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LATE ALBIAN KIOWA–SKULL CREEK MARINE TRANSGRESSION, LOWER DAKOTA FORMATION, EASTERN MARGIN OF WESTERN INTERIOR SEAWAY, U.S.A.

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ABSTRACT: **An integrated geochemical–sedimentological project is studying the paleoclimatic and paleogeographic characteristics of the mid-Cretaceous greenhouse world of western North America. A critical part of this project, required to establish a temporal framework, is a stratigraphic study of depositional relationships between the Albian–Cenomanian Dakota and the Upper Albian Kiowa formations of the eastern margin of the Western Interior Seaway (WIS). Palynostratigraphic and sedimentologic analyses provide criteria for the Dakota Formation to be divided into three sedimentary sequences bounded by unconformities (D_0, D_1, and D_2) that are recognized from western Iowa to westernmost Kansas. The lowest of these sequences, defined by unconformities D_0 and D_1, is entirely Upper Albian, and includes the largely nonmarine basal Dakota (lower part of the Nishnabotna Member) strata in western Iowa and eastern Nebraska and the marine Kiowa Formation to the southwest in Kansas. The gravel-rich fluvial deposits of the basal part of the Nishnabotna Member of the Dakota Formation correlate with transgressive marine shales of the Kiowa Formation. This is a critical relationship to establish because of the need to correlate between marine and nonmarine strata that contain both geochronologic and paleoclimatic proxy data.**

The basal gravel facies (up to 40 m thick in western Iowa) aggraded in incised valleys during the Late Albian Kiowa–Skull Creek marine transgression. In southeastern Nebraska, basal gravels intertongue with carbonaceous mudrocks that contain diverse assemblages of Late Albian palynomorphs, including marine dinoflagellates and acritarchs. This palynomorph assemblage is characterized by occurrences of palynomorph taxa not known to range above the Albian Kiowa–Skull Creek depositional cycle elsewhere in the Western Interior, and correlates to the lowest of four generalized palynostratographic units that are comparable to other palynological sequences elsewhere in North America.

Tidal rhythmites in mudrocks at the Ash Grove Cement Quarry in Louisville (Cass County), Nebraska record well-developed diurnal and semimonthly tidal cycles, and moderately well developed semiannual cycles. These tidal rhythmites are interpreted to have accumulated during rising sea level at the head of a paleoestuary that experienced at least occasional mesotidal conditions. This scenario places the gravel-bearing lower part of the Nishnabotna Member of the Dakota Formation in the mouth of an incised valley of an Upper Albian transgressive systems tract deposited along a tidally influenced coast. Furthermore, it provides a depositional setting consistent with the biostratigraphic correlation of the lower part of the Nishnabotna Member of the Dakota Formation to the marine Kiowa Formation of Kansas.

INTRODUCTION

Mid-Cretaceous strata along the eastern margin of the Western Interior Seaway (WIS) record paleoclimatic and paleoecologic conditions of a greenhouse world on the cratonic margin of a foreland basin (Fig. 1). Cratonic margins of these basins have the potential to provide data less complicated by tectonic events than orogenic margins. Our study is focused on Albian–Cenomanian strata of the Dakota Formation, and paleogeographic and paleoclimatic interpretations of this succession. In this paper, we show that the nonmarine Nishnabotna Member of the Dakota Formation correlates to parts of Kiowa–Skull Creek marine transgressive mudrocks, on the basis of results from sequence stratigraphic and biostratigraphic analyses.

Local and regional studies of the Dakota Formation indicate that large trunk river systems drained the North American craton west of the Appalachians and flowed from northeast to southwest across the region at this time, and emptied into the WIS (e.g., Bowe 1972; Brenner et al. 1981; Munter et al. 1983; Ludvigson and Bunker 1979; Ludvigson et al. 1994; Ravn and Witzke 1994, 1995; Whitley 1980; Witzke and Ludvigson 1987, 1994, 1996; Witzke et al. 1983). Numerous wells that penetrate Cretaceous strata in northwestern Iowa were used to demonstrate that river valleys were incised into pre-Cretaceous strata during a long erosional episode that preceded the Kiowa–Skull Creek marine transgression (Ludvigson and Bunker 1979; Witzke and Ludvigson 1987, 1994). The pre-Cretaceous erosional surface has up to 80 m (262 ft) of relief in northwestern Iowa (Fig. 2). We will show that the coarse-grained facies of the lower part of the Dakota Formation were deposited along a tidally influenced coastline of the WIS, where conglomeratic sandstone bodies aggraded as estuarine and fluvial incised-valley fill in response to base-level rise during the Kiowa marine transgression. In addition, this paper provides stratigraphic and depositional analogs for the cratonic margins of other foreland basins.

Methods

New data presented in this paper were generated from lithostratigraphic and biostratigraphic studies of: (1) outcrops in Guthrie County, Iowa; (2) quarry exposures and core samples from the lower Platte River Valley in Sarpy and Cass counties, Nebraska; (3) quarry exposures and core samples from the Yankee Hill properties in Lancaster County, Nebraska; (4) quarry, road-cut, and river-bank exposures in Jefferson County, Nebraska; and (5) core samples from Lincoln, Republic, and Stanton counties, Kansas (Fig. 3). Cores drilled from the Ash Grove Cement Quarry in Louisville, Cass County, Nebraska, provided well-preserved rhythmites of silt-rich and clay-rich lamina. Thicknesses of individual laminae and lamina sets were measured in the selected interval. These measurements were analyzed using the discrete Fourier transform (DFT) and compared with modern tidal data. Kanasewich (1981), Kvale et al. (1995), and Brenner et al. (in prep.) explain this method of numerical analysis and discuss its application to comparing rhythmic stratification in the rock record to modern-day tidal rhythmites.

Palynostratigraphic (fossil pollen and spore) samples were analyzed as part of an ongoing project to construct a nonmarine biostratigraphic frame-

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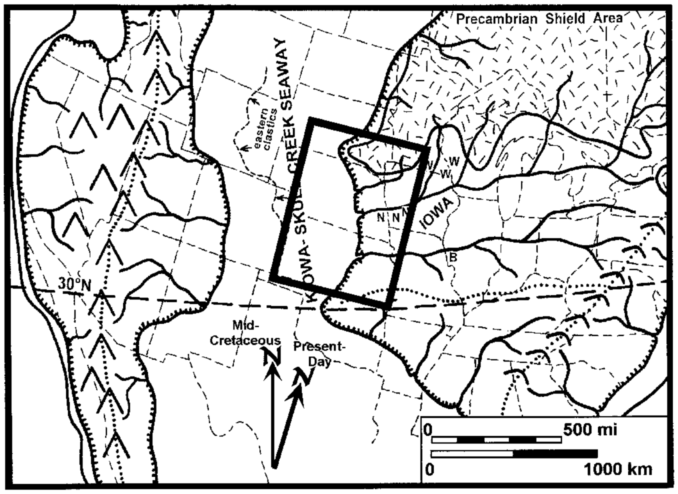

FIG. 1.—Mid-Cretaceous paleogeography of the Kiowa–Skull Creek Seaway in the Western Interior Seaway in the United States during latest Albian time with westernmost advance of east-derived siliciclastics shown by dashed line. The letters ''N'', ''W'', and ''B'' indicate general outcrop regions for the Nishnabotna Member of the Dakota Formation, the Windrow Formation, and the Baylis Formation, respectively. Rectangle encloses the study area shown in Figure 3. From Witzke and Ludvigson (1996).

work for the eastern margin of the WIS (e.g., Ravn and Witzke 1994, 1995; Ravn et al. 1996; Witzke et al. 1996). Samples were collected and analyzed from all surface sections and well cores that penetrate the Dakota Formation (see Figure 3 for all locations).

Definition of the Nishnabotna Member of the Dakota Formation

In all localities studied, the Dakota Formation fines upward. The lower, sandstone-dominated part of the formation is referred to as the Nishnabotna Member, and the mudrock-dominated upper part of the formation is referred to as the Woodbury Member (Fig. 4; White 1870a, 1870b). Although this twofold subdivision appears to be valid throughout the region, the boundary between members is less definite, inasmuch as sandstone richness varies considerably even within individual counties (Fig. 5).

