MID-CRETACEOUS FLUVIAL DEPOSITS OF THE EASTERN MARGIN, WESTERN INTERIOR BASIN: NISHNABOTNA MEMBER, DAKOTA FORMATION

A field guide to the Cretaceous of Guthrie County

Geological Survey Bureau
Guidebook Series No. 17

Iowa Department of Natural Resources
Larry J. Wilson, Director
May 1996

Cover: Conglomeratic sandstone strata of the lower Nishnabotna Member, County Pit, Guthrie County, Iowa. Geologist Richard Heathcote for scale. See Stop 1 for further discussion (units 1 and 2). Photograph by Brian Witzke.

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Field Trip No. 1

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INTRODUCTION

by Greg A. Ludvigson and Brian J. Witzke

Historical Background

Cretaceous exposures visited during this field trip are located within the historic region that encompasses western Iowa and eastern Nebraska where the original concepts and definition of the Dakota Formation were formulated. These rocks were first described in the written literature as exposures of "soft sandstone" along the bluffs of the Missouri River near the Omaha Indian's Blackbird burial grounds in the 1804 journal of Captain Clark, as recorded by the historic Lewis and Clark Expedition of the American West (see Tester, 1931). Meek and Hayden (1862) named the "Dakota Group" after exposures of sandstone alternating with shale and lignite in the "hills back of the town of Dakota [City]" in Dakota County, Nebraska (see circled type Dakota area, Fig. 1). In Iowa, rock strata presently included in the Dakota Formation were subdivided by White (1870), into a lower "Nishnabotany [sic] sandstone," and upper "Woodbury sandstones and shales." White's (1870) early conception of the Dakota interval as being comprised of two distinctly different lithostratigraphic units was subsequently confirmed and revived by hydrogeologic research drilling studies in western Iowa (Ludvigson and Bunker, 1979; Whitley, 1980; Whitley and Brenner, 1981; Witzke and Ludvigson, 1982; Munter et al., 1983; Witzke et al., 1983; Witzke and Ludvigson, 1994). A comprehensive summary of the historical background of stratigraphic studies in the type Dakota region is presented by Witzke and Ludvigson (1994).

The Nishnabotna Member of the Dakota Formation is the principle bedrock aquifer of western Iowa (Munter et al., 1983; Hunt and Runkle, 1985; Ludvigson and Witzke, 1992; Hansen et al., 1992). In many upland sites in the western part of the state, this confined aquifer is the only available large-capacity source of potable water supply. Chert and quartz-pebble conglomerate facies of the Nishnabotna are also developed as economic sand and gravel deposits where the unit crops out in southwest Iowa. Iron oxide-cemented ledges of Nishnabotna sandstone have been used as local building stones in southwest Iowa and southeast Nebraska, and massive ironstone deposits from similar coarse-grained facies of the Windrow Formation were once mined as economic iron ores in northeast Iowa and southeast Minnesota. Mudrock facies of the Dakota Formation are used for brick manufacturing, with operating clay pits located in Iowa, Minnesota, Nebraska, and Kansas.

Stratigraphic Nomenclature

Cretaceous stratigraphic units in Iowa include in ascending order: (1) the Dakota Formation, which includes the lower Nishnabotna Member and upper Woodbury Member; (2) Graneros Shale, (3) Greenhorn Limestone, and (4) Carlile Shale (Fig. 2). Detailed description and discussion of Woodbury and younger strata in the Iowa area can be found in Witzke and Ludvigson (1987, 1994), Ludvigson et al. (1994), and Ravn and Witzke (1994, 1995).

White (1870) first recognized that "Nishnabotany [sic] sandstones" exposed in the Nishnabotna and Raccoon River valleys of southwest Iowa (see circled type Nishnabotna area, Fig. 1) occupied a stratigraphic position below that of strata exposed in the Big Sioux River of Woodbury County in northwest Iowa; the type Dakota area (Fig. 1; see Witzke and Ludvigson, 1987, 1994). Current conceptions of the Dakota Formation in Iowa recognize these two major units: (1) a lower Nishnabotna Member with sheet geometry that chiefly consists of chert pebble conglomerates and coarse-grained to fine-grained sandstone (83% arenaceous units by volume) with lesser amounts of noncalcareous kaolinitic mudrock and lignite, and (2) an upper Woodbury Member that chiefly consists of noncalcareous kaolinitic mudrocks,

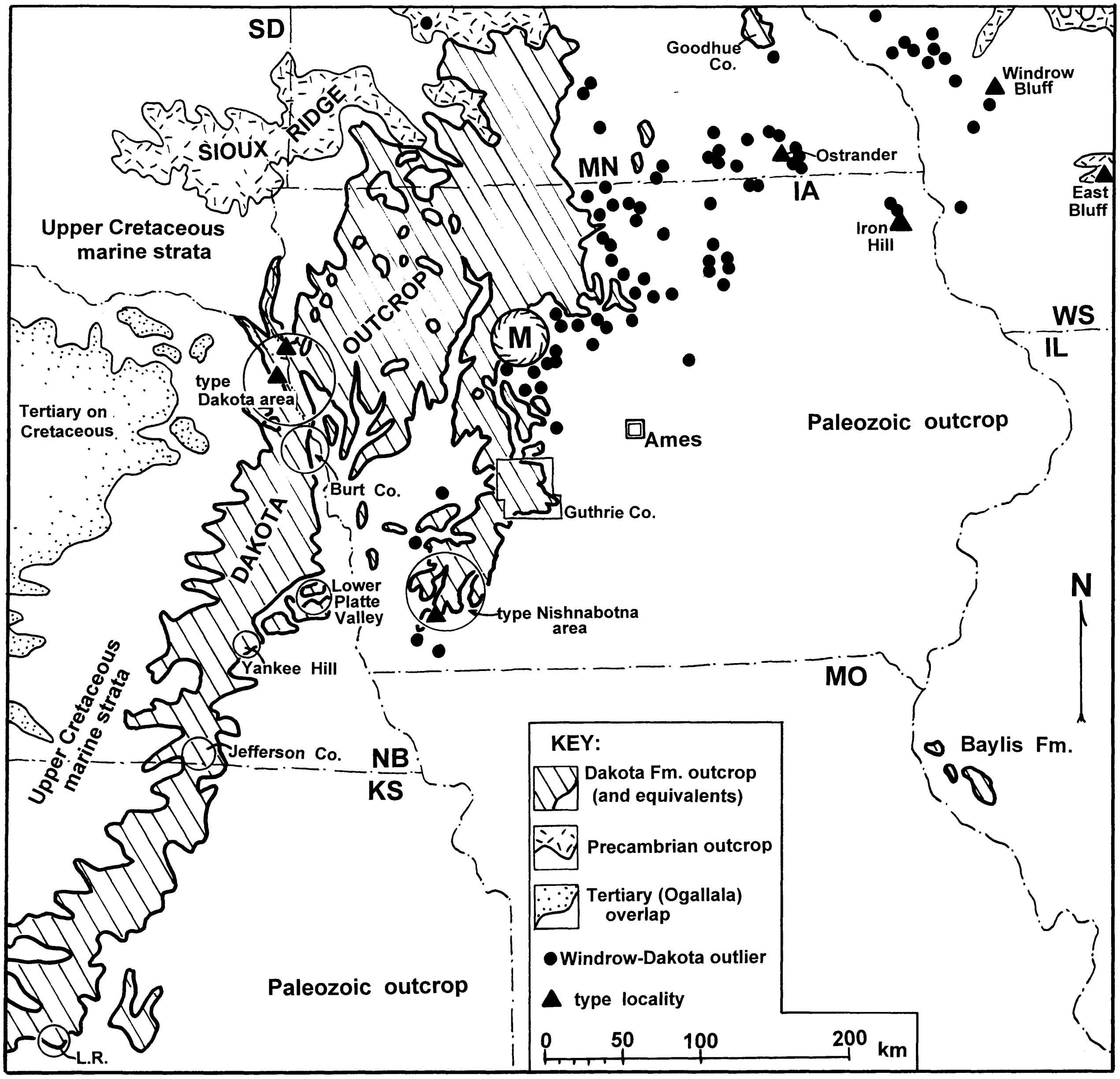


Figure 1. Regional outcrop of Dakota Formation and equivalent strata between southern Minnesota (MN) and northern Kansas (KS). Cross-ruled outcrop denotes Dakota Formation (Nishnabotna and Woodbury members) in western Iowa (IA) and eastern Nebraska (NB)(Witzke and Ludvigson, 1994), Dakota Formation (Terra Cotta and Janssen members) in southeast Nebraska and Kansas (Hamilton, 1994), the Kiowa Formation (Longford Member) in Kansas, and units K1 and K2a in Minnesota (Setterholm, 1994). Eastern outliers (dots) of equivalent strata include Dakota Formation in Iowa; Windrow Formation in Iowa, Wisconsin (WS), and Minnesota; and Baylis Formation in western Illinois (IL) (Frye et al., 1964). Cretaceous strata lap the margins of the Sioux Ridge, a long-lived topographic feature composed of resistant Precambrian quartzite. Map is adapted from Bunker et al. (1988), Setterholm (1994), Andrews (1958), and new Cretaceous bedrock geologic map of Iowa (unpublished, IDNR-Geological Survey Bureau, GIS coverage). General study areas are circled and labeled; Guthrie County is outlined. Abbreviations: L.R., Little River; M, Manson Impact Structure (of late Campanian age). State boundaries are dashed.

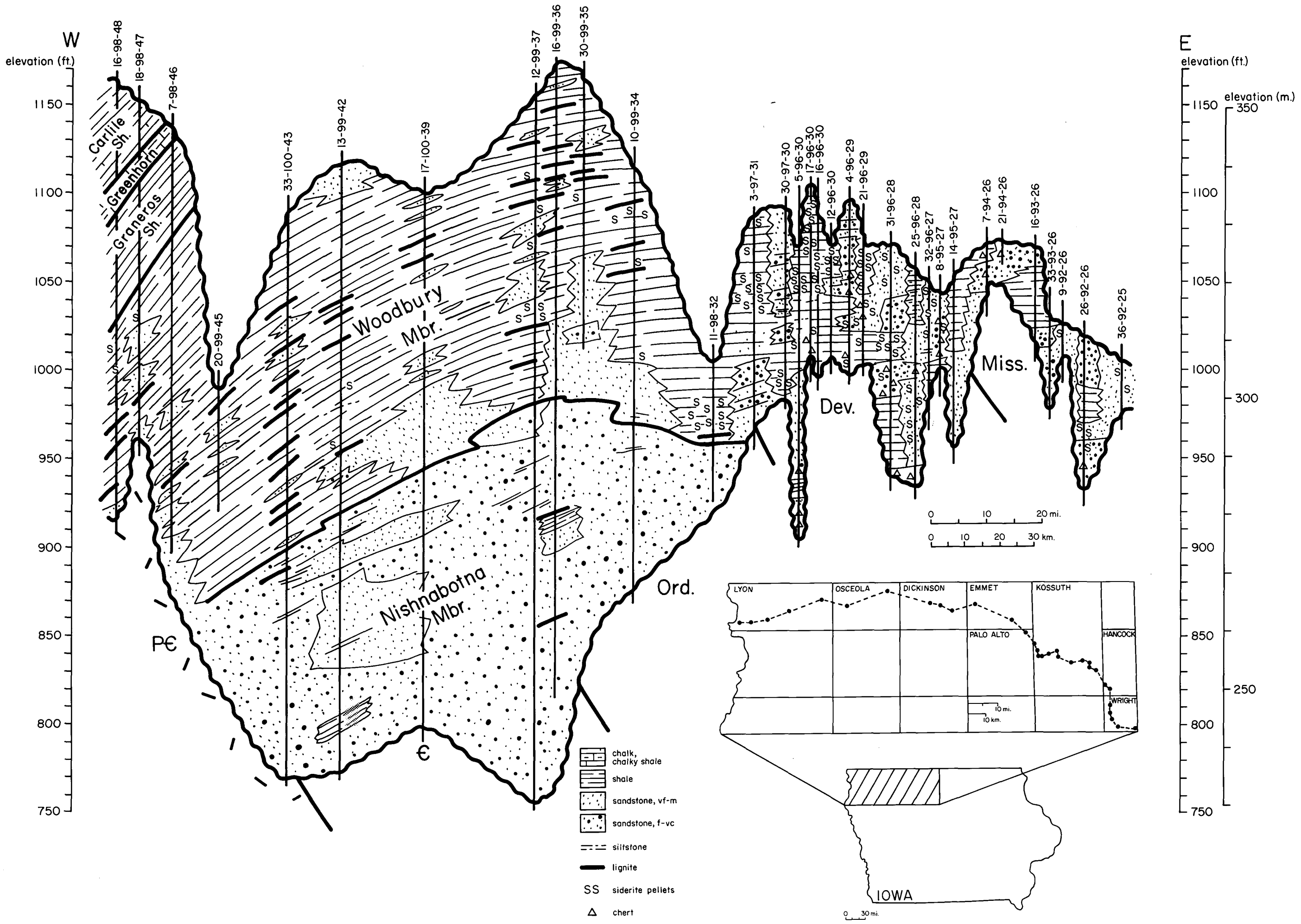


Figure 2. East-west subsurface cross-section of Cretaceous strata across northwestern Iowa. Datum is mean sea level. Upper Dakota strata of the Woodbury Member overstep the eastern edge of the lower Dakota Nishnabotna Member. Well records on file at IDNR-Geological Survey Bureau. Figure from Witzke and Ludvigson (1994).

with lenticular very fine-grained sandstones and lignites (Fig. 2; Witzke and Ludvigson, 1982; Munter et al., 1983; Witzke et al., 1983, Witzke and Ludvigson, 1994, Ravn and Witzke, 1994). In northern Iowa, the Nishnabotna is geographically confined to a major paleovalley system bounded by paleohighlands of Precambrian rocks of the Sioux Ridge to the northwest and a bounded to the southeast by a paleoescarpment cut into southeastward dipping Devonian and Mississippian carbonates (figs. 1 and 2). Farther south, the Nishnabotna laps the Devonian-Mississippian cuesta and rests on Pennsylvanian strata where it extends into southwestern Iowa (Fig. 1).

Regional stratigraphic investigations by Witzke et al. (1983) showed that in eastern Nebraska, the Nishnabotna passes westward (basinward) into mudrock-dominated strata (Fig. 3).

Studies of the Dakota Formation in Guthrie County

The best and most extensive exposures of the Nishnabotna Member of the Dakota Formation

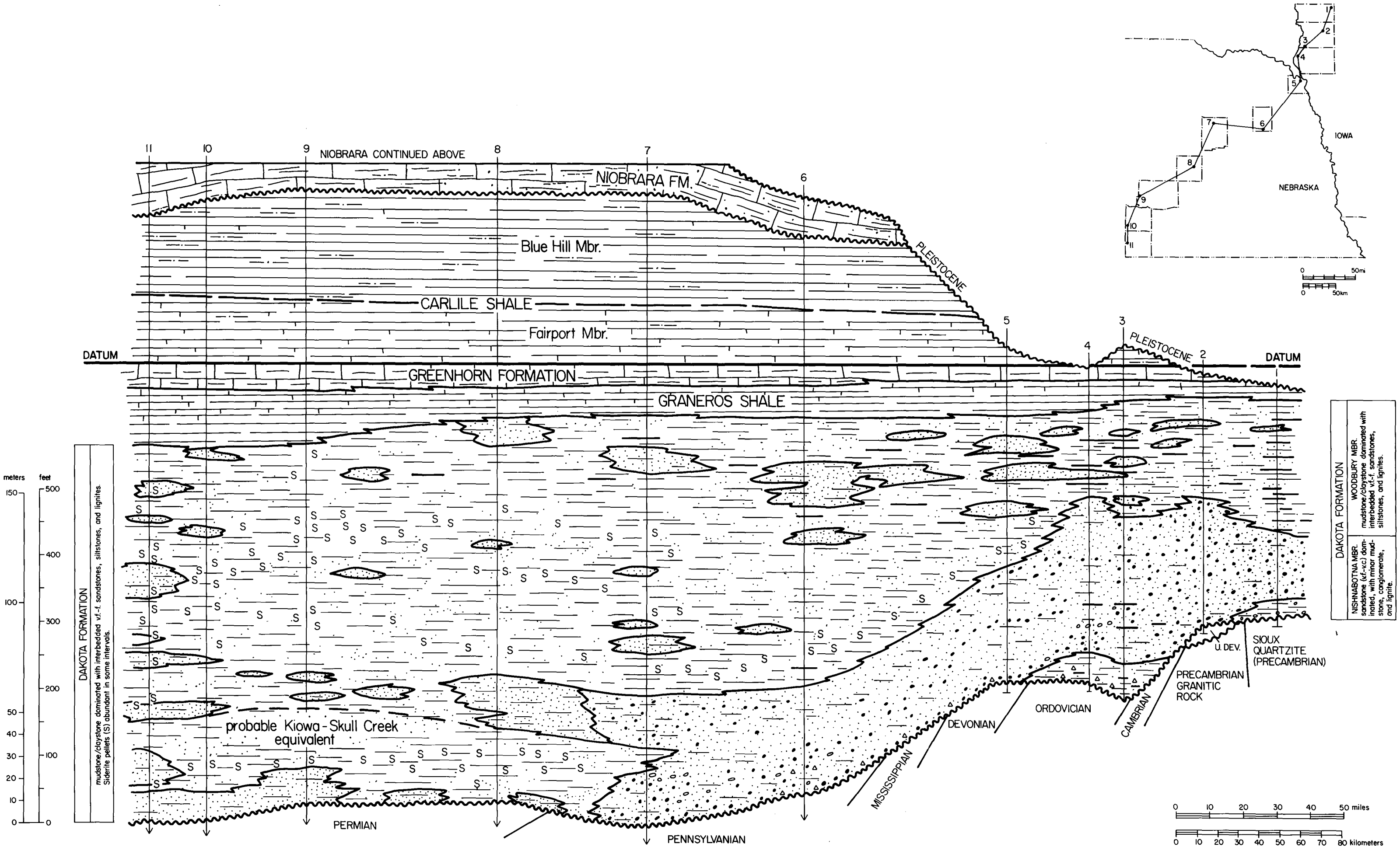


Figure 3. Intrepretive sub-Niobrara Cretaceous stratigraphic cross-section, northwestern Iowa and eastern Nebraska. Symbols as in Figure 2. Position of probable Kiowa Formation equivalent (?Longford member) schematically illustrated for south-central Nebraska. Based on unpublished well files (and examination of well cuttings and geophysical logs) stored at the Nebraska Conservation and Survey offices (Lincoln) and the IDNR-Geological Survey Bureau. Figure from Witzke et al. (1983).

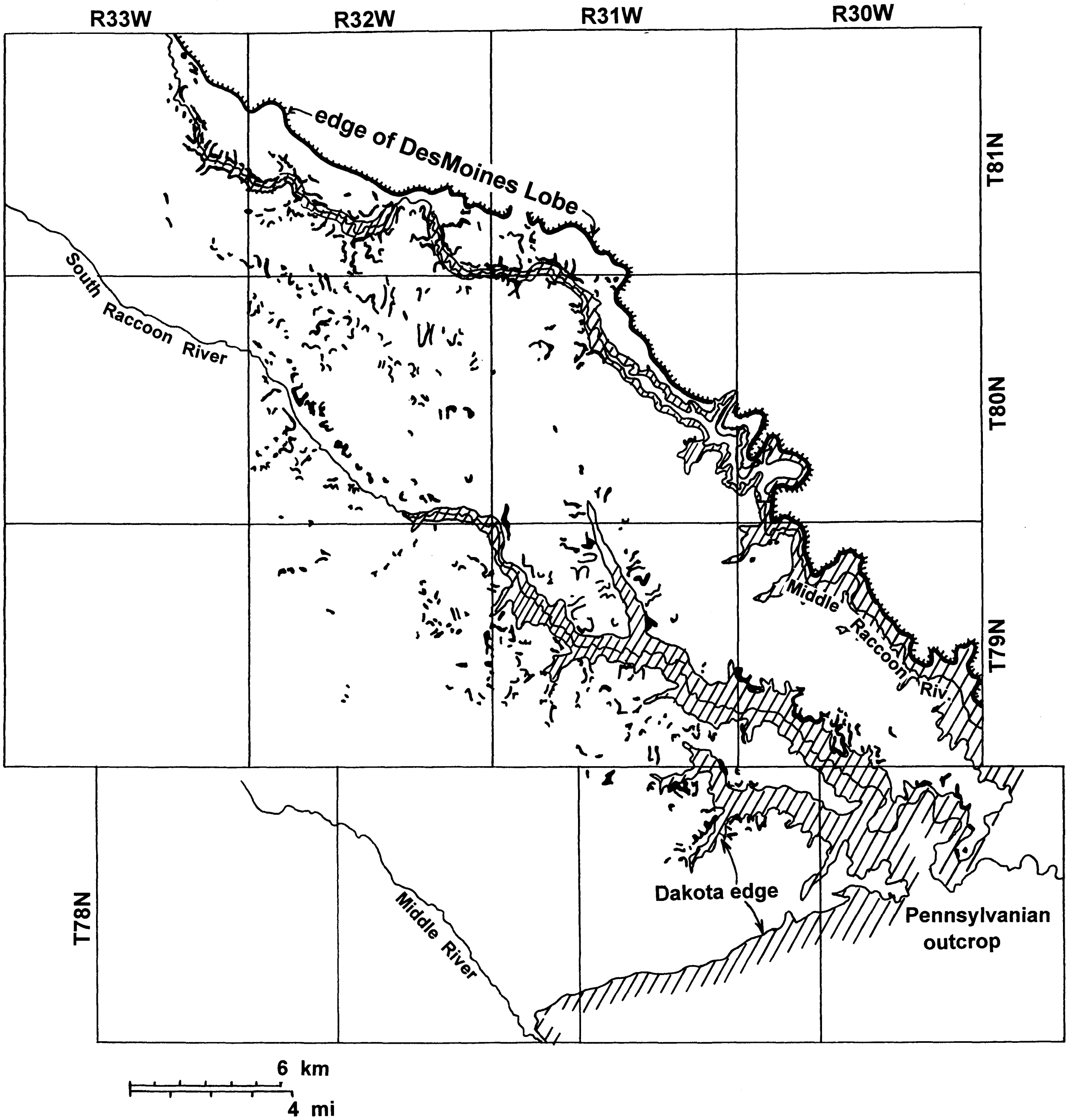


Figure 4. Generalized geology of Guthrie County Map shows edge of DesMoines Lobe (Wisconsinan ice-marginal glacial deposits), outcrop edge of Pennsylvanian (cross-ruled) beneath Cretaceous cover (Dakota Fm.), general exposure of Dakota strata (blackened areas), major rivers, and township and range boundaries. Geology adapted from Witzke and Ludvigson (1982) and Cretaceous geologic map of Iowa (unpublished, IDNR-Geological Survey Bureau, GIS coverage). Cretaeous bedrock exposure largely adapted from Guthrie County soils maps (U.S. Soil Conservation Service).

occur in Guthrie County, Iowa, in the valleys of the Middle and South Raccoon rivers and their tributaries (Fig. 4). The Middle Raccoon River occupied an ice-marginal position adjacent to the Late Wisconsinan Des Moines Lobe (Fig. 4), and outwash gravels containing large erratic clasts carried by Wisconsinan meltwater discharges are evident along the valley. The relatively recent (approx. 14 Ka) deep glaciofluvial incision of this river valley resulted in extensive bedrock exposure along the valley walls. St. John (in White, 1870) and Bain (1897) described a number of stratigraphic sections of Nishnabotna strata and underlying Pennsylvanian units which were mined for coal in Guthrie County, particularly in the Middle Raccoon River Valley between Panora and Springbrook State Park (area now flooded by the construction of the Lake Panorama reservoir). Andrews (1958) investigated the mineralogy of Cretaceous sands and gravels in Guthrie County. Frye et al. (1964) investigated the clay mineralogy of Nishnabotna mudstones, and showed that they are dominantly kaolinitic, with lesser amounts of illite and montmorillonite. More recent studies of the stratigraphy and sedimentology of Nishnabotna strata in Guthrie County (Witzke and Ludvigson, 1982), the type area in the Nishnabotna valley (Witzke and Ludvigson, 1994), and new work in the lower Platte River Valley (see circled area in Fig. 1) and other localities in eastern Nebraska provide the basis for an improved understanding of the depositional history of the unit.

REGIONAL DAKOTA SEDIMENTATION

by B.J. Witzke, G.A. Ludvigson, R.L. Brenner, and R.M. Joeckel

A general overview of Dakota sedimentation in Iowa and surrounding states is provided in previous papers (especially Witzke et al., 1983; Witzke and Ludvigson, 1994). A review of these prior interpretations, which are supplemented with important new information, will provide trip participants with some necessary background for placing the Guthrie County Cretaceous exposures in a broader regional context.

The lower Dakota Nishnabotna Member, a sandstone-dominated interval, is the only Cretaceous lithostratigraphic unit in western Iowa and eastern Nebraska that contains significant coarse-grained and pebbly sandstone lithologies. Nishnabotna strata overlie an irregular eroded surface of Precambrian and Paleozoic rocks (Figs. 2, 3) with up to 80 meters of local relief developed in southwest-trending paleovalleys. The Nishnabotna sandstones are overstepped eastward in north-central Iowa by upper Dakota strata of the Woodbury Member (Fig. 2) and are erosionally beveled beneath Quaternary deposits across southwestern Iowa.

The coarse sandstone-dominated strata of the Nishnabotna Member extend westward into eastern Nebraska (Fig. 3). These more distal regions of the coarse Nishnabotna facies incorporate proportionately more mudrock than observed in western Iowa. Farther westward and southwestward, the coarse-grained Nishnabotna sandstone facies are laterally replaced by a mudrock-dominated interval in which coarse-grained and pebbly lithologies are rare to absent. This regional facies transition occurs in the subsurface of central Nebraska as well as the outcrop belt of southeastern Nebraska, where the interval in question has been variably referred to the lower Terra Cotta Member of the Dakota Formation and/or nearshore and nonmarine facies of the Kiowa Formation (Longford Member). The stratigraphic relationships between these various units have been difficult to resolve, and Kiowa and lower Dakota strata have been interpreted by different workers to be either 1) lateral facies equivalents, or 2) separated by a significant regional unconformity.

The gross lithofacies of these units constrain some regional patterns for late Albian sedimentation in the eastern-margin area of the Western Interior (Fig. 5A). The interpretations presented here are further discussed by Witzke et al. (1983) and Witzke and Ludvigson (1994) who considered Kiowa and lower Dakota strata to be partial facies equivalents. The coarse-grained Nishnabotna facies are interpreted to represent deposits of an aggrading alluvial plain comprised of westward- and southwestward-flowing braided stream systems which drained the eastern landmass. This regional aggradation is considered to be a response to rising base levels associated with nearby transgression of the Kiowa seaway, and it represents the first regional depositional episode of the Cretaceous in the Iowa area.

Coarse-grained Nishnabotna facies persist upward through the entire thickness of the Nishnabotna Member in the northwestern Iowa subsurface, closest to the edge of the eroding source areas (Fig. 5A). However, upper Nishnabotna strata are dominated by fine-grained sandstones in more distal regions of southwestern Iowa (including Guthrie County) and eastern Nebraska. This indicates decreasing stream competence in distal areas through time, which probably resulted from declining stream gradients across the coastal lowlands due to the combined effects of regional aggradation (filling of accommodation space) and rising base levels. The succeeding sea-level lowstand (late late Albian) which separates the large-scale Kiowa-Skull Creek and Greenhorn marine cycles would be predicted to be associated with a decline in fluvial base-levels producing regional degradation and widespread paleosol development (Witzke and Ludvigson, 1994).

