. 16. Marine deposits in the Schrader Bluff Formation, lower Colville River region, Alaska. A, hummocky cross-stata, climbing small-scale cross-beds, parallel laminations and shell debris at base of beds (section 25, Fig. 3). B, hummocky cross-strata containing mud rip-up clasts interbedded with silty bioturbated beds (section 25, Fig. 3). C, cross-bedded and laminated sand with shell fragments in interbedded silty beds. Scale is 22 cm long.

Late Cretaceous sedimentation. The section described consists predominately of nonmarine deposits that are capped by bay and shallow marine strata, a reflection of a significant marine transgression. Sediment in the Late Cretaceous floodplain was deposited within a low-gradient, low-relief, coastal lowland that was periodically inundated with marginal-marine and marine waters. Evidence of marginal-marine influence in the floodplain is documented by the presence of arenaceous foraminifera (Brouwers & De Deckker, 1993) found in a distributary stream deposit in section 4 and in the lower part of section 8 (Fig. 3a). The occurrence of bimodal opposed small-scale cross-bed sets in a distributary channel in section 15 (Fig. 3b) also suggests tidal influence within some of the low energy streams.

The major rivers, comparable in size to the present-day Colville River, meandered across the floodplain, carrying sediment primarily as a suspended load. The eastward paleocurrent trend suggests structural control; the Barrow arch to the north and the ancestral Brooks Range to the south may have constrained the rivers to flow between these highs. This trend also reflects a continuation of the eastward direction of progradational Colville Basin filling that was established in early Cretaceous time (Molenaar, 1988; Bird & Molenaar, 1992). Overbank sheet-flow and crevasse splays represent the major effects of river flooding along the lower, marine-influenced, coastal plain. Likewise, the small distributary streams, like the larger channels, meandered on the coastal-plain, carried a suspended sediment load, were slow moving, had vegetated banks and sometimes vegetated channels, and supported a mollusk fauna. The overall view of this coastal lowland is of a vegetated low-relief surface containing scattered ponds and marshes cut by low-energy meandering rivers and streams (Fig. 17).

The coastal-plain was extensively vegetated containing a ground cover of wetland plants, ferns and horsetails, as well as aquatic plants (Spicer, 1987; Spicer & Parrish, 1990b). An understory cover of moderately diverse angiosperms (Frederiksen, 1991), and a scattered forest of small deciduous conifers existed on the coastal plain (Spicer, 1987; Parrish & Spicer, 1988; Spicer & Parrish, 1990a,b; Frederiksen, 1991; Spicer & Corfield, 1992).

The water table on the coastal plain was probably high. Evidence for a moist environment includes the lack of mudcracks, the presence of abundant wetland plants, and the abundant organic-rich beds that represent a reducing environment caused by organic decay under moist conditions. Shallow ponds and marshes occupied topographically low areas and contained aquatic plants (Parrish & Spicer, 1988). Besides river flooding of the coastal plain, rainfall, which during the Cretaceous in the northern latitudes may have been frequent in the winter months and abundant during the summer (Ziegler et al., 1988), would have contributed abundant water to the coastal lowlands and probable snowfall in the winter months. The temperatures in this northern region ranged from 2 to 8 °C with probable periods of freezing (Spicer & Parrish, 1990a).

