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Aggradation of gravels in tidally influenced fluvial systems: upper Albian (Lower Cretaceous) on the cratonic margin of the North American Western Interior foreland basin

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Abstract

Alluvial conglomerates were widely distributed around the margin of the Early Cretaceous North American Cretaceous Western Interior Seaway (KWIS). Conglomerates, sandstones, and lesser amounts of mudstones of the upper Albian Nishnabotna Member of the Dakota Formation were deposited as fill-in valleys that were incised up to 80 m into upper Paleozoic strata. These paleovalleys extended southwestward across present-day northwestern Iowa into eastern Nebraska. Conglomerate samples from four localities in western Iowa and eastern Nebraska consist mostly of polycrystalline quartz with lesser amounts of microcrystalline (mostly chert), and monocrystalline quartz. Previous studies discovered that some chert pebbles contain Ordovician–Pennsylvanian invertebrate fossils. The chert clasts analyzed in this study were consistent with these findings. In addition, we found that non-chert clasts consist of metaquartzite, strained monocrystalline quartz and 'vein' quartz from probable Proterozoic sources, indicating that parts of the fluvial system's sediment load must have travelled distances of 400–1200 km. The relative tectonic stability of this subcontinent dictated that stream gradients were relatively low with estimates ranging from 0.3 to 0.6 m/km.

Considering the complex sedimentologic relationships that must have been involved, the ability of low-gradient easterly-sourced rivers to entrain gravel clasts was primarily a function of paleodischarge rather than a function of steep gradients. Oxygen isotopic evidence from Albian sphaerosiderite-bearing paleosols in the Dakota Formation and correlative units from Kansas to Alaska suggest that mid-latitude continental rainfall in the Albian was perhaps twice that of the modern climate system. Hydrologic fluxes may have been related to wet-dry climatic cycles on decade or longer scales that could account for the required water supply flux. Regardless of temporal scale, gravels were transported during 'high-energy' pulses, under humid climatic conditions in large catchment areas.

An overall rising sea level during the late Albian created accommodation space for the gravelly lithofacies equivalent to the Kiowa-Skull Creek rocks. As Western Interior sea level rose, regional stream gradients were reduced, resulting in regional fluvial aggradation. The conglomeratic lower parts of the Nishnabotna Member of the Dakota Formation formed the transgressive systems tract within an upper Albian sequence that is defined by two unconformities that can be traced from marine Kiowa strata in western Kansas northeastward into western Iowa (Brenner et al., 2000). Mud-draped cross-bedded sandstone bodies, laminated mudstone intervals, and vertical burrows in the lower strata of the Nishnabotna Member indicate that estuarine conditions existed at the mouths of the river system, and tidal effects were transmitted at least 200 km inland from the interpreted late Albian coast. These observations suggest that estuarine conditions stepped up the incised valleys as fluvial sediments aggraded in response to regional transgression that continued through the Late Albian.

Keywords: Gravels; Tides; Rivers; Cretaceous; Western Interior Seaway

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1. Introduction

1.1. Purpose of this paper and review of previous work

The purpose of this paper is to elaborate on the origin and depositional setting of conglomerates deposited in the upper Albian Nishnabotna Member of the Dakota Formation, adjacent to the eastern margin of the North American Cretaceous Western Interior Seaway (KWIS). Witzke & Ludvigson (1982, 1994, 1996) reported on the general characteristics of these strata. Brenner et al. (2000) presented a stratigraphic scheme that used palynologic biostratigraphy and sequence stratigraphy to show that the nonmarine Dakota Formation in western Iowa and eastern Nebraska correlates with the marine Kiowa Formation to the west. They also proposed a preliminary sedimentologic explanation for coarse-grained siliciclastic transportation to the seaway edge and deposition in tide-influenced lower fluvial valleys. The use of oxygen isotopic data from early paleosol cements to determine paleoclimatic proxies were reviewed in Ludvigson et al. (1998), and paleoprecipitation calculations and new geochemical data were published by White et al. (2001), and Ufnar et al. (2002). Since publication of the Brenner et al. (2000) paper, additional petrographic data on the conglomeratic sandstones and additional geochemical data have been gathered (e.g., White et al., 2001; Ufnar et al., 2002). In this paper, the new petrographic data are presented and the new geochemical calculations are used to elaborate on the origin and depositional settings of these upper Albian conglomerates.

1.2. Geologic setting

Alluvial conglomerates were widely distributed around the margin of the eastern subcontinent of North America during the Early Cretaceous. Conglomerates occur within the upper Albian Nishnabotna Member of the Dakota Formation, which was deposited within valleys incised into Paleozoic strata in Iowa and eastern Nebraska (Fig. 1). These valleys cut down more than 30 m over distances of a few kilometers in the present-day area in the lowermost Platte River Valley of eastern Nebraska (Joeckel et al., 2001), and up to 80 m in northwestern Iowa (Brenner et al., 2000). An age of incision of 160–105 Ma for these paleovalleys is suggested based on the presence of Upper Jurassic (Oxfordian Fort Dodge Formation) deposits preserved on interfluves in western Iowa (Anderson & McKay, 1999; Ludvigson, 1999). Conglomerates are exposed in quarries in Sarpy and Cass counties, Nebraska and correlate with marine fossil-bearing mudrocks to the west (Brenner et al., 2000).