Significant mudrock intervals occur within lower Dakota strata along the western limits of

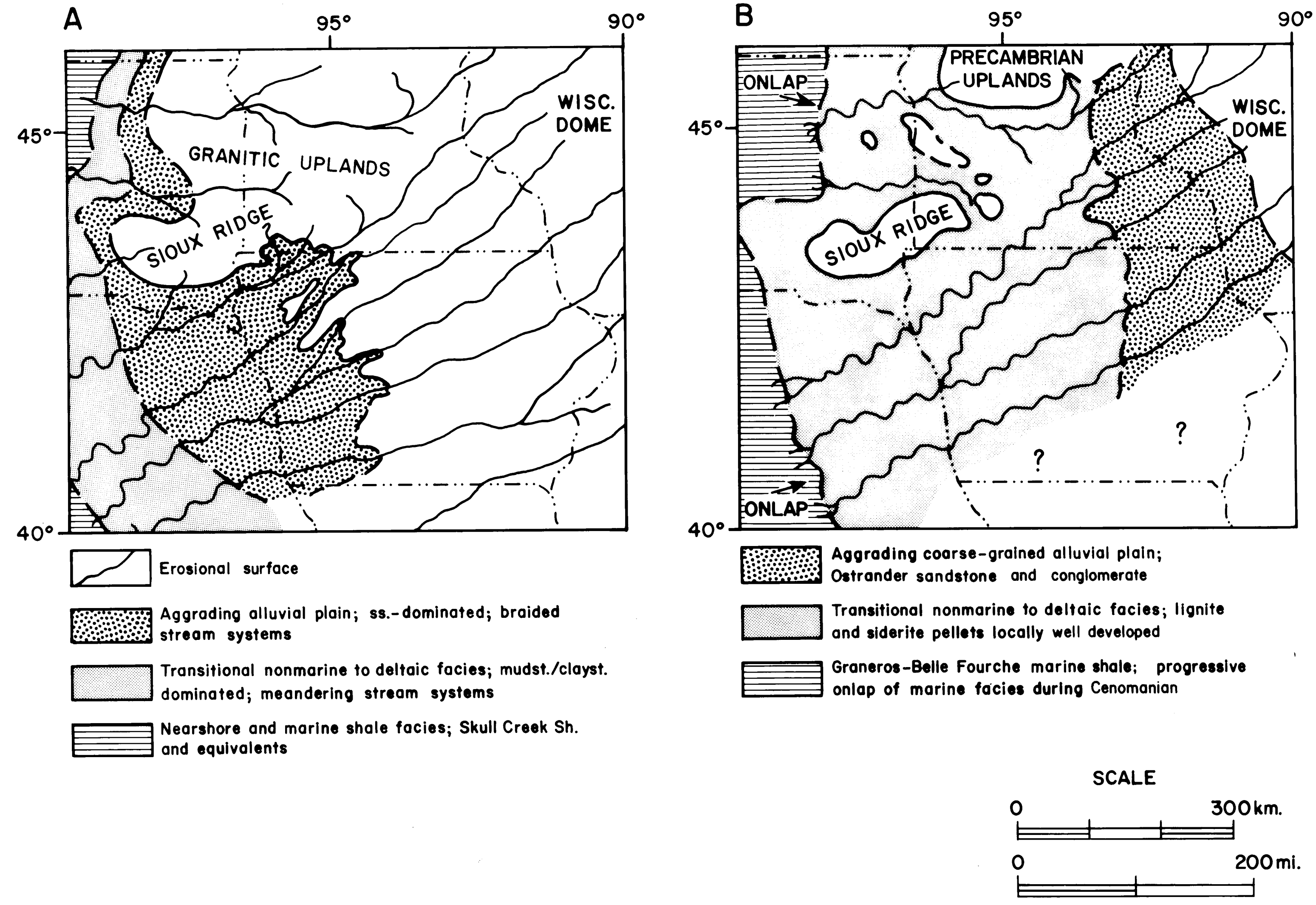


Figure 5. Schematic paleogeography of Dakota sedimentation in the Iowa area. A) Generalized map-view of lower Dakota sedimentation, late Albian. Aggrading coarse-grained fluvial deposition (lower Nishnabotna Member) is depicted as concurrent with rising base levels associated by marine transgression of the Kiowa-Skull Creek marine cyclothem. B) Generalized map-view of upper Dakota sedimentation, mid Cenomanian. Eastward displacement of mudstone-dominated fluvial facies (Woodbury Member) by marine shales ("Graneros") occurred during onlap of the Greenhorn marine cyclothem. Eastern coarse-grained facies of the Windrow Formation are interpreted to be correlative. Figure from Witzke and Ludvigson (1982) and Witzke et al. (1983).

pebbly conglomeratic Nishnabotna facies in eastern Nebraska (Fig. 6, Ash Grove, Maystrick), although sandstone-dominated sequences persist in this area (Fig. 6, Cullom) consisting of stacked sequences of sandstone and conglomerate. These latter occurrences are largely indistinguishable from Nishnabotna sequences in southwestern Iowa, and may represent deposition in areas more closely associated with a major trunk stream system. Nearby mudrock-bearing Nishnabotna exposures (Fig. 6), however, are significantly different from anything seen in western Iowa. Recent investigations (1994-1995) of these exposures have clarified some long-standing questions concerning lower Dakota correlations and also uncovered evidence of interfingering relationships between marine-related sediments (equivalent to the Kiowa marine shales) and distal coarse-grained facies within the Nishnabotna Member. This latter discovery came as a bit of a surprise, as the eastward depositional limits of typical Kiowa-Skull Creek marine shales were known to occur over 200 km west of the Lower Platte Valley sections (Fig. 6; see Fig. 5A for approximate location of marine shale margin).

The evidence for marine-related sedimentation in the Lower Platte Valley area is twofold: 1) occurrences of marine organic-walled microfossils in the mudrock intervals, and 2) the discovery of well-preserved tidal rhythmites (upper mudrock unit at Ash Grove, Fig. 6; see Zawistoski et al., 1996). The lower mudrock intervals at both Ash Grove and the Maystrick Pit (Fig. 6) have produced marine dinoflagellates and acritarchs (see later discussion on palynomorphs), and it must be assumed that some nearshore marine or restricted-marine waters were present at least temporarily in the area during deposition. This may have occurred in either of two ways: 1) marine transgression flooded some existing river channels producing estuarine systems and introducing marine or restricted-marine organisms to the area; or 2) large-scale storm surges episodically spread marine waters across areas of the coastal lowlands. The lower mudrock interval at both localities (Fig. 6) was subsequently subjected to deep pedogenic alteration, suggesting changes in local or regional base levels and an episode of degradation and soil development.

The upper mudstone/siltstone unit at Ash Grove (Fig. 6; based on surface exposures and bedrock coring) provides exceptional evidence that tidally-influenced estuarine environments did, in fact, penetrate a considerable distance up the shallow river valleys contemporaneous with Nishnabotna sedimentation. This interval records a second aggradational event in the sequence that is also likely represented by the upper section at the Maystrick Pit (Fig. 6). The alternations of mud and silt laminae in the interval provide evidence of well-developed neap-spring tidal cycles that preserve an approximate 3-year record of tidal sedimentation, possibly diurnal (Zawistoski et al., 1996). The presence of such sedimentary features indicates that at least meso-tidal ranges (ibid.) occurred a considerable distance up this paleoestuary. Further evidence for marine-related sedimentation is provided by occurrences of a relatively diverse assemblage of marine dinoflagellates and acritarchs (see later discussion). However, attempts to extract foraminifera from the interval have been unsuccessful. The conglomeratic sandstone below the tidal unit at Ash Grove preserves the depositional pinch-out of a lobate gravel bar (Fig. 6), which is draped by the rhythmite interval. Channel incision above the tidal sequence at Ash Grove indicates a subsequent lowering of base level.

Seaward from the distal margin of the Nishnabotna Member, the lower Dakota sequence is dominated by mudrocks with secondary sandstone. Lignites and carbonaceous shales are recognized. Well-developed paleosols (Joeckel, 1987, 1992), including red-mottled strata bearing siderite pellets and deep plinthic units, are common. These mudrock-dominated facies have generally been assigned to the lower Terra Cotta Member in Nebraska. The eastward incursion of estuarine facies into adjacent Nishnabotna facies indicates that at least part of this mudrock-dominated facies tract must include equivalents of the Kiowa Formation. Similar strata in Kansas have been included in the Longford Member of the Kiowa Formation and the lower portion of the Terra Cotta

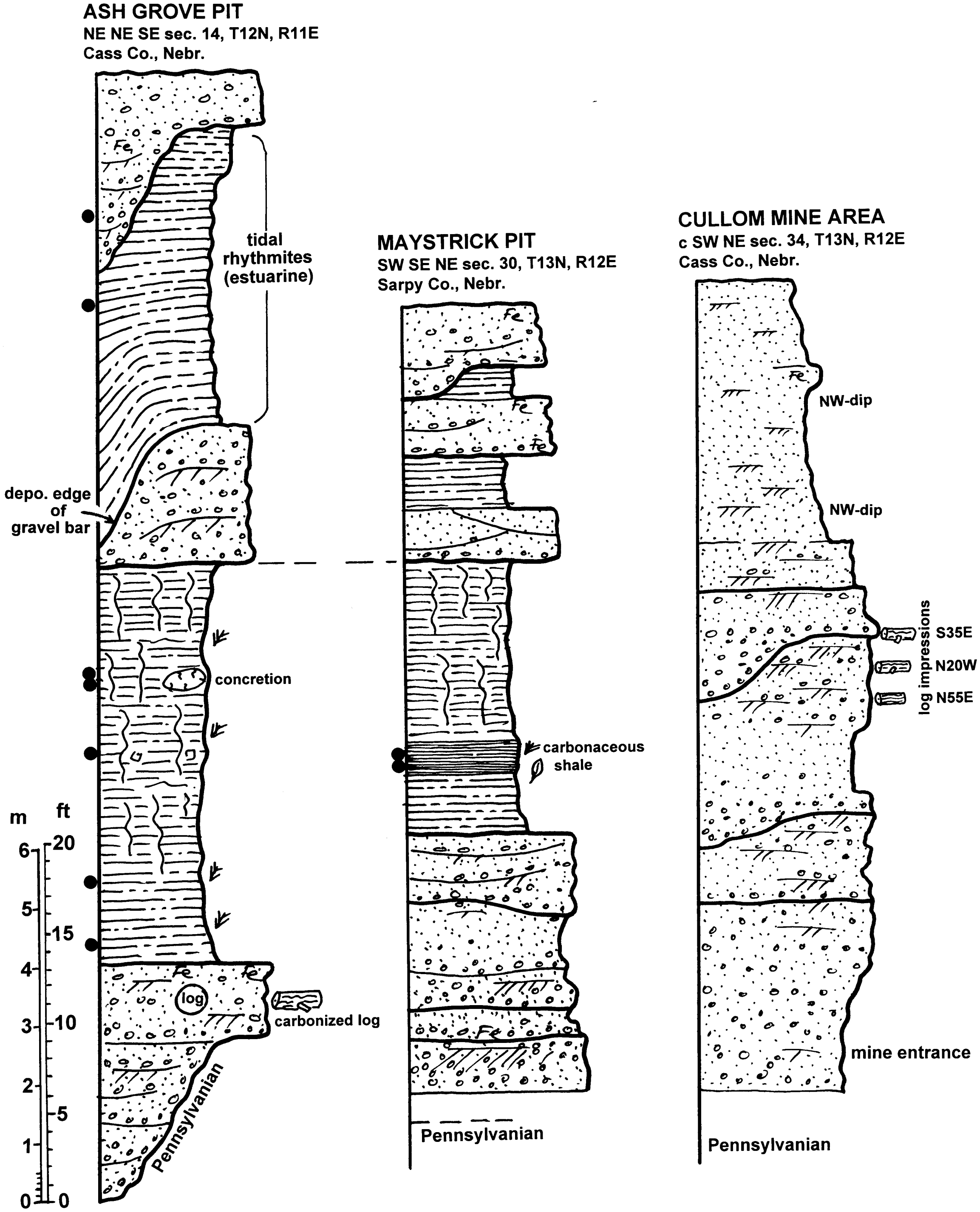


Figure 6. Graphic sections of representative exposures of Nishnabotna Member strata in the lower Platte River Valley, eastern Nebraska. See Figure 1 for general location; see Figure 16 for symbols used. The Cullom section displays coarse-grained and conglomeratic fluvial facies closely similar to characteristic lower Nishnabotna facies seen in western Iowa. Nearby exposures (Ash Grove, Maystrick) display interbedded mudrock intervals, pedogenically-modified in part, that have yielded palynomorphs (dots). Well developed tidal rhythmite laminations characterize the upper Ash Grove section, suggestive of marine influences in an estuarine depositional setting (correlative with the transgressing eastern shoreline of the Kiowa-Skull Creek marine cylothem).

Member. The eastward stratigraphic relationships of Longford and Terra Cotta units have been largely conjectural until recently.

Mudrock-dominated facies of the Longford and lower Terra Cotta were deposited across the late Albian coastal lowlands bordering the Kiowa-Skull Creek seaway. The transecting fluvial systems were less competent than in the eastern Nishnabotna facies tract, probably forming lower-gradient meanderbelt systems; overbank mud deposition was extensive across the broad floodbasins. Nevertheless, coarse and pebbly sediments were delivered to these coastal lowland settings, especially low in the depositional sequence, providing some lithologic continuity with the adjacent Nishnabotna facies tract. Thin pebbly conglomeratic units occur in this mudrock-dominated Albian facies tract as far west as central Kansas (circled area "L.R." on Fig. 1), where rounded pebbles (1-10 cm) of chert, vein quartz, and jasper, comparable to the Nishnabotna gravels in Iowa, are recognized (Feldman, 1994).

In addition to the predominant nonmarine sedimentation across this mudrock-dominated facies tract (fluvial, pedogenic), marine-related deposition is also indicated. An exhaustive and detailed sedimentary analysis of this facies tract has not been completed in Nebraska, although the presence of marine indicators suggests that estuarine, deltaic, and/or coastal wetland environments were part of the regional depositional mosaic. Occurrences of marine palynomorphs in some mudrock units of the area (including the Yankee Hill area and Jefferson County, Fig. 1) provides further marine-related linkages with estuarine facies of the distal Nishnabotna facies tract.

A second episode of regional fluvial aggradation was associated with transgression of the Greenhorn marine cycle, which began in the latest Albian and culminated in widespread marine transgression as far east as eastern Minnesota by the latest Cenomanian and early Turonian (Witzke et al., 1983). Depofacies tracts largely indistinguishable from those described for the Kiowa-Skull Creek cycle can be found in these younger units, but such tracts occur at positions notably farther to the east than found for the lower Dakota-Kiowa interval (Fig. 5B). This reflects the greater eastward extent of the marine inundation associated with the Greenhorn marine cycle. The broad mudrock-dominated coastal-lowland facies tract corresponds essentially to the upper Dakota Woodbury Member in Iowa and Nebraska, and includes strata of the upper Terra Cotta and Janssen members in southeastern Nebraska and Kansas.

Coarse-grained lithologies are generally absent across most of the Woodbury Member facies tract. However, coarse and pebbly sandstones are identified in the proximal areas where Woodbury strata overstep the Nishnabotna edge to directly overlie the eroded Paleozoic surface (Fig. 2). The Cretaceous outcrop belt erosionally terminates east of this coarsening transition, although a number of Cretaceous outliers in southeastern Minnesota, northeastern Iowa, western Wisconsin, and western Illinois (Fig. 1) provide considerable evidence of a coarse-grained and conglomeratic facies tract that developed eastward of the Woodbury Member (Fig. 5B). Most of these outliers are included in the Windrow Formation; the Baylis Fm. in Illinois is probably equivalent.

Coarse-grained sandstones and iron-oxide-cemented pebbly conglomerates of the Windrow Formation (Ostrander, Iron Hill, East Bluff members) are, for the most part, lithologically indistinguishable from facies seen in the Nishnabotna Member of western Iowa (Thwaites and Twenhofel, 1921; Andrews, 1958). Windrow sedimentation is considered to be directly analogous with that of the Nishnabotna, deposited in similar fluvial environments and sourced from the same eastern landmass. Further analogy with the distal Nishnabotna facies of the Lower Platte Valley is seen in Goodhue County, Minnesota (Fig. 1), where marine-related mudrocks (with shark teeth and marine ichnofauna) are associated with the Windrow conglomerates (Witzke et al., 1983).

AGE AND CORRELATION OF THE NISHNABOTNA MEMBER

by B.J. Witzke, R.L. Ravn, G.A. Ludvigson, R.M. Joeckel, and R.L. Brenner

The age and regional correlation of the Dakota Formation in western Iowa and eastern Nebraska, particularly the basal portion represented by the lower Nishnabotna Member, has been difficult to determine due to lithostratigraphic uncertainties and a paucity of biostratigraphic control. Uppermost Dakota strata (top 10-15 m of Woodbury Member) and the overlying "Graneros" Shale in the type Dakota area contain late Cenomanian marine mollusks and foraminifera, constraining the upper limits of the formation in western Iowa (see summaries in Witzke and Ludvigson, 1994, and Ravn and Witzke, 1995). Recent palynostratigraphic studies (Ravn and Witzke, 1994, 1995) have identified abundant and diverse palynofloras in nonmarine strata of the Woodbury Member in western Iowa, and these indicate an early to middle Cenomanian age for the lower and middle portions of the member. As such, the Nishnabotna Member is constrained to an age no younger than early Cenomanian, and a late Albian age is reasonably suggested (see earlier suggestions of Whitley and Brenner, 1981; Ravn, 1981).

Previously established lithostratigraphic relationships between lower Dakota strata in its type area and the Newcastle/Muddy/Mowry formations of eastern Wyoming generally supported an uppermost Albian correlation for at least part of the Nishnabotna Member (see summary by Witzke et al., 1983). Biostratigraphically significant spores (*Plicatella jansonii, Impardecispora marylandensis*) were subsequently recovered from subsurface strata of the lower Nishnabotna Member in northwestern Iowa by Ravn and Witzke (1994, 1995), strongly supporting an upper Albian correlation. Twenhofel (1924), Tester (1931), and Witzke et al. (1983) had previously suggested that lower Nishnabotna strata in Iowa should correlate with marine strata of the Albian Kiowa Formation in Kansas, but biostratigraphic verification of this was not at hand. Their interpretation differed from that presented by Franks (1975, 1979), Bowe (1972), Schoon (1971), Karl (1976) and others who correlated lower Dakota strata in eastern Nebraska and the type area to an entirely post-Kiowa position. In the absence of firm biostratigraphic data, two basic options remained through 1994: 1) lower Nishnabotna strata correlate with some portion of the Kiowa-Skull Creek marine cycle in the Western Interior, or 2) the Nishnabotna is a post-Kiowa interval deposited during the latest Albian and earliest Cenomanian (lower Greenhorn cycle). As discussed in the previous section, the discovery of tidal-related deposits with marine microfossils in lower Nishnabotna strata of eastern Nebraska would seemingly make the first option preferable.

Field studies progressed into the lower Platte River Valley of eastern Nebraska (Fig. 1) during 1994 and 1995, and unoxidized mudrocks were recognized interbedded with pebbly conglomeratic sandstones typical of the lower Nishnabotna Member (see earlier discussion; Fig. 6). These were sampled for palynomorphs, and a diverse palynoflora was identified during 1995-1996 (see Table 1). All identifications are by R.L. Ravn. The assemblages are clearly older than anything that was previously identified in Dakota strata of the region, significantly expanding our understanding of Dakota chronostratigraphic relationships. These palynologic collections, in conjunction with other published and unpublished collections from eastern Nebraska and western Iowa, enable a preliminary palynostratigraphic framework to be erected for the entire Dakota Formation in the region. This is summarized below, but further studies will undoubtedly expand and refine these general statements. A Cenomanian framework was published previously (Ravn and Witzke, 1994, 1995), although important new collections have notably expanded our knowledge of the palynostratigraphy of both lower and upper Dakota units during the time these publications were in press.

Dakota Palynostratigraphic Framework, Iowa and Nebraska

To date, 167 genera and 321 species of Cretaceous palynotaxa have been recognized in Dakota Formation samples from western Iowa and eastern Nebraska (indeterminate taxa may increase this to over 360 species). The great diversity makes this region one of the world's richest sources of palynologic information yet known for the mid Cretaceous. Abundant and well-preserved palynomorph assemblages are routinely recovered from unoxidized lignitic and mudrock units in the formation. Although dark-gray carbonaceous units are generally the most productive, other types of mudrocks also commonly yield abundant palynomorphs (including light- to medium-gray silty mudstones/claystones and unoxidized domains within pedogenically-modified red mudstones).

Upper Dakota strata have been extensively sampled from surface exposures and subsurface core and cuttings from the type Dakota area (Fig. 1) and elsewhere in northwestern Iowa (see Ravn and Witzke, 1995; sample intervals 6 through 16, Fig. 7). Recent supplemental upper Dakota samples from Burt and Jefferson counties, Nebraska (Fig. 1), the Winnebago and Omaha Indian Reservations (Hamid, 1995), and new cores from Sergeant Bluff, Iowa, have expanded and refined the ranges of many taxa (sample intervals 5 through 16, Fig. 7). Lower Dakota samples are largely derived from southeastern Nebraska, including natural outcrops, pit exposures, and cores from the Lower Platte Valley, the area in and around Yankee Hill, and Jefferson County (Fig. 1). Nishnabotna strata were previously sampled from western Iowa, and these had earlier yielded limited but instructive palynofloras (see above; also Ravn and Witzke, 1995). The Lower Platte Valley samples (see Fig. 6; sample intervals 1 and 2 on Fig. 7) were derived from strata approaching the westward limits of the coarse-grained and conglomeratic lower Nishnabotna Member. Lower Dakota samples from Yankee Hill and Jefferson County (sample intervals 2 through 4, Fig. 7) are from strata generally assigned to the Terra Cotta Member (a Kansas term). These strata are from mudrock-dominated facies distal to the coarse-grained channels of the lower to upper Nishnabotna; coarse units persist into this region, but sandstone bodies are subordinate. Additional lower Dakota samples from Guthrie County, Iowa (see Stop 5 discussion and diagrams), were processed during late 1995 and early 1996, but as of this writing the palynoflora has not yet been fully identified; preliminary observations suggest relationships with the Lower Platte Valley samples.

The diverse Dakota palynofloras are typically dominated by spores of various pteridophytes (ferns), lycophytes, and bryophytes. Pollen grains from gymnosperms and angiosperms are generally less abundant, but the diversity of these forms is notable. The relative abundances of these higher-level palynotaxa are almost inversely proportional to that seen in the Dakota compression floras of the region, where angiosperm leaves are overwhelmingly dominant over fern and conifer foliage. This seeming discrepancy is related in part to the lower production of pollen from angiosperm taxa compared with the greater volume of spore and pollen rain from the ferns and gymnosperms. The paleobotanical affinities of the various palynomorphs indicate that a rich flora inhabited the fluvial floodbasins and coastal lowlands of the eastern-margin area of the Western Interior.

Conifers grew in the lowland environments, including pines and cypress-like taxodiaceans. The diversity of conifer pollen, however, is not reflected in the compression floras, and it may be that much of the gymnosperm pollen rain was derived from conifer forests in less saturated influve areas and nearby regions of slightly higher elevation. The conifer pollen rain suggests the presence of pines, podocarps, taxodiaceans, sequoias, and araucariaceans in the region. Additional gymnosperms include cycadophytes, gnetaleans (shrubs), and various incertae sedis.

Angiosperm pollen shows an overall increase in diversity and complexity upward through the Dakota Formation. Compression floras also provide glimpses of the angiosperms that inhabited the region (Ravn and Witzke, 1995), but the taxonomic relationships of the fossil foliage and pollen

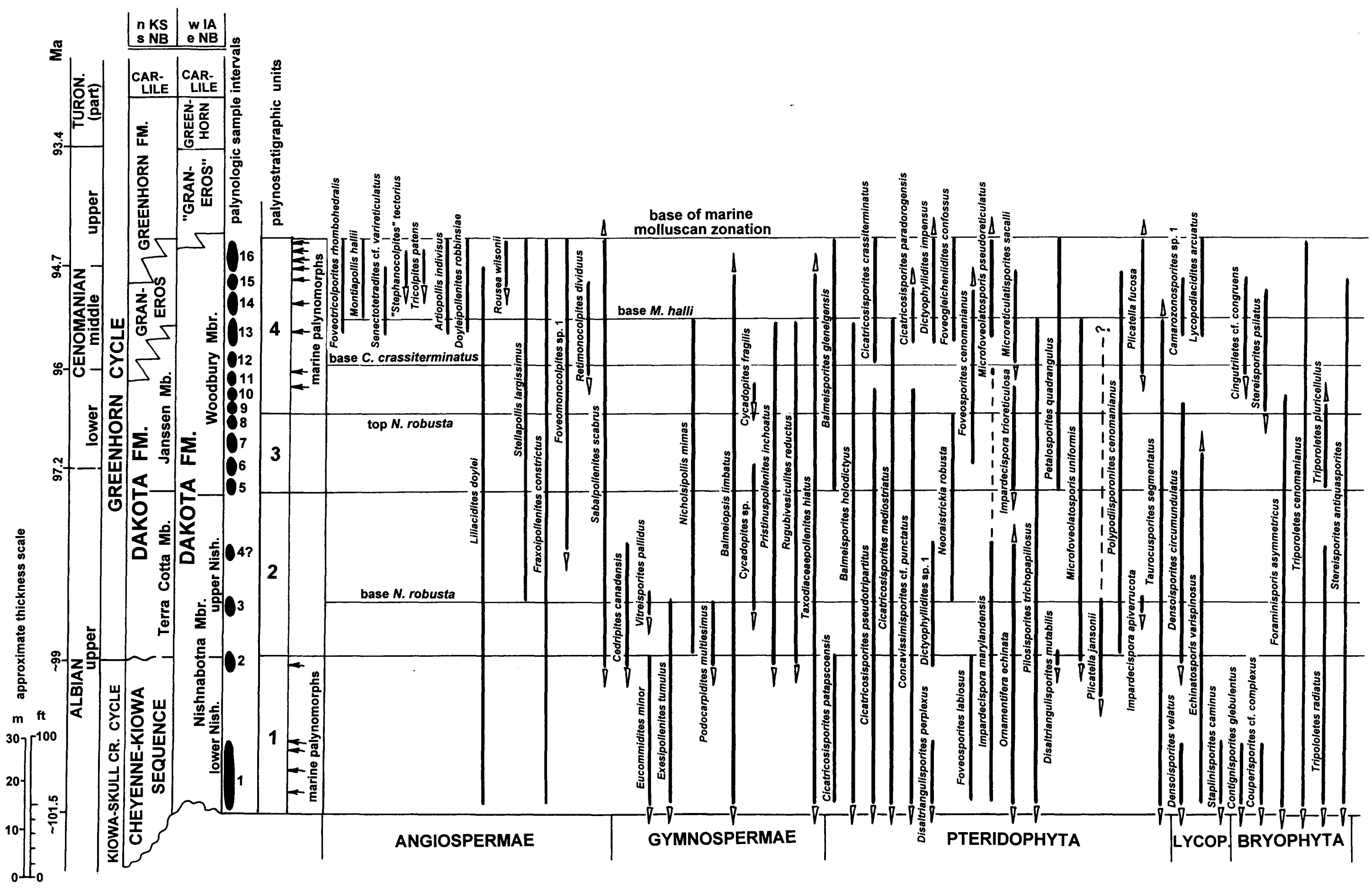


Figure 7. Ranges of selected palynomorph taxa in the Dakota Formation of western Iowa (w IA) and eastern Nebraska (e NB), modified in part from Ravn and Witzke (1995) with significant additions and range extensions derived from extensive unpublished data (identifications of R. Ravn). Ages in Ma (million years) interpreted from Kauffman et al. (1993). Arrows on range bars indicate known range extensions at other North American localities. Sample intervals 5 through 16 based largely on objective sequences from cores at Hawarden and Sargeant Bluff, Iowa, and exposures in Thurston Co., Nebraska (Hamid, 1995); intervals 1 is section at Ash Grove, Nebraska (see Fig. 6) and Guthrie Co., Iowa (Figs. 26, 27); intervals 2 through 4 are based on relative stratigraphic positions of lower Dakota exposures in the Yankee Hill and Jefferson County study areas, southeastern Nebraska (see Fig. 1). Tentative lithstratigraphic correlations with northern Kansas (n KS) are illustrated.

remain problematic. These early angiosperms probably grew as shrubs, vines, and trees in the lowland forests. Lower Dakota compression floras (see Stop 2) are dominated by large platinoid (sycamore-like) angiosperm leaves with a few additional forms present (simple to multi-lobed and serrate forms). Middle Dakota angiosperm compressions show an overall increase in diversity, including a variety of pinnate and platinoid leaves; the appearance of simple unlobed magnoliid leaf types is noteworthy. Possible palm pollen also appears (palm compressions are known from the Dakota of Kansas). Upper Dakota strata in the region yield additional angiosperm compressions, typically dominated by simple to lobed magnoliid types; a variety of additional taxa also occur (in-

Table 1. Palynomorphs from lower Nishnabotna Member, Ash Grove and Maystrick Pits, Nebraska; identifications by Robert L. Ravn

BRYOPHYTA
Aequitriradites spinulosus
Contignisporites glebulentus
Couperisporites cf. *complexus*
C. tabulatus
Foraminisporis asymmetricus
F. wonthaggiensis
Stereigranisporis regius
Stereisporites antiquasporites
S. psilatus
S. sp. indet.
Triporoletes cenomanianus
T. laevigatus
T. radiatus
T. reticulatus
T. simplex
T. sp. 1

LYCOPHYTA
Camarozonosporites ambigens
C. sp. (small)
Densoisporites circumundulatus
D. microrugulatus
D. velatus
Echinatisporis varispinosus
E. sp. indet.
Kraeuselisporites breviculus
K. hastilobatus
Lycopodiacidites canaliculatus
L. triangularis
L. sp. indet.
Retitriletes austroclavatidites
R. singhii
R. spp. indet.
Sestrosporites pseudoalveolatus
Staplinisporites caminus

PTEROPHYTA
Antulsporites distaverrucosus
A. sp. (invag. angles)
Balmeisporites holodictyus
Biretisporites potoniei
Cibotiumspora juncta
Cicatricosisporites apicanalis
C. aralicus
C. australiensis
C. claricanalis
C. goniodontos
C. cf. *hughesii*
C. mediostriatus
C. minutaestriatus
C. patapscoensis
C. potomacensis
C. psuedotripartitus
C. venustus
C. spp. indet.
Cingulatisporites cf. *levispeciosus*
C.? sp. indet.
Concavissimisporites granulosus
C. punctatus
C. cf. *variverrucatus*
Converrucosisporites sp. indet.
Corniculatisporites sp. indet.
Costatoperforosporites foveolatus
Crybelosporites pannuceus
C. striatus
C. sp. indet.
Deltoidospora hallii
D. cf. *maculosa*
D. mesozoica
D. minor
Dictyophyllidites cf. *harrisii*
D. cf. *impensus*
D. incomptus
D. sp. indet.
Disaltriangulisporites irregularis
D. mutabilis
D. perplexus
Divisisporites? sp. indet.
Foveogleicheniidites cf. *confossus*
Foveosporites labiosus
F. pantostiktos
F. senomanicus
F. subtriangularis
F. sp. indet.
Gleicheniidites senonicus
G. sp. (small, thick)
Granulatisporites michinus
G.? sp. indet.
Impardecispora apiverrucata
I. marylandensis
I. minor
I. purverulenta
I.? sp. indet.
Interulobites? sp. indet.
Ischyosporites crassimacerius
I. disjunctus
I. foveolatus
I. pseudoreticulatus
I. sp. indet.
Laevigatosporites gracilis
L. haardtii
L. sp. (large)
Leptolepidites sp. indet.
Lophotriletes babsae
Microfoveolatisporis sp. indet.
Microreticulatisporites sacalii
M.? sp. indet.
Neoraistrickia robusta
N. truncata
Nevesisporites simiscalaris
Nodosisporites stellantis
N. sp. indet.
Ornamentifera echinata
Osmundacidites wellmanii
Pilosisporites cf. *notensis*
P. trichopapillosus
P. spp. indet.
Plicatella cf. *fucosa*
P. jansonii
P. matesovae
P. potomacensis
P. cf. *problematica*
P. tricornitata
P. unica
P. sp. indet.
Polycingulatisporites reduncus
Psilatriletes radiatus
Punctatisporites couperi
P. globosus
P. sp. indet.
Reticulosporis elongatus
Rogalskaisporites cicatricosus
Scopusporis excavatus
S. lautus
S. sp. indet.
Stoverisporites lunaris
Taurocusporites segmentatus
Tigrisporites scurrandus
T. verrucatus
Tribosporites canadensis
Undulatisporites undulapolus
U.? sp. indet.
Verrucosisporites rotundus
V. sp. indet.