LITHOFACIES

Lithologies encountered in this study are presented as seven descriptive lithofacies: (1) cobble–pebble conglomerates, (2) large-scale cross-bedded sandstone and conglomerate, (3) fine- to medium-grained sandstone and silty mudrocks, (4) mottled gray claystone, (5) lignites and carbonaceous mudrocks, (6) rhythmically laminated mudstone, and (7) red and gray vertically mottled mudstone (Table 1).

(1) Quartz-pebble conglomerates are generally subrounded to rounded monocrystalline and polycrystalline (chert) quartz pebble- to cobble-size clasts in a quartz-rich sandstone matrix (Fig. 6). They occur in the lower part of the Dakota Formation in Guthrie and Cass Counties, Iowa and at the Ash Grove, Cullom Mine, and Maystrick Pit sections in Cass and Sarpy counties, Nebraska (Figs. 3, 5).

(2) The most common lithologies in the Nishnabotna Member of the Dakota Formation are large-scale cross-bedded sandstone and conglomerate (Fig. 7). This lithofacies is exposed along the Raccoon River and its tributaries on the Garst Family Properties in Guthrie County, where up to 30 m of sandstone, conglomerate, mudstone, and siltstone overlies Pennsylvanian rocks (Witzke and Ludvigson 1996). It is also exposed in basal parts of the Dakota in the Ash Grove Cement Quarry and the Cullom Mine in Cass County, Nebraska and the Maystrick gravel pit in Sarpy County, Nebraska.

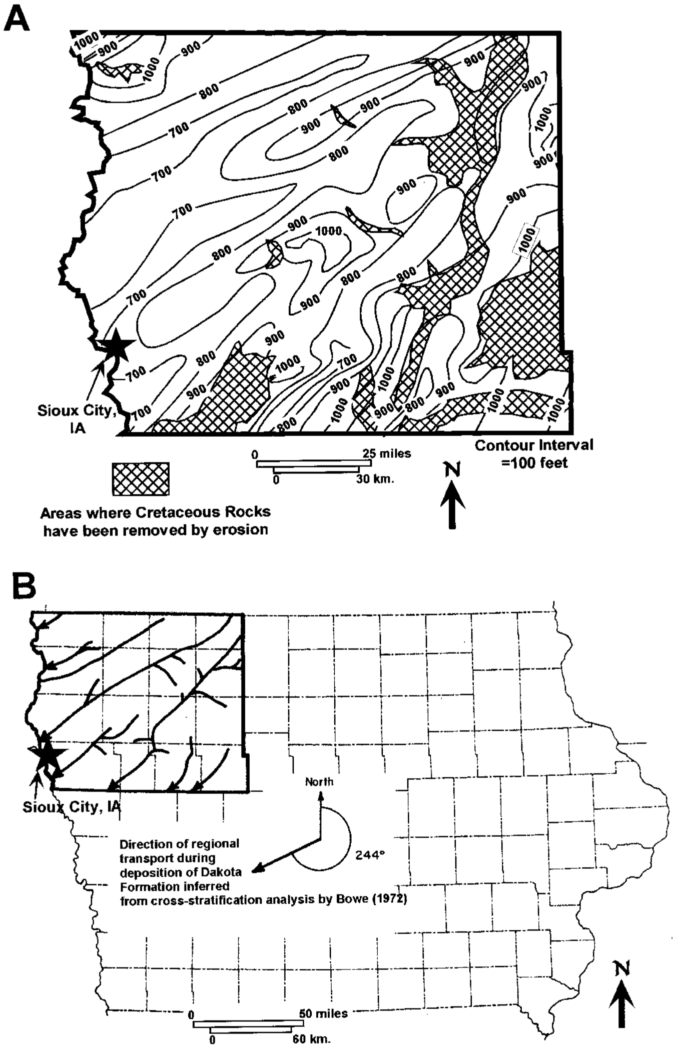

FIG. 2.—Maps showing incised nature of sub-Cretaceous unconformity and southwestward transport directions indicated by cross-bedded sandstones in the lower part of the Dakota Formation in northwestern Iowa. **A)** Contour map (feet above sea level) of the base of the Cretaceous in northwestern Iowa based on water-well data. Modified from Ludvigson and Bunker (1979). **B)** Inferred regional transport directions in the lower part of the Dakota Formation based on Part A and on cross-stratification analyses of Dakota outcrops. Modified from Ludvigson and Bunker (1979), based in part on data from Bowe (1972).

(3) At localities in Guthrie County, Iowa and in Cass, Sarpy, and Jefferson counties, Nebraska, fine- to medium-grained, cross-bedded sandstone bodies overlie siltstone and silty mudstones within the Nishnabotna. Sandstone units are characterized by trough cross-bed sets, generally less than 1 m thick, with pebble conglomerate limited to set bases (Fig. 8).

(4) Mottled gray claystone and silty claystone units occur in all sections and cores studied. They range in color from dark gray to medium light gray (N3–N6), and in most localities they contain highly diverse assemblages of palynomorphs. Pedogenic features such as root structures, microfaults, and iron oxide and carbonate nodules plus distorted silty ripple forms, carbonaceous plant fragments, and some distinct vertical burrows were observed in the Ash Grove cement quarry in Cass County, Nebraska (Brenner et al., in prep.).

(5) Minor amounts of lignite and carbonaceous shale are observed in the lower Dakota Formation at nearly all locations studied. At most localities,

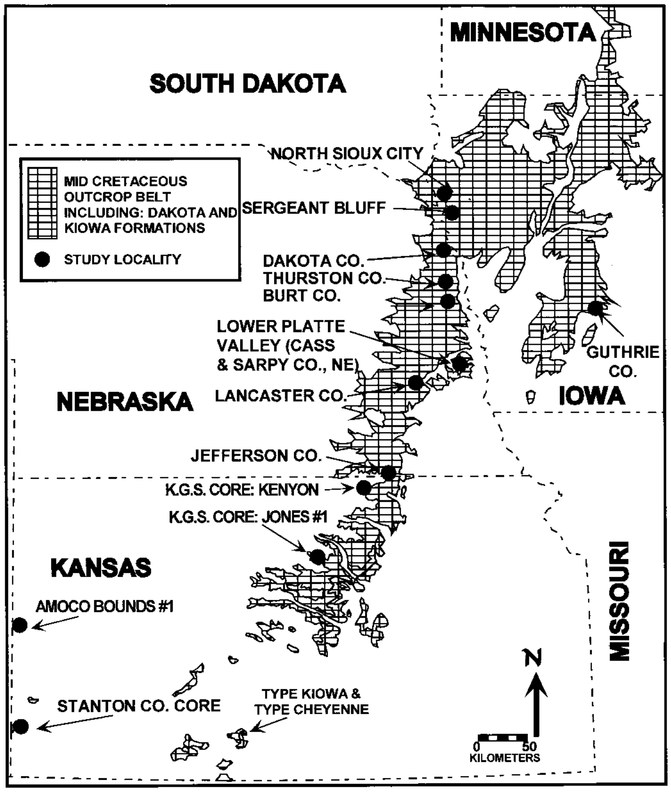

FIG. 3.—Map of study area showing location of outcrops and well cores studied in Iowa, Nebraska, and Kansas. Patterned area shows subcrop of Cretaceous strata in the study area. Modified from Witzke and Ludvigson (1996).