1.3. Paleoclimatic setting

The break-up of the supercontinent Pangaea in the Mesozoic had major consequences for the paleoclimatic regime in North America. Northward drift of North America transported the western Iowa–eastern Nebraska area on the eastern margin of the KWIS from a dry latitudinal region less than 30° north of the equator, to a position with a humid temperate climate lying more than 40° north (Blakey, 1999; Ludvigson, 1999; Scotese, 1991).

Sedimentologic evidence (Witzke & Ludvigson, 1994) and climate model simulations (Slingerland et al., 1996) have indicated that Early Cretaceous paleoenvironments of western Iowa were located in an area of net rainfall surplus. In addition, increased rates of Early Cretaceous global ocean crust production may have led to elevated concentrations of volcanically-derived CO_2 in the Earth's atmosphere, which would have resulted in global greenhouse warming (Caldeira & Rampino, 1991). Climatic modelling suggests that increased atmospheric moisture transport in a mid-Cretaceous 'Greenhouse World' could have resulted in a 28% increase in globally averaged precipitation over that of current levels (Barron et al., 1989). Global marine phosphorus burial data suggest that the mid-Cretaceous, especially at about 100 Ma, was a time of greatly accelerated continental weathering (Fölmi, 1995). These lines of evidence indicate that Early Cretaceous precipitation on a global scale was significantly higher than it is today.

Mid-Cretaceous (Albian–Turonian) paleoclimatic studies have provided lithostratigraphic and stable isotope evidence that is in agreement with a model that suggests that the precipitation rates along the cratonic coast of the WIS ranged from ca. 2500 to ca. 4100 mm/year during this time (White et al., 2001). A more recent study that focused on the mid-Albian at 45°N paleolatitude suggests values between 4550 and 5740 mm/year (Ufnar et al., 2002). For comparison, the present-day average precipitation rate at 45° N is ca. 840 mm/year (Barron et al., 1989). Paleoprecipitation values were based on combining $\delta^{18}O$ values obtained from sphaerosiderite nodules recovered from seasonally saturated paleosols (Ludvigson et al., 1998) with model-driven paleotemperature estimates (White et al., 2001), and empirically derived paleotemperature estimates (Ufnar et al., 2002). By reconstructing paleolatitudinal precipitation $\delta^{18}O$, White et al. (2001) and Ufnar et al. (2002) were able to estimate the mid-Cretaceous precipitation rates. They concluded that warm seawater that flowed northward along the eastern margin of the Albian Western Interior Seaway of North America was the primary source of water vapor for this part of the basin (White et al., 2001; Ufnar et al., 2002). Therefore the ca. 4‰ to 4.3‰ offset between estimated $\delta^{18}O$ values for late Albian precipitation in the KWIS region, and