GYMNOSPERMAE
Abietineaepollenites sp. indet.
Balmeiopsis limbatus
Callialasporites dampieri
Cedripites canadensis
Corollina echinata
C. torosa
Cycadopites sp. indet.
Equisetosporites cf. *concinnus*
E. sp. indet.
Eucommiidites minor
E. troedssonii
Exesipollenites tumulus
E.? sp.
Jiaohepollis cf. *flexuosus*
Laricoidites magnus
Nicholsipollis mimas
Parvisaccites radiatus
Piceaepollenites sp. indet.
Pinuspollenites constrictus
Podocarpidites multesimus
P. sp. indet.
Pristinuspollenites inchoatus
P. sulcatus
P. sp. indet.
Rugubivesiculites reductus
R. rugosus
R. woodbinensis
Taxodiaceaepollenites hiatus
Thomsonisporites rasilis
Tsugaepollenites sp. indet.
Vitreisporites pallidus
indet. bisaccate pollen

ANGIOSPERMAE
Foveomonocolpites? sp. indet.
Fraxinoipollenites constrictus
F. venustus
Liliacidites doylei
Phimopollenites? sp. indet.
Quadricolpites reticulatus
Retimonocolpites dividuus
R. sp. indet.
Rousea sp. indet.
R.? sp. (strongly prolate)
Sabalpollenites scabrus
Tricolpites sp. indet.
Verrumonocolpites sp. indet.

MISCELLANEA OR INCERTAE SEDIS
Ovoidites majusculus
O. parvus
Schizosporis reticulatus
linear septate fungal hypha

MARINE PALYNOMORPHS
Hystrichodinium cf. *pulchrum*
Impletosphaeridium? sp. indet.
Leiosphaeridia sp. (large)
Lophosphaeridium? sp. indet.
Micrhystridium sp. indet.
Systematopphora? sp.
Veryhachium sp. indet.
indet. angular ?dinocyst
indet. gonyaulacoid dinocyst
indet. skolochorate dinocyst spp.
indet. large leiosphere
indet. small leiosphere
indet. large alate, sparse spine

REWORKED PENNSYLVANIAN SPORES
Auroraspora cf. *solisorta*
A. sp.
Calamospora cf. *breviradiata*
C. spp. indet.
Corbulispora cf. *reticulocingulum*
Crassispora kosankei
Densosporites sp. indet
Emphanisporites sp. indet.
Endosporites globiformis
Florentinia pumicosus
F. cf. *volans*
Florinites mediapudens
F. visendus
Grandispora sp. indet.
Lophotriletes sp. indet.
Lycospora pellucida
L. rotunda
Potonieisporites elegans
P. solidus
Punctatisporites sp. indet.
Triquitrites crassus
T. sculptilis
Wilsonites delicatus

cluding pinnate, serrate, and platinoid leaf forms). The mid Cretaceous was a time of dramatic and rapid botanical diversification, particularly within the angiosperms. The dramatic diversification of the flowering plants during this interval is one of the most important episodes in the history of life on earth. These great changes set the primary stage, an inexorable motion if you will, for the subsequent co-evolution of the terrestrial biosphere. It initiated a trend that ultimately produced the angiosperm-dominated landscape (and its associated complex animal communities) that we see in the modern world.

The mid Cretaceous plant communities of the eastern-margin region, in addition to the gymnosperms and angiosperms, also included an understory or groundcover of many additional plants, as indicated by the diverse palynofloras (and to a lesser extent, the compression floras). These include mosses and liverworts (bryophytes), lycopods and selaginellaceans (lycophytes), and fungi. Additional palynomorphs were apparently produced by freshwater algae (chlorophytes) in wetland or ponded settings. A tremendous variety of ferns and fern-like taxa must have thrived in the region, as indicated by the abundance and diversity of pterophyte spores (e.g., Table 1). These include probable representatives of the osmundaceans, schizaeaceans, gleicheniaceans, matoniacaeans, marsiliaceans, polypodiaceans, and others. Some of these probably grew as tree ferns or "trunked" forms (including *Tempskya*, see Stop 2 discussion).

A final group of palynomorphs recovered in Dakota strata encompasses a variety of organic-walled microfossils, primarily dinoflagellates and acritarchs, which are indicative of marine or marginal-marine environments (e.g., see Table 1). These forms are restricted to horizons or beds within the lower Nishnabotna/lower Terra Cotta members of eastern Nebraska and the middle to upper Woodbury Member in Iowa and Nebraska (Fig. 7). These occurrences provide evidence of marginal marine environments or tidal influences in the distal reaches of the Dakota fluvial and fluvial-deltaic systems during two general phases of regional marine transgression.

A series of generalized palynostratigraphic units (Fig. 7), when supplemented with first or last appearance datums of key taxa, permit a higher level of chronostratigraphic resolution in the nonmarine Dakota sequence than heretofore possible. The palynomorph assemblages are comparable to other well-known palynological sequences elsewhere in North America. Lower Dakota strata have not yet been as thoroughly sampled as the upper Dakota, and it seems likely that further biostratigraphic refinement may be possible within the upper Albian interval. A preliminary summary of general palynostratigraphic units (labeled units 1 through 4 on Fig. 7), in ascending order, follows.

1) Palynostratigraphic unit 1 (Fig. 7) is recognized in lower Nishnabotna strata and correlative lower Terra Cotta 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, including *Eucommidites minor*, *Disaltriangulisporites perplexus*, and *Foveosporites labiosus* (and probably *Cicatricosisporites goniodontos, C. patapscoensis, Stoverisporites lunaris*, and others). Numerous other Albian indicators are present (e.g., *Impardecispora marylandensis, Staplinisporites caminus, Densoisporites velatus, Disaltriangulisporites irregularis, D. mutabilis, Quadricolpites reticulatus*, others). Occurrences of marine palynomorphs indicate marine influences in distal areas of the Nishnabotna fluvial facies, likely marginal to the Kiowa-Skull Creek seaway.

2) Palynostratigraphic unit 2 is characterized by the highest occurrences of typical Albian palynomorphs (e.g., *Cedripites canadensis, Vitreisporites pallidus, Podocarpidites multiesimus, Impardecispora apiverrucata, Triporoletes radiatus, Cicatricosisporites aralicus, Plicatella jansonii, Exesipollenites tumulus*, others). Cenomanian indicators and marine palynomorphs are absent. Unit 2, particularly the lower portion, contains a palynoflora that shares much in common with the Muddy Sandstone of Wyoming, an upper Albian unit of the basal Greenhorn cycle (Ravn, 1995). The lowest occurrence of

Neoraistrickia robusta is shown on Figure 7 in sample interval 3; recent collections indicate that its range should be lowered to include sample intervals 1 and 2.

3) Unit 3 is recognized in strata of the lower Woodbury Member. The top is drawn at the last-appearance datum of *Neoraistrickia robusta* (see Ravn and Witzke, 1995). A number of characteristic Cenomanian taxa make their appearance at or near the base of the unit (e.g., *Balmeisporites glenelgensis, Foveosporites cenomanianus, Petalosporites quadrangulus, Triporoletes pluricellulus*). Marine palynomorphs are absent in unit 3.

4) Unit 4 is marked by a general upward increase in angiosperm diversity and a general upward loss of forms common in older Albian assemblages (e.g., *Nicholsipollis mimas, Cycadopites fragilis, Cicatricosisporites mediostriatus, Impardecispora trioreticulosa, Cingutriletes congruens*). A number of angiosperm pollen taxa make their first appearance in unit 4 (see Fig. 7), including morphologically complex forms (e.g., *Montipollis hallii*). Some important spore taxa also have their first appearances in unit 4, including *Cicatricosisporites crassiterminatus, Dictyophyllidites impensus, Foveogleicheniidites confossus*, and *Lycopodiacidites arcuatus*. The first-appearance datums of *M. hallii* and *C. crassiterminatus* are used to subdivide unit 4 (see Ravn and Witzke, 1995). Marine palynomorphs are scattered at certain stratigraphic levels in unit 4, generally increasing in abundance upward; these reflect marine influences in distal fluvial settings during regional transgression of the adjacent Greenhorn seaway.

COARSE-GRAINED EASTERN FACIES

by B.J. Witzke and G.A. Ludvigson

Mid-Cretaceous coarse-grained fluvial facies are widespread in the eastern-margin region of the Western Interior, primarily known from strata of the lower Dakota and Windrow formations. As discussed in more detail by Witzke and Ludvigson (1994), these coarse-grained sandstones and pebbly conglomerates were deposited in westward- and southwestward-flowing stream systems that drained the eastern landmass of North America. These general transport directions are reflected in Guthrie County by the orientations of trough axes within the Nishnabotna sandstones, which show a general northeast-southwest trend on average (Fig. 8). By contrast, planar and tabular foreset directions in Guthrie County show considerable dispersion (Witzke and Ludvigson, 1982), with eastward and northward directions not uncommon. The planar foreset directions bear no clear relationship to the trough axes orientations and probably represent, in part, lateral accretion along the migrating channel margins.

Composition and Source Areas

Coarse-grained eastern facies of the Dakota and Windrow formations are characterized by quartzose compositions, including quartzarenitic sandstones and quartz/chert pebble conglomerates. The Nishnabotna sandstones of southwestern Iowa average over 96% quartz, primarily first-cycle quartz grains derived from Precambrian crystalline source areas (Witzke and Ludvigson, 1994). The quartz fraction of silt- and sand-sized grains includes a minor fraction of chert grains (generally less than 2%) derived primarily from Paleozoic sources. The Nishnabotna sandstones also include minor amounts of feldspar, lithic grains, muscovite, and heavy minerals (leucoxene, zircon, tourmaline, rutile, staurolite, others) (Witzke and Ludvigson, 1994; Andrews, 1958). Quartz grains which enclose accessory minerals, including rutilated quartz (Fig. 9E) and zircon in quartz (Fig. 10F), provide further evidence of derivation from igneous and metamorphic sources.

The pebble/granule fraction of the conglomeratic units (commonly known as "peanut rock" or "puddingstone") are proportionately more chert-rich than the sand-size fraction. Point-counts of Nishnabotna conglomerates from southwestern Iowa average over 33% chert (Witzke and Ludvigson, 1994), and non-quantitative estimations in Guthrie County suggest that the pebble fraction of some lower Nishnabotna conglomerates is over 70% chert. The chert granules, pebbles, and cobbles are generally rounded and polished, and, as discussed shortly, are primarily from Paleozoic sources. The remaining pebble fraction is dominated by polished clear to milky quartz clasts, many with coarse-crystalline fabrics resembling igneous vein quartz and pegmatitic quartz varieties. Many of these quartz clasts show strained extinction patterns indicating derivation from metamorphosed or tectonized source regions (Fig. 9A); a few rare quartz grains show planar deformation features (Fig. 9B) suggestive of impact-related or high-pressure tectonic sources. Many quartz granules/pebbles display tectonite fabrics (e.g., Fig. 9C,D), further indicating origins from eastern Precambrian shield or orogenic sources. Additional quartzose grains include chalcedony (Fig. 10B), quartzite (Fig. 9F), and jaspery cherts. The quartzite grains resemble Baraboo-interval (Proterozoic) quartzites from Minnesota and Wisconsin. The jaspery cherts, commonly red or black in color, are likely derived from metamorphic terranes of the eastern subcontinent.

Mudrocks associated with the coarse-grained units of the Dakota and Windrow formations are mixtures of clay and quartz silt/sand. Many are pedogenically modified to varying degrees, displaying red mottlings/streaks, argillans, or oriented clays (Fig. 10E). Associated clay clasts

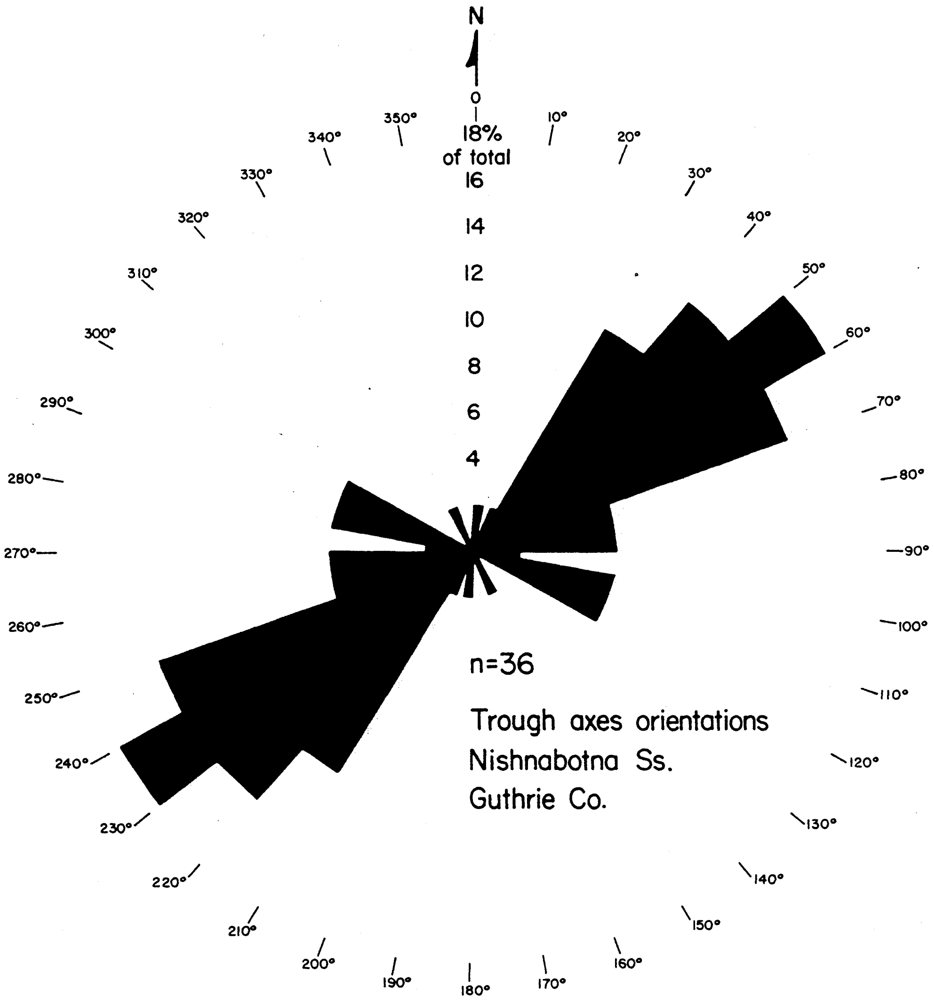


Figure 8. Trough axes orientations, upper Nishnabotna Member sandstones, Guthrie County, Iowa (from Witzke and Ludvigson, 1982).

within the coarse sandstones represent rip-ups from overbank and channel-margin muds; these locally form a mud-rich pseudomatrix for some Nishnabotna sandstones (Fig. 10D). The clay minerals which comprise these mudrocks are dominated by kaolinite with lesser illite (Frye et al., 1964). As discussed by Witzke et al. (1983) and Witzke and Ludvigson (1994), the dominant sources of these kaolinitic muds were likely the sub-Cretaceous kaolinitic regoliths developed on deeply-weathered Precambrian shield areas in Minnesota and Wisconsin (and likely Upper Michigan and Ontario as well). Additional kaolinitic regoliths were developed on weathered argillaceous Paleozoic bedrock in the region.

The source strata for many of the chert clasts in the Dakota and Windrow conglomerates can be identified with a high degree of confidence based on the recognition of various Paleozoic fossil grains. The taxonomic identity of various silicified fossils collected from these conglomerates have been compiled or noted by a number of geologists. Silicified Pennsylvanian fossils (brachiopods, crinoid debris, fusulinids) are noted in the lower Dakota conglomerates of western Iowa and eastern Nebraska where Dakota strata overlie Middle and Upper Pennsylvanian units, but Pennsylvanian fossils are absent to the east. The Guthrie County conglomerates have produced notable collections of Paleozoic fossils (Witzke and Ludvigson, 1982; Bain, 1897); Silurian corals numerically dominate these collections, but a variety of Ordovician, Silurian, Devonian, and Pennsylvanian invertebrates are also recognized (see list for Stop 1). Silicified Silurian corals and Pennsylvanian brachiopods are also known from the Lower Platte River Valley of eastern Nebraska (Woodruff, 1906, p. 196; personal observations). Silicified Paleozoic fossils are also recognized as grains within coarse sandstones in the region (Fig. 10C).

Conglomeratic strata of the Windrow Formation in northeastern Iowa, southeastern Minnesota, and western Wisconsin have also produced collections of silicified Paleozoic fossils, dominated by Ordovician and Silurian forms (see summary in Thwaites and Twenhofel, 1921). The fossils were recovered from basal Cretaceous strata variably overlying Precambrian, Cambrian, or Ordovician units. The common occurrence of Silurian fossils is of particular note, as these could not have been derived from local sub-Cretaceous units but must have been transported into the region. Silurian fossils in Windrow conglomerates above the Precambrian quartzites at Devils Lake (East Bluff, Fig. 1) and elsewhere in western Wisconsin are of particular note, as the nearest source for these would apparently be the Silurian outcrop which rims the western margin of the Michigan Basin at least 250 km to the east. The common occurrence of Silurian fossils in the Nishnabotna conglomerates of western Iowa and eastern Nebraska indicates even longer distance transport, as the nearest possible source for these would be the Silurian outcrop belt of eastern Iowa, northwestern Illinois, and southwestern Wisconsin at least 350 to 600 km to the east.

To summarize, the suite of sediments identified in the Cretaceous fluvial deposits of the Iowa area was sourced entirely from erosion of the eastern subcontinent, the vast area of North America that lay eastward from the margins of the Western Interior seaway. As discussed above, the Dakota-Windrow quartz pebbles were derived from crystalline bedrock terranes. The closest potential source for these pebbles is the vast Precambrian Shield (Canadian Shield) area of the Upper Great Lakes region (Fig. 11), indicating transport distances of at least several hundred kilometers. In addition to the quartz pebbles, a significant proportion of the eastern detritus, including kaolinitic clays and much of the first-cycle quartz sand, was also likely sourced from crystalline terranes of the Precambrian Shield. Deeply-weathered kaolinitic regoliths of probable Cretaceous age are known from the Precambrian shield area (Witzke et al., 1983). The Precambrian Shield extends farther into Ontario and Quebec, and, depending on the size of the original drainage catchment, there is no *a priori* reason why these regions may not also have been potential source areas for the Dakota sediments. A hypothetical lower Dakota drainage network is illustrated transecting the Paleozoic bedrock regions of the upper Midwest as well as

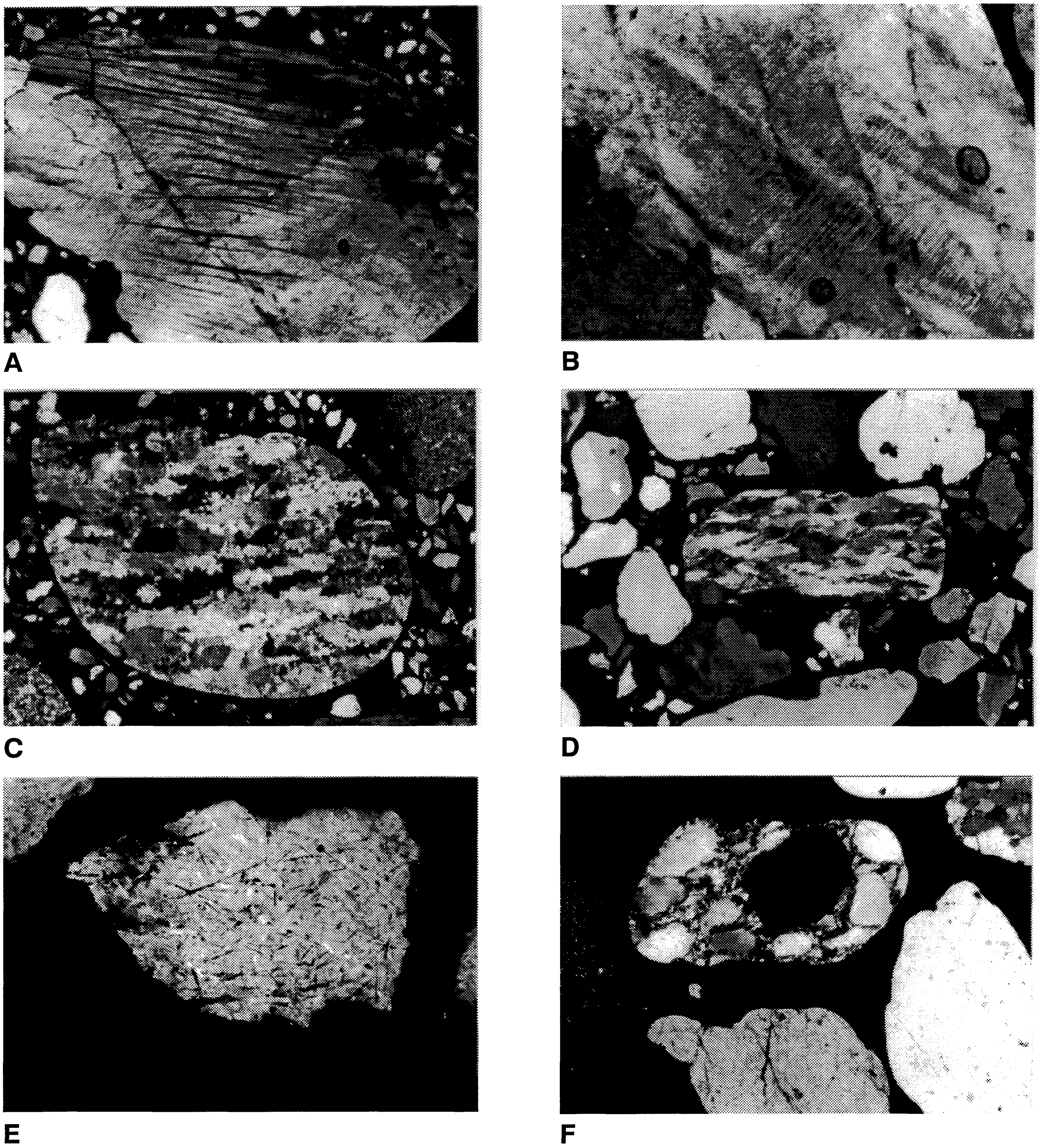


Figure 9. Quartz morphologies seen in coarse-grained Nishnabotna and Windrow facies; photomicrographs, cross-polarized light, 3.2 mm field of view unless noted. Localities: A,B,C (Loc. 38 of Witzke and Ludvigson, 1994), D (Goodhue Co., MN), E (Loc. 41 of ibid.), F (Loc. 39 of ibid.). A) Quartz granule displaying complex strained extinction pattern under cross-polarized light. B) Quartz grain displaying parallel planar deformation features; 1.3 mm field. C) Tectonite fabric in quartz granule, metamorphic fabric. D) Tectonite fabric in quartz grain; other monocrystalline quartz grains. E) Rutilated quartz grain; 0.65 mm field. F) Quartzite granule displaying consituent sand grains internally.

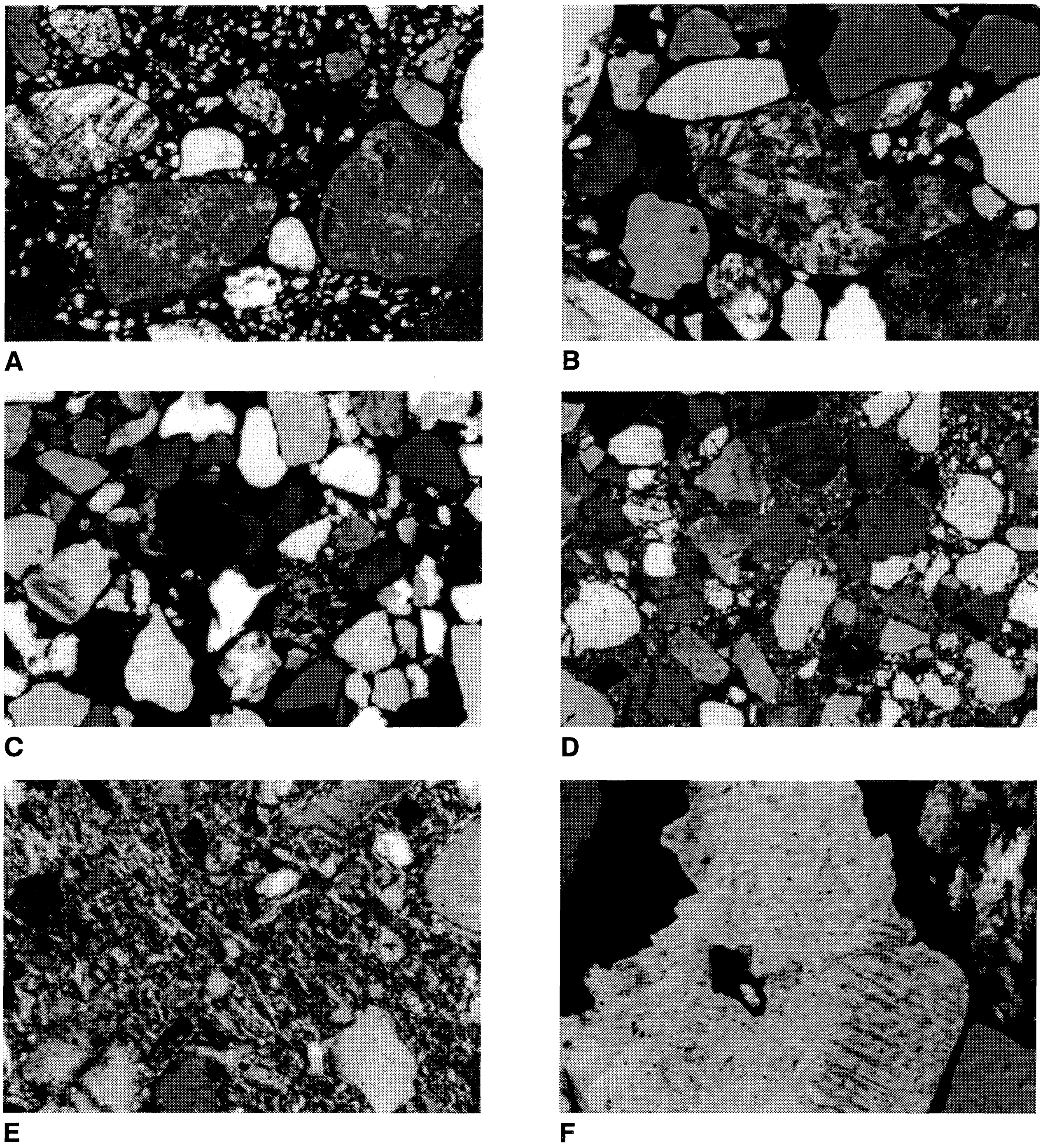


Figure 10. Rock fabrics, Nishnabotna and Windrow facies; photomicrographs, cross-polarized light; 3.2 mm field of view unless noted. Localities: A,E (Loc. 38 of Witzke and Ludvigson, 1994), B (Goodhue Co., MN), C,D (D7 core, Loc. 16 of ibid.), F (Loc. 41 of ibid.). A) Paleozoic chert granules with miscellaneous quartz silt and sand grains; 6.4 mm field. B) Chalcedony grain with radiating crystal fabrics, other miscellanceous quartz grains. C) Medium to coarse sand grains, subangular to subrounded, primarily monocrystalline quartz, chert grains include silicified bryozoan. D) Medium to coarse sand grains in argillaceous-silty pseudomatrix; 6.4 mm field. E) Silty kaolinitic mudstone, displays oriented clays (sepic plasmic fabric); 0.65 field. F) Quartz grain with zircon inclusion.

large areas of the southern Precambrian Shield (Fig. 11).