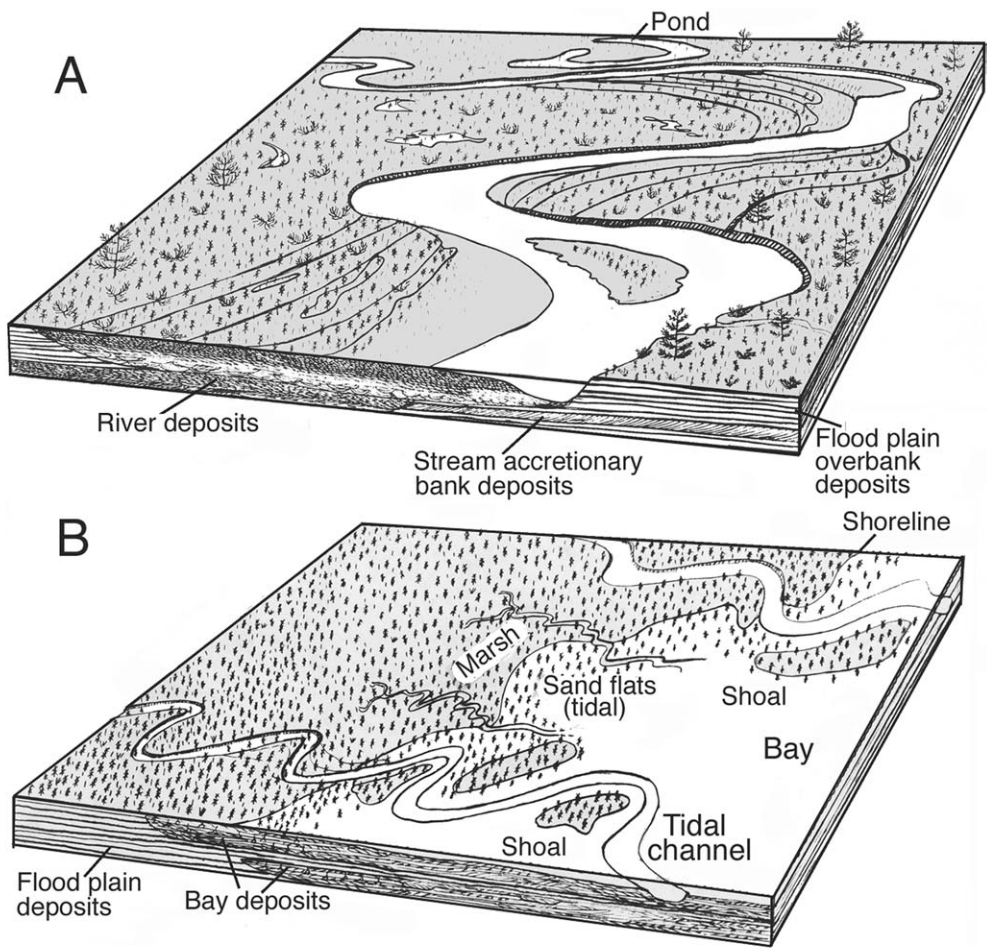

Fig. 17. Interpretation of floodplain depositional environments of the Prince Creek Formation and part of the Schrader Bluff Formation in the lower Colville River region, Alaska. A, the floodplain depositional environment was dominated by a major river up to 10 m deep, migrating laterally across the floodplain. Small trees (deciduous conifers), ferns, horsetails and mosses apparently formed much of the vegatation cover on the floodplain. B, schematic diagram showing floodplain and shallow-bay depositional environments of the Prince Creek Formation and part of the Schrader Bluff Formation. A muddy marsh environment grades into a broad, plant-covered, sand-flat environment which in turn grades to a shallow-bay environment. A storm-dominated bay and marine environment existed seaward of the coastal plain.

Within this marine-influenced wetland hadrosaurs, with abundant juveniles, were periodically present. A coastal plain setting was apparently a favored environment for these herbivores. An investigation of Late Cretaceous environments and occurrences of hadrosaurs by Nadon (1993) has suggested that these dinosaurs preferred a wetland setting for survival. The wetlands provided abundant food, and along with a combination of flooding and soft substrate, would have greatly reduced the ability of large carnivores to move and capture prey in this environment.

The gently sloping coastal-plain graded into and interfingered with a marginal-marine environment that consisted of shallow bays. Shallow channels, extensive vegetated tidal flats, and storm-wave reworked, shallow-water deposits are the dominant features of the bays. The fringing sand flats contained a vegetative cover of aquatic plants. The water within the bays was probably slightly brackish to fresh, as suggested by the aquatic vegetation and ostracodes (Brouwers & De Deckker, 1993).

The shallow bays were either very large or open directly to the Arctic Ocean, allowing storm waves to rework the sediments as well as to transport benthic foraminifers from the offshore marine environment. The coastal fringing bays were probably similar to the present-day Harrison Bay and Colville River delta-front region in having scattered shoals at the river mouths and in lacking barrier islands (Fig. 17).

The Late Cretaceous transgressive, shallow-marine sediments record periodic storm events. As within Cretaceous marine deposits in the western interior of North America where virtually every prograding shoreface sequence contains storm-induced hummocky cross-stratification (Swift & Nummedal, 1987), these northern-latitude deposits located on the northwest end of the Late Cretaceous seaway likewise record storm events. Ziegler et al. (1988) suggested that Cretaceous cyclones would have tended to move north along interior seaways and enter the Arctic Ocean. The marine deposits at Ocean Point may record some of these periodic storm events.

The sand-size sedimentary grains record two main sources: (1) a sedimentary-metamorphic source, as indicated by abundant quartz, mica, and mica-schist grains; and (2) a volcanic source recorded in the tephra beds and glass shards. The metamorphic bedrock source may be similar to that of the Early–Late Cretaceous Umiat Delta of the Nanushuk Group, which also records a metamorphic source from the Brooks Range (Huffman & Ahlbrandt, 1979; Bartsch-Winkler, 1979). The volcanic source is unknown, but is probably similar to the source(s) for tephra deposits found throughout the Upper Cretaceous on the North Slope.

5. Conclusions

1 Late Cretaceous strata along the lower Colville River, Alaska, record three distinct depositional environments that in ascending order consist of nonmarine floodplain, interdistributary bay, and a transgressive, shallow, storm-dominated shelf.
2 Rivers up to 10 m deep, and distributary streams carrying a suspended sediment load, meandered in an easterly direction across the coastal plain. Extensive overbank flooding with the development of crevasse splays resulted in the formation of repeated fining-upward strata. The flood events were episodic, as recorded by the development of organic-rich beds up to 89 cm thick over many of the fining-upward beds.
3 The coastal plain was extensively vegetated, as indicated by abundant roots, the ground cover consisting of wetland plants, mosses, ferns, and horsetails. Small deciduous conifers supplied abundant needles to the organic-rich beds.
4 Vertebrate concentrations, other than fluvial channel lag occurrences, are found as bone beds in dark organic-rich sediments suggesting, in two examples, transport and concentration of previously deposited bones on the floodplain during periodic flood events. The association of skeletal remains with two tephra beds may indicate that air fall of ash may have aided the demise of these dinosaurs.
5 The floodplain grades into, and interfingers with, a marginal marine environment that consisted of shallow bays less than 7 m deep. Extensive vegetated and bioturbated sand flats, shallow channels, and storm-wave-reworked sediment are the dominant features of the bay deposits. Thin deposits of prograding marsh and floodplain sediments overlie the bay strata.
6 A Late Cretaceous marine transgression is recorded above the bay deposits. The fossiliferous shallow marine shelf sediments record repetitive storm events with the formation of beds of hummocky cross-strata.

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