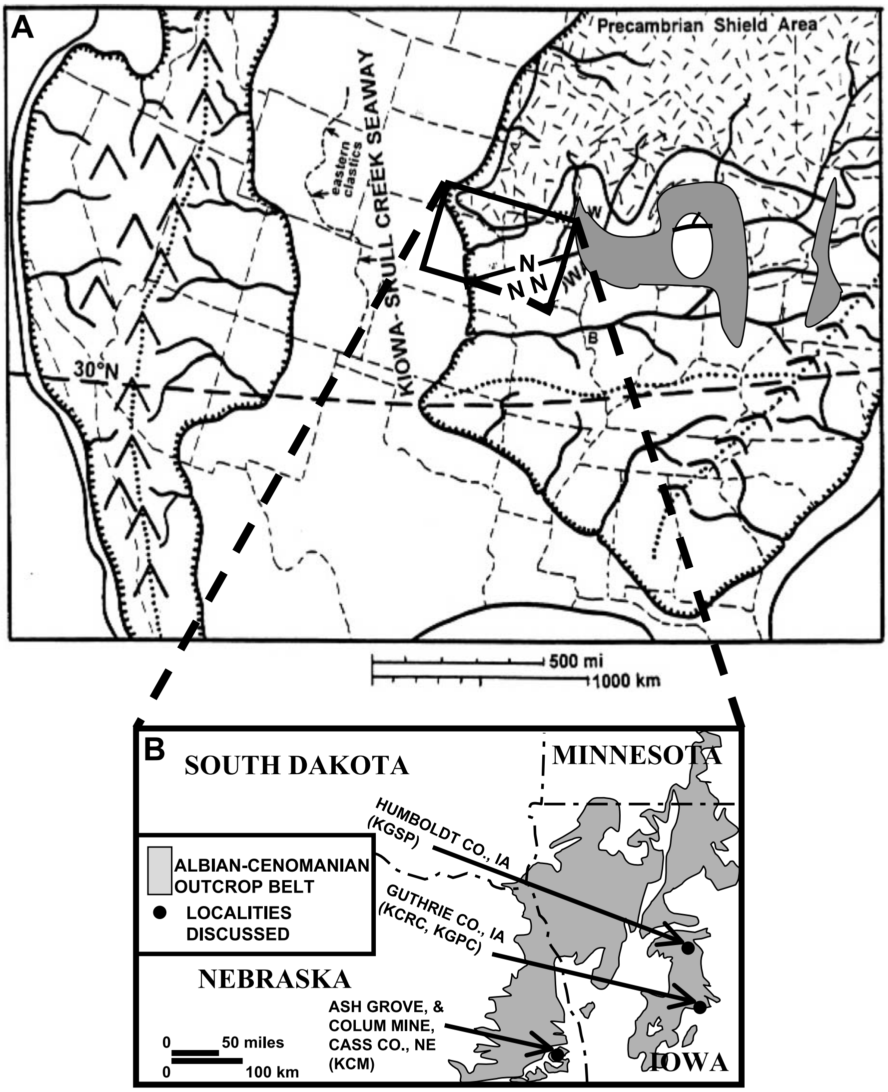

Fig. 1. A, mid-Cretaceous paleogeography of the US. Shaded areas represent potential lower Paleozoic siliciclastic source areas in the drainage basin of late Albian river systems. Open space in shaded area represents the Wisconsin Dome area where lower Paleozoic strata were removed by erosion prior to Cretaceous time. Letter "N" shows approximate locations of Nishnabotna conglomeratic sandstone outcrops, and dashed line labelled 'eastern clastics' marks the westernmost extent of Albian–Turonian siliciclastic sediments derived from the eastern part of North America. B, shows the Albian–Cenomanian (Dakota Formation) outcrop belt, collecting localities and codes of samples collected at each locality. Modified from Brenner et al. (2000).

modern values is most probably a result of increased Cretaceous precipitation rates. Under such conditions, the sediment source areas for the sandstones of the Albian Nishnabotna Member were subjected to intense chemical weathering in very humid subtropical paleoenvironments.

2. Nishnabotna (Lower Dakota) conglomerates

2.1. Conglomerate characteristics

Conglomeratic sandstone bodies in the Nishnabotna Member of the Dakota Formation in western Iowa and eastern Nebraska contain clasts that range in diameter from granule size (2 mm) to over 40 cm. Some of the larger clasts were found the Ash Grove Cement Quarry in Cass County, Nebraska (located on Fig. 1), and consist of angular cobbles of weathered chert (Fig. 2). The angularity of these clasts suggests short transport from sources in the valleys incised into Pennsylvanian carbonate strata. In addition, there are a variety of well-rounded clasts that range up to 18 cm in diameter that were found in lenses within sandstone unit 3 at Ash Grove (Fig. 3A). Many of these clasts consist of 'vein quartz', quartzite, jasper, and iron silicate ironstone, similar to lithologies (Fig. 3B) described in the bedrock

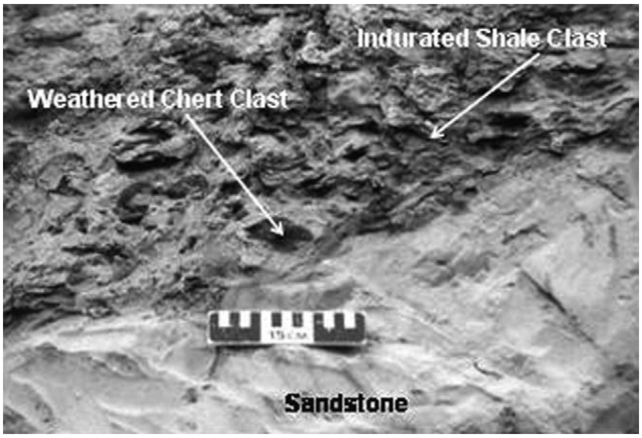

Fig. 2. Weathered chert and well-indurated shale clasts in a Nishnabotna sandstone body exposed in the Ash Grove Cement Quarry, Cass County, Nebraska.

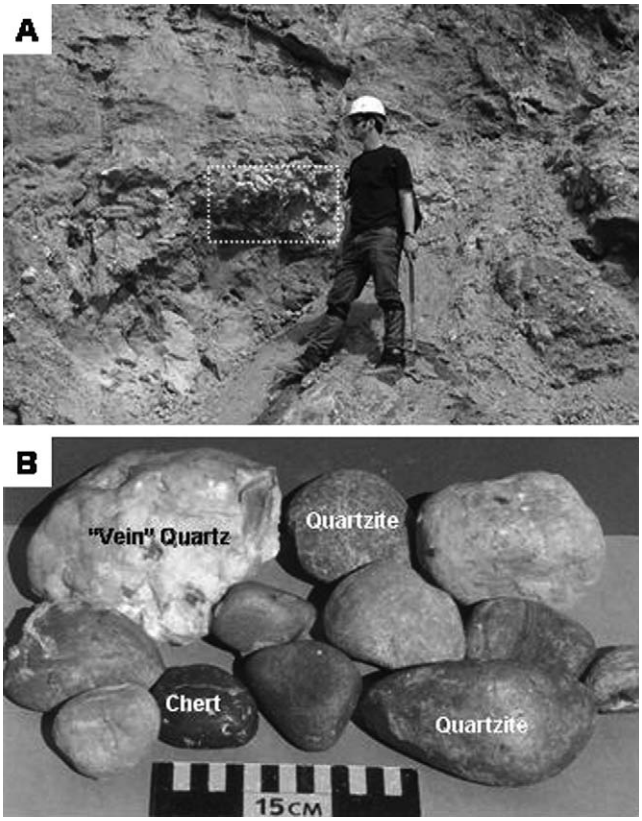

Fig. 3. A, conglomeratic pockets in sandstone unit 3 of the Nishnabotna Member exposed in the Ash Grove Cement Quarry, Cass County, Nebraska. B, clasts of rounded 'vein' quartz quartzite and chert collected from the conglomerate outlined by the rectangle in A.

of the Canadian Shield region to the north and northeast, but not exposed locally (Witzke & Ludvigson, 1994).