The only other potential source for the igneous and metamorphic component of the eastern detritus would be crystalline terranes within the Appalachian orogen. Such an idea may seem far-fetched at first, until one realizes that the Appalachians form the only geologically-realistic eastern boundary to the westward-draining mid-Cretaceous catchment basins of the eastern subcontinent. No tectonic events or glacial processes can be invoked to create a mid-Cretaceous drainage divide between the central Appalachians and Iowa. Any water flowing off the west side of the central Appalachians would presumably continue unabated to the eastern margin of the Western Interior seaway. The subsequent evolution of the Mississippi Embayment during the Late Cretaceous would alter this general pattern, forming a southward diversion to the westward-flowing streams.

Some geologic observations are pertinent to a consideration of the central Appalachians as a potential source of detritus for Dakota deposition. First, mid-Cretaceous fluvial deposits of the Tuscaloosa Formation in the southeastern United States were likely deposited in a separate southeastward-flowing drainage headwatered in the southern Appalachians. While the Tuscaloosa systems are disjunct with those of the Dakota, some sedimentary similarities are noteworthy. Chert-rich gravels, coarse quartz sands, and kaolinitic mudstones characterize the Tuscaloosa as far west as southern Illinois and western Kentucky and Tennessee (e.g., Willman and Frye, 1975). Similar Appalachian-sourced sediments may have been delivered to the Dakota fluvial systems. The sub-Tuscaloosa surface preserves deeply-weathered kaolinitic paleosols and local karstic bauxites (Sigleo and Reinhardt, 1988). Second, remnants of Cretaceous strata (lignites, sandstone, clay, iron oxides) are fortuitously preserved above a deeply-weathered sub-Cretaceous regolith (residuum) within the folded and faulted central Appalachian Mountains of southern Pennsylvania (Pierce, 1965) and elsewhere. Evidence of deep weathering and a thick regolith (30-75 m thick) in the central Appalachians enhances the likelihood that significant quantities of sediment could have been eroded from Appalachian sources and delivered to the westward-draining Cretaceous river systems.

Inter-Regional Considerations of Mid-Cretaceous Gravel Deposition

Eastern Subcontinent

Deposition of coarse-grained quartzose fluvial sediments were remarkably widespread in North America during the mid Cretaceous. Quartzose gravelly strata are widely distributed around the margins of the eastern subcontinent, particularly along the western coastal lowlands which bordered the Western Interior seaway. The following mid-Cretaceous stratigraphic units contain quartzose gravels: 1) Tuscaloosa Formation (Cenomanian) of the Gulf Coast and middle Mississippi Valley; 2) Baylis Formation (?Cenomanian) of west-central Illinois; 3) lower Dakota, Nishnabotna Member (upper Albian) of western Iowa, eastern Nebraska, and extreme southwestern Minnesota; 4) Cheyenne Sandstone, Longford Member of Kiowa Formation, and lower Terra Cotta Member of Dakota Formation (upper Albian), central Kansas and southern Nebraska; 5) lower Trinity Group and Antlers Formation (Albian) and Woodbine Formation (Cenomanian) of southern Oklahoma and Arkansas; 6) Windrow Formation and upper Dakota Formation (Cenomanian\Turonian?) of northeastern Iowa, southeastern Minnesota, and western Wisconsin; 7) Dakota, "Lakota," and "Fall River" sandstones (upper Albian) of eastern North and South Dakota; 8) Coleraine Formation (Cenomanian) of northern Minnesota; 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). Ouachita-sourced quartzose gravels are also known from Lower Cretaceous (Neocomian) strata of Arkansas.

These various stratigraphic units provide evidence of coarse-grained fluvial deposition within large-scale drainage basins which transected the eastern subcontinent. Several generalized drain-

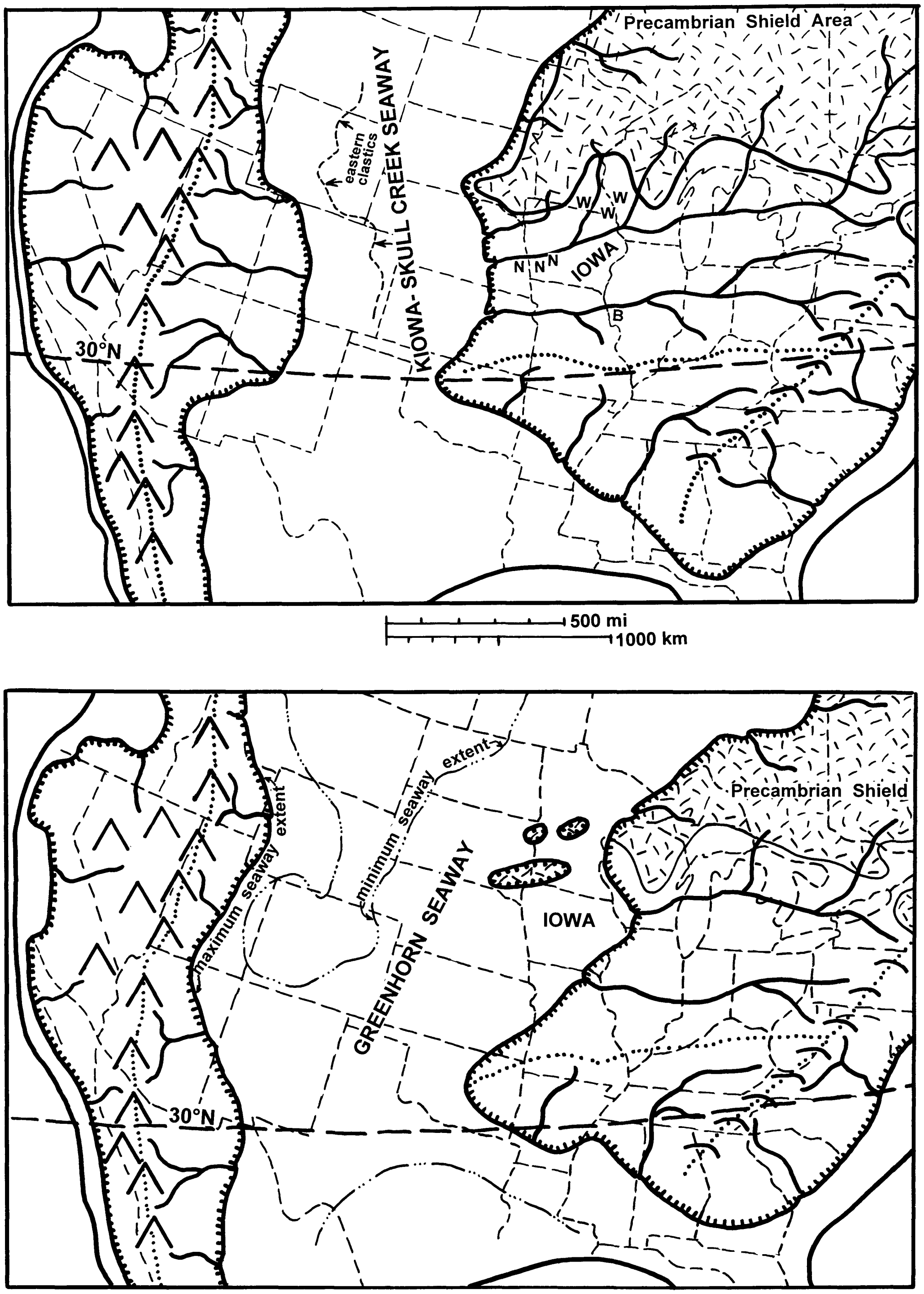


Figure 11. Mid-Cretaceous paleogeographic reconstructions of the region encompassing the present-day United States. State and province outlines are dashed; Iowa labeled. Hypothetical river drainages are schematically depicted; major drainage divides are dotted. Shorelines are hachured; mountainous regions are shown by inverted-Vs; Precambrian shield region with dashed pattern. Upper map shows an interpretation of maximum transgression of the Kiowa-Skull Creek seaway during the Late Albian. The maximum known westward extent of eastern-sourced Albian sandstones is shown by dashed line with arrows. General outcrop regions of Nishnabotna Member (N), Windrow Formation (W), and Baylis Formation (B) are marked. Lower map shows an interpretation of maximum extent of the Greenhorn seaway during the Early Turonian. Generalized shoreline position marking minimum seaway extent for the Greenhorn cyclothem shown by dashed and dotted lines. Paleolatitudes (30°N) interpolated from Scotese et al. (1988); Turonian map adapted from Witzke and Ludvigson (1994).

ages are hypothesized (Fig. 11). First, southern fluvial systems drained the southern Appalachians and Ozark and Ouachita uplifts (represented by stratigraphic units 1 and 5 listed above). Second, central westward-flowing river systems transected much of the heartland of the eastern subcontinent, draining a vast region which spanned the Midwestern Paleozoic basins, the southern Precambrian Shield (Canadian Shield), and the central Appalachians (units 2, 3, 4, 6, and 7 above). Third, northwest-flowing fluvial systems drained the northern Canadian Shield and the cratonic basins of eastern Canada (Moose River and Hudson Bay basins)(units 8, 9, and 10 above).

Pebbles of vein-type quartz and other igneous and metamorphic quartzose morphologies are recognized in the medial to distal reaches of these three general drainage systems of the eastern subcontinent. Occurrences of quartz pebble lithologies in certain stratigraphic units are of particular interest, as substantial transport distances need to be invoked to derive them from geologically reasonable source terranes. This is especially true for vein-quartz pebbles in the Kiowa Formation of central Kansas (Franks, 1975; Feldman, 1994) and the Baylis Formation of western Illinois, as these occurrences require transport distances of at least 600 to 1000 km. As previously noted, Silurian chert pebbles in Nishnabotna strata of southeastern Nebraska and southwestern Iowa require transport distances of at least 350 to 600 km. As these occurrences provide only minimum transport distances, it is likely that the river systems that transported these gravelly sediments extended even greater distances across the interior of the eastern subcontinent. River systems that extended 1000 km and more are not insignificant continental drainages, and it is not unreasonable to suggest that some of these large mid-Cretaceous trunk river systems had flows comparable to (if not greater than) some of the great eastern rivers of the present day, including the Ohio and Tennessee. Considering the evidence for widespread humid conditions (Ludvigson et al., 1992) and deep continental weathering across the eastern subcontinent, as well as the results of various climate models for the mid-Cretaceous "greenhouse world" (Barron et al., 1989) it is likely that an even greater discharge was carried off the eastern subcontinent than comparable drainage systems of the modern eastern United States and Canada. The implications of this will be considered later.

The Western Cordilleran Subcontinent and the Central Western Interior Basin

Lower and mid Cretaceous chert-rich quartzose fluvial gravels are also widespread along the western margin of the Western Interior, where Cretaceous river systems drained the rising Cordilleran (Sevier) orogen. Such gravel units trend from New Mexico northward to British Columbia, and are thickest and best developed in areas juxtaposed to the rising orogen and the developing thrust sheets. Some upper Neocomian-Aptian gravel units are known to have spread eastward over 600 km from the orogenic belt into the central regions of the foreland (or proto-foreland) basin. These latter units are typified by lower Cloverly strata in Wyoming and the Lytle Formation in Colorado. The deposition of extensive gravelly deposits has commonly been used to mark the initiation of Sevier thrusting in the western subcontinent, but their distribution has also been vexing for some geologists. For example, Heller and Paola (1989, p. 869) indicated a supposed "paradox": "the gravels appear to indicate the initiation of thrusting in the Sevier belt, yet their distribution is unusual for thrust-derived foreland-basin deposits" [where coarse deposits are typically more proximally located]. They (ibid., p 873-874) suggested that "regional uplift is required to explain the distribution of the gravel," but that regional east-dipping slopes "on the order of 1m/km" were sufficient to transport the gravelly bedloads.

If the wide distribution of Cretaceous gravel units poses theoretical problems for the tectonically-active Cordilleran subcontinent, how are we to explain the equally remarkable deposition of mid-Cretaceous gravels across the stable and low-lying eastern subcontinent? While the eastward transport of cherty gravels up to 600 km into Wyoming may seem remarkable, it is important to recall that gravel clasts were transported even greater distances across the low-lying eastern subcontinent without the benefit of a rising orogen to increase regional stream gradients.

Cretaceous exposures in the central region of the Western Interior Basin, including the flanks of the Black Hills and Bighorn Mountains, have for historic and physiographic reasons, been allied in the minds of most geologists with sedimentary sequences to the west. However, the initial fluvial filling of the developing foreland basin, as marked by Lower Cretaceous nonmarine sequences across the Western Interior, must be evaluated with respect to fluvial drainage networks and sediment source areas. Two points are raised here concerning the early phases of Cretaceous basin filling.

First, eastern-derived detrital sediments are known to have spread as far west as central Wyoming during the late Albian (see Fig. 11; summary in Witzke and Ludvigson, 1994). Provenance studies of the older upper Neocomian and Aptian-lower Albian detrital sequences in the central Western Interior Basin are generally insufficient to define the precise distribution of eastern vs western sediments across the basin, but some observations are intriguing. For example, these older strata in the Black Hills of South Dakota (Lakota Formation) have generally been inferred to be of western origin. One type of gravel in the Lakota is composed of a variety of polished chert, quartzite, and common "white quartz" pebbles (Waagé, 1959, p. 36); such gravel compositions are not typical of the western Cloverly sections but are reminiscent of the chert-quartz gravels seen in the Nishnabotna Member. Northeastward transport directions apparently dominate across Wyoming, but westward paleocurrent indicators are also evident in the Lakota and Cloverly formations at localities in central and eastern Wyoming (e.g., DeCelles and Burden, 1992; Heller and Paola, 1989). An eastern quartzose petrofacies of the Cloverly Formation in Wyoming displays westward transport directions and includes white-chert conglomerates (DeCelles and Burden, 1992). Although DeCelles and Burden (1992, p. 306) acknowledged that this "eastern petrofacies" could "reflect input from cratonic sources to the east," they rejected this idea because "no major source of chert grains . . . exists to the east." We suggest that perhaps they didn't go far enough to the east and consider the same cratonic chert sources that supplied detritus to the mid-Cretaceous fluvial systems of Nebraska and Iowa. MacKenzie and Poole (1962) had previously included some upper Cloverly sandstones in the Bighorn Mountains within their "eastern suite," which they derived from eastern cratonic and Precambrian shield sources. Are some of the Aptian sediments in the central Western Interior Basin from eastern sources? It seems a reasonable suggestion, but further study is encouraged.

The second point raises theoretical considerations about the Early Cretaceous physiography and fluvial drainage systems that developed across the subsiding Western Interior foreland basin prior to Albian marine flooding. Subsidence in the basin was highly asymmetric. Maximum Cretaceous subsidence occurred along the western margin of the basin adjacent to the rising orogen, marking the structural axis of the basin. Prior to large-scale basin filling, the axial trend of the subsiding basin would form a natural boundary which separated eastward-draining (steeper) slopes on the west side from westward-draining (gentler) slopes to the east. These patterns of eastward and westward continental slopes are largely inescapable from a simple consideration of basinal geometry – a significant part of the basin should have had westward slopes during portions of the Early Cretaceous. The associated fluvial systems would, thereby, drain the eastern subcontinent, and eastern-derived Neocomian or Aptian clastics might be expected a considerable distance westward in the basin during the early phases of regional aggradation.

The mass of western-derived sediment began infilling the western part of the basin during the Neocomian. Once the supply of western sediment began to exceed the creation of new accommodation space, depositional margins would begin to shift eastward and western sediment could begin to prograde into the central basin area. This phase represents the "overfilled foreland basin" in which "sediment derived from the thrust belt progrades well beyond the cratonward limit of lithospheric flexure" (DeCelles and Burden, 1992, p. 292).

Overfilling resulted in eastward progradation of western clastics into the central basin by the Aptian, although the eastward limits of this progradation are not known with certainty. Eastern detritus is recognized in the central basin area during the late Albian, but the westward limits of this eastern aggradation in not known with certainty for the Aptian and early Albian. Subsequent deposition across the basin is marked by a general eastward migration of open-marine facies (central seaway) during maximum transgressive phases of successive depositional cycles (Albian through Paleocene). Such a trend may reflect an eastward tectonic shift of the basinal axis and/or a progressive increase in the relative rates of basinal filling from western sources through time.

Paleohydrologic and Paleogeographic Considerations

The transport and aggradation of coarse fluvial sediments on the eastern subcontinent during the mid Cretaceous has important paleohydrologic implications. The coarsest traction load can help constrain maximum flow velocities for a given stream, which probably reflect episodic flood discharge events. The transport of pebbles and small cobbles, like those seen in the Nishnabotna gravels, requires notable stream velocities. Although overly simplistic, the standard "Hjulstrom diagram" indicates stream velocities ranging between about 75 and 350 cm/sec to transport such a bedload, providing some generalized constraints. Such velocities are all the more remarkable considering the overall low regional stream gradients that probably characterized much of the low-lying eastern subcontinent.

Mid-Cretaceous stream gradients for the Iowa area are difficult to precisely determine, but stratigraphic configurations may constrain some estimates. First, the slope of the modern-day sub-Cretaceous surface may approximate Cretaceous gradients if subsequent tectonic processes have not significantly altered the slope configuration (e.g., use elevation differences along a transect like that shown for Figure 2). While such an assumption is specifically false, the relative tectonic stability of the Iowa cratonic region may make such estimates of general interest. Second, the sub-Cretaceous surface can be "normalized" to a regional Cretaceous datum; the broad regional uniformity of Greenhorn (Turonian) deposition makes this stratigraphic unit a good choice for a regional datum (e.g., calculate sub-Cretaceous slope with respect to Greenhorn datum on a stratigraphic cross-section like that shown for Figure 3). Either approach produced similar slopes for the western Iowa region, ranging between about 0.3 and 0.6 m/km. This range is significantly less than Aptian gradients inferred by Heller and Paola (1989) for the western-sourced fluvial systems (consistent with the asymmetric basin geometry).

If relatively low stream gradients characterized the eastern landmass, the transportation of significant gravelly deposits by the Albian rivers takes on even greater significance. Since both eastern- and western-sourced rivers of the Aptian-Albian are known to have carried gravelly bedloads distances of at least 600 km, and since the western gradients were probably greater than those of the east, it logically follows that paleodischarge would necessarily have been greater in the eastern rivers. Of course, the relationship between paleovelocity and paleodischarge is a complex one, and critical flow conditions depend on a number of factors that are difficult to constrain geologically, including channel depth/width and regional gradients (Maizels, 1983). Nevertheless, it seems reasonable to suggest that the ability of the low-gradient eastern rivers to entrain gravel clasts was primarily a function of paleodischarge. As transgression of the Kiowa seaway progressed during the late Albian, base levels would rise in the Nishnabotna fluvial systems thereby decreasing regional stream gradients. This would lead to a decrease in stream competency in the distal stream systems, progressively stranding the coarse bedload in more proximal areas during regional fluvial aggradation.

As discussed above, the long-distance transport of gravelly sediments by low-gradient Albian rivers on the eastern subcontinent seems most easily explainable if the rivers are considered to have been large-scale high-discharge systems. We envisage the Dakota fluvial environments of southwestern Iowa to have been associated with a major trunk river system (or systems) that extended 1500 km eastward, draining portions of the southern Canadian Shield and likely extending to the central Appalachians (Fig. 11).

The input of freshwater to the mid-Cretaceous Western Interior seaway was clearly derived from both eastern and western sources. The relative contribution of river discharge from each side of the Cretaceous seaway has, until recently, been considered by most geologists to have been largely dominated by the western influx. This collective perception over the past several decades was apparently based on the simple geologic observation that the total volume of fluvial sediment influx along the western side of the seaway clearly exceeded that from the east. However, the volume of sediment influx is certainly not a proxy for paleodischarge — the volume of sediment shed off a rising orogen is hardly analogous with the sediment load derived from low-lying, and presumably heavily vegetated, stable continental interiors. The point here is that other factors need to be considered in an evaluation of the relative input of freshwater to the Kiowa-Skull Creek and Greenhorn seaways. In general, the freshwater input should more logically be related to two primary factors: climate (especially precipitation/evaporation) and catchment area.

The general climate of the eastern subcontinent need not be belabored here, but it is pertinent to note that general humid warm temperate to subtropical conditions persisted across much of the eastern subcontinent during the mid Cretaceous (e.g., summary in Witzke and Ludvigson, 1994). Deep-weathering profiles with kaolinitic to bauxitic regoliths on the Precambrian Shield and the Appalachian trend are of special note. There is a complete absence of mid-Cretaceous arid paleoclimatic indicators along the eastern margin of the Western Interior basin. By contrast, calcareous paleosols are known from the western-margin area (e.g., Mantzios and Vondra, 1987), suggesting a drier climate or rain-shadow effects, in part. As noted previously, the presence of extensive eastern coarse-grained mid-Cretaceous fluvial systems further supports the idea of a humid eastern subcontinent with a significant net surplus of freshwater draining to the Western Interior seaway.

The fluvial drainage basins previously outlined delineate generalized mid-Cretaceous freshwater catchments of the eastern subcontinent. These westward-draining catchments occupied several million square kilometers of the eastern subcontinent during the late Albian (Fig. 11). The immensity of this region, situated in a humid climatic regime, underscores the potential significance the eastern-margin region likely played in the delivery of freshwater to the Western Interior seaway. However, eastward-draining catchments of the western Cordilleran subcontinent during the late Albian sea-level highstand occupied a notably smaller region (Fig. 11). The western drainage divide would most likely have been located along the axis of the rising orogen, probably near the locus of eastward thrusting. This mountainous divide and its associated high-altitude precipitation (snow and rain) would lie only 200 to 600 km west of the western margin of the Albian seaway during highstand (Fig. 11). The relative sizes of the eastern and western catchments leads to a logical proposal: the eastern subcontinent delivered a greater influx of freshwater to the Western Interior seaway than the western subcontinent.

While such a proposal may run counter to more traditional Rocky Mountain perspectives, it may provide an impetus for developing contrasting models of water balance and circulation for the Cretaceous Western Interior seaway. The significant role of the eastern freshwater influx to the mid-Cretaceous seaway was borne out by recent supercomputer-based numerical climate modeling (simulations) for the Turonian of North America (Slingerland et al., in press). The results of their model run provide significant food for thought for students of the Western Interior Cretaceous — freshwater runoff into the seaway included 1.9 x 10^{12} m^3 of water per year from the west and 2.6 x 10^{12} m^3/yr from the east. The dominance of the eastern freshwater influx indicated by Slingerland et al. (in press) is conceptually important, and the volume of freshwater influx to the seaway is thought-provoking ("for perspective, the Mississippi discharge is 0.58 x 10^{12} m^3/yr").

We suggest that the relative proportion of eastern runoff into the seaway (58% of total) may be even greater than indicated by Slingerland et al. for the Albian and Cenomanian seaways. Even for the Turonian, the North American drainage divides used in their model run are generalized and may be conservative with respect to the eastern influx. Compared to our interpreted drainage divides for the Turonian (Fig. 11), their modeled divides essentially bisect each subcontinent. We favor a more eastward position for both eastern and western subcontinental divides, which has the effect of reducing the western catchment and further increasing the eastern catchment.

The relative marine inundation of eastern and western subcontinents during the Cretaceous was proportionately different for maximum highstand and lowstand episodes, primarily because of differences in elevation and continental slope. The low-relief western lowlands of the eastern subcontinent were dramatically flooded during early Turonian maximum marine transgression (at least as far as southeastern Minnesota), but the eastern shoreline apparently lay some 700 to 1000 km westward during the preceding late Albian lowstand (Fig. 11). Marginal to the Cordilleran uplands, the western shoreface advanced only about 100 to 300 km between the late Albian lowstand and early Turonian highstand (Fig. 11). These observations lead to a logical deduction: the eastern subcontinent supplied proportionately more freshwater to the Western Interior seaway during lowstands than during highstands.

We agree with the Turonian paleogeography used in Slingerland et al.'s model which portrays a major eastward marine transgression into the Hudson Bay Basin (the "Hudson Arm" of Witzke and Ludvigson, 1994). Mid-Cretaceous (Aptian-Cenomanian) units are now actually known from the Hudson Bay Basin, including mention of "marine strata" (Sanford and Grant, 1990), so this arm is not merely some hypothetical construct. The Hudson Arm represents the farthest eastward transgression of the Western Interior seaway onto the eastern subcontinent, possibly connecting with the North Atlantic marine realm via east Greenland and the Hudson Strait (as proposed by Williams and Stelck, 1975). During marine regression, seaway withdrawal from the Hudson Arm would increase the land area in this region by an even greater proportion than elsewhere on the eastern subcontinent.

We conclude this discussion in the hopes that trip participants and other interested geologists will gain a greater appreciation of the geologic significance of the eastern-margin area of the Cretaceous Western Interior basin. We want to underscore the important role this eastern region plays in defining the water balance of the associated interior seaway, and, in particular, examine evidence in the Nishnabotna Member for high-discharge coarse-grained fluvial systems on the eastern subcontinent. As discussed above, it seems likely that the eastern region supplied more water to the Cretaceous seaway than the Cordilleran runoff. When it comes to freshwater input, in other words, the eastern margin "rules." It is hoped that this and other eastern perspectives will influence and enhance a more comprehensive understanding of the Western Interior Cretaceous as a whole.

DIAGENESIS OF IRON MINERALS IN THE DAKOTA FORMATION

by Greg A. Ludvigson, Luis A. González, Brian J. Witzke, Robert L. Brenner, and Ron A. Metzger.

Within its outcrop belt, exposures of coarse-grained facies of the Nishnabotna Member are noteworthy for massive cementation by intergranular goethite cements with botryoidal fabrics as seen in thin section. On outcrop, this cementation occurs as meter- to decimeter-scale roll-front deposits with prominent liesegang banding. Such diagenetic features record the penetration of oxidizing groundwaters into sandstone aquifers that previously had been saturated with reducing groundwaters. Oxidation of dissolved ferrous iron (Fe^{2+}) into insoluble ferric iron (Fe^{3+}) leads to precipitation of ferric oxide cements that record the former positions of oxidation fronts that migrated down the fluid flowpath away from the recharge areas of oxidizing groundwaters. This process is analogous to the formation of epigenetic sandstone uranium deposits (Galloway, 1983).

When did these secondary deposits form? Does liesegang banding in Nishnabotna sandstones record the intrusion of oxidizing groundwaters attending Neogene or Quaternary landscape evolution and river incision in western Iowa, or alternatively, could these features be related to Cretaceous paleohydrologic processes? What can other regional observations on the diagenesis of iron minerals in the Dakota Formation tell us?

Where buried by younger Cretaceous units, Nishnabotna sandstones cored from the subsurface of northwest Iowa have not been observed to contain liesegang ferric oxide banding. Petrographic studies of these rocks have shown that early pore-filling siderite cements are common, with later pyrite cements (Ludvigson et al., 1987; Witzke and Ludvigson, 1994). If intergranular pyrite and siderite cements had been present in Nishnabotna sandstones before their exhumation in the outcrop belt in western Iowa, the dissolution of these reduced iron minerals in oxidizing weathering environments might have provided a source of dissolved iron that subsequently was precipitated in the liesegang banding.

Observations of massive ferric oxide impregnations of stratigraphic contacts between sandstone and mudstone units in the Nishnabotna (as seen at stop 2) are also paralleled by the observation of ferric oxide crusts armoring mudstone intraclasts in the sandstones. How can these features be interpreted? Probably the most instructive observations come from the recently-exposed Nishnabotna section at the Ash Grove Cement Quarry at Louisville, Nebraska (Fig. 6). Massive siderite cementation at the contact between the lowermost conglomerate and the overlying mudstone (Fig. 6) is now rapidly weathering to form a pseudomorphic ferric oxide impregnation of the contact. The similarity in sedimentary contexts suggests that analogous ferric oxide features (cementation of sandstone-mudstone contacts; armoring of mudstone intraclasts) observed in the Nishnabotna outcrop belt might have originated as siderite cements.

Paleosols of the Dakota Formation

Probably some of the most significant observations on iron mineral diagenesis in the Dakota Formation come from investigations of paleosols in the unit. Red-mottled mudstone paleosols are well-known from within the Dakota, from both surface and subsurface investigations (Witzke et al., 1983; Joeckel, 1987; 1991, 1992; Witzke and Ludvigson, 1994), and record the early diagenetic formation of pedogenic ferric oxides. Many of the paleosols in the Dakota also contain sphaerosiderite nodules, whose formation always precedes that of ferric oxide minerals wherever they coexist (Ludvigson et al., 1994b, 1995a, 1995b). Petrographic and geochemical studies of sphaerosiderite horizons in paleosols of the Dakota Formation are helping to yield new insights into the stable isotope paleohydrology of the Cretaceous Western Interior Basin. In addition, initial investigations of the paleomagnetism of red-mottled paleosols in the Dakota Formation are opening a new avenue of inquiry that may eventually lead to an improved understanding of iron mineral diagenesis and its paleoenvironmental significance throughout the unit.