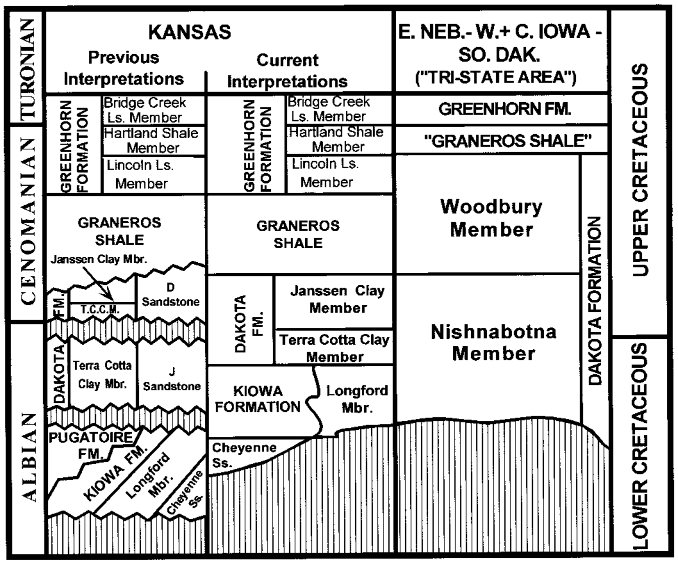

FIG. 4.—Stratigraphic nomenclature chart showing Albian and Cenomanian subdivisions of the Dakota Formation and associated stratigraphic units in the ''Tri-State Area'' of eastern Nebraska, west and central Iowa, and eastern South Dakota compared to correlative units in Kansas, along the eastern margin of the Western Interior Seaway. Temporal relationships between lithostratigraphic units reflect interpretations made in this paper. ''Previous Interpretations'' below the Graneros Shale represent work summarized by Hamilton (1994) and modified for westernmost Kansas by Scott et al. (1998), above the Graneros Shale from Dean and Arthur (1998).

gray mudstone units contain carbonized plant fragments that include angiosperm leaf cuticles and carbonized fern fragments.

(6) In the Ash Grove Cement Quarry in Cass County, Nebraska, prior to its removal during quarrying operations, a head-wall section was exposed that included a 5.5-m-thick mudrock interval containing rhythmically stratified laminae. Basal parts of this unit fill swales in the upper surface of an underlying lenticular sandstone unit. The results of sedimentological and numerical analyses of an 18 cm laminated interval from one of three cores cut by the Nebraska Conservation and Survey Division are reported by Brenner et al. (in prep.) and summarized in an interpretive section below (Fig. 9).

(7) The lower Dakota Formation penetrated by wells in Kansas (e.g., KGS Jones #1, well), and exposed in southeastern Nebraska (e.g., localities in Jefferson Co.), are characterized by intervals of red claystone (mostly 10R6/2) that are vertically mottled with medium light gray claystone (mostly 5Y5/1) and resemble plinthitic soils (Fig. 10).

PALEODEPOSITIONAL INTERPRETATIONS

Transportation and Aggradation of Conglomerates

Many studies dealing with the transportation and accumulation of gravel along orogenic margins of foreland basins correlate these deposits with tectonic events that both uplifted siliciclastic source areas and simultaneously increased basin subsidence rates, creating accommodation space for sediments to accumulate (e.g., Beer and Jordan 1989; Burbank et al. 1988; Flemings and Jordan 1989; Heller et al. 1989). Along the cratonic margins of foreland basins, such as the eastern margin of the WIS, tectonic activity played lesser roles in determining sedimentary dynamics.

Geographic Distribution.—Quartzose conglomeratic units are widely distributed around the margin of the eastern subcontinent of North America. The following mid-Cretaceous stratigraphic units contain quartz-rich gravel conglomerate: (1) Tuscaloosa Formation (Cenomanian) of the Gulf Coast and middle Mississippi Valley (Willman and Frye 1975); (2) Baylis Formation (?Cenomanian) of west-central Illinois (Frye et al. 1964); (3) Nishnabotna Member in the lower part of the Dakota Formation (upper Albian) of western Iowa, eastern Nebraska, and extreme southwestern Minnesota (Witzke and Ludvigson 1994); (4) Cheyenne Sandstone, Longford Member of Kiowa Formation, and Lower Terra Cotta Member of the Dakota Formation (upper Albian), central Kansas and southern Nebraska (Franks 1975, 1979); (5) lower Trinity Group and Antlers Formation (Albian) and Woodbine Formation (Cenomanian) of southern Oklahoma and Arkansas (Huffman et al. 1975; Hart and Davis 1981; Cifelli et al. 1997); (6) Windrow Formation and upper Dakota Formation (Cenomanian–Turonian?) of northeastern Iowa, southeastern Minnesota and southwestern Wisconsin (Andrews 1958; Sloan 1964); (7) Dakota, ''Lakota'', and ''Fall River'' sandstones (upper Albian) of eastern North and South Dakota (Shurr et al. 1987); (8) Coleraine Formation (Cenomanian) of northern Minnesota (Austin 1972); (9) unnamed unit (upper Albian) of western Ontario (Zippi and Bajc 1990); and (10) Mattagami Formation (upper Albian) of the James Bay lowlands, eastern Ontario (Try et al. 1984).

Paleogeographic Implications.—Three generalized fluvial catchments were hypothesized by Witzke and Ludvigson (1996) to account for these mid-Cretaceous conglomeratic deposits: (1) southern systems that drained the southern Appalachians and Ozark and Ouachita uplifts (stratigraphic units 1 and 5 listed in ''Geographic Distribution'' section above); (2) central westward-flowing systems that drained a vast region covering the Midwestern Paleozoic basins, the southern Precambrian Canadian Shield, and the central Appalachians (stratigraphic units 2, 3, 4, 6, and 7 in section above); and (3) northward-flowing systems that drained the northern Canadian Shield and the Moose River and Hudson Bay basins of eastern Canada (stratigraphic units 8, 9, and 10 in section above).