Fig. 4. Chert pebble conglomerate from the Nishnabotna Member exposed in a pit operated by the Guthrie County (Iowa) Engineer's Office, Guthrie County, Iowa.

About 200 km to the east, in Guthrie County, Iowa, bedded deposits of cross-bedded and graded beds of pebble-sized clasts occur within the Nishnabotna member. Quartz-rich conglomerates exposed in a pit operated by the Guthrie County Engineer's Office are exposed in the lower 2 m of an operating pit and consist of tabular bodies of conglomerate approximately 25–50 cm thick, some fining upward into 5–10-cm thick intervals of medium-grained sandstone. Individual units are cross stratified and display unidirectional, southeast-dipping foresets. The conglomeratic bodies are laterally bevelled or truncated by large-scale shallow trough channel forms. The gravel fraction of these beds is dominated by polycrystalline quartz, metaquartzite, and chert pebbles approximately 1–2 cm in diameter (Fig. 4). However, much larger clasts are scattered in the unit, including quartzite cobbles that commonly range up to 8–10 cm in diameter with some approaching 20 cm. Chert pebbles contain identifiable silicified Silurian and Ordovician fossils including the Silurian coral *Favosites* (Fig. 5), as well as Pennsylvanian fusulinids (Witzke & Ludvigson, 1982, 1994, 1996; Brenner et al., 2000). Table 1 contains a list of fossils identified by previous workers in Cretaceous conglomerate chert clasts in western Iowa and eastern Nebraska that was originally published in an Iowa Geological Survey Bureau guidebook by Witzke & Ludvigson (1996).

Specimens of conglomerate were assigned locality-specific labels for ease of discussion. Samples from these specimens were analyzed from three localities in western Iowa (KCRC, and KGPC from Guthrie County, and KGSP from Humboldt County) and one from eastern Nebraska (KCM from Cass County in the Lower Platte Valley; see Fig. 1 for locations). Point count analyses showed that similar grain compositions were represented in each of the four samples, but that their percentages varied. Cretaceous specimen KCRC contains 36% monocrystalline quartz and 64% polycrystalline quartz.

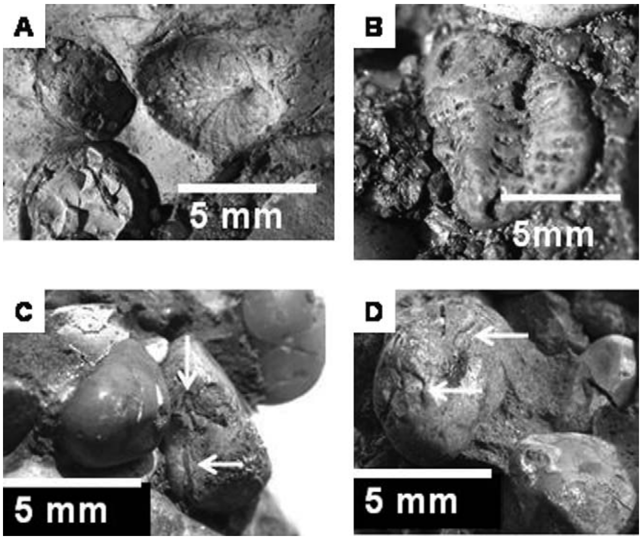

Fig. 5. Macro-photographs of fossil fragments in chert pebbles from conglomerate specimens of the Nishnabotna Member of the Dakota Formation in western Iowa and eastern Nebraska. A, molds of small unidentified brachiopods from Guthrie Co., Iowa. B, silicified *Favosites* coral fragment from Guthrie County, Iowa. C, chertified biomicrite containing unidentified brachiopod shell fragments (white arrows) from Cass County in the Lower Platte River Valley, Nebraska. D, unidentified brachiopod shell fragments (white arrows) in a reddish brown chert clast from Cass County in the Lower Platte River Valley, Nebraska.

Microscopy shows that the polycrystalline quartz consists of morphologically elongated crystals (Fig. 6), indicative of a metamorphic source. In specimen KGCP, 60.9% is monocrystalline quartz and 39.1% is polycrystalline quartz. Cretaceous specimen KGSP includes 25.9% monocrystalline quartz and 74.1% polycrystalline quartz. The most distal sample collected is KCM, which contains 15% polycrystalline quartz. The matrix materials of these Cretaceous samples are mostly a mixture of fine to silt-sized quartz, clay materials, and iron oxides.

The large amounts of quartz and chert found in the Cretaceous specimens KCRG, KCRC, and KGCP along with the fact that these silica clasts are well rounded further suggests that the sediments represented by these samples were transported long distances.