Stable Isotope Paleohydrology of the Cretaceous Western Interior Basin

Carbon and oxygen isotopic data from the sedimentary fill in the Western Interior Basin have been used by a number of workers to investigate North American Cretaceous paleoclimatology and paleohydrology (Arthur et al., 1985; Pratt, 1985; Barron et al., 1985; Wright, 1987; Glancy et al., 1993; Pratt et al., 1993; Kyser et al., 1993; Jewell, 1993; Ludvigson et al., 1993; 1994a, 1994b; 1995a, 1995b; Dettman and Lohmann, 1994). All of the early studies and many of the recent ones have focused on marine records from the Western Interior Seaway to make inferences about continental climate systems. However, recent research (Glancy et al., 1993; Ludvigson et al., 1993; 1994a, 1994b; 1995a, 1995b; Dettman and Lohmann, 1994) explicitly focused on extracting records from biotic and authigenic freshwater carbonates to improve our understanding of continental paleoclimates. These studies have shown that freshwater carbonates from the Cordilleran landmass (i.e. the orogenic margin of the basin) have strongly depleted $\delta^{18}O$ values (Fig. 12) generally less than -10 ‰. These data indicate dominance of freshwater sources by runoff from high-altitude meltwaters. Sampling of seasonal growth layers in nonmarine unionid bivalves from Campanian through Paleogene deposits in the Cordillera have shown periodic $\delta^{18}O$ oscillations of up to 8 ‰, indicating seasonal alternations between river flows dominated by high altitude meltwater and base flows from low altitude rainfall (Dettman and Lohmann, 1993, 1994).

Concretionary carbonates that formed in meteoric-marine mixing zone phreatic environments in the Turonian Carlile Formation of northwestern Iowa and southeastern South Dakota, have meteoric $\delta^{18}O$ end-member values of -6.75 ‰, compared to marine $\delta^{18}O$ end-member values of -2.35 ‰ (Ludvigson et al., 1994a). This marine-meteoric fluid shift of about 4 ‰ corresponds to magnitudes that are typically expected in low to mid latitude coastal settings (Dansgaard, 1964; Yurtsever and Gat, 1981). This geochemical observation, when considered along with petrographic observations of pervasive dissolution of aragonite components prior to meteoric calcite cementation, suggests that the Carlile Formation was penetrated by dilute meteoric fluids, and indicates that humid terrestrial environments were developed along the eastern margin of the Western Interior seaway during the Turonian (ibid.).

Representative mid-Cretaceous continental isotopic paleoclimate records free of orographic complications are readily available from the cratonic eastern margin of the Western Interior Basin (Fig. 12). Oxygen isotopic data from early meteoric phreatic carbonates in terrestrial sequences can be used to delineate shallow groundwater $\delta^{18}O$ compositions and paleotemperature trends through time and space for the Albian-Turonian of the eastern margin of the Western Interior Basin, which could be used by paleoclimate modelers to validate applications of an emerging generation of general circulation models (GCMs) that include hydrological tracers (Charles et al., 1994; Hoffman, 1995; Hoffman and Heimann, 1994) to studies of Cretaceous climate systems. Using fractionation equations given by Carothers et al. (1988) for siderite, and Friedman and O'Neil (1977) for calcite, modeled mean annual fields for rainfall $\delta^{18}O$ values and temperatures could be tested against the paleogeographic distributions of empirical freshwater carbonate $\delta^{18}O$ data for specific time intervals, providing a feedback to GCM simulations.

Sphaerosiderite Paleohydrology: A Climate History Archive in the Dakota Formation

Investigations on secular variations in the carbon and oxygen isotopic compositions of mm-scale sphaerosiderite nodules in the Dakota Formation are currently in progress. Given their

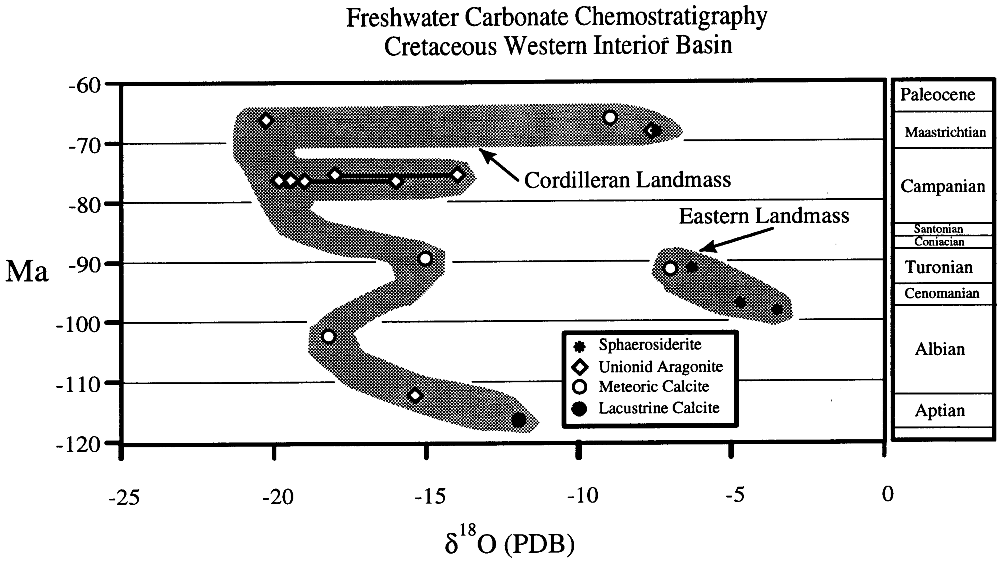


Figure 12. Secular variation of Cretaceous freshwater carbonate $\delta^{18}O$ values in the North American Western Interior Basin. Note differences between published $\delta^{18}O$ values of freshwater carbonates reported from the Cordilleran landmass and published and unpublished $\delta^{18}O$ values for freshwater carbonates from the eastern landmass recently developed by the co-PIs. Siderite $\delta^{18}O$ values from the Dakota Formation are corrected for phosphoric acid digestion at 73°C by the relation of Carothers et al. (1988), while other siderite values shown are uncorrected. Cretaceous time scale is that of Kauffman and Caldwell (1993) after Obradovich (1993). Depleted $\delta^{18}O$ values in the Cordillera are believed to reflect dominance of freshwater sources by meltwaters from snowfields at high altitudes in the Sevier orogen. Data sources for Cordilleran freshwater carbonates are Bloch (1990), Carpenter et al. (1988), Drummond et al. (1993), Fritz et al. (1971), Glancy et al. (1993), Machemer and Hutcheon (1988), and Dettman and Lohmann (1994; and personal communication). Horizontal lines span the range of $\delta^{18}O$ values collected from single well-preserved aragonitic shells of nonmarine unionid bivalves, and show the magnitudes of seasonal changes in riverine $\delta^{18}O$ recorded by fossil freshwater clams (David Dettman, 1995, personal communication). Data sources for eastern margin freshwater carbonates are Ludvigson et al. (1994a, 1995b, and other unpublished data). From Ludvigson and González (manuscript in preparation).

widespread stratigraphic and geographic distribution in mudstone facies of the Dakota Formation (see S symbols in figs. 2 and 3), these authigenic carbonate cements have great potential as an archive for mid-Cretaceous paleoenvironmental information. The studied sphaerosiderite nodules were extracted from a 60 m interval of kaolinitic fluvial mudstones punctuated by fluvial sandstones, paleosols, and lignites in a group of closely-spaced cores at Sergeant Bluff, Iowa, and one surface exposure in Nebraska. Sphaerosiderite, a variety of radial-spherulitic siderite ($FeCO_3$), has been shown to form in modern riparian wetland soils (Stoops, 1983; Stoops and Eswaran 1985; Landuydt, 1990). Ancient sphaerosiderite horizons typically occur in poorly-drained paleosols in coal-bearing stratigraphic intervals, and probably formed in phreatic environments below the positions of ancient water tables (Tucker, 1981; Retallack, 1981; Leckie et al., 1989; Browne and Kingston, 1993; Witzke and Ludvigson, 1994; Ludvigson et al., 1994b, 1995a,b).

Sphaerosiderite nodules in the Dakota Formation occur in discrete horizons that are contained in successions of multiple amalgamated paleosols (Fig. 13). Where discrete paleosol profiles are bounded by strata with primary sedimentary structure (e.g. interval from 142' to 145' in Fig. 13), sphaerosiderite horizons are concentrated at the base of the profile. Broken surfaces from the

Sergeant Bluff cores show that sphaerosiderite nodules are arrayed along dark clay-filled horizontal root traces. Dakota sphaerosiderites are largely free of detrital inclusions, and comparison with their modern analogues (Stoops, 1983) suggests that sphaerosiderite crystallized as a void-filling phreatic cement in open root channels. Epifluorescence studies of polished thin sections of Dakota Formation sphaerosiderites by laser scanning confocal microscopy have shown that each sphaerosiderite horizon is characterized by a unique pattern of constructive concentric fluorescent zonation. The fluorescence zonation corresponds to subtle concentrically-zoned color changes as seen in reflected visible light. These results, along with supporting light microscopic and cathodoluminescence studies, have failed to disclose any other coexisting generations of diagenetic carbonate. In light of geochemical relationships discussed below, these observations indicate that the concentric growth zonation in sphaerosiderites of the Dakota Formation preserve a primary record of changing pore fluid chemistry in mid-Cretaceous coastal wetland soils.

Meteoric Siderite Lines

Carbon and oxygen isotopic data from discrete sphaerosiderite horizons in the Dakota Formation plot in two different types of trends. Horizons with highly variable $\delta^{13}C$ values and relatively invariant $\delta^{18}O$ values (Fig. 14A) define linear trends that are analogous to the meteoric calcite lines found in limestones stabilized in meteoric phreatic environments (Lohmann, 1988; Swart et al., 1993), and which we define as meteoric siderite lines (MSL). The pattern of concentric zonation has been used to investigate spatial controls on the stable isotopic composition of Dakota sphaerosiderites. Concentric sampling has shown a systematic isotopic zonation, with the interior portions of sphaerosiderite nodules plotting at the ^{13}C-depleted end member of meteoric siderite lines (Fig. 3A), and the outer portions plotting at the ^{13}C-enriched end member. Extremely negative $\delta^{13}C$ values, including some lower than -50 ‰ in the Dakota Formation, are indicative of sphaerosiderite formation in a zone of *anaerobic* oxidation of biogenic methane, possibly by iron-reducing bacteria (Chapelle, 1993, p. 330). The invariant siderite $\delta^{18}O$ values defining the meteoric siderite lines are interpreted to record equilibrium siderite precipitation from shallow groundwater at the mean annual temperature of the respective wetland paleosol. Since early meteoric phreatic diagenesis integrates the mean annual oxygen isotopic composition of local precipitation and the mean annual temperature (Hays and Grossman, 1991; Swart et al., 1993), the $\delta^{18}O$ values of MSLs in the Dakota Formation can potentially be used to calculate paleotemperatures and groundwater $\delta^{18}O$ utilizing the siderite ^{18}O fractionation equation of Carothers et al. (1988).

Estimated siderite paleotemperatures for the two MSLs shown in Figure 14A are shown in Figure 15. Significantly, at early diagenetic temperatures (10°-30°C) the curves suggest groundwater $\delta^{18}O$ values that are reasonable for coastal lowland rainfall at northern mid-latitudes (Yurtsever and Gat, 1981). Furthermore, these values overlap with those estimated for calcite defining a meteoric calcite line of -7 ‰ reported from the Turonian Carlile Formation by Ludvigson et al. (1994a). These results indicate that a geochemical record of early meteoric phreatic diagenesis is preserved in mid-Cretaceous coastal plain successions in the area around Sioux City, Iowa. Given that the $\delta^{18}O$ of meteoric water is highly temperature dependent (e.g. Yurtsever and Gat, 1981), the temporal changes between the two MSLs (-4.69 ‰ for sphaerosiderite horizon SCB4B-119.6; -2.86 ‰ for sphaerosiderite horizon SCB4A-139; Figs. 14A, 15) are most likely controlled by climatically-induced changes in the isotopic composition of groundwater. These data strongly suggest that a record of climatic change is preserved in these authigenic carbonates.

Mixing Zone Sphaerosiderite

As noted by Ludvigson et al. (1995b), a different type of isotopic trend is recognized in sphaerosiderite horizons for which there is independent micropaleontological, sedimentologic,

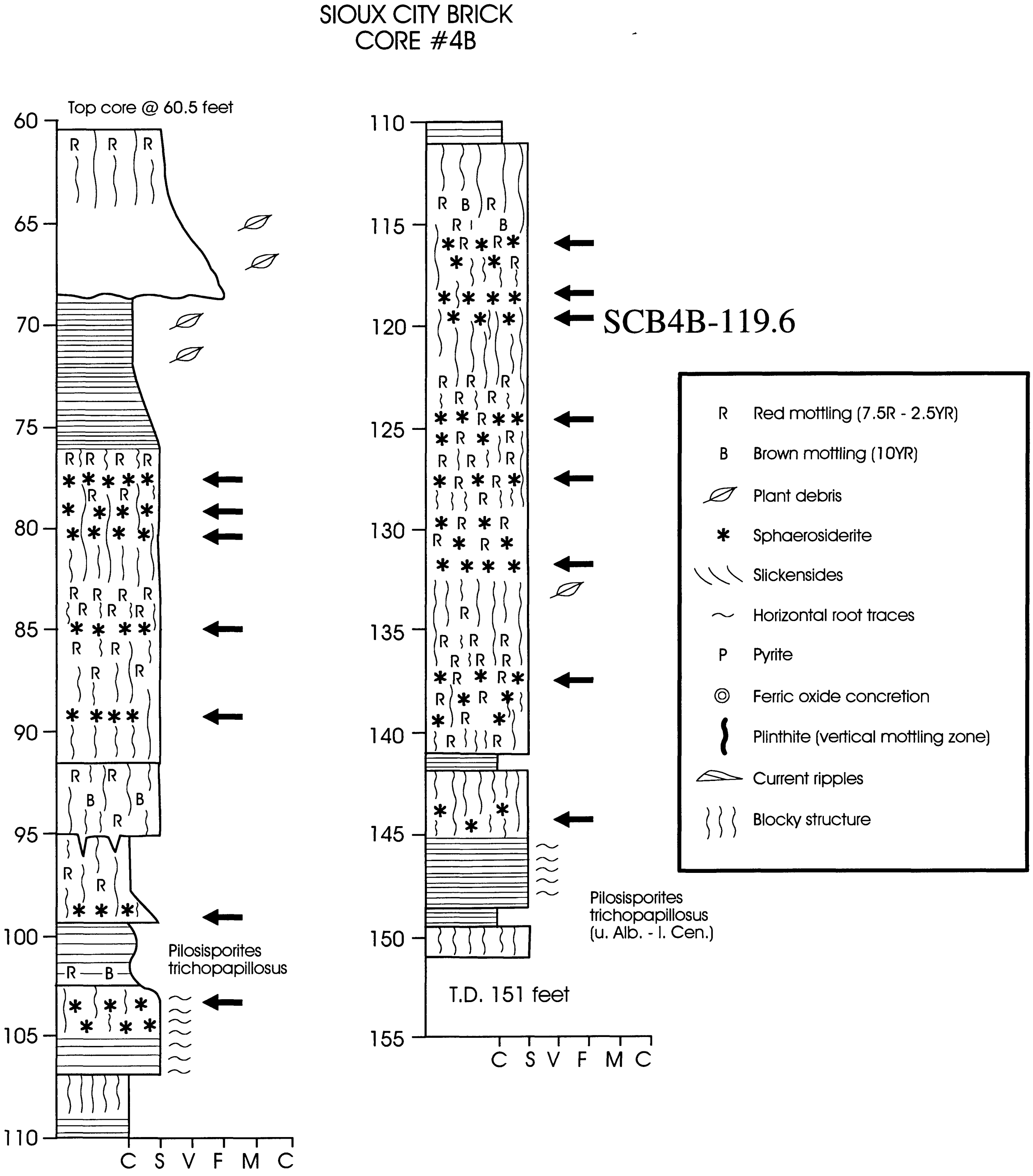


Figure 13. Sedimentologic log of Sioux City Brick exploration core #4B from Sergeant Bluff, Iowa. Arrows denote the position of major sphaerosiderite horizons within the succession, which mostly consists of discrete and stacked amalgamated siliciclastic mudstone paleosols. A generalized legend to the right contains explanatory material for a set of exploration cores drilled in 1993. Occurrences of the mid-Cretaceous palynomorph *Pilosisporites trichopapillosus* are noted from carbonaceous intervals sampled from the core. Isotopic data and paleohydrologic interpretations of sphaerosiderite horizon SCB4B-119.6 are shown in figures 14 and 15.

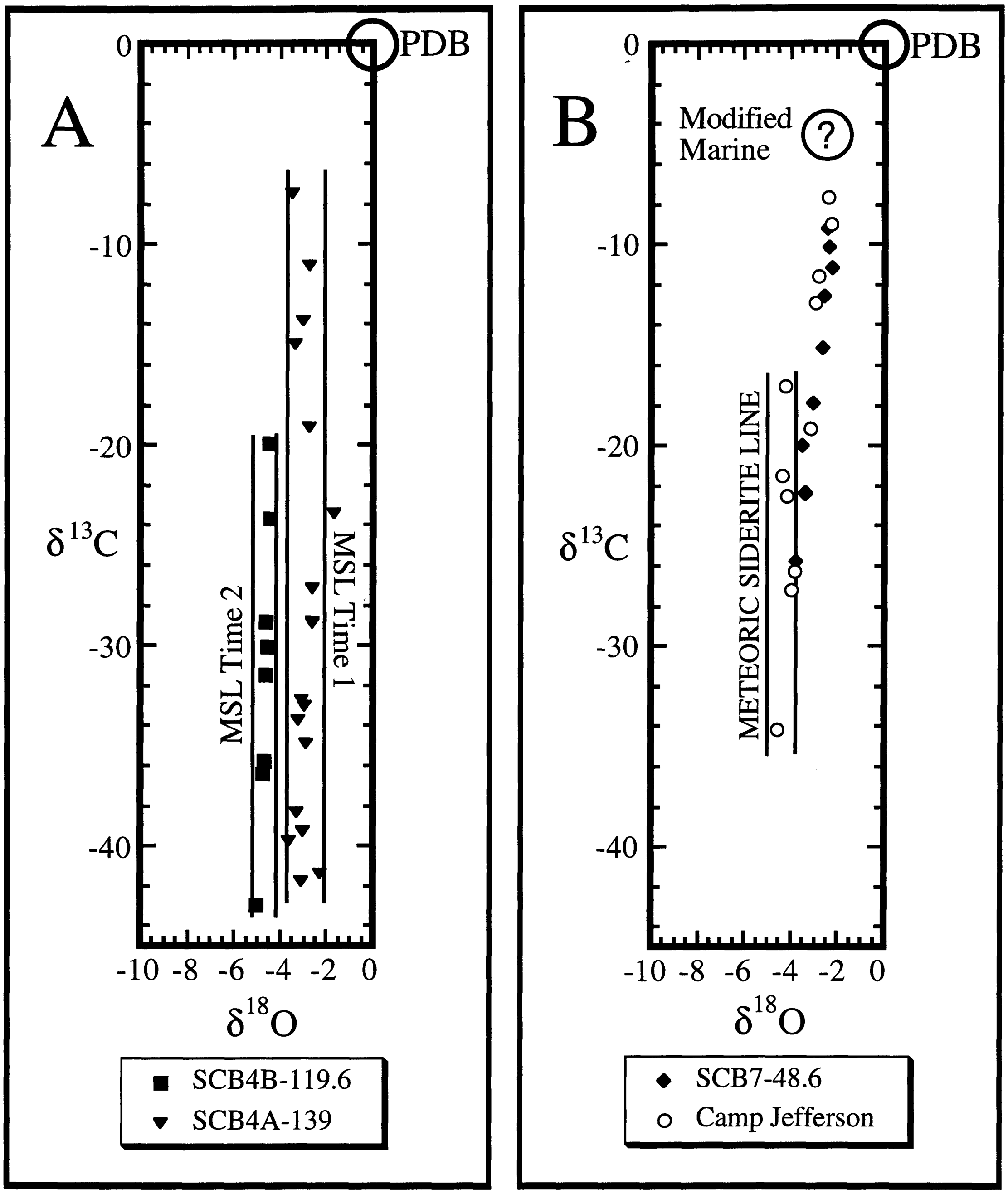


Figure 14. Carbon and oxygen isotope plot of selected sphaerosiderite horizons sampled from the Dakota Formation of western Iowa and eastern Nebraska. All $\delta^{18}O$ values are corrected for siderite-phosphoric acid-liberated CO_2 fractionation at 73°C after the relation of Carothers et al. (1988). Data are discussed in Ludvigson et al. (1995b). A. Meteoric siderite lines (MSL) with invariant $\delta^{18}O$ values from two Cenomanian sphaerosiderite horizons sampled from exploration cores in the Dakota Formation at Sergeant Bluff, Iowa. B. Albian-Cenomanian sphaerosiderite horizons from Iowa and Nebraska interpreted to record mixing of meteoric and modified-marine phreatic fluids, defined by positive covariant $\delta^{13}C$ and $\delta^{18}O$ trends.

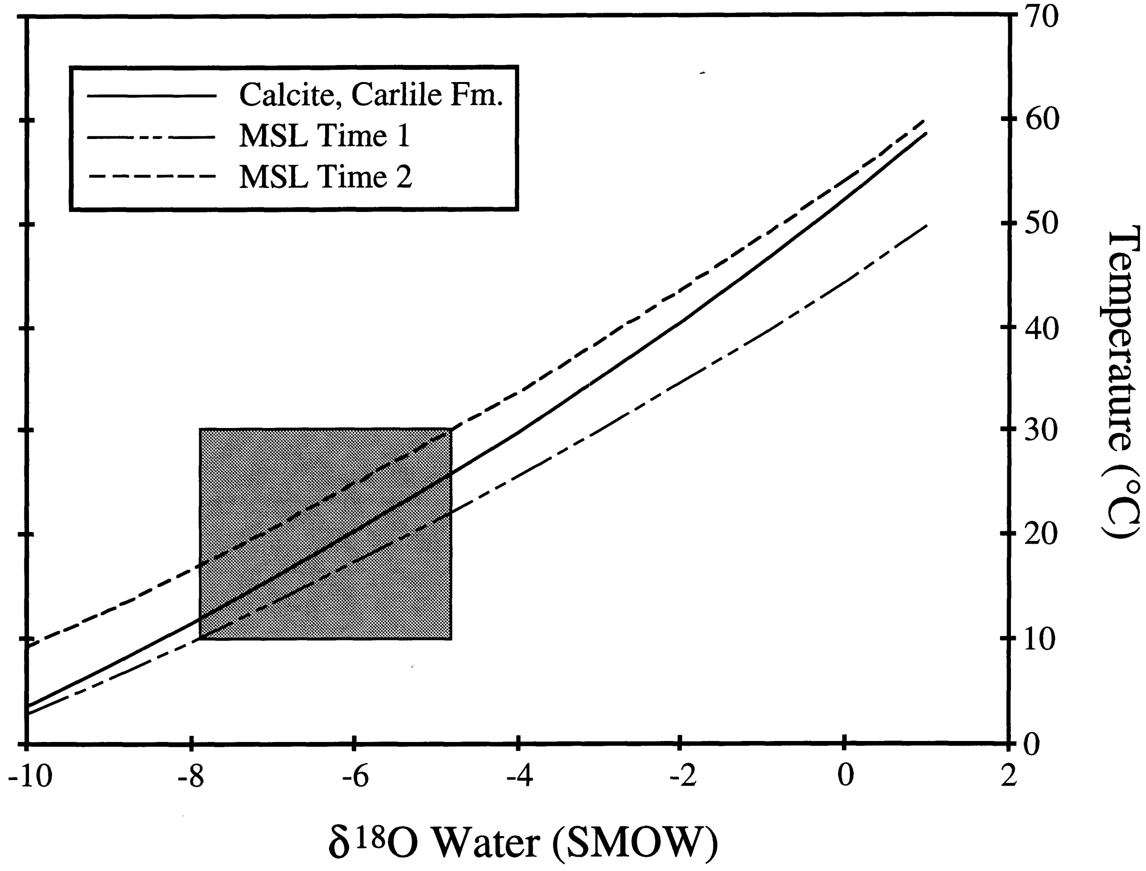


Figure 15. Estimates of paleotemperatures and groundwater $\delta^{18}O$ values calculated from mid-Cretaceous meteoric phreatic carbonates in the area around Sioux City, Iowa. Estimates based on the Cenomanian meteoric siderite lines in Figure 14A ($\delta^{18}O$ MSL Time 1 = -2.86 ‰ PDB; $\delta^{18}O$ MSL Time 2 = -4.69 ‰ PDB) are calculated using the siderite ^{18}O fractionation equation of Carothers et al. (1988). An estimate based on the Turonian meteoric calcite line of Ludvigson et al. (1994a) from the Carlile Fm ($\delta^{18}O$ MCL = -7 ‰ PDB) is calculated using the calcite ^{18}O fractionation equation of Friedman and O'Neil (1977). The shaded area shows that over the range of early diagenetic temperatures (10°-30°C), the curves suggest groundwater $\delta^{18}O$ values ranging between about -5 to -8 ‰ SMOW, which are reasonable values for mean annual coastal lowland rainfall at northern mid-latitudes (Yurtsever and Gat, 1981; Hoffman and Heimann, 1994).

petrographic, and geochemical evidence for marine influences on coastal plain sequences in the Dakota. Horizons with positive covariant $\delta^{13}C$ and $\delta^{18}O$ trends are shown from SCB7-48.6 and the Camp Jefferson section (Fig. 14B).

The SCB7-48.6 sphaerosiderite horizon (Fig. 14B) is contained within the interval of the Middle Cenomanian "Sergeant Bluff Lignites", which contain marine dinoflagellate cysts (Witzke and Ludvigson, 1994; Ravn and Witzke, 1994). Estuarine sandstones from this interval contain marine burrowing fabrics and tidal bundling sequences (Witzke and Ludvigson, 1994). Finally, thin sections show that pyrite inclusions are ubiquitous in SCB7-48.6 sphaerosiderite nodules, indicating that microbial sulfate reduction was coeval with siderite formation in reducing soil pore waters. The Camp Jefferson sphaerosiderite horizon (Fig. 14B) was sampled from a Late Albian plinthic paleosol (Joeckel, 1992) in the Terra Cotta Member of the Dakota Formation (unit 6, locality 2 of Joeckel, 1987). Recent palynostratigraphic sampling of gray claystones in lateral accretion sets immediately below the paleosol (units 1-3 of Joeckel, 1987) revealed the presence of marine dinoflagellate cysts and acritarchs, indicating marine influences during deposition. Small pyrite inclusions are also present in these sphaerosiderite nodules, indicating that anaerobic sulfate reduction was concurrent with siderite formation.

The Camp Jefferson section appears to record the paleohydrologic influence of the Late Albian Kiowa-Skull Creek marine cycle (Cycle T_5 of Kauffman, 1977), while the SCB7-48.6 horizon appears to record the paleohydrologic influence of the Middle Cenomanian onset of the Greenhorn marine cycle in the area (Cycle T_6 of Kauffman, 1977). Meteoric-marine fluid mixing processes in coastal wetland paleosols of the fluvial-estuarine environments of the Dakota Formation may have been facilitated by tidal pumping (Ludvigson et al., 1995b), or possibly by storm surges.

Sphaerosiderite horizons with positive covariant $\delta^{13}C$ and $\delta^{18}O$ trends (Fig. 14B) are interpreted to record fluid mixing between meteoric phreatic and modified marine phreatic fluids. Isotopic data from the Camp Jefferson horizon (Fig. 14B) define a meteoric siderite line, but also show a trend toward concurrent $\delta^{13}C$ and $\delta^{18}O$ enrichment toward a modified marine phreatic end member. A similar isotopic trend is shown for the SCB7-48.6 horizon (Fig. 14B). In concentrically-sampled nodules, the ^{13}C and ^{18}O-depleted end-member compositions are obtained from the centers of the nodules, and the ^{13}C and ^{18}O-enriched end-member compositions from the periphery.

Electron microprobe transects of the full diameters of sphaerosiderites with positive covariant $\delta^{13}C$ and $\delta^{18}O$ trends show that these nodules mostly consist of greater than 95 mole % $FeCO_3$, although at their periphery, Fe contents drop below 80 mole % and Mg and Ca contents increase to about 10 mole % each. Observations of concentric elemental zoning in these sphaerosiderites suggest that while $FeCO_3$ end-member compositions in the interior growth zones are consistent with Mozley's (1989) criteria for siderite formed during early meteoric diagenesis, the concurrent ^{18}O, Mg, and Ca enrichments in the exterior growth zones provide supporting evidence for fluid mixing between meteoric and modified marine pore waters. Results from the Camp Jefferson sphaerosiderites (Fig. 3B) suggest that with adequate sampling, the $\delta^{18}O$ of meteoric siderite lines can be determined from sphaerosiderite horizons that formed in marine-influenced wetland settings.

PRELIMINARY PALEOMAGNETIC STUDY OF PLINTHIC PALEOSOLS OF THE DAKOTA FORMATION

by James E. Faulds, Greg A. Ludvigson, and Robert L. Brenner

Paleomagnetic studies of sedimentary rocks within the stable interiors of cratons can be fruitful for establishing the position of paleopoles (e.g., May et al., 1986; Globerman and Irving, 1988; Diehl, 1991) and for estimating the age of diagenesis or alteration (e.g., Globerman and Irving, 1988). The upper Albian to Cenomanian Dakota Formation of Nebraska and Iowa provides an excellent opportunity to better define the mid-Cretaceous paleomagnetic reference pole for North America. Good exposures of sandstone and mudstone occur along entrenched drainages and within operating clay pits in the region. Plinthic paleosols in the mudstone facies have the greatest potential, because diagenesis and the attendant formation of magnetic carriers such as goethite and hematite accompanied soil-forming processes immediately after deposition (Joeckel, 1987; 1991, 1992). Here, we report the findings of a preliminary paleomagnetic study of the Terra Cotta Member of the Dakota Formation in southeastern Nebraska (a lateral equivalent of the Nishnabotna Member of Iowa). Five paleomagnetic sites were collected, including three sites from mudstone facies in the Endicott Clay Products Pit near Fairbury, and two sites from a sandstone lens near Steele City, all in Jefferson County, Nebraska (Fig. 1).