These expansive systems required the existence of high-capacity trunk

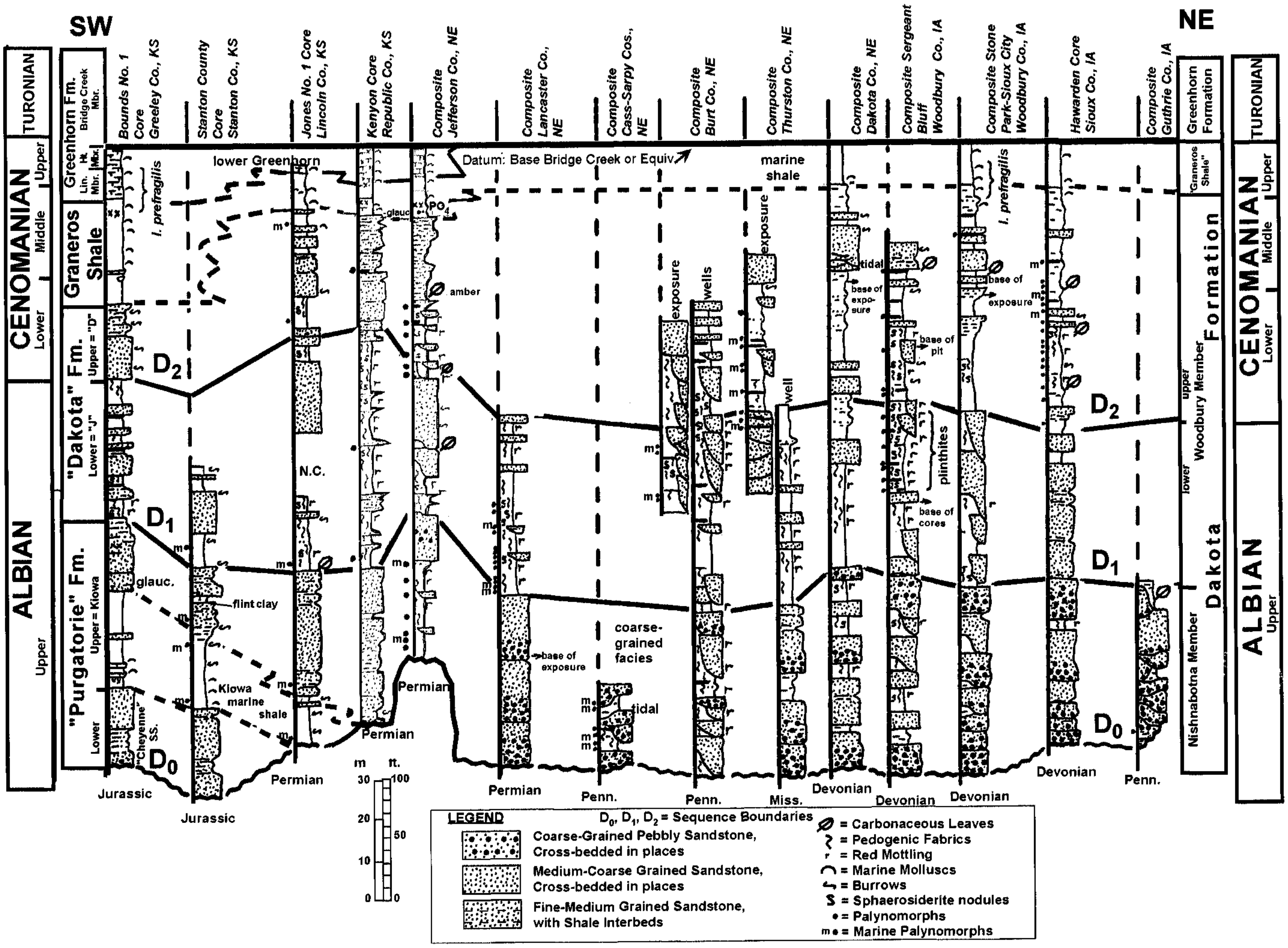

FIG. 5.—Regional cross section of the Dakota Formation and temporal equivalents within three unconformity-bounded sequences based on lithostratigraphy and biostratigraphy carried out in this study. Lithologies are based on measured sections, well cores, and composites of both as noted. Solid lines represent sequence boundaries (D_0, D_1, D_2); dashed lines represent major facies boundaries.

rivers capable of transporting sand- to pebble-size sediment hundreds of kilometers. The Kiowa Formation of central Kansas (Franks 1975; Feldman 1994) and the Baylis Formation of western Illinois require transport distances of 600 to 1000 km (Witzke and Ludvigson 1996). The Nishnabotna sediments require transport distances of at least 350 to 600 km to bring silicified Paleozoic fossils that occur in chert pebbles from their source areas to southwestern Iowa and southeastern Nebraska. Considering the evidence for widespread humid conditions (Ludvigson et al. 1992) and deep continental weathering across the eastern subcontinent (Pierce 1965; Sigleo and Reinhardt 1988), as well as the results of general circulation model experiments for the mid-Cretaceous ''greenhouse world'' (e.g., Barron et al. 1989), it is likely that an even greater discharge was carried off the eastern subcontinent by Mid-Cretaceous fluvial systems than comparable drainage systems of present-day eastern North America.

Paleohydrologic Considerations.—The transport and aggradation of coarse-grained fluvial sediments on the eastern margin of the WIS has important paleohydrological implications. The coarsest traction load can help constrain maximum (flood) flow velocities for a given stream system. The transport of pebbles and small cobbles, such as those in the Nishnabotna in Iowa and eastern Nebraska, required highly competent fluvial systems. However, the relative tectonic stability of the eastern North American Craton dictated that stream gradients were relatively low. We combined our sparse outcrop and well data with relations determined in modeling studies in order to characterize these fluvial systems.

In order to constrain the range of possible gradients, Witzke and Ludvigson (1996) calculated slopes in the range of 0.3 to 0.6 m/km, on the basis of a calculated sub-Cretaceous surface (Fig. 2) normalized to the regional Greenhorn (Turonian) datum. Because both eastern-sourced and western-sourced fluvial systems carried gravelly bedloads for distances of at least 600 km, and because the western gradients were probably greater than those of the east (Heller and Paola 1989), paleodischarge must have been greater in the eastern fluvial systems. Although the sedimentologic relationships between paleovelocities, paleodischarge, gradients, and particle sizes are complex and involve parameters such as channel widths and depths (Maizels 1983), it seems reasonable to suggest that the ability of low-gradient eastern rivers to entrain gravel clasts was primarily a function of paleodischarge.

Komar (1987) used flume experiments to show that sediment mixes that range from medium-grained sand to gravel require lower flow stresses to move the larger particles than required to entrain that size from a uniform bed load. Robinson and Slingerland (1998) investigated the question of whether a particular rate of downstream fining can be used to predict the characteristics of a particular ancient fluvial system. They used a sediment transport model to explore relationships between grain-size gradients and

TABLE 1.—*Lower Dakota Formation—Kiowa Formation lithofacies, western Iowa, Nebraska, and Kansas.*

Facies #	Lithofacies	Descriptions	Interpretations
1	Cobble-Pebble Conglomerates	Subrounded to rounded clasts of pegmatitic (monocrystaline) quartz (30% of clasts in Iowa to 67% in Kansas), and chert (mostly silicified fossiliferous carbonates containing Paleozoic invertebrates—70% in Iowa to 33% in Kansas) in a quartz-rich fine matrix. Clasts are graded in some beds.	Large clasts deposited during high-flow events; sands deposited as infills as currents waned in coarse-grained fluvial systems.
2	Large-Scale Cross-Bedded Sandstone and Conglomerate	Coarse-grained sandstone and conglomerate at the base to fine- to medium-grained sandstone with numerous carbonized plant fragments and logs up to 0.5 m thick. Gravel clasts, consisting mostly of chert and quartz, range up to 7 cm in diameter and form lenses up to 0.35 m thick within coarse-grained sandstone cross-bedded sets. Lenses of quartz and chert pebbles and shale-chip conglomerates are found within and between bodies.	Dune forms migrated down fluvial channel system.
3	Fine-Medium-Grained Sandstone and Silty Mudrocks	Fine- to medium-grained sandstone; trough cross-bedded with amplitudes of averaging about 15 cm, with abundant mudstone intraclasts ranging up to 1 cm in diameter. Quartz pebbles up to 5 mm in diameter are scattered throughout exposure areas.	Reworked fluvial sediments as dunes and waves in high-energy estuarine settings.
4	Mottled Gray Claystone	Clayey mudstone with some silty layers. Pedogenic features such as distorted silty ripple forms, carbonaceous plant fragments, rooting structures, micro-faulting, iron-oxide nodules and carbonate nodules and some vertical burrows occur within this interval.	Suspension deposition, periodic subaerial exposure in fluvial-valley-floodplain and tidal-flat settings.
5	Lignites and Carbonaceous Mudrocks	Medium to dark gray claystone (N5-N8), commonly with carbonized wood fragments and sphaerosiderite nodules. Some exposures have thin light gray siltstone lamina and blocky pedogenic fabrics.	Wetlands (bogs) periodic flooding in fluvial valley settings.
6	Rhythmically Laminated Mudstone	Rhythmically stratified laminae that vary in thickness from 0.2 to 1.0 mm. Numerical analyses of lamina thickness and spacing demonstrate that rhythmic strata at Ash Grove Quarry display diurnal, semimonthly and semiannual tidal cycles (Kvale et al. unpublished study).	Fluctuating energy conditions in subtidal mud-flat environment displaying diurnal, semimonthly, and semi-annual tidal cycles.
7	Red and Gray Vertically Mottled Mudstone	Red claystone (most 10R6/2) vertically mottled with medium light gray claystone (mostly 5Y5/1). Gray mudstone contains carbonized leaf cuticles and wood fragments, and spherosiderite nodules in places.	Pedogenesis of previously deposited mudrocks formed paleosols in interfluve settings.

FIG. 6.—Photograph of unsorted pebble conglomerate exposed in the county gravel pit in Guthrie County, Iowa. Scale is in centimeters.