2.2. Potential gravel sources

The long-distance transport of pebbles containing lower Paleozoic fossils, and cobbles of quartzite and siliceous ironstone with Precambrian affinities, suggest that this paleodepositional system must have been highly competent and tapped sediments from northern and eastern sources that were from a few hundred to over 1000 km away (see Fig. 1 for relative positions). Tectonic stability dictated that stream gradients were relatively low. There is neither petrographic evidence to support polycyclicity, nor preserved pre-Cretaceous strata containing similar clasts that could have served as intermediate sediment storage receptacles or sources west of these proposed source areas. Therefore, the presence of chert pebbles with Ordovician and Silurian fossils, and quartzite clasts with Precambrian affinities, indicate that parts of the sediment load must have travelled from at least as far away as present-day southwestern Minnesota, northeastern Iowa, and western Wisconsin (Fig. 1). One question that must be addressed is: What mechanism could have moved pebbles and cobbles hundreds of kilometers down low-gradient fluvial systems to sites close to the Albian shoreline?

Table 1
Fossils in Nishnabotna chert clasts identified by Witzke & Ludvigson (1982), Bain (1897), and unpublished identifications by the first permanent state director of the Iowa Geological Survey, Samuel Calvin. Originally published by Witzke & Ludvigson (1996), table 3, p. 46).

Taxa	Temporal Range
Corals	
Alveolites sp.	Silurian–Devonian
'Amplexus' sp.	Silurian–Mississippian
Arachnophyllum sp.	Silurian
Astrocerium sp.	Silurian–Devonian
Astrocerium venustum	Silurian
Favosites favosus	Silurian
Favosites niagarensis	Silurian
Favosites spp. indet.	Silurian–Devonian
Pleurodictyum sp.	Devonian
Ptychophyllum expansum	Silurian
'*Streptelasma*' sp.	Ordovician–Devonian
'*Streptelasma*' *spongaxis*	Silurian
Striatopora sp.	Silurian–Devonian
Syringopora sp.	Silurian
'*Zaphrentis*' sp.	Silurian–Mississippian
'*Zaphrentis*' *stokesi*	Silurian
indet. solitary coral	Ordovician–Pennsylvanian
Brachiopods	
'*Atrypa*' sp.	Silurian–Devonian
Eospirifer eudora	Silurian
Lepidocyclus gigas	Upper Ordovician
indet. rhynchellid	Ordovician–Permian
indet. strophomenids	Ordovician–Pennsylvanian
indet. brachiopod fragments	Ordovician–Pennsylvanian
Bryozoans	
?*Rhinidictya* sp.	Ordovician–Silurian
fenestellid sp.	Silurian–Pennsylvanian
indet. bryozoans	Ordovician–Pennsylvanian
Trilobites	
indet thoracic segments	Paleozoic
Echinoderms	
large crinoid stem pieces	Ordovician–Pennsylvanian
assorted crinoid fragments	Ordovician–Pennsylvanian
Plants	
petrified wood (gymnospermous?)	Cretaceous?
Vertebrates	
dinosaur bone fragments	Cretaceous

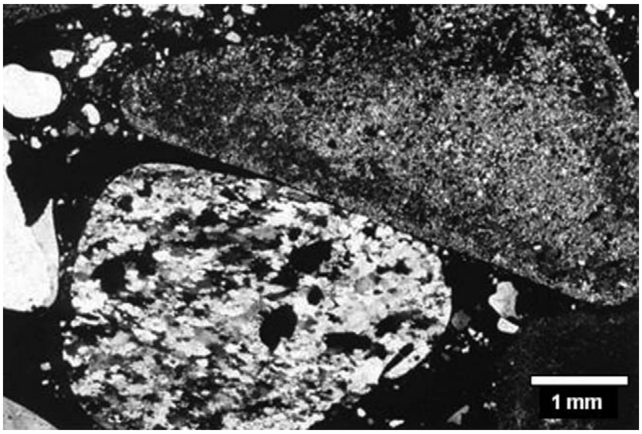

Fig. 6. Photomicrograph of microcrystalline quartz (chert) pebble with an iron-oxide rim (above) and a polycrystalline quartz pebble (below). The crystallites of the polycrystalline quartz clasts are elongated in a preferred direction, indicating that this clast was originally derived from a metamorphic source.

2.3. Sedimentology of long-distance transport

Low regional relief and high precipitation rates, coupled with transportation and eventually deposition of coarse-grained material in coastal settings, suggest that the ability of low-gradient rivers to entrain gravel clasts was primarily a function of paleodischarge. Flume experiments by previous workers (e.g., Komar, 1987) have shown that sediment mixes ranging from sand to gravel require lower flow stresses to move the larger particles than required to entrain that size from a uniform bed load. Robinson & Slingerland (1998) used a variety of combinations of values and parameters, and concluded that varying sediment feed and subsidence rates exert the strongest influence on downstream fining trends, and that the varying of water discharge rate is balanced by increase in channel width. They found that fluvial beds do not fine downstream in models that were run without subsidence. Flume and computer-modelling studies suggest that high-flow conditions, even if they are infrequent in human time terms, given geologic intervals of time could move gravel-size materials hundreds of kilometers down low-gradient slopes.