Characteristic remanent magnetizations (ChRM) were isolated using progressive alternating field (AF) and thermal demagnetization techniques and principal component analysis (e.g., Kirschvink, 1980). Site and locality mean directions were calculated using Fisher (1953) statistics. AF demagnetization with inductions ranging up to 100 milli-Tesla (1,000 oersteds) failed to remove any appreciable magnetization (< 10 %). This suggests that titanomagnetite is not a major carrier of the ChRM within either the sandstone or mudstone. Nearly all samples demagnetized along discrete linear paths when subjected to thermal demagnetization (Fig. 16a). Median destructive unblocking temperatures (T_{ub}) within the mudstone ranged from 400°C to 640°C. In all cases, the magnetization was completely removed by 665°C. This suggests that the primary magnetic carriers are maghemite and hematite. Some of the hematite may have been produced by the dehydration of goethite. Any conversion of goethite to hematite was not induced by the thermal demagnetization, as evidenced by the consistency in orientation of the ChRM within and between sites.

The ChRM has a northerly declination and moderate positive inclination ($D = 356.4^\circ$, $I = 59.4^\circ$, $\alpha_{95} = 5.59^\circ$, $N/N_0 = 5/5$ sites) (Fig. 16b) and is essentially identical for the sandstone and mudstone facies (Table 2). Four sites yield a ChRM of normal polarity, whereas one sandstone site has a dominant magnetization of reverse polarity ($D = 166.9^\circ$, $I = -55.8^\circ$, $N/N_0 = 5/8$). No tilt corrections are needed, because the units are flat-lying. At the 95% confidence interval, the group site mean (reverse polarity site inverted) overlaps both the 100 Ma and 20 Ma expected directions (Fig 16c).

Although firm conclusions are precluded by the small number of sites, these data imply that the ChRM was acquired sometime after deposition. This is most evident with the reverse polarity site, because the suspected 100 Ma age of the unit falls within a long period (~120 to 84 Ma) of normal polarity (e.g., Helsley and Steiner, 1969; Irving and Couillard, 1973). Several features of the sandstone exposures, including variable amounts of both cement and iron staining and proximity to the modern weathering zone, suggest that significant alteration post-dated deposition. Thus, the ChRM within the sandstone may commonly represent a chemical remanent magnetization (CRM) acquired well after deposition. Relatively high porosity within the sandstone probably permitted ready access of iron-bearing and/or oxidizing solu-

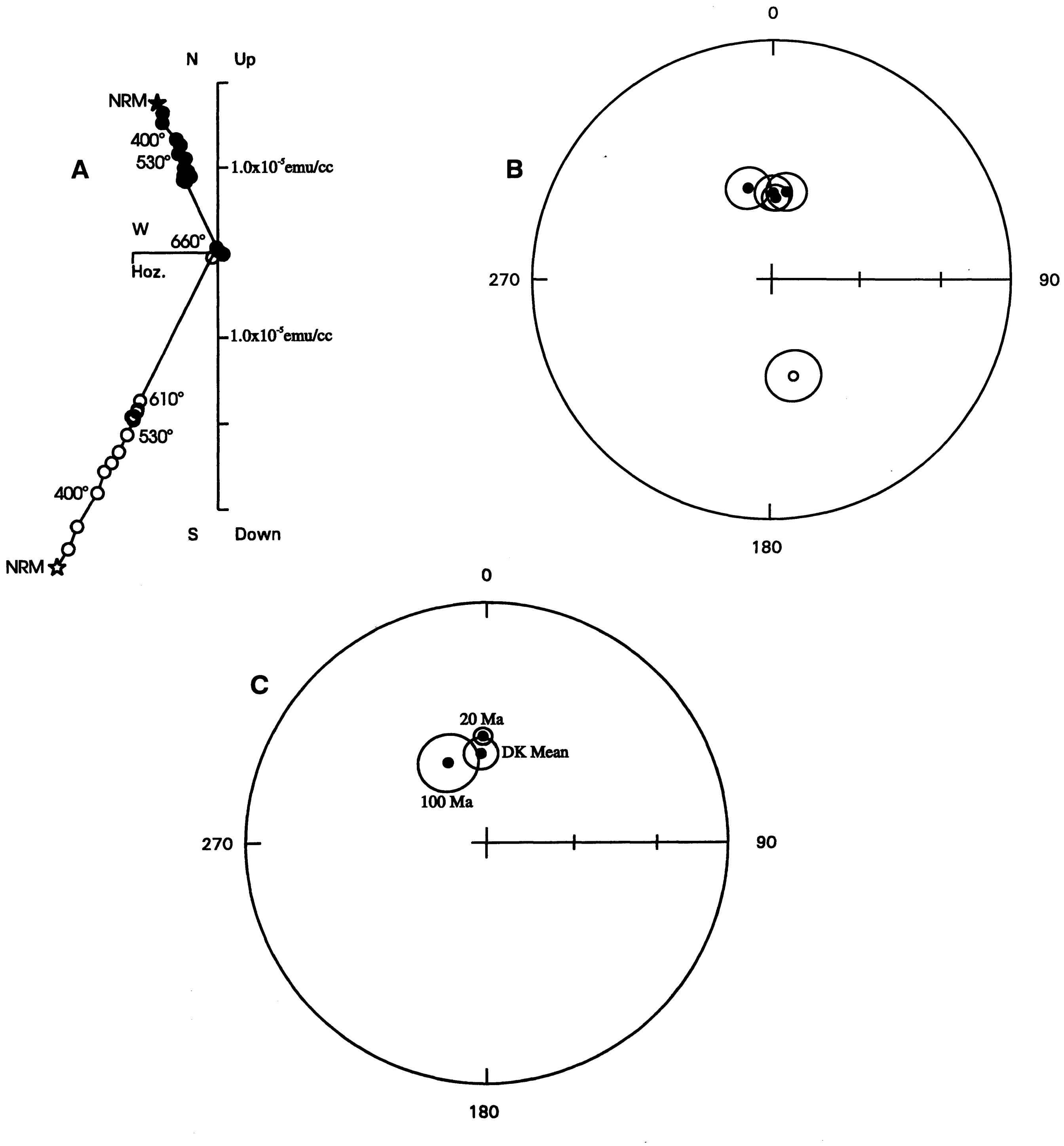


Figure 16. Paleomagnetic data from the Dakota Formation. (a) Representative orthogonal demagnetization diagram from a plinthic mudstone paleosol within the Terra Cotta Clay Member of the Dakota Formation showing the progressive demagnetization behavior of a sample during thermal demagnetization. The endpoint of the magnetization vector is projected onto the both the horizontal (solid circle) and vertical planes (open circles) over a series of demagnetization steps. Peak temperatures are given in degrees Celsius. In this case, the direction of the magnetization component (D = 338.0°, I = 62.7°) was isolated between 100 °C and 660 °C, with a mean angular deviation of 1.9°. (b) Equal-area projection of site mean magnetizations in the Dakota Formation, southeastern Nebraska. Solid symbols are projections on the lower hemisphere; open symbols on the upper hemisphere. The projected cones of 95 % confidence are also shown for each site. (c) Equal area stereoplot comparing the group site mean of the Dakota Formation with the expected 100 Ma and 20 Ma reference directions, which were derived from the paleomagnetic poles of Irving and Irving (1982). .

Table 2. Paleomagnetic Data, Dakota Formation, Southeastern Nebraska.

Site	Rock Type	Declination	Inclination	k	α_{95}	N/N_0
DK1	sandstone	9.2	59.6	85.8	6.56	7/7
DK2	mudstone	0.7	60.4	82.3	6.14	8/8
DK3	mudstone	2.4	62.1	179.9	4.51	7/7
DK4	mudstone	345.2	57.6	70.1	7.26	7/8
DK5	sandstone	166.9	-55.8	73.1	9.01	5/8
DK1-3	mudstone	355.7	60.3	233.5	8.09	3/3
DK1-5	mudstone and sandstone	356.4	59.4	188.1	5.59	5/5
20 Ma[1]	--	358.0	53.3	149	3	--
100 Ma[1]	--	334.3	59.6	597	10	--

[1] Expected directions derived from Irving and Irving (1982). K = estimate of precision (Fisher, 1953); α_{95} = semi-angle of cone at 95 % confidence level; N/N_0 = number of samples (sites) calculated for site mean/ number of samples (sites) measured.

tions and ultimately promoted acquisition of the CRM. In contrast, the mudstone facies is relatively impermeable and was sampled from freshly exposed strata in an operating clay pit that were far removed from any post-Cretaceous weathering phenomena. The preservation of abundant palynomorphs within thin lignite beds in the mudstone succession at the Endicott pit further shows that since they were buried, these strata have not been subjected to alteration in oxidizing environments. However, the dehydration of primary goethite to hematite ("burial reddening" of Retallack, 1991) may have produced a secondary magnetization within the mudstone paleosols, possibly during Tertiary time. It should be noted, however, that the Albian paleomagnetic reference pole for North America is not particularly well defined. It is based primarily on 20 sites from 100 Ma intrusions in Arkansas (Globerman and Irving, 1988). This 100 Ma reference pole is compatible though with other mid to late Cretaceous reference poles (e.g., Irving et al., 1993; Diehl, 1991; Shive and Frerichs, 1974). Many additional sites must be analyzed within the Dakota Formation to determine whether significant overprinting of magnetization occurred during Tertiary time or if the Albian reference pole should be slightly revised. Perhaps the most important finding of this preliminary study is that both the mudstone and sandstone facies of the Dakota Formation carry a stable remanent magnetization that may provide important information concerning the age and conditions of diagenesis.

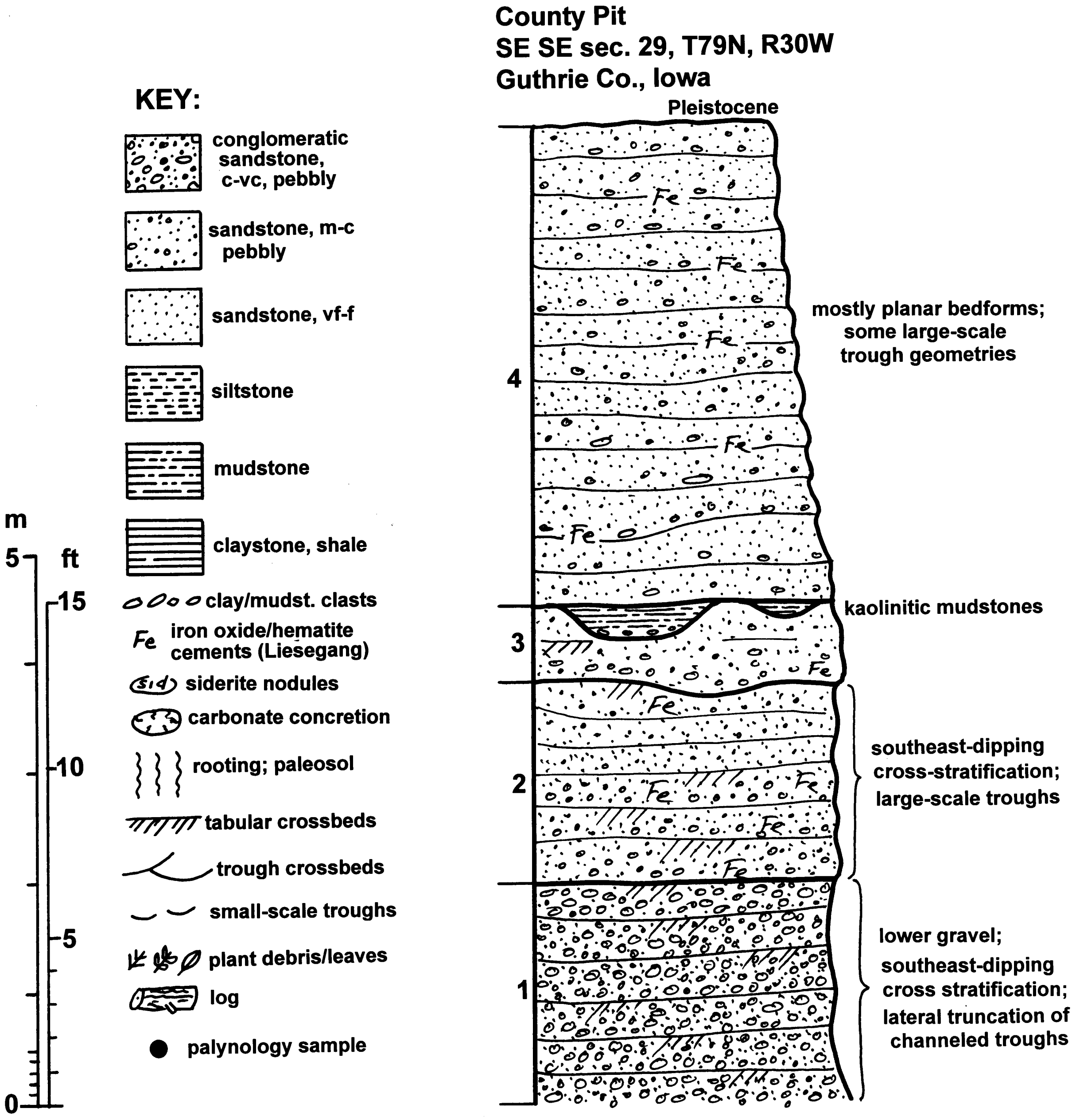


Figure 17. General stratigraphic section of lower Nishnabotna Member strata exposed at Stop 1, Guthrie Co., Iowa.

STOP 1: Chert-rich conglomerates of the lower Nishnabotna, Guthrie County sand and gravel pit

Instructive exposures of coarse-grained lower Nishnabotna fluvial facies are well displayed in Jackson Township bordering the valley of the South Raccoon River. Numerous pits, both active and abandoned, have been opened in these coarse deposits to quarry high-quality sand and gravel aggregate, particularly the pebbly fraction of the so-called "peanut gravels." The Cretaceous strata unconformably overlie Middle Pennsylvanian units of the Marmaton Group in this area, with Pennsylvanian shale and limestone exposures seen at lower elevations in the nearby valley bottom edges.

We will examine one of these pits, the County Pit (managed by the Guthrie County Engineer's Office). This was one of the stops visited on an earlier field trip (Witzke and Ludvigson, 1982), but operations since then have significantly expanded the pit area laterally and deepened it to expose a chert-rich conglomerate (unit 1) not previously seen. A generalized composite section is illustrated in Figure 17, and some of the variation documented earlier in the pit area by Witzke and Ludvigson (1982) is shown in Figure 18 to provide a feeling for lateral variability within the lower Nishnabotna Member. Unit 1 (Fig. 17) lies at or near the base of the Cretaceous section, probably within a few feet of the Pennsylvanian surface.

The deepest excavations in the central area of the pit operations expose about 2 m of the coarsest facies yet identified in the Cretaceous of western Iowa (unit 1, lower gravel). These beds are displayed in the face as tabular bodies of conglomerate approximately 25 to 50 cm thick, some fining upward into thin (5-10 cm) capping intervals of medium-grained sandstone. Individual beds are cross-stratified, displaying unidirectional southeast-dipping foresets. Lateral tracing of the conglomerate beds reveals lateral beveling or truncation of bedforms by large-scale shallow trough channels. The gravel fraction of these beds is dominated by chert and quartz pebbles approximately 1 to 2 cm in diameter. However, much larger clasts are scattered in the unit, including Paleozoic chert cobbles up to 8-10 cm diameter (some possibly to 18 cm). In addition, quartzite and quartz tectonite clasts up to 8 cm have also been identified.

Units 2 through 4 (Fig. 17) are well displayed in the central and western regions of the pit. Unit 2 (1.8-2.1 m) is a pebbly coarse-grained sandstone, conglomeratic in the lower meter; tabular cross-sets (25 to 40 cm thick) all dip to the southeast. Lateral tracing of beds indicates that the bedsets form larger-scale shallow trough channels that are tens of meters in lateral dimension. The unit shows iron-oxide cementation in Liesegang patterns. Unit 3 (40-70 cm) is coarser-grained conglomerate with clasts to 5 cm; its surface is cut in places by swale-fillings of pale gray sandy kaolinitic mudstone (up to 25 cm thick). The contact with overlying unit 4 displays 20 to 30 cm of relief in the central pit area.

The highest Dakota strata in the pit are included in unit 4 (to 4.5 m thick). This interval is dominantly a conglomeratic sandstone with chert and quartz clasts averaging about 1 cm in diameter (some to 2-5 cm; one 13-cm clast of fossiliferous chert noted). The interval is irregularly cemented by iron oxides in Liesegang patterns. Unit 4 primarily displays planar bedforms, with minor clast imbrication observed in a few beds. Some trough geometries are observed with lateral dimensions of 2 to 3 meters or more.

Excellent exposures of Nishnabotna strata are also displayed in the east pit area. The central east pit shows an erosional contact at the base of unit 4, with at least 75 cm of relief on the underlying surface (see also Fig. 18, southeast pit). Underlying beds show alternations between coarse conglomeratic sandstone and medium-grained sandstone. The far east pit area is particularly interesting, and displays complex channel and trough geometries, primarily in the middle strata (probably units 2 and 3). Large-scale channel cut-outs locally truncate up to 1.5 m of strata in this area.

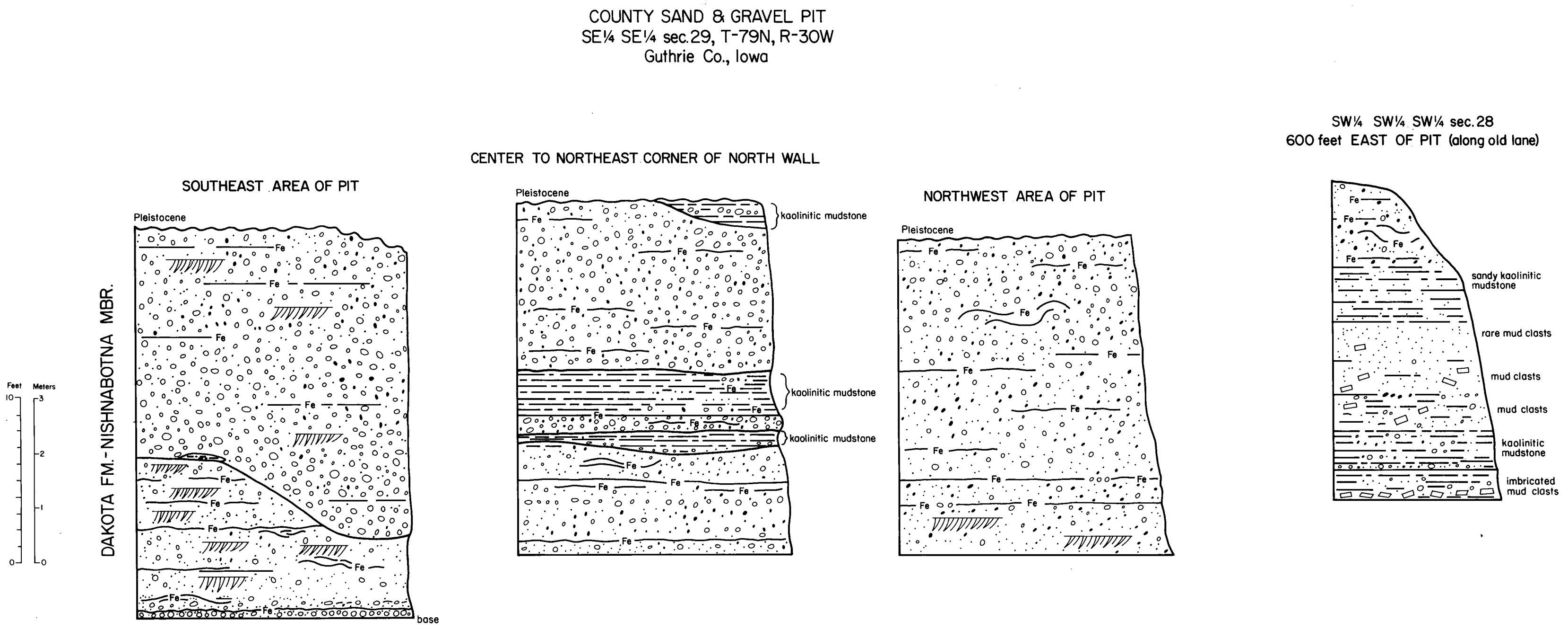


Figure 18. Sections of lower Nishnabotna Member strata previously exposed at Stop 1 (from Witzke and Ludvigson, 1982), duplicated here to show lateral variability of sandstone, conglomerate, and mudstone lithologies over a small area. The illustrated sections include units 2, 3, and 4 from Figure 17. Symbols as in Figure 17.

The larger channels display mudclast conglomerates and scattered chert cobbles in their axial portions.

Paleozoic Fossils in the Cretaceous Gravels

Fossiliferous chert clasts within the Nishnabotna "peanut gravels" of Guthrie County have been investigated by St. John (*in* White, 1870), Calvin and Bain (*in* Bain, 1897) and Witzke and Ludvigson (1982). St. John (*in* White, 1870, p. 103) noted that the Cretaceous gravels in the county contain "pebbles of silicified corals, probably of Devonian or Silurian age, among which *Favosites* and Cyathophylloid forms were recognized." Witzke and Ludvigson's (1982) investigation was undertaken entirely in the County Pit (Stop 1); fossiliferous chert clasts and silicified fossils were high-graded by surface collecting units 2 through 4. The results of these investigations are summarized in Table 3. The contained fossils, with two minor exceptions, are of Paleozoic marine invertebrates, especially solitary and tabulate corals and indeterminate brachiopod and crinoid fragments. Taxa that can be recognized at generic or specific levels are dominantly of Silurian forms, with a component of Devonian and Upper Ordovician taxa. No uniquely Mississippian or Pennsylvanian fossils are identified, but conceivably may be represented (possibly the crinoid stems). [Pennsylvanian fossils, including fusulinids and brachiopods, are, however, identified in the Nishnabotna gravels of southwest Iowa and the lower Platte Valley, Nebraska.]

It can be concluded that the westward flowing coarse-grained mid-Cretaceous river systems transported silicified fossil grains from eroding surfaces of Upper Ordovician, Silurian, and Devonian bedrock. The closest possible source region for these grains presently lies in east-central Iowa and adjacent Wisconsin and Illinois extending over 200 miles (320 km) to the east. For reasons discussed earlier, and because the less-eroded westward edges of the identified Paleozoic sources would lay even farther east during the Cretaceous, significant transport distances for much of the Paleozoic silicified pebbly material can be confidently recognized. Even greater transport distances need to be invoked for the quartz grains and pebbles, including igneous vein-type quartz, quartz tectonite, jasper, and quartzite, which can only logically have been sourced from Precambrian shield areas to the northeast (Wisconsin, Minnesota, Upper Michigan, Ontario; see earlier).

Dinosaur Bone and Wood Fragments

Reworked Paleozoic fossil grains are the main fossils identified in the Nishnabotna gravels. However, a small component of arguably Cretaceous fossil material is also recognized, but these fossils are rare. These include rounded pebbles of silicified wood and bone (Table 3; 3 cm diameter specimens). The petrified wood is probably gymnospermous, and displays coarse annual growth rings. Similar wood has not been recognized in any Paleozoic unit of the Iowa area, but it resembles petrified wood seen in many Cretaceous nonmarine units of the Rocky Mountain region. In addition, large pieces of similar petrified wood are associated with Cretaceous Tempskya fossils in coarse-grained basal Cretaceous sediments of northern Iowa (Floyd Co.; Ravn and Witzke, 1995). The Guthrie County specimen was obviously transported, but it likely represents a reworked fragment of Cretaceous wood.

No dinosaur fossil has yet been firmly identified from Cretaceous strata anywhere in the State of Iowa. Nevertheless, dinosaur material has been recognized nearby in Dakota Formation strata of eastern Nebraska (large ornithopod bone, large theropod tooth) and Kansas (nodosaurid)(Witzke, 1981). The Cretaceous fluvial sandstones of the Dakota Formation in Iowa certainly have the potential to yield dinosaur fossils, and it is hoped that some diligent or exceptionally lucky collector will one day produce an identifiable bone. The best we can presently offer is a tantalizing rounded fragment of apparent fossil bone (Fig. 19).

A silicified pebble that showed bone-like vascular morphology was collected by the authors from the County Pit in 1982. The resemblance to bone was apparent from prior experiences collect-

Table 3. Silicified fossils identified in lower Nishnabotna gravels, Guthrie Co., Iowa. Data primarily from Witzke and Ludvigson (1982), County Pit, Stop 1; number of specimens collected and the known stratigraphic range in the Iowa area of the various fossil types are noted. Supplemental collections of Bain (1897), as identified by Sam Calvin, are denoted by asterisk (*).

CORALS		
Alveolites sp.	1	Sil.-Dev.
"*Amplexus*" sp.	2	Sil.-Miss.
Arachnophyllum sp.	1	Sil.
Astrocerium sp.	2	Sil.-Dev.
Astrocerium venustum(*)	-	Sil.
Favosites favosus(*)	4	Sil.
Favosites niagarensis	15	Sil.
Favosites spp. indet.(*)	7	Sil.-Dev.
Pleurodictyum sp.	1	Dev.
Ptychophyllum expansum(*)	-	Sil.
"*Streptelasma*" sp.(*)	2	Ord.-Dev.
"*Streptelasma*" *spongaxis*(*)	-	Sil.
Striatopora sp.	6	Sil.-Dev.
Syringopora sp.	6	Sil.
"*Zaphrentis*" sp.	2	Sil.-Miss.
"*Zaphrentis*" *stokesi*(*)	-	Sil.
indet. solitary corals[a]	48	Ord.-Penn.
([a]includes forms probably assignable to *Ptychophyllum*, *Enterolasma*, "*Cyathophyllum*," etc.)		
BRACHIOPODS		
"*Atrypa*" sp.	1	Sil.-Dev.
Eospirifer eudora(*)	-	Sil.
Lepidocyclus gigas	1	U. Ord.
indet. rhynchonellid	1	Ord.-Penn.
indet strophomenids	2	Ord.-Penn.
indet. brachiopod frags	23	Ord.-Penn.
BRYOZOANS		
?*Rhinidictya* sp.	2	Ord.-Sil.
fenestellid sp.	3	Sil.-Penn.
indet. bryozoans(*)	2	Ord.-Penn.
TRILOBITES		
indet. thoracic segment	1	Paleozoic
ECHINODERMS		
large crinoid stem pieces	2	possibly Penn. types
crinoid debris in chert	x	Ord.-Penn.
PLANTS		
petrified wood	1	probably Cretaceous (gymnospermous)
VERTEBRATES		
dinosaur bone fragment	1	Cretaceous

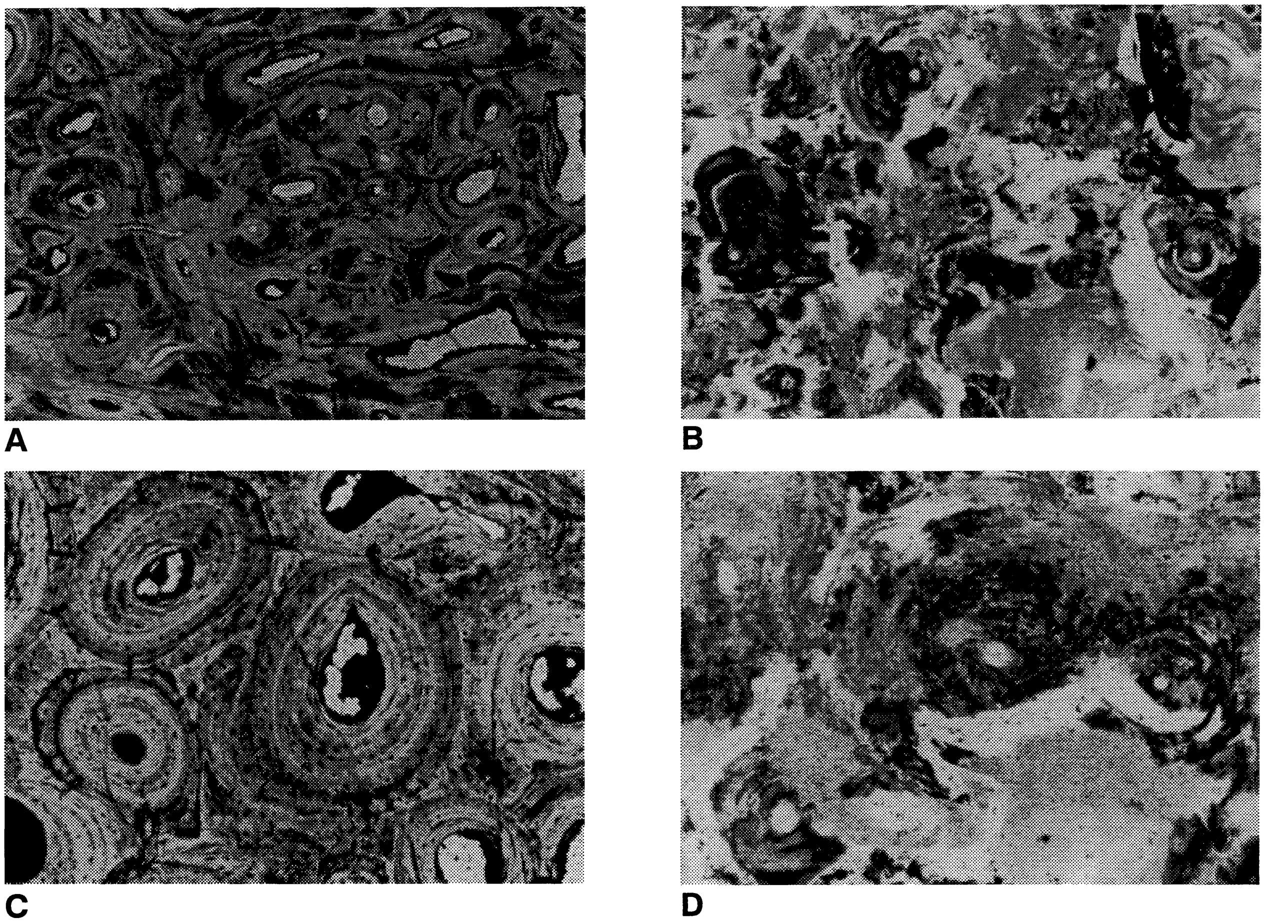


Figure 19. Photomicrographs of probable dinosaur bone fragment from Stop 1 (B and D) compared with known Cretaceous dinosaur bone (A and C; *Triceratops* frill, Lance Fm., Weston Co., Wyoming). All illustrate dense Haversian bone structure with a complex network of secondary osteons (vascular canals). The Guthrie County sample (B and D) is silicified; some regions are darkened by iron mineral staining. A and B with 3.2 mm field of view; C and D with 1.3 mm field; all taken under plane light.

ing fossil bone, including dinosaur material from the Western Interior. A thin-section was prepared from this specimen to establish its internal micromorphology. Interestingly, the specimen showed definitive histologic structure for dense Haversian bone (Fig. 19). Dense Haversian bone is formed by the vascular remodeling of primary bone, especially in mature individuals of large-sized animals (including humans). Ongoing processes of bone resorption and remodeling by multiple generations of vascular networks (Haversian systems) produce this distinctive type of bone (Ricqlès, 1980). The only vertebrates known to produce dense Haversian bone are mammals, birds, and dinosaurs (and rarely a few reptile taxa).