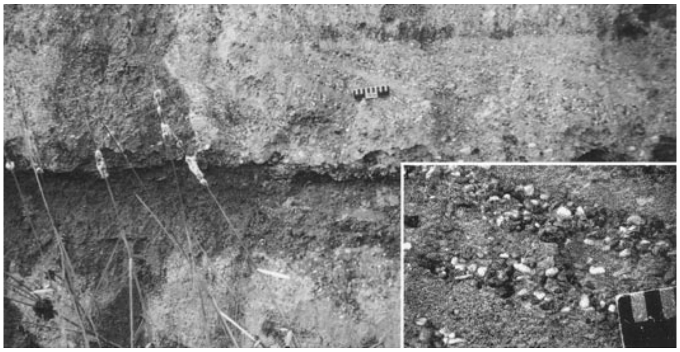

FIG. 7.—Cross-bedded pebble conglomerate and coarse-grained sandstone from Maystrick Pit, Sarpy Co., Nebraska. Inset shows close-up of cross-stratification. Scale is in centimeters.

a river's aggradation rate, hydraulic geometry, sediment and water feed rates, and grain-size distribution in transport. Earlier studies by Ashworth and Ferguson (1989), Parker (1990), and Bridge and Bennett (1992) established values of hiding constant (*m*) for a variety of modern rivers. Empirical data from modern streams show that the fluid shear stress ($\boldsymbol{\tau}_{cij}$) at the bed necessary to mobilize the *i*th size fraction can be expressed as a ratio of the size of the individual grain (D_i) to the median grain size in the bed (D_{50}):

$$\boldsymbol{\tau} = \Theta_{c50}\,(\boldsymbol{\sigma}_j - \boldsymbol{\rho})g\,D_i\,(D_{ij}/D_{50})^{-m}$$

where Θ_{c50} is the empirically based critical Shields parameter for median size, ($\boldsymbol{\sigma}_j - \boldsymbol{\rho}$) is the immersed density, *g* is gravitational acceleration, and *m* is a hiding constant that accounts for small grains that ''hide'' in a poorly sorted sediment mix containing much larger clasts. Different values of *m* determine both sediment accumulation rates and downstream fining trends (Robinson and Slingerland 1998).

Using a variety of combinations of values and parameters, Robinson and Slingerland (1998) concluded that varying sediment feed and subsidence rates exert the strongest influence on downstream fining trends, and that the varying of water discharge is balanced by increases in channel width. These studies suggest that high-flow conditions, even if they are infrequent in human time terms, could move gravel-size materials hundreds of kilometers down low-gradient slopes given geologic intervals of time. In addition, observations and stratigraphic modeling by Angevine et al. (1990)

FIG. 8.—Fine- to medium-grained cross-bedded sandstone in the lower part of the Dakota Formation exposed in the Rose Creek section (Jefferson County, Nebraska, composite in Figure 5). Note pebble-size clasts along reactivation surface (to left of scale).

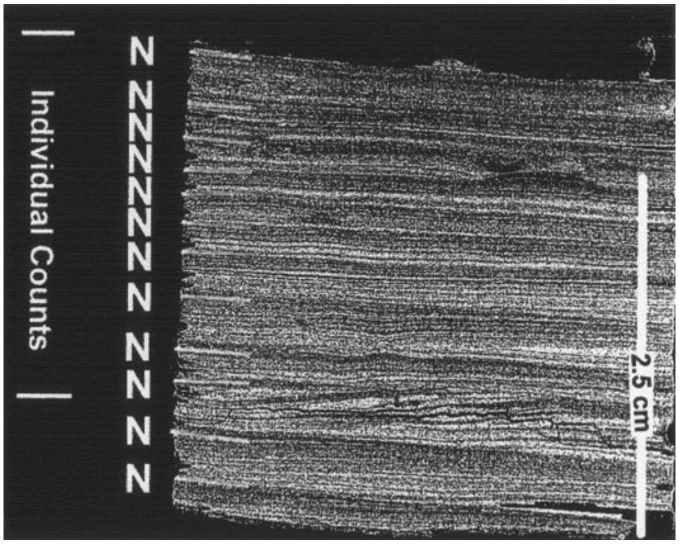

FIG. 9.—Computer-scanned image of slabbed core sample AH95–2, sec. C from well core taken at Ash Grove Quarry. The rhythmic thickening and thinning of the laminae suggests deposition under tidal influence. Individual laminae thicknesses were measured in the area marked ''individual counts.'' The distances between neap events, indicated by ''N,'' were also measured. See Brenner et al. (in prep.) for complete discussion.

show that discharge alone cannot account for large gravel accumulations, and that such deposits are flux-driven, implying that gravels were transported down fluvial systems in pulses related to high-flow (flood) events. Because the conglomerates in this study were derived from anorogenic sources, flux may have been related to wet-season (monsoon) versus dry-season flow regimes, similar to those experienced in the tropics and subtropics today. Although pebbles and clasts were undoubtedly transported during ''high-energy'' pulses, there is no petrographic evidence that they are polycyclic. Additionally, there are no preserved pre-Cretaceous strata containing similar clasts that could have served as intermediate storage receptacles west of the Appalachian Mountains.

Humid climatic conditions coupled with large catchment areas resulted in a significant contribution of fresh water to the WIS by east-derived rivers. Numerical climate simulations for the Turonian of North America (Slingerland et al. 1996) support the idea that the eastern landmass supplied greater freshwater volume to the WIS than did the western landmass. As sea level rose during marine transgression, regional stream gradients would have decreased, resulting in loss of competency of distal stream systems, progressively stranding the coarse-grained bedload in more proximal areas and stratigraphically recording regional fluvial aggradation.

Fluvial Sedimentation in Braided Systems

The Nishnabotna Member in western Iowa shows features that are characteristic of sand-fill channels in braided fluvial systems. These include: (1) lithologies dominated by medium- to coarse-grained sandstone and conglomerate; (2) relatively poor grain sorting; (3) mudstones occurring as only thin beds and drapes; (4) horizontal and planar cross bedding dominates in coarse-grained bodies; (5) trough cross beds dominate in finer-grained sandstone bodies; (6) polymodal apparent paleocurrent directions that commonly differ from actual trough-axis orientations (summarized by Witzke and Ludvigson 1994 from Ore 1964; Cant 1978; Rust 1978; Miall 1978).

Paleocurrent directions recorded as trough axes of three-dimensionally exposed cross-bedded sets, and steeply dipping cross-beds of less well-exposed sets, show dominantly northeastward and southwestward modes in Guthrie County, Iowa (Witzke and Ludvigson 1982). In addition, Bowe (1972) produced many rose diagrams for both the ''lower'' and ''upper'' Dakota in eastern Nebraska with similar polymodal characteristics, but with northeastward and southwestward modes dominant in the lower Dakota Formation (Fig. 2B). The low density of outcrops relative to the area covered precludes using all the cross-bedding data that we have as statistically valid paleocurrent indicators. In some places, such as in Nishnabotna outcrops in Guthrie County, Iowa, the most visible cross-sets show transport direction at right angles to fluvial flow directions as indicated by trough axes and regional incision patterns. These characteristics are compatible with published descriptions of multiple current flow directions in sand-rich, braided fluvial systems (e.g., Ore 1964; Cant 1978; Miall 1978; Rust 1978). Therefore, fluvial systems that drained the eastern craton during the mid-Cretaceous were probably large-scale high-discharge systems that had highly variable flow rates. Nishnabotna deposition in Iowa and Nebraska was probably associated with a major trunk river system that extended 1500 km eastward, draining parts of the southern Canadian Shield and probably the central Appalachians (Fig. 1).

FIG. 10.—Dominantly red claystone (mostly 10R6/2, dark gray in photograph), vertically mottled with medium light gray claystone (mostly 5Y5/1) at Camp Jefferson section (Jefferson County, Nebraska, composite in Figure 5).

Tidal Cycles

At the Ash Grove Cement Quarry in Cass County, Nebraska, a 20 m section of the lower Dakota Formation displays characteristics of tidally influenced sedimentation. Petrographic and numerical analyses of a rhythmically laminated mudstone unit (Facies 6 on Table 1) demonstrate that it records tidal cycles (Brenner et al., in prep.). Combined with palynomorphic data (discussed below), we interpret that this section records the Late Albian filling of estuarine bays as sediments that were deposited by fluvial and tidal processes filled lower parts of incised fluvial valleys.