Paola et al. (1992) constructed two-dimensional grain-size partitioning models that indicate that discharge alone cannot account for large gravel accumulations, and that such deposits are driven by either flux increases in sediment or water supply. These models varied four parameters, sediment flux, subsidence, gravel fraction, and diffusivity, in both quasi-equilibrium and non-equilibrium time modes. Changes in the quasi-equilibrium model runs were carried out in sinusoidal cycles with frequencies that were one order of magnitude less than that deemed to be equilibrium time. Non-equilibrium model runs were carried out in similar cycles, but with frequencies ten times faster than equilibrium times. Since the eastern margin of the KWIS is anorogenic, changes in flux of sediment supply due to tectonic activity seem unlikely. However, fluctuations in water supply to Cretaceous fluvial systems seem very likely given the wet, warm paleoclimate indicated by both models and lithostratigraphy. The model that Paola et al. (1992) ran to test effects of rapid variations in diffusivity (water supply) under conditions of steady sediment supply, low subsidence, and steady gravel supply, shows that relatively thin tongues of gravel extend basinward within the fluvial sand body. The results of this run imply that gravels were transported down fluvial systems in pulses related to repeated reworking of materials deposited in the wake of previous high-flow episodes. White et al. (2001) and Ufnar et al. (2002) utilized sphaerosiderite oxygen isotope data from upper Albian paleosols in the lower part of the Dakota Formation and correlative units from Kansas to Alaska to model Early Cretaceous hydrologic fluxes. They concluded that mid-latitude continental rainfall in the late Albian was substantially higher, perhaps more than twice that of the modern climate system (White et al., 2001; Ufnar et al. 2002). Pebbles and cobbles in the Dakota Formation conglomerates deposited on the cratonic margin of the KWIS, were transported in systems where changes in water fluxes were probably related to wet versus dry climatic cycles that may have had frequencies in the decade-to-century range, or longer.

2.4. Gravel deposition and aggradation

As sea level rose during the late Albian transgression, the distal parts of regional stream valleys were flooded, creating accommodation space, resulting in progressive filling of valleys with coarse-grained siliciclastic sediments upstream. Valley deposits graded into estuarine-shoreline deposits as documented in the Ash Grove Cement Quarry in Cass County, Nebraska (located on Fig. 1), where conglomeratic sandstone beds pinch out in marine-palynomorph-bearing, rhythmically-laminated mudrocks (Brenner et al., 2000). The marine flooding of lower stream valleys coupled with the short-term episodes (decade-scale or smaller?) of flooding, or longer-term wet-dry climatic cycles, resulted in aggradation of gravels and gravel-bearing sands in the lower portion of the Nishnabotna Member.

3. Fluvial-estuarine characteristics and settings

3.1. Sedimentologic and stratigraphic characteristics

Lower Dakota conglomeratic sandstone facies have been described in localities that range from present-day eastern Nebraska, eastward at least as far as Guthrie County, Iowa (Fig. 1), which may have been more than

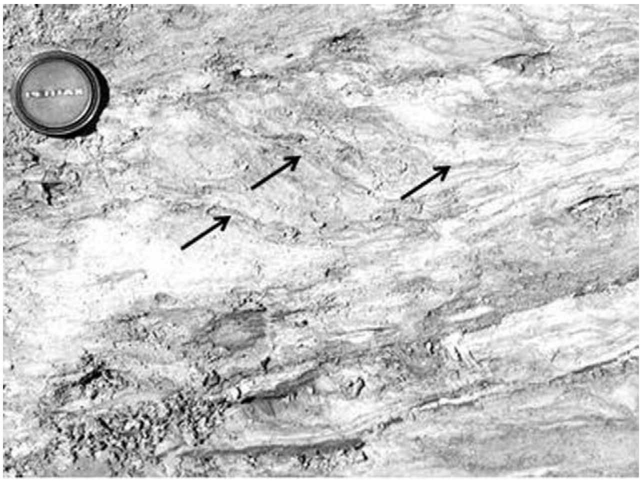

Fig. 7. Clay-draped cross-stratified sets in lower part of the Nishnabotna Member of the Dakota Formation exposed along a tributary of the Middle Raccoon River, Garst Farm Resort, Guthrie County, Iowa. Arrows point to some of the clay drapes; lens cap is 50 mm in diameter.

200 km inland from the synchronous shoreline (Brenner et al., 2000). These facies are overlain by medium-grained sandstone bodies, some of which have clay-draped cross-stratified sets (Fig. 7). Three successive coarsening-upward intervals or parasequences, each capped by coarse-grained fluvial sediments, are exposed in the lower Platte River Valley in eastern Nebraska (intervals capped by sandstone units 1, 3 and 5 on Fig. 8A). In the second of these intervals, sparsely burrowed inclined heterolithic strata (IHS) sets suggest bed forms that were at least 5 m in height (Unit 2 on Fig. 8B). This strata-type documents active growth of large-scale features, such as those observed in tidally influenced point-bar complexes (Thomas et al., 1987). The upper interval contains rhythmical-laminated mudrocks (Unit 4 on Fig. 8B, C) with both marine and nonmarine palynomorphs (Brenner et al., 2000). The characteristics of the sediments observed in the lower Platte River Valley area suggest that during the late Albian transgression, at least two parasequences back-stepped up the paleovalleys. The terminus of this valley is represented by the exposures in the Ash Grove Cement Quarry (Fig. 8A–C).