The occurrence of a bone fragment in the Nishnabotna gravels constrains it to an age no younger than the mid-Cretaceous. No bone of this morphology is known from any Paleozoic strata in the region, but Haversian bone is recognized in Jurassic and Cretaceous strata of the central United States. What type of animal could potentially be the source of this fragment? The dense Haversian structure indicates either a mammal, bird, or dinosaur. Further, how large would an animal need to be to produce a fragment of dense bone 3 cm in diameter? No Jurassic or Cretaceous mammal or bird is known to have been large enough to yield such a fragment. By a process of elimination and deduction, thereby, we are left with identifying the County Pit bone fragment as dinosaurian — a dinosaur of unknown affinities to be sure, but a dinosaur nonetheless, and the first recognized in Iowa. The microstucture (histology) of the Guthrie County fragment is closely comparable to known dinosaur bone, as shown in Figure 19.

STOP 2: Finer-grained Nishnabotna facies, sandstone and mudstone; Bar-L Ranch exposure

The Bar-L Ranch along Highway 25 south of Guthrie Center is nestled along a prominent north-trending bedrock ridge which forms the west valley wall of the South Raccoon River. We will visit an interesting sandstone exposure up the hill slope just beyond the old barn (which was built in 1849). The Bar-L is a horse ranch that offers summer activities and horseback experiences for boys and girls, now in its 40th year. We wish to gratefully acknowledge the generosity of Bill and Cindy Bortell and the Bar-L Ranch in enabling access to their property. Please be mindful of the horses, gates, and fences.

The Bar-L sandstone exposure is considerably finer grained than the sandstones seen at Stop 1, and it probably occupies a slightly higher stratigraphic position within the Nishnabotna Member. Three general units are recognized (Fig. 20). The exposure of the lower unit has been expanded from that seen during the last field trip (Witzke and Ludvigson, 1982), and up to 4 m may be represented. It is a fine- to medium-grained sandstone with small-scale (10 to 40 cm amplitude) trough crossbeds. It is a fairly well-sorted unit, but some quartz and chert pebbles are present in the upper part. Trough dimensions generally increase upward, with troughs up to 3 m wide near the top. The upper surface is truncated by overlying strata, with up to 20 cm of erosional relief.

The middle unit locally exceeds 4 m in thickness, but it is significantly thinned by incision of the upper mudstone channel fill. The middle sandstone unit is coarse and pebbly at the base, with quartz and chert clasts up to 3 cm diameter. Mudclasts (up to 5 cm) are common in the basal 5 to 25 cm. The basal conglomeratic interval grades upward into medium- to coarse-grained and fine- to medium-grained sandstones displaying planar cross-stratification. The upper half of the middle unit is primarily a fine-grained sandstone with prominent trough crossbeds; some planar foresets show a southerly dip. The unit is cut by a channeled erosional surface with 2.6 m of relief displayed over a horizontal distance of 15 m.

The upper channel-filling unit is a light gray silty kaolinitic mudstone up to 4 m thick (Fig. 20). The basal erosional surface is marked by a hard iron-oxide-cemented ledge (probably secondary after siderite). A thin sandstone lens with mudclasts occurs within the mudstone unit. The upper mudstone unit contains scattered to abundant plant debris and leaf compressions. This mudstone probably represents a floodbasin overbank or paludal deposit which infilled an abandoned channel.

The Bar-L section contains finer-grained fluvial sediments than seen in the basal Nishnabotna Member (Stop 1), and changes in stream competence during regional fluvial aggradation is indicated. The sequence shows alternating episodes of fluvial sedimentation and channel incision, providing evidence of changes in local or regional base levels and/or local channel migration. The sub-mudstone erosional surface at the Bar-L section records a base-level fall associated with incision of a channel sandstone body (middle unit), followed by a base-level rise associated with subsequent burial of this surface by a floodbasin mudstone (upper unit). The upper mudstone was probably deposited as overbank muds or an oxbow lake/marsh fill some distance from the sand-transporting channels of the main river trunk system. The regional significance, if any, of the erosional surfaces and fills seen in the Bar-L section is not known. Nevertheless, a regional base-level fall is predicted to have occurred in the eastern fluvial systems coincident with the sequence boundary that separates the Kiowa-Skull Creek and Greenhorn marine cycles in the Western Interior during the late Albian (Witzke and Ludvigson, 1994). This boundary would likely correlate to a position somewhere near the middle part of the Nishnabotna Member in Iowa and Nebraska, possibly spanning the section at the Bar-L Ranch.

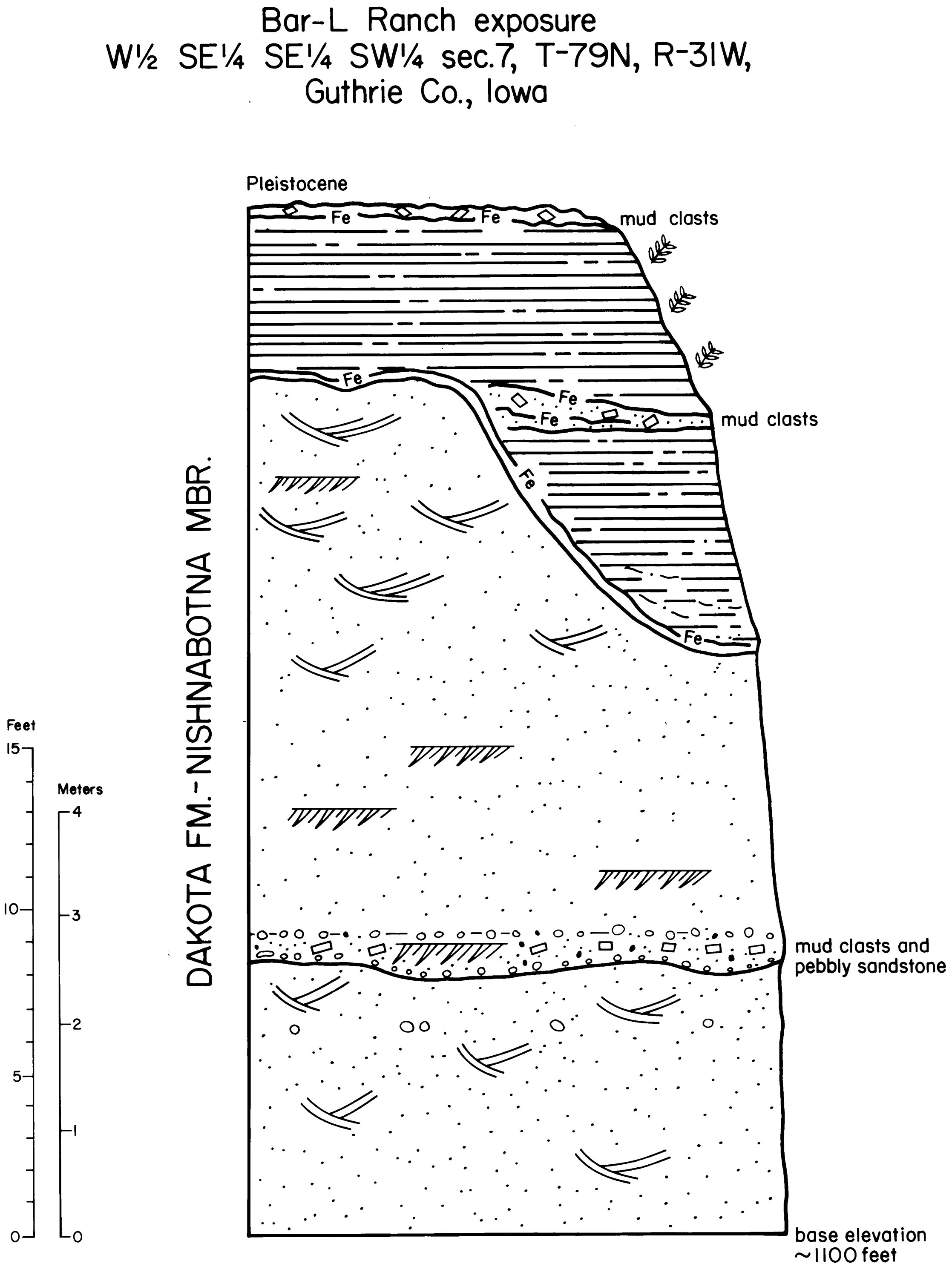


Figure 20. General section of Nishnabotna Member exposed at Stop 2, Bar-L Ranch near Guthrie Center, Iowa (from Witzke and Ludvigson, 1982). Symbols as in Figure 17. Compression flora recovered from upper mudstone.

Compression Floras in the Nishnabotna Member

Plant fossils are relatively rare in the Nishnabotna Member, but the early discovery of "netted-vein" angiosperm leaves in Nishnabotna strata of southwestern Iowa was significant in suggesting a Cretaceous age (White, 1867, 1870; Lonsdale, 1895; Udden, 1901). In Guthrie County, St. John (*in* White, 1870, p. 104) observed "shaly sandstone containing impressions of linear leaves" along Beaver Creek (south of Montieth), and Bain (1897) noted Cretaceous plant remains in sandstone near Glendon. The upper mudstone at the Bar-L Ranch locality was recognized to contain a compression flora in 1982, and a small collection of netted-vein angiosperm leaf fragments was secured at that time. An attempt was made to extract palynomorphs from these mudrocks in 1983, but the deposits are apparently too oxidized to be productive. Matt Klare, then a Ph.D. paleobotany student at the University of Iowa, became interested in learning more about the Guthrie County site, and he made some collecting forays to the Bar-L Ranch in 1984. This collection presently resides with J. T. Schabilion in the paleobotany collections of the Biology Department, University of Iowa, and a few preliminary statements are made here concerning its composition (see also Ravn and Witzke, 1995, p. 104).

The collection is dominated by large craspedodromous leaves and leaf fragments of early platanoid (sycamore-like) angiosperms (Fig. 21 A-D); these have commonly been referred to the form-genus *"Platanus."* Additional angiosperm fossils include indeterminate small leaf fragments with serrate margins, simple and multi-lobed forms resembling the primitive *"Sterculia"* and *"Sapindopsis,"* and a grape-sized fruit (Fig. 21 G). A minor component of gymnosperms is identified, primarily pine needles 1.5 to 5 cm long (*"Pinus," "Abietites"*). Twigs with small flat foliage or scalelike leaves on cone branches are of probable taxodiacean affinities (*"Sequoia," "Glyptostrobus"*). Small fern fronds and pinnules are also recognized, including forms resembling *"Gleichenia"* (Fig. 21 E,F), *"Cladophlebis," "Onychiopsis,"* and *"Asplenium."*

The compression flora at the Bar-L Ranch provides a glimpse of one of the plant communities that inhabited the broad floodbasins of the eastern continental lowlands during the Late Albian. The abundant palynofloras of the Nishnabotna Member, discussed earlier, further demonstrate that diverse assemblages of bryophytes, lycopsids, ferns, gymnosperms, and angiosperms grew in the region. The vegetated lowlands included conifer forests of pines, podocarpaceans, and cypress-like taxodiaceans (possibly in swamps). These were mixed with an abundance of smaller trees, bushes, and vines of early angiosperms. The vegetated forest floor contained small lycopsids, mosses, liverworts, and fungi. The exotic cycadophytes were locally important. The understory and forest breaks must have been carpeted with a rich and diverse assemblage of ferns. Among the ferns, some groups apparently developed trunk-like false stems (Cyathaceae, Osmundaceae); the diagnostic mid-Cretaceous "trunks" of *Tempskya* ferns are identified from petrifactions elsewhere in Iowa (Fig. 21 H).

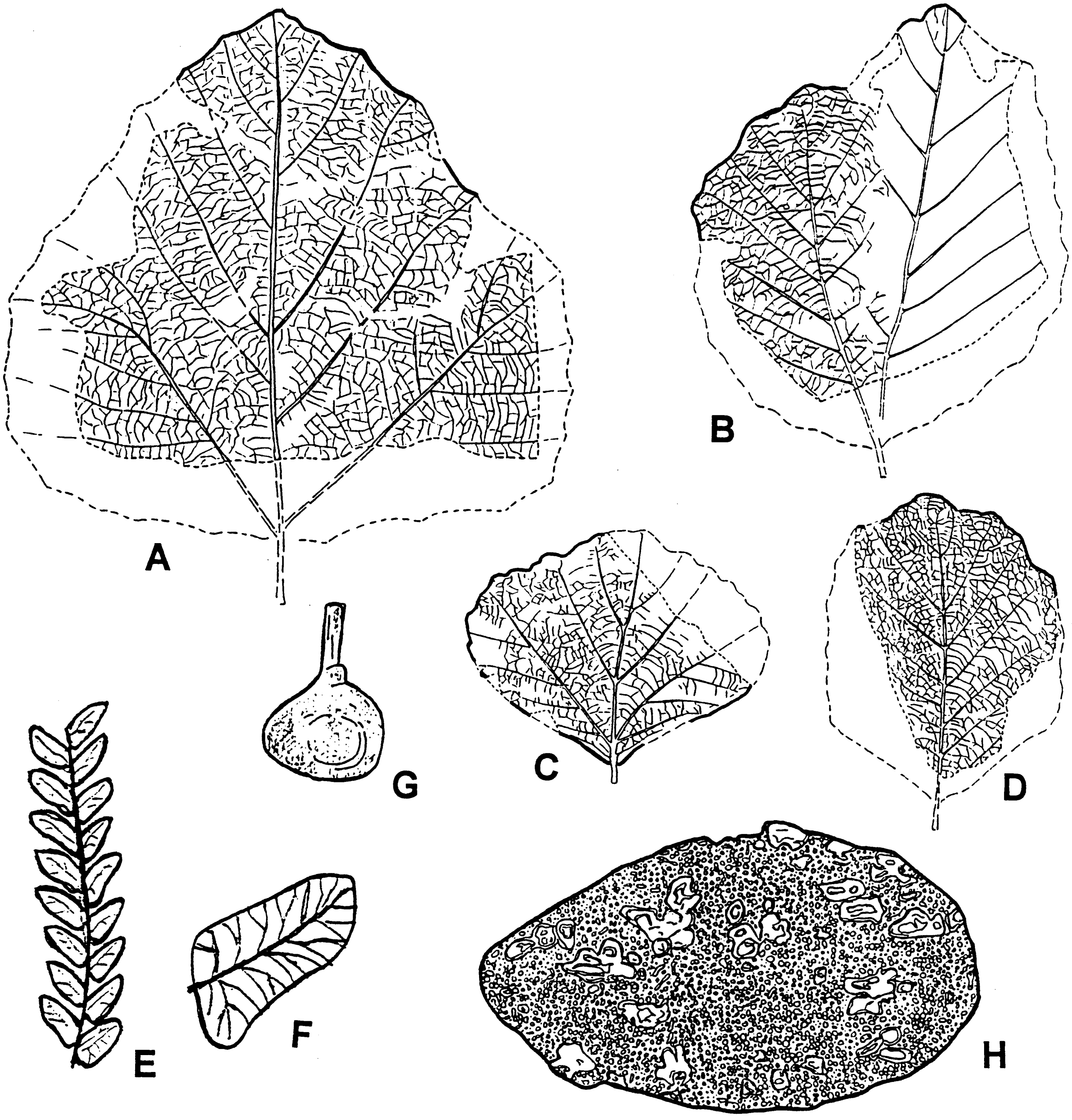


Figure 21. A portion of the compression flora recovered from Stop 2 (A-G). All are photo tracings. A, B, C, D. Large platinoid angiosperm leaves; reconstructed margins are dashed; all x0.5. E, F. Fern frond and pinnule, *Gleichenia* sp.; E (x3.5), F (x11). G. Angiosperm fructification (fruit), x1. (Note: photograph of specimens C and G is found in Witzke and Ludvigson, 1994, p. 57). H. *Tempskya* sp.; transverse section through silicified "false-trunk" of this distinctive fern "wood"; stems are surrounded by dense mass of small adventitious roots; this is the first *Tempskya* known from the eastern side of the Western Interior; Floyd Co., Iowa (Loc. FL in Ravn and Witzke, 1995).

STOP 3: Roadcut exposures of the Nishnabotna Member, Dakota Formation along Iowa State Highway 25 and overview of Middle Raccoon River valley

This stop provides a look at sandstone from the Nishnabotna Member, as well as the opportunity to examine relationships between the stratigraphy of the Nishnabotna and exposures within the Middle Raccoon River Valley. The north-south Iowa State Highway 25 here crosses an east-west segment of the river valley, and the highway right-of-way was used for a 1982 drilling transect of the landscape stratigraphy of the valley during a regional investigation of the groundwater resources of West-Central Iowa (Witzke and Ludvigson, 1982; Hunt and Runkle, 1985). Exposures in the south valley wall at STOP 3 are part of an area of extensive bedrock exposure that continues downstream to Springbrook State Park (Fig. 22). During the drive to the next stop, please take note of the many natural exposures of Dakota sandstones and mudrocks in the north and south valley walls.

The 10 meter Nishnabotna roadcut section on the east side of the highway is illustrated in Figure 23. Although the section has grown over considerably since our original description (Witzke and Ludvigson, 1982), a number of features still are readily apparent. Tabular cross bedding occurs in the lower part of the section, and large-scale iron-cemented trough cross bedding can be seen at the top of the section. While fine- to medium-grained sandstones comprise most of this section, coarser trough cross-bedded units at the top of the section contain scattered quartz granules. The sedimentary units at this section bear some resemblance to those seen at the previous stop at the Bar-L Ranch.

What is the stratigraphic relationship between these sandstones and the conglomeratic facies visited at STOP 1? The drill hole transect along Highway 25 addresses this question, in part. Figure 24 shows that: (1) conglomeratic facies occur near the base of the Nishnabotna Member; below the stratigraphic position at this roadcut at STOP 3, and (2) this roadcut section appears to be laterally equivalent to a mudrock interval in the adjacent drillhole WC-114, and (3) fluvial incision of the Middle Raccoon River cut below the base of the Dakota Formation, although aggradation of Quaternary alluvium buries the Cretaceous-Pennsylvanian contact along the transect.

Observations at the first three stops have illustrated that while the Nishnabotna Member of the Dakota Formation is dominated by coarse-grained clastic material, minor mudstone facies do occur with some frequency. Moreover, reduced mudstone units have been found to produce abundant palynomorphs, which are yielding important new insights into lateral relationships between coarse-grained Nishnabotna fluvial facies and more mudrock-dominated facies in basinward positions farther to the west in Nebraska.

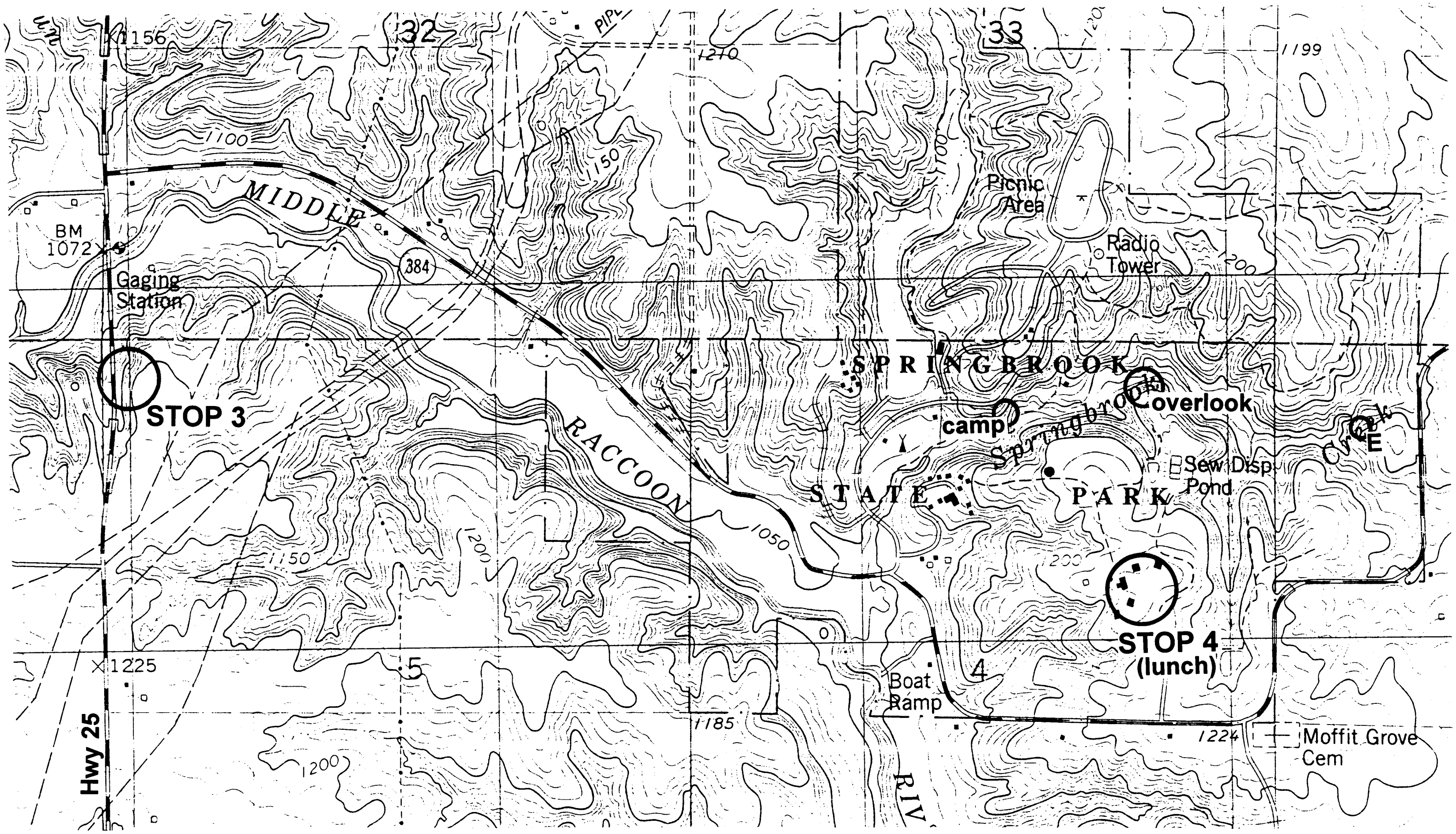
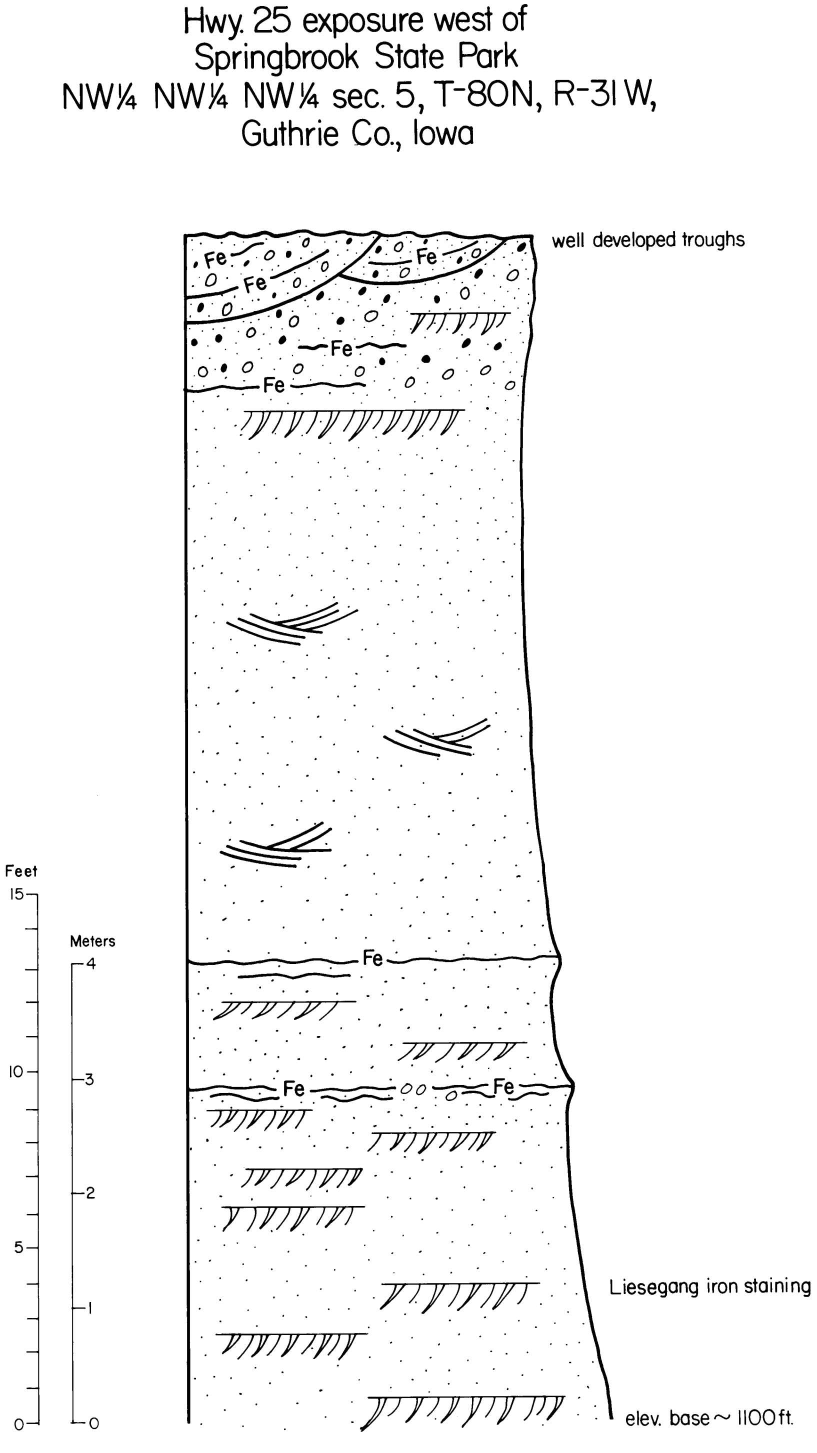


Figure 22. Enlargement of topographic map (Bagley Quadrangle) showing Stops 3 and 4, Highway 25 exposure and Springbrook State Park area. Nishnabotna Member strata are exposed along the valley walls of the Middle Raccoon River and its tributaries, including Springbrook Creek. Stop 4 will serve as lunch stop (Conservation Education Center), with options to hike to sandstone exposures along Springbrook Creek (circled exposures include camp and overlook sections [see Fig. 25], eastern section [E]). 10-foot contour interval.



Hwy. 25 exposure west of
Springbrook State Park
NW¼ NW¼ NW¼ sec. 5, T-80N, R-31 W,
Guthrie Co., Iowa

Figure 23. Generalized graphic section of Nishnabotna Member strata exposed along Highway 25 west of Springbrook State Park, Stop 3. Symbols as in Figure 17. From Witzke and Ludvigson (1982).