Lamina thicknesses in tidal rhythmites are proportional to both tidal heights and tidal-current flow velocities (Dalrymple and Makina 1989; Kvale et al. 1995; Archer 1996). Therefore, rhythmic variations in thicknesses of tidal laminae reflect lunar and solar cycles that affect tidal heights. Analyses carried out by Brenner et al. (in prep.) suggest that three orders of cycles are preserved in the Ash Grove rhythmites: (1) individual laminae (daily cycle); (2) thickening and thinning of the individual laminae (neap–spring cycle); and (3) rhythmic change in the neap–spring cycle thicknesses (semiannual cycle).

Incised-Valley-Fill Model: Estuarine Settings

Distribution of lithofacies in time and space may provide the strongest line of evidence needed to demonstrate that the Kiowa Formation and the

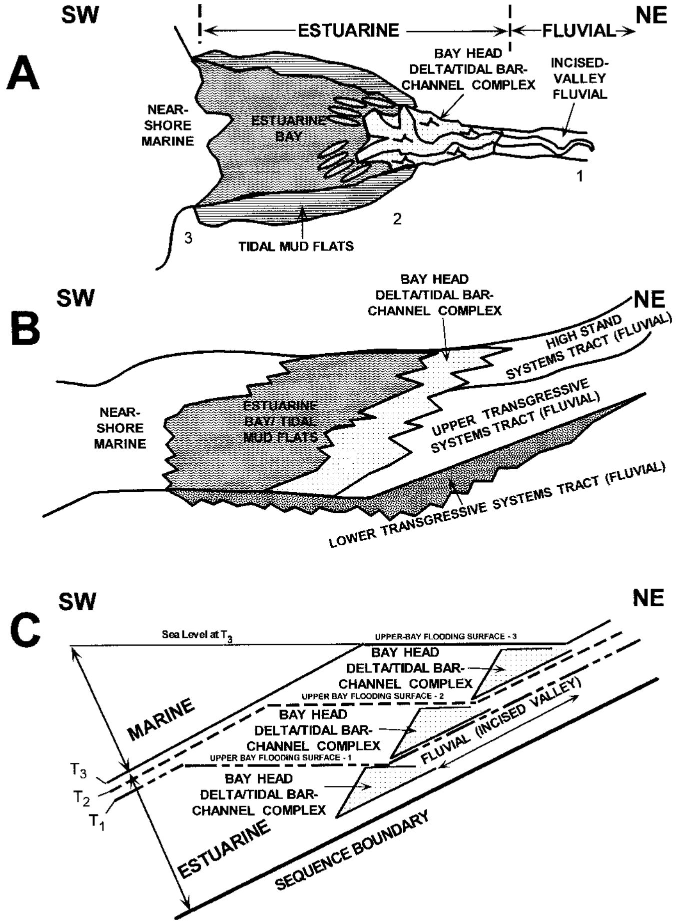

FIG. 11.—Model of estuarine backfilling of incised valley during marine transgression. No scales are implied, and directions are approximate. **A)** Generalized distribution of depositional environments, with numbers 1–3 representing the approximate locations of: 1 = Guthrie County, Iowa; 2 = Ash Grove Cement Quarry, Louisville, Cass County, Nebraska; and 3 = Jones #1 Core, Lincoln Co., Kansas (see Figure 3 for locations). **B)** Generalized longitudinal depositional systems section of lower Dakota Formation strata from western Iowa to central Kansas. **C)** Incised-valley-fill model showing retrogradation of bay-head deltas during marine transgression. T_1, T_2, and T_3 represent upper-bay flooding surfaces during three hypothetical marine transgressions. Modified from Thomas and Anderson (1994).

Nishnabotna Member of the Dakota Formation are coeval within marine transgressive systems tracts. It is well established that the Nishnabotna Member of the Dakota Formation in northwestern Iowa fills incised valleys (e.g., Ludvigson and Bunker 1979; Witzke and Ludvigson 1994) with up to 80 m in relief (Fig. 2A). For this reason, we compared our lithostratigraphic and biostratigraphic reconstructions presented above to a modified incised-valley-fill model in an estuarine setting (Fig. 11). This model is modified from Dalrymple et al. (1992), Nichol et al. (1994), Thomas and Anderson (1994), and Zaitlin et al. (1994).

In wave-dominated estuaries, bay-head deltas form where sand and gravel accumulate (Dalrymple et al. 1992). These deltas may have morphologies that vary depending on degree of system confinement, and the resulting relative energies of fluvial, wave-generated, and tidally generated currents (Dalrymple et al. 1992). Dalrymple et al. (1992) report that tidal bar–channel complexes in tide-dominated estuaries replace bay-head deltas as a result of net sediment transport being ''headward'' (~landward) during storm-reinforced and spring tidal current events. Because tidal features are well preserved in the lower Dakota, wave action was of relatively minor significance in this part of the WIS during the filling of Late Albian estuarine bays.

The lithofacies at the Ash Grove Cement Quarry in Cass County, Nebraska, along with fluvial deposits observed to the east (e.g., Guthrie County, Iowa), represent the Late Albian Kiowa–Skull Creek sediment package that filled incised valleys (Fig. 11A). Conceptually, the fluvial deposits of the Nishnabotna Member of the Dakota Formation can be divided into transgressive and highstand systems tracts, reflecting an overall rising sea level (Fig. 11B). Sedimentary structures and features observed in the lower Platte Valley in Cass and Sarpy counties, Nebraska, indicate that sand deposition was rapid and took place in pulses. At Ash Grove, features in sandstone bodies, such as intraclasts of clay shale, siltstone, and sandstone, indicate episodic high-energy deposition. Likewise, in the Maystrick Pit, graded gravel to coarse-grained sandstone beds in cross-bedded sets indicate that deposition took place in pulses. These characteristics suggest that sands were deposited during high-energy events, such as storms and floods, perhaps reinforced by spring tidal flows. Prominent but discontinuous reactivation surfaces within these sandstones suggest that each body represents an amalgamation of sand deposited during multiple high-energy events during a relatively short period of time. Low-energy mud deposition dominated between these high-energy intervals, and probably represents estuarine bay and marginal mudflat deposits that were out of reach of any synchronous sand-deposition events that may have taken place.

In a time-stratigraphic realm (T_1 to T_3 in Figure 11C), a potential hybrid bay-head delta and tidal bar–channel complex, estuarine bay deposits, and rhythmic mudflat deposits are retrogradational within the incised valley deposited during marine transgression, allowing estuarine sediments to be preserved up-gradient from the original shoreline. Each conceptual time line in Figure 11C could represent an upper-bay flooding surface that would allow delineation of ''parasequences'' within the valley-fill sequence. Ongoing stratigraphic studies indicate that each flooding surface may represent a time interval of low sedimentation rates and sediment compaction between episodes of high-energy, sand-depositing events. Mud-draped cross-bedded sandstone bodies, laminated mudstone intervals, and vertical burrows exposed on a cut-bank exposure of lower Nishnabotna Member strata along a tributary of the Middle Raccoon River in Guthrie County, Iowa, indicate that estuarine conditions may have existed several hundred kilometers inland from the interpreted Late Albian coast. These observations support the concept that estuarine conditions stepped up the incised valleys as regional transgression continued through the Albian, and may provide a tool to help evaluate sequence stratigraphy in nonmarine parts of similar anorogenic foreland-basin margins elsewhere.