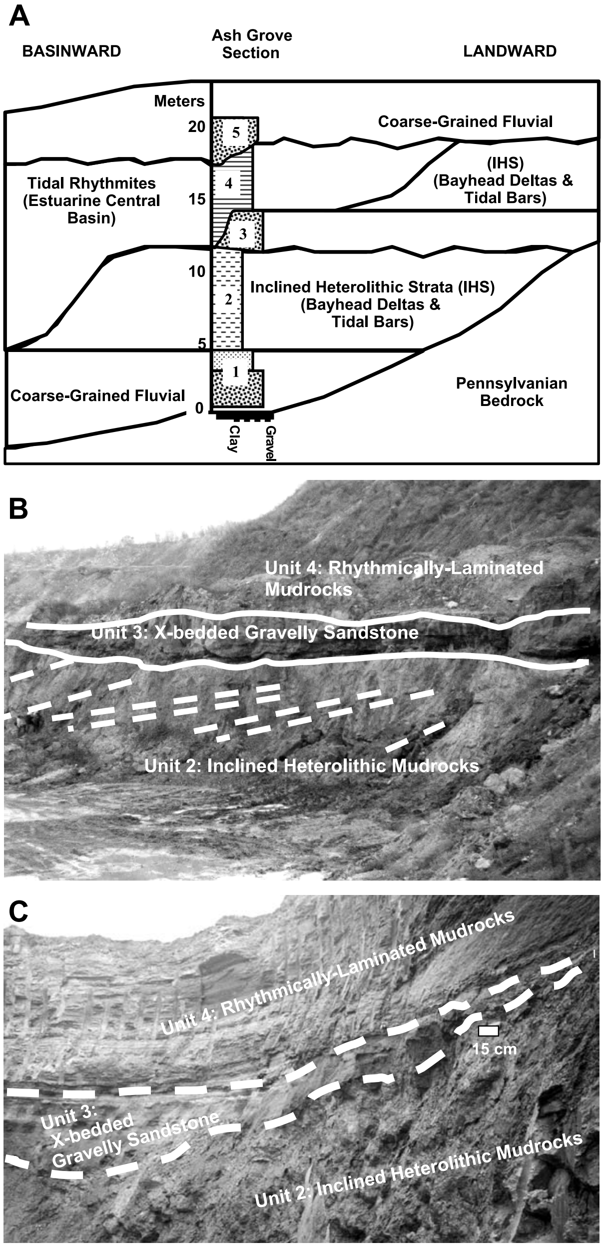

Fig. 8. A, five lithologic units and stratigraphic relations between three coarsening-upward intervals exposed in the Ash Grove Cement Quarry, Cass County, Nebraska. Numbered units relate to lithologies mentioned in the text and pictured in Fig. 2, Fig. 3, and Fig. 7. B, cross-bedded gravelly sandstone (Unit 3) overlain by rhythmically laminated mudrocks (Unit 4) and underlain by mudrocks with a prominent set of inclined heterolithic stratification (Unit 2; dashed lines represent visible bedding plane surfaces). These lithologies represent estuarine facies formed by bayhead deltas and tidal bars (Brenner et al., 2000) exposed in the Ash Grove Cement Quarry, Cass County, Nebraska. For scale, note the three geologists near the center-left edge of the photograph. C, photograph taken in 1994 showing pinchout of Unit 3 in the Ash Grove Cement Quarry, Cass County, Nebraska (subsequently removed by quarry operations). Note the pronounced banding visible in overlying Unit 4.

Extension of estuarine conditions landward to at least Guthrie County, Iowa, was documented by Phillips & White (1998) who described exposures of laminated siltstones with bioturbated intervals in strata of the lower Nishnabotna Member along a tributary of the Middle Raccoon River (Fig. 9; Guthrie County on Fig. 1). Albian palynomorph assemblages lack marine forms, but contain early pyrite cementation, rhythmites, and a sparse ichnofauna including *Chondrites*, *Teichichnus*, *Arenicolites*, and *Cylindrichnus*, suggesting tidal influence. This ichnoassemblage consists of near vertical to U-shaped forms that were dominantly dwelling traces and are analogous to *Skolithos* ichnofacies of Seilacher (1967). Although the ichnogenera identified and listed

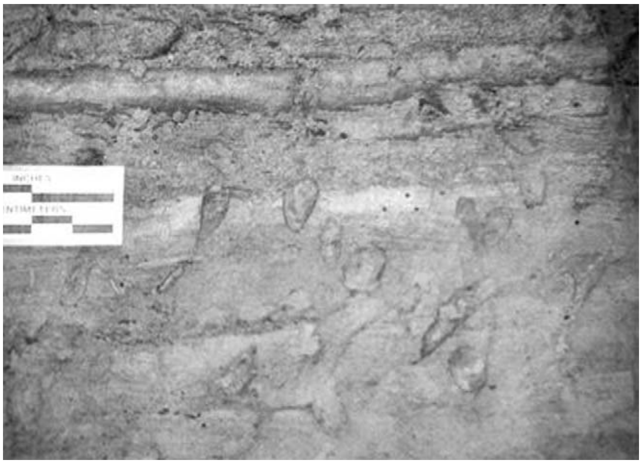

Fig. 9. Vertical burrows in the lower part of the Nishnabotna Member of the Dakota Formation, exposed along a tributary of the Middle Raccoon River, Garst Farm Resort, Guthrie County, Iowa.

above have been reported individually as occurring in environments that range from tidal to abyssal (Basan, 1978), the association of this ichnoassemblage with mud-draped cross sets within a valley-fill deposit strongly suggests deposition in an estuarine setting (Ludvigson et al., 2001). The stratigraphic position of these mudrocks beneath conglomeratic sandstone bodies suggests that early during the Albian transgression, estuarine conditions extended eastward through the low-gradient valleys for perhaps 200 km or more from the low-stand Albian shoreline of the KWIS.