STRATIGRAPHIC INTERPRETATIONS: THE KIOWA–DAKOTA INTERVAL

Previous Regional Correlations

The regional correlation of Cretaceous marine strata in the WIS using molluscan biostratigraphy is well established (Kauffman et al. 1993). Hamilton (1994) divided Albian–Cenomanian Cretaceous strata in Kansas into three unconformity-bounded sequences based on lithofacies relationships (''Previous Interpretations'' in Figure 4). His lowest sequence consists of the Albian Cheyenne Sandstone and overlying Longford Member and the laterally equivalent marine Kiowa Formation (Hamilton 1994). In southern Kansas, the time-transgressive Cheyenne Sandstone has been interpreted as representing a meandering river system that crossed a coastal plain and graded laterally into the marine part of the Kiowa Formation in central Kansas (Franks 1979; Hamilton 1994). These deposits have been interpreted to be bounded above by a regional unconformity that separates them from the overlying massive gray to red-mottled mudrocks and sandstones included in the Terra Cotta Clay Member and the overlying lignitic mudrocks of the Janssen Clay Member of the Dakota Formation (Franks 1975, 1979; Siemers 1971). This lacuna was reported to span the Albian–Cenomanian biostratigraphic boundary, and has been traced throughout most of

TABLE 2.—*Summary of palynostratigraphic zones recognized in the mid Cretaceous along the eastern margin of the Western Interior Basin. Modified from Ravn and Witzke (1995).*

Unit	Key Taxa	Stratigraphic Position	Lithostrati-graphic Occurrence	Interpretations
1.	*Cedripites canadensis, Vitreisporites pallidus, Podocarpidites multiesimus, Impardecispora apiverrucata, Triporoletes radiatus*	Not above Albian Kiowa-Skull Creek depositional cycle	Lower Nishnabotna strata	Marine palynomorphs (dinoflagellates, acritarchs) indicate marine influences in distal areas of the Nishnabotna fluvial facies
2.	Highest occurrence of: *Cedripites canadensis, Vitreisporites pallidus, Podocarpidites multiesimus, Impardecispora apiverrucata, Triporoletes radiatus*	Highest occurrences of typical Albian palynomorphs; basal Greenhorn Cycle	Upper Nishnabotna strata	Lack of marine palynomorphs indicate nonmarine conditions
3.	Make their appearance at or near the base of the unit: *Balmeisporites glenelgensis, Foveosporites cenomanianus, Petalosporites quadrangulus, Triporoletes pluricellulus*	Characteristic Cenomanian taxa.	Lower Woodbury Member	Lack of marine palynomorphs indicates nonmarine conditions.
4.	First appearance in this unit: *Cicatricosisporites crassiterminatus, Dictyophyllidites impensus, Foveogleicheniidites confossus, Lycopodiacidites arcuatus, M. hallii, C. crassiterminatus.* Upward loss of Albian Taxa: *Nicholsipollis mimas, Cycadopites fragilis, Cicatricosisporites mediostriatus, Impardecispora trioreticulosa, Cingutriletes congruens*	Transgression of adjacent Greenhorn seaway	Upper portion of Woodbury Member and above	Upward increase in angiosperm diversity

the WIS (Weimer 1984; Ravn and Witzke 1994, 1995; Scott et al. 1998). The Janssen Clay Member, which comprises the upper part of the Dakota, was interpreted to represent a transitional environmental setting where a series of landward-stepping, shallowing-upward parasequences record eastward expansion of the transgressive Graneros sea (Hamilton 1994).

Scott et al. (1998) found that gray clayrocks in the Dakota Formation in the Amoco No. 1 Rebecca K. Bounds core in Greeley County, Kansas, rest unconformably on fine-grained sandstone of the Purgatoire Formation, the equivalent to the Kiowa Formation in central Kansas (Fig. 5). These clayrocks contain zones of sphaerosiderite that they interpreted to have formed in a paleosol that developed on a regional unconformity that crosses the WIS. Samples from the lower part of the Dakota Formation in the Bounds core contain marine dinoflagellates whose diversity and abundance decrease up the section, suggesting a decrease in marine affinity upward (Scott et al. 1998). Graphic correlation techniques used by Scott et al. (1998) indicate that the unconformity at the base of the Dakota in the Bounds well is at 98.2 Ma and that the top of the Purgatoire/Kiowa is at 99.4 Ma, clearly within the Albian.

New Stratigraphic Data

Samples of the lower Dakota Formation collected in Nebraska from the Yankee Hill clay pits of Lancaster County and exposures in Jefferson County are from strata generally assigned to the Terra Cotta Clay Member of the Dakota Formation (see Figure 5). These strata are mudrock-dominated facies interpreted to be distal equivalents of the coarse-grained channel fills of the lower to upper Nishnabotna Member of the Dakota Formation; coarse-grained units persist into this region, but sandstone bodies are subordinate. Samples of the lower Dakota Formation from the Garst Family property sections in Guthrie County, Iowa, yielded a paleoflora similar to that seen in Nishnabotna strata of the lower Platte Valley, Nebraska. There are five species that have been reported in both the Bounds core and in the basal Dakota Formation at Ash Grove. Each of these species spans the Purgatoire–Dakota contact in the Bounds core. They are *Foraminisporis asymmetricus, Neoraistrick robusta, Rugubivesiculites rugosus, Scopusporis lautus,* and *Taurocuspoites sementatus.*

In preliminary studies (Ravn and Witzke 1995) and in this study, 167 genera and 321 species of Cretaceous palynotaxa were identified in Dakota Formation samples from western Iowa and eastern Nebraska. The Dakota Formation of western Iowa and eastern Nebraska has been subdivided into 16 sample intervals for compilation of palynostratigraphic data, which have, in turn, provided a basis for recognizing four general palynostratigraphic units in the region (Table 2).

A series of generalized palynostratigraphic units, when supplemented with first-appearance datum or last-appearance datum of key taxa, permit a higher level of biostratigraphic resolution and regional stratigraphic correlation in the nonmarine Dakota sequence than previously possible (Witzke et al. 1996). The palynomorph assemblages are comparable to other well-known palynological sequences elsewhere in the North American Western Interior and Gulf Coast. Preliminary subdivisions recognize four general units containing distinctive and biostratigraphically significant palynomorph assemblages (Table 2, and Witzke et al. 1996). The lowest palynostratigraphic unit (Palynostratigraphic Unit 1 in Table 2), is recognized in lower Nishnabotna strata and lower Terra Cotta Clay Member units in the region. It is characterized by occurrences of palynomorph taxa not known to range above the Albian Kiowa–Skull Creek depositional cycle elsewhere in the Western Interior (e.g., *Impardecispora marylandensis* and *Nicholsipollis mimas*). Occurrences of marine palynomorphs (e.g., dinoflagellate cyst, *Impletosphaeridium* sp., and an acritarch, *Veryhachium* sp.) indicate marine influences on distal areas of the Nishnabotna fluvial facies. Palynomorphs from Palynostratigraphic unit # 1 (Table 2) were collected from: (1) the Ash Grove and Maystrick quarries in Cass County, Nebraska; (2) Jefferson County, Nebraska; (3) Guthrie County, Iowa; (4) the lower Dakota Terra Cotta Clay Member in the Jones #1 core in Lincoln County, Kansas; and (5) the Kiowa Formation in the Stanton County core, western Kansas (see Figure 3 for locations).

Correlation of Lithostratigraphic Units

The Nishnabotna Member of the Dakota Formation unconformably overlies Precambrian to Permian rocks, with up to 80 m of relief, along the eastern margin of the WIS (surface D_0 in Figure 5). The pebbly-sandstone-bearing basal part of the Nishnabotna in Guthrie County, Iowa, is replaced by a nearly equal mixture of sandstone and mudstone to the west in Cass County, Nebraska. Farther westward and southwestward the interval is dominantly mudstone with lesser amounts of coarse-grained, pebbly sandstones (Fig. 5).

Well-developed paleosols including red and gray mottled units that contain sphaerosiderite nodules are common in southeastern Nebraska (Witzke et al. 1996; Ludvigson et al. 1995; Joeckel 1987, 1992). This mudrock-dominated interval has generally been assigned to the lower Terra Cotta Clay Member in Nebraska. Lithologically similar strata in Kansas have been included in both the Longford Member of the Kiowa Formation and the lower part of the Terra Cotta Clay Member of the Dakota Formation. Study of the Jones #1, Kenyon, and Stanton County cores in Kansas show that Kiowa marine shales are overlain by paralic facies of the Dakota Formation.

Combining our new stratigraphic data with previously published data, three sedimentary sequences can be defined by unconformities denoted as D_0, D_1, and D_2 in this paper (Fig. 5). The lowest unconformity, D_0, represents a regional lacuna that separates Paleozoic rocks from the overlying Cretaceous. The D_1 unconformity is traced through the upper part of the Nishnabotna Member in Iowa and eastern Nebraska southwestward into western Kansas using biostratigraphically constrained erosional surfaces and paleosols. Similarly, the D_2 unconformity is traced across the eastern margin of the WIS from the Woodbury Member of the Dakota Formation in western Iowa to the Bounds core in western Kansas.

Our stratigraphic analysis confirms earlier interpretations (e.g., Hamilton 1994; Scott et al. 1998) that the Albian–Cenomanian boundary lies above the top of the Kiowa Formation in Kansas. The regional unconformity that previous studies place at this boundary has not been identified at this stratigraphic position in our lithostratigraphic and palynostratigraphic analyses. In addition, the Longford Member of the Kiowa Formation as discussed by Hamilton (1994) appears to be equivalent to the marine units of the Kiowa Formation and possibly the lower part of the Terra Cotta Clay Member of the Dakota Formation. Our palynostratigraphic analysis shows that these strata in southeastern Nebraska and central Kansas correlate to the lower part of the Nishnabotna Member of the Dakota Formation in easternmost Nebraska and western Iowa (as indicated in Figure 5).

Discussion of Sedimentologic and Stratigraphic Relations

Sedimentation in the mid-Cretaceous Nishnabotna fluvial system was strongly influenced by varying sediment feed rates, a relatively constant (cratonic) subsidence rate, and high water discharge that was balanced by increased channel widths. Humid conditions provided high discharge, especially during monsoonal floods. These conditions allowed pebble-size particles to be transported hundreds of kilometers from their sources to the eastern margin of the WIS.

In the Nishnabotna Member of the Dakota Formation, sharp erosional breaks are common in fluvial and estuarine units, and are restricted to deposits associated with incised valleys. Erosional surfaces in interfluve areas are marked by paleosols, some of which show signs of multiple pedogenic episodes. Careful tracing of units between areas of exposures indicate that there are three visible breaks (D_0, D_1, and D_2) that could be interpreted as regional unconformities that extend across the eastern margin of the WIS from western Iowa to western Kansas. We have not been able to trace the extensive unconformities that were previously thought to define the Cheyenne–Kiowa Sequence (Hamilton 1994) into the Nishnabotna Member of the Dakota Formation. There is a multitude of disconformable horizons within the coarse-grained lithofacies of the Nishnabotna. Our palynologic and lithologic studies combined were used to define the two unconformities within the Dakota Formation. The lower Dakota (Upper Albian) sequence bounded by unconformities D_0 and D_1 (Fig. 5) show that the Kiowa marine shales are temporally equivalent to the Nishnabotna Member of the Dakota Formation. Superposition of Kiowa lithologies over Cheyenne Sandstone in the Bounds and Stanton County wells show that the Kiowa is younger than the Cheyenne Sandstone. This puts the geographic extent of Frank's (1975) Longford Member of the Kiowa–Dakota Formation in question. The Longford is a marginal paralic facies of the Kiowa that Scott et al. (1998) suggest should not be used beyond its geographically restricted exposure along the Kiowa outcrop belt in central Kansas. Our observations in the Jones #1 core suggest that the Longford may represent a transitional facies between the marine Kiowa and lower Terra Cotta Clay Member mudrocks to the west and the fluvial–estuarine sandstones of the lower part of the Nishnabotna Member of the Dakota Formation to the east, rather than a transitional unit between the Cheyenne Sandstone and Kiowa Formation as was suggested by Hamilton (1994).

The occurrences of Upper Albian mudrock units containing both tidal rhythmites and marine palynomorphs (dinoflagellates and acritarchs) intertonguing with distal parts of the Nishnabotna Member of the Dakota Formation in easternmost Nebraska dictate the existence of coeval marine sedimentation farther to the west. Supporting evidence for this conclusion is the increase in mudrocks to the west, the additional occurrences of marine palynomorphs in Jefferson County, Nebraska, and the relegation of sandstone to only a minor component southwestward into Kansas. The palynostratigraphic discussion above suggests that the lower part of the Nishnabotna and correlative strata in the lower part of the Terra Cotta Clay Member of the Dakota Formation contain palynomorph assemblages that are not known to range above the Kiowa–Skull Creek depositional cycle elsewhere in the WIS. These lines of evidence all indicate that marine mud was being deposited seaward of the Nishnabotna sandstone facies at the time that previously incised channels were being filled with pebbly sandstones.

CONCLUSIONS

We have shown that the nonmarine Nishnabotna Member of the Dakota Formation in western Iowa and northeastern Nebraska correlates to parts of Kiowa–Skull Creek Formation marine transgressive mudrocks in Kansas. This forges an important chronostratigraphic link between the nonmarine Upper Albian strata of the eastern margin of the WIS and the previously well studied marine parts of the basin. Our lines of evidence include new lithostratigraphic and sedimentologic data, as well as new biostratigraphic data from Late Albian paleodepositional systems along the eastern margin of the basin.

Nishnabotna incised-valley fills contain identifiable chertified fossils that range from Ordovician to Pennsylvanian in age, indicating that parts of the sediment load must have traveled from at least as far away as present-day northeastern Iowa and western Wisconsin. Rock fragments in Dakota sandstones appear to have been derived from Canadian Shield sources, indicating even greater transport distances. These observations dictate that episodes of high discharges characterized mid-Cretaceous fluvial systems that must have operated under widespread humid conditions during times of deep continental weathering.

The pinchout of a thick, pebbly conglomeratic sandstone body beneath tidal rhythmites at Ash Grove indicates that southwestward-flowing rivers terminated in estuarine environments in at least this part of the WIS during the Late Albian. Estuarine geometry could have amplified the tidal wave so that the tidal ranges in the estuary were great enough to produce tidal rhythmites (Brenner et al. 1996).

Assemblages with Albian affinities found in the Kansas well cores include abundant dinoflagellate cysts as well as similarities with samples associated with the Nishnabotna exposures and cores in eastern Nebraska and western Iowa. This, along with the physical interfingering of lithologies observed in the Ash Grove Cement Quarry, demonstrates that the Nishnabotna and lower Kiowa strata are Albian in age and are coeval. Our study shows that the Cheyenne Sandstone is stratigraphically below Kiowa marine shales that are temporally equivalent to the lower Terra Cotta and Nishnabotna members of the Dakota Formation (Fig. 5). The Nishnabotna Member in the lower part of the Dakota Formation and the marine mudrocks of the Upper Albian Kiowa Formation contain palynomorphs that are not known to range above the Albian Kiowa–Skull Creek depositional cycle elsewhere in the North American Western Interior.

The conglomerates and sandstones of the Nishnabotna Member of the Dakota Formation and correlative Kiowa Formation mudrocks accumulated in accommodation space that was created as incised valleys were flooded by rising sea level. This scenario places the gravel-bearing lower parts of the Nishnabotna Member of the Dakota Formation in the transgressive systems tract within an Upper Albian sequence (bounded by surfaces D_0 and D_1 in Figure 5). Previous stratigraphic interpretations that place an interregional unconformity at the top of the Albian would dictate that sea level was falling and accommodation space decreasing during the Late Albian. However, an unconformity at that stratigraphic position cannot be traced into the nonmarine settings within the Iowa–Nebraska region. In addition, recent studies of the Dakota Formation along the eastern margin of the WIS show a general filling of incised fluvial valleys during the Late Albian and Early Cenomanian (e.g., Ludvigson et al. 1992; Munter et al. 1983; Witzke and Ludvigson 1994, 1996). During this marine transgression, base level was such as to allow sediments to accumulate up-gradient from the original shoreline.

The integration of biostratigraphy, sedimentary petrography, and sedimentology can be used to delineate sedimentary sequences that encompass nonmarine and marine strata, and help establish marine–nonmarine stratigraphic frameworks along cratonic margins of other foreland basins.

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