3.2. Fluvial-estuarine setting

Features of estuarine conditions that are found many kilometers landward of synchronous shorelines are characteristic of salt-water wedge estuaries. The present-day east coast of North America has analogous features landward of the estuaries of drowned river valleys. For example, the tidal range for the Hudson River estuary in New York at its mouth averages about 1.3 m, with a spring tidal range of ca. 1.9 m (Biological Science Department, University of South Carolina, 2001). The tidal range on the river 150 km landward at Kingston, NY is measured at about 1.1 m, with a recent spring tidal range at ca. 1.2 m. (Biological Science Department, University of South Carolina, 2001). The effects of these tidal changes in river level have been observed in a small tidal pool that has been created where Black Creek flows into the Hudson River about 10 km south of the gauging station. During a tidal cycle within 24 hours of a new moon spring tide, the pool filled to a level of just over 1 m at high tide, and nearly emptied six hours later (Fig. 10).

We suggest that the flood-tide incursion of salt-water wedges up estuaries along the eastern margin of the KWIS caused the back-up of river waters during high tide, accounting for estuarine conditions being observed as far landward as Guthrie County, Iowa. As the Hudson River example illustrates, even microtidal (0–2 m) conditions have recognizable effects tens to hundreds of kilometers upstream.

4. Transgressive systems tract aggradation during the late Albian Kiowa-Skull Creek marine cycle

Studies of the Dakota Formation along the eastern margin of the KWIS show a general filling of incised fluvial valleys during the late Albian–early Cenomanian (e.g., Witzke & Ludvigson, 1994, 1996). The conglomerates and sandstones of the Nishnabotna Member of the Dakota Formation and correlative marine mudrocks accumulated in accommodation space created as incised valleys were flooded by rising sea level (Brenner et al., 2000). This resulted in the formation of a transgressive systems tract that consists of a fluvial–estuarine incised valley fill. At the mouths of incised river valleys, conglomerates grade directly into estuarine and marine mudrocks (Fig. 8C). In more proximal portions of the incised valley system, conglomerates and fluvial sandstone bodies overlie estuarine and fluvial deposits.

5. Conclusions

Previous workers have shown that during the Cretaceous, alluvial gravels were deposited along the western margin of the KWIS where gradients were relatively steep and subsidence rates were significant. Our study provides an explanation for similar deposits along the relatively low gradient, low subsidence environments along the eastern margin of the KWIS. The movement of gravels from as much as 1000 km westward from eastern sources, through fluvial valleys that crossed the low-lying coastal plain, and into the estuarine embayments of the KWIS, has been documented using petrographic and stratigraphic methods. Oxygen isotopic data from upper Albian sphaerosiderite-bearing paleosols in the Dakota Formation and correlative units (Kansas to Alaska) suggest that mid-latitude continental rainfall in the Albian was substantially higher, perhaps twice that of the modern climate system (White et al., 2001; Ufnar et al. 2002). Specifically, we conclude that:

1) Clasts over 40 cm in diameter were deposited in valleys in low-gradient, low subsidence environments along the eastern margin of the KWIS.
2) Although some of these clasts are subangular weathered chert that may have been transported relatively short distances from Pennsylvanian rocks exposed in valley walls, well rounded pebble–cobble-sized clasts were transported hundreds of kilometers from

Fig. 10. Tidal pool visible from Winding Brook Road at the junction of Black Creek and the Hudson River, about 145 km upstream of the mouth of the Hudson River. Photograph on the left was taken at high tide, and that on the right ca. 6 hours later during low tide. This cycle took place ca. 24 hours prior to a new moon spring tide.

eastern and northern sources of early Paleozoic to Precambrian age.

3) Long-distance movement of gravel appears to have been directly related to hydraulic flux, perhaps related to decade-to-century-long climatic conditions, or to some undetermined longer-term climatic cycles that may have characterized the mid-Cretaceous in this portion of North America.
4) Tidal rhythmites and nonmarine and marine palynomorphs (acritarchs and dinoflagellates) occur in mudrocks that intertongue with conglomeratic sandstone bodies in the Ash Grove Cement Quarry in Cass County, Nebraska (see Fig. 1 for location), where marine–nonmarine correlations can be observed.
5) Estuarine conditions extended at least 200 km inland from the coeval Albian coastline, as indicated by the presence of mud-draped cross sets, and an ichnoassemblage that includes *Chondrites*, *Teichichnus*, *Arenicolites*, and *Cylindrichnus*.
6) Estuarine clays and silts were deposited synchronously with more proximal fluvial gravels as the Western Interior sea level rose, creating sediment accommodation space and raising base level, progressively stranding coarse-grained bedload in areas that were more proximal, resulting in regional fluvial aggradation.

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