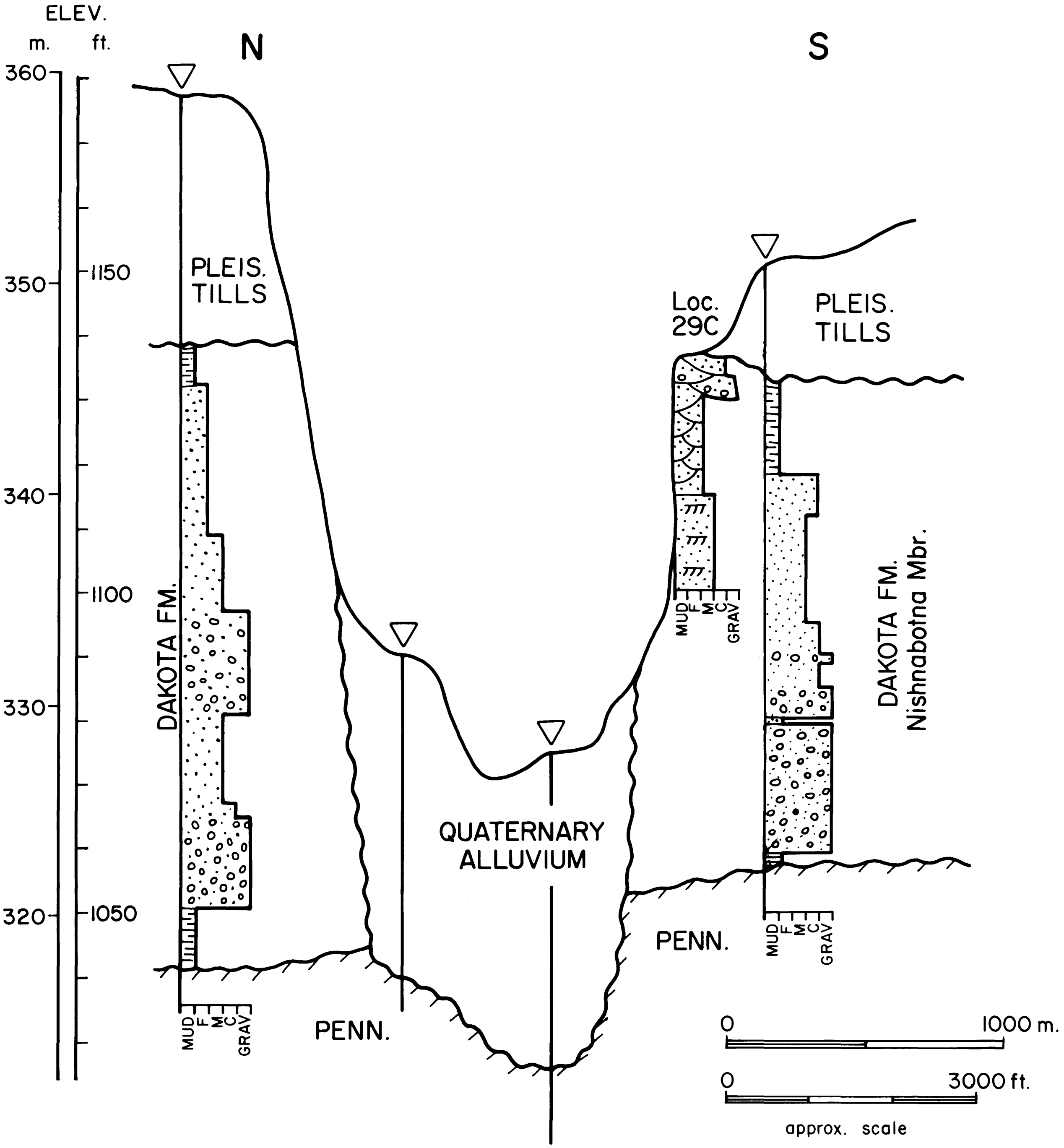


Figure 24. Drill transect across Middle Raccoon River Valley along Highway 25 west of Springbrook State Park. Note position of Stop 3 (labeled Loc. 29C). Nisnabotna strata unconformably overlie Pennsylvanian shale and are unconformably overlain or crosscut by Quaternary units. Grain size distributions (coarsest fraction present) are shown for Pennsylvanian and Cretaceous units. Note lateral and vertical variations in grain size in the Dakota sections. Samples are from rotary drill rig (1982 drilling, West-Central project drillholes WC-106, 107, 108, 114; Hunt and Runkle, 1985). From Witzke and Ludvigson (1994; see also Witzke and Ludvigson, 1982).

STOP 4: Lunch stop and natural exposures of Dakota Formation in Springbrook State Park

As the field trip proceeds to the lunch stop in Springbrook State Park, keep an eye out for natural exposures of Dakota Formation along the valley walls of the Middle Raccoon River Valley. The lunch stop will be in the Picnic Area in Springbrook State Park. The park was established in 1926 and contains a number of buildings constructed by the Civilian Conservation Corps in the 1930s. After lunch, we will proceed to the Springbrook Conservation Education Center for a short walk to visit a natural exposure of the Dakota Formation in the park. The Conservation Education Center was established in 1970, and is used for K-12 teacher workshops and school groups, with the aim of furthering public appreciation of a wide range of natural resource issues in Iowa. A foot trail leading northward from the Conservation Education Center leads to the Trail Overlook exposure.

Springbrook State Park straddles the terminal moraine of the late Wisconsinan Des Moines Lobe, and is bordered to the northeast by comparatively low-relief uplands underlain by the Wisconsinan Dows Formation. At the terminus, superglacial facies of the Morgan Member of the Dows Formation are juxtaposed with older terranes underlain by loess and/or paleosols over pre-Illinoian glacial tills. The park contains the confluence of two steep-walled stream valleys which drained glacial meltwaters from the Des Moines Lobe into the Middle Raccoon River. The southward-draining valley of Springbrook Creek has been dammed to create a recreational lake, but the westward-draining valley has been largely left in its natural condition. Three natural exposures of the Nishnabotna can be viewed in this valley of Springbrook Creek.

The Trail Overlook exposure (Fig. 25) forms a prominent north-facing 10-meter escarpment along the south valley wall. It consists of fine- to medium-grained sandstones with trough cross-bedding (largely obscured by weathering and vegetation). Mudclasts are scattered through the upper part of the section. Note that the base of this section (at approximately 1,100 feet above sea level) occurs above the top of the conglomerate units encountered in the drill hole transect along Iowa State Highway 25 (Fig. 24). At the eastern section (E on Fig. 22), about 4 meters of fine- to medium-grained sandstone with large-scale trough crossbeds, and mudclasts up to 20 cm is exposed, with the base of the section also at about 1,100 feet above sea level.

The Campground exposure (Fig. 25) is located on an east-facing cutbank of Springbrook Creek at the far eastern end of the campground. The 3-meter section consists of sandy conglomerate and pebbly fine- to coarse-grained sandstone. Planar cross beds, mudstone clasts, and liesegang iron oxide cementation are noteworthy features. A thin weathered mudstone is present at the top of the section, overlain by colluvial deposits. Note that the base of the section (at approximately 1,060 feet above sea level) places this unit within the conglomeratic interval encountered in the drill hole transect along Highway 25 (Fig. 24). Geologic observations in Springbrook State Park indicate that the lithostratigraphic succession of sandstones over conglomerates identified along Highway 25 extends laterally for over two miles. Observations at the next stop further indicate that conglomerates of the Nishnabotna consistently occupy a position near the base of the unit.

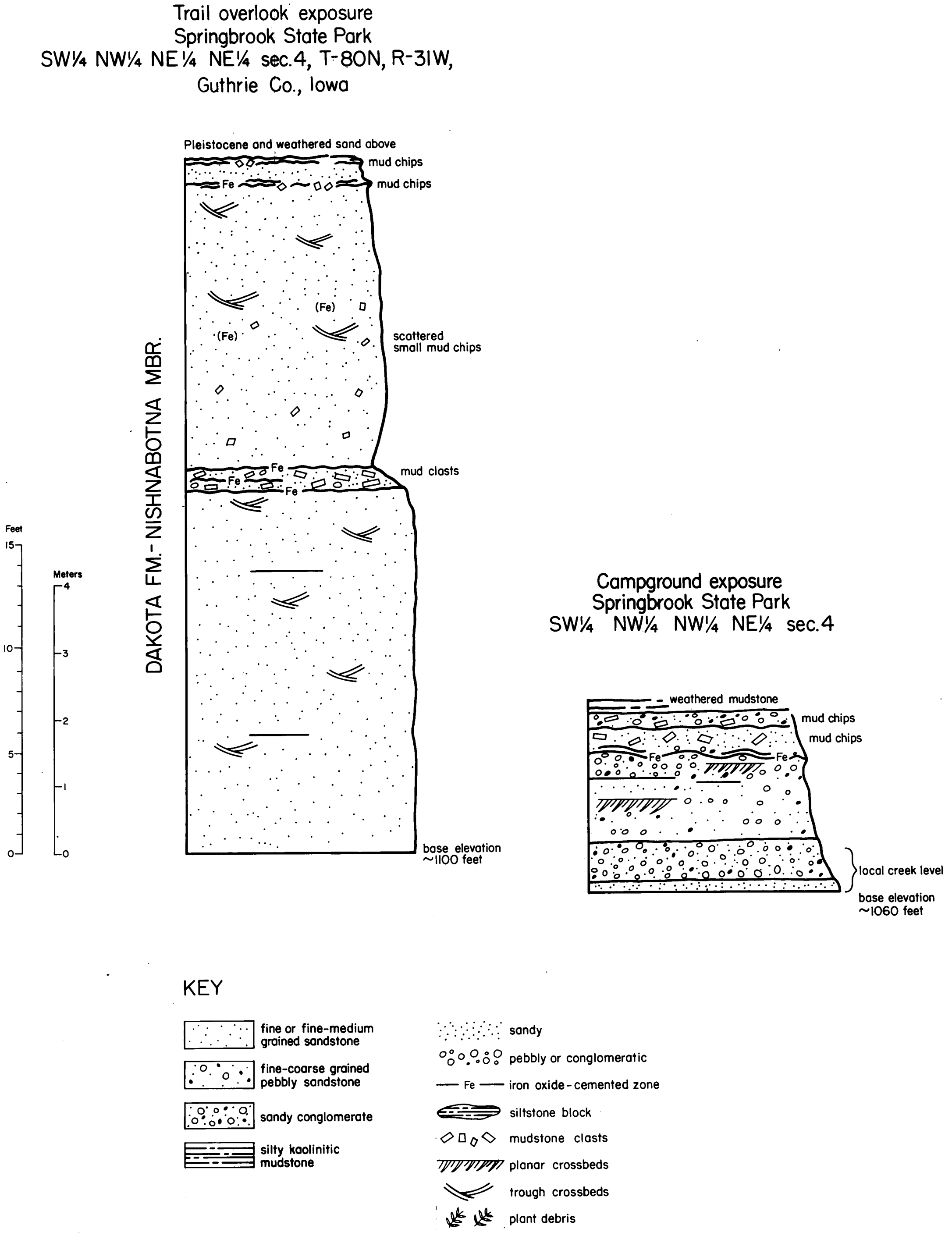


Figure 25. Representative graphic sections of Nishnabotna Member exposures in Springbrook State Park. See Figure 22 for locations of trail overlook and campground (camp) exposures.

STOP 5: Nishnabotna fluvial facies and sedimentary geometries, Garst property sections, Middle Raccoon River

The beautiful stretch of river corridor bordering the Middle Raccoon River southeast of Coon Rapids contains instructive and spectacularly-displayed exposures of Cretaceous strata. The best exposures lie within a segment of land owned and managed by the Garst family. The family has a strong interest in Iowa's natural heritage, and this magnificent piece of land is a tribute to the family's ongoing efforts concerning the protection of Iowa's natural areas and wildlife habitat. Steve Garst, general partner of the Garst Company, a farm supply operation in Coon Rapids, was awarded the Hagie Heritage Award, Iowa's prime conservation award, by the Iowa Natural Heritage Foundation in 1995 for his commitment to the protection of Iowa's natural environment. Some trip participants may recall the historic visit of Soviet premier Nikita Khrushchev to the Garst family farm (Roswell Garst) near Coon Rapids in 1959.

Trip participants will park at the "River House" immediately east of the bridge over the Middle Raccoon River (Fig. 26). We will first proceed across the bridge and follow the river downstream a short distance to the prominent cutbank and bluff exposure locally known as the "Whiterock" section (Stop 5A; Fig. 26). The final stop of the day will entail a hike upstream along the east bank of the river (approximately 0.8 mile) to visit a dramatic exposure of Cretaceous sandstone (Stop 5B; Fig. 26). The river corridor through the Garst property displays sandstone-dominated sections of the Nishnabotna Member in the valley walls. These strata unconformably overlie Pennsylvanian mudstone- and shale-dominated units (coal-bearing in part) of the Cherokee Group, which are locally exposed in the lower portions of the valley. Pre-Illinoian glacial tills and other Quaternary deposits cap the upper bluffs.

We wish to thank the Garst family for their interest and support in allowing access to these important Cretaceous exposures, in particular Steve and Mary Garst of Coon Rapids and their daughter Liz Garst (Raccoon Valley State Bank).

STOP 5A: Whiterock section

The "Whiterock" cutbank and bluff exposure provides the largest vertical section of lower Dakota strata known in Iowa (Fig. 27). Water-saturated muds are common along the exposure slope, and rubber boots may be desirable for the access. Recent spalling and slumping of the lower strata during and after the 1993 floods have freshly exposed the basal Dakota beds and permitted a detailed examination of complex sedimentary structures and channel geometries a short distance above the Pennsylvanian-Cretaceous unconformity. At least 2.5 m of relief is displayed along this unconformity at Stop 5A, and elevations at the base of the nearby creek section (Figs. 26, 27) indicate at least 5 m of relief in the immediate area. Pennsylvanian mudstones (unit 1) are best exposed in the easternmost area a short distance above river level.

Exposure of units 2 through 5 (Fig. 27) is particularly instructive, but close-up examination may be hazardous. These units are displayed along an actively retreating bluff face, and, depending on the degree of water saturation, active spalling or slumping could occur during the field trip visit. These lower units display a complex mosaic of mutually cross-cutting channels which formed via channel migration and base-level changes during regional aggradation of the lower Nishnabotna fluvial systems above the eroded Paleozoic surface.

A basal claystone and sandstone interval (unit 2), with a pebbly conglomeratic base, directly overlies the Pennsylvanian mudstones. This unit is overlain by pale siltstones ("whiterock") of unit 3, which form prominent large-scale lenses of laminated siltstone in the exposure face; plant debris is common. The siltstone body displays an erosionally beveled and sculpted upper surface beneath complex cross-cutting channel-forms of pebbly sandstone and conglomerate (unit 4). Unit 3 directly overlies Pennsylvanian mudstone in the

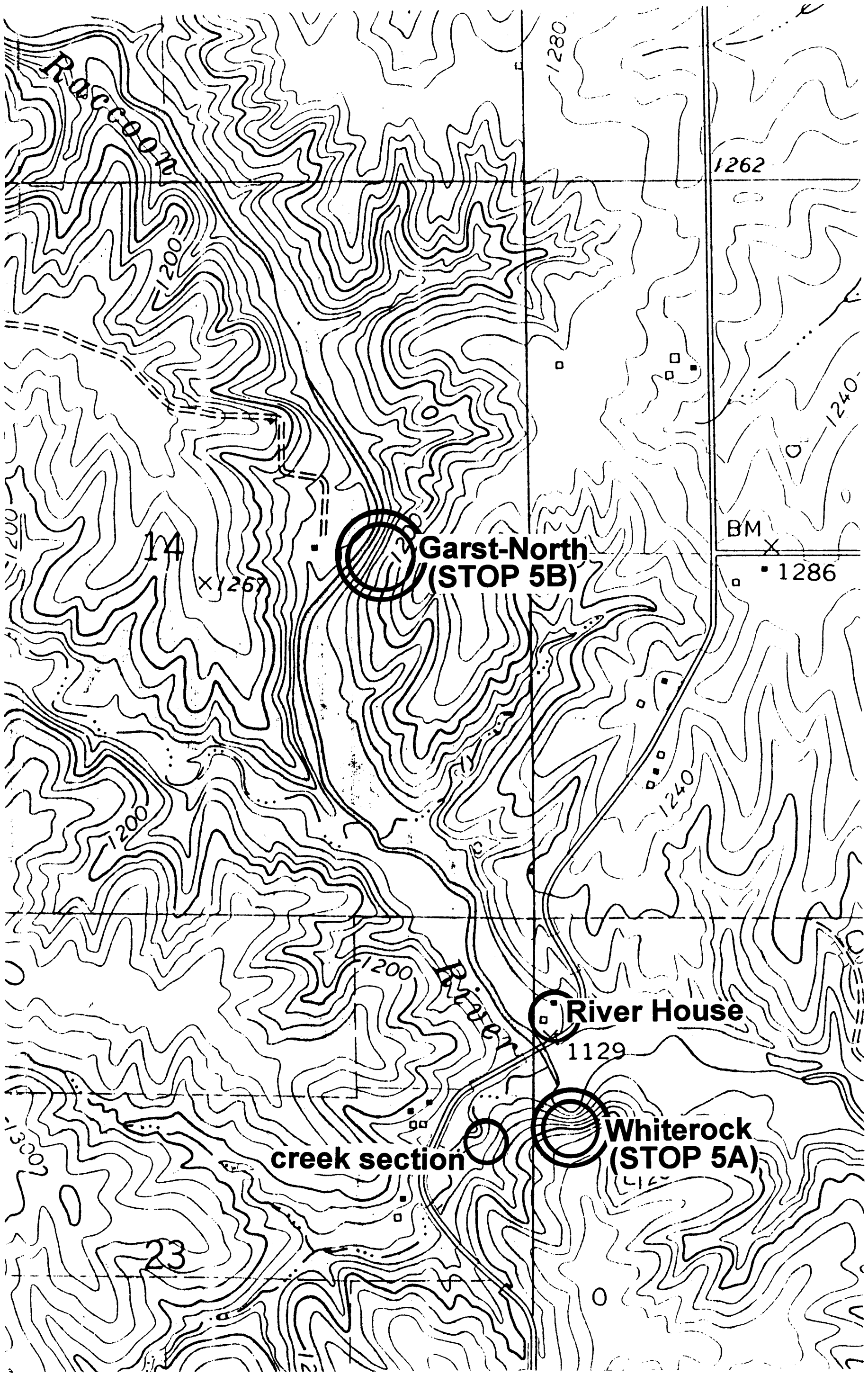


Figure 26. Enlargement of topographic map (Coon Rapids South Quadrangle) showing locations of Stops 5A and 5B in the Middle Raccoon River Valley, Guthrie County, Iowa. 20-foot contour interval.

western area of the exposure, where it includes a prominent lens of pebbly conglomeratic sandstone that is laterally truncated beneath the upper pale siltstone lens. Unit 4 includes a giant clast of mudstone (4 m long) enclosed within a pebbly sandstone near the west edge of the cutbank face. The upper part of the exposed face (unit 5) includes cross-stratified bedforms of coarse pebbly conglomeratic sandstone, in part forming resistant beds and ledges cemented by Liesegang patterns of iron oxide minerals.

Above the main cutbank face, a recessive and water-saturated slope partially exposes a relatively thick interval (2.65 m) of soft kaolinitic mudstone and claystone (unit 6, Fig. 27). Unlike Dakota mudrock sections exposed elsewhere in Guthrie County and southwestern Iowa, this mudrock interval is not pervasively oxidized or pedogenically mottled, and medium gray hues are recognized (providing encouragement for palynologic sampling). Unit 6 yielded palynomorphs in 1995, the first recovered from the Nishnabotna outcrop belt of Iowa. We hope to have an update on the contained palynofloras at the time of the field trip, but spore and pollen identifications were not completed as of this writing. A sandstone body apparently cuts the mudstone unit in the western area of the exposure.

Medium- to coarse-grained sandstones, pebbly in part, continue above the mudstone unit, and these display southwest-dipping trough crossbeds (unit 7). The basal part of unit 8 is also coarse and pebbly, but the overlying Cretaceous sandstone strata are significantly finer grained and the scale of the sedimentary structures is reduced. With few exceptions, coarse conglomeratic sandstones characterize the lower units, whereas fine-grained sandstones typify the upper strata throughout the Nishnabotna outcrop belt of western Iowa. This basic subdivision can be used to informally separate upper and lower intervals within the Nishnabotna Member (see Fig. 27), which further constrains general patterns of regional fluvial aggradation during the Late Albian.

Upper Nishnabotna strata (units 8-11) are exposed in the forested slopes in the middle to upper portions of the valley wall, but these strata are partially covered and lateral relationships are not readily seen. Unit 8 is primarily a fine- to medium-grained sandstone, and overlying units (9-11) are well-sorted very fine- to fine-grained sandstone. The purity and homogeneity of these upper sandstones makes recognition of sedimentary structures difficult, although small-scale trough crossbeds and thin horizontal bedsets are evident. The absence of coarse sand and quartz/chert pebbles in the upper Nishnabotna is of particular note. Compared to fluvial deposition of the lower strata, a decrease in stream competence is indicated for sedimentation of the upper fine-grained interval.

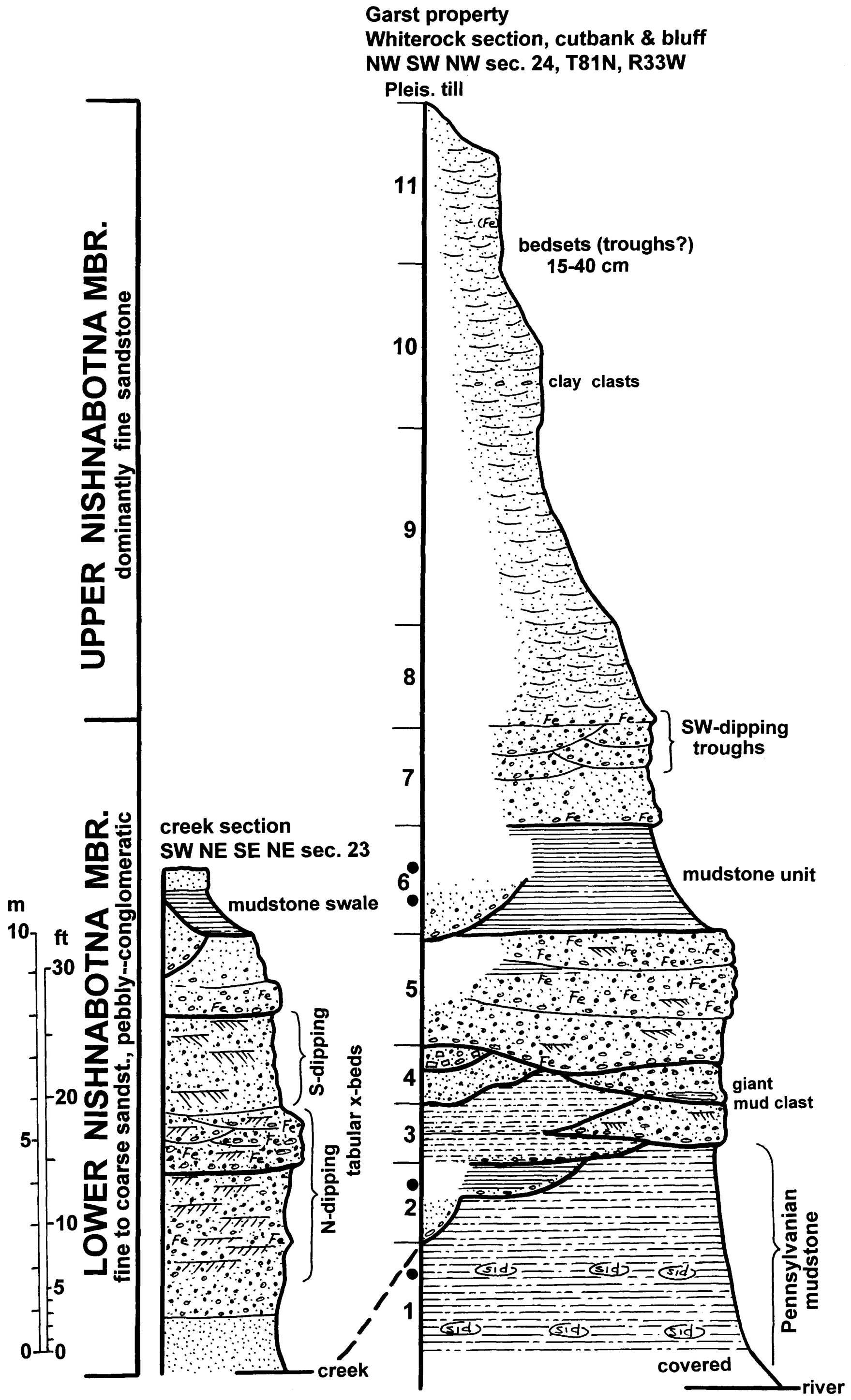


Figure 27. Generalized graphic section, Stop 5A, cutbank and bluff exposures along Middle Raccoon River, Guthrie County, Iowa. Symbols as in Figure 17. Location of Whiterock and creek sections shown on Figure 26.

Whiterock Section
NW SE NW sec. 24, T81N, R33W, Guthrie Co.
measured 10/18/1995, B. Witzke, G. Ludvigson

Lower Cretaceous
Dakota Formation
Nishnabotna Member

Unit 11. Sandstone, vf-f; reactivation surfaces spaced 15-40 cm, mostly horizontal bedsets, possible low-angle dip with troughs; scattered iron-oxide-cemented nodules; upper 1.5 m is sloped and weathered; Pleistocene till with erratic boulders above. Total thickness 4.1 m.

Unit 10. Sandstone, vf-f, in bedsets 15-35 cm, possibly troughs; lower 2.1 m forms ledge, scattered clay intraclasts 1 m above base; upper 1.9 m is sloped and part covered. Total thickness 4.0 m.

Unit 9. Sandstone, vf-f, possible small-scale trough crossbeds; unit is poorly exposed along forested slope. Total thickness 4.65 m.

Unit 8. Sandstone, dominantly f-m; lower 25 cm is sandstone, coarse, with mudclasts and pebbles near base; remainer of unit lacks pebbles and coarse grains, small-scale (10 cm thick) trough crossbeds. Total thickness 2.5 m.

Unit 7. Sandstone, f-c, dominantly m, scattered pebbles; basal 15-20 cm is iron-oxide-cemented with mudclasts to 1 cm; upper 1.1 m includes coarse to pebbly sand at base of southwest-dipping trough crossbeds (about 50 cm thick). Total thickness 2.3 m.

Unit 6. Mudstone to claystone, light to medium gray, slightly silty; becomes lighter gray and more oxidized upward, sharp base; mudstone is cut by sandstone channel in western area of exposure; palyno-samples WR3, WR4. Total thickness 2.65 m.

Unit 5. Sandstone, f-c, granules, pebbly to conglomeratic, scattered to common mudclasts (locally to 5 cm); part cemented by iron oxides into resistant ledges and Liesegang patterns; interval consists of mutually cross-cutting bedforms 40 cm to 1.5 m thick, internally with planar to low-angle cross-stratification, typically fining-upward bedforms (locally to sandstone, f-m), mudclasts most common at bases; minor lens of mudrock observed near top of unit; sharp contact above. Total thickness varies 2.5 to 3.6 m.

Unit 4. Sandstone, m-c, granules, pebbly to conglomeratic; includes mudclast conglomerate (clasts to 5-10 cm); mutually cross-cutting channeled bedforms 40 to 100 cm thick; unit 4 locally truncated by unit 5; west edge of main cutbank section contains a giant mudclast (4 m long x 15 cm thick) within the conglomeratic sandstone. Total thickness varies from 0 to 1.5 m.

Unit 3. Siltstone-dominated unit, pale gray ("whiterock") to light gray, micaceous, laminated in part, scattered to common fine plant debris, possible fern pinnules noted; siltstone becomes coarser upward, becomes vf sandstone to siltstone in upper part, irregular Liesegang oxidation patterns in part; basal 12 cm of siltstone is sandy with scattered mudclasts (to 2 cm); siltstone is erosionally beveled and truncated by unit 4 sandstones, upper siltstone surface with irregular complex erosional forms (part showing wave-like sculpting); siltstone directly overlies unit 1 mudstones in western part of main cutbank section, above unit 2 to east; a wedge of westward-thickening sandstone(to 1.0 m thick), m-c, pebbly, mudclasts, splits the siltstone unit to the west and is erosionally truncated by the upper siltstone interval (this sandstone wedge is, in turn, erosionally beveled by unit 4 sandstone channels). Total thickness varies from 1.0 to 2.35 m.

Unit 2. Dominated by mudstone to claystone, light medium gray (palynology sample WR2); basal 20 cm (below claystone) is sandstone, f, with scattered mudclasts and rare irregular chert pebbles (to 4 cm), unconformably overlies unit 1; unit is not identified in western area of exposure, but apparently thickens eastward, where a sandstone body (to over 1 m thick) is identified, sandstone, f-m, friable, scattered small mudclasts. Total thickness varies, where measured, between 0 and 80 cm; probably thickens to about 1.5 m to east.

Middle Pennsylvanian
Desmoinesian Series
Cherokee Group

Unit 1. Mudstone, silty, medium gray, blocky, micaceous, scattered carbonaceous plant debris (palynology sample WR1); unit becomes progressively more oxidized upsection; mudstone is part laminated with fine silt laminae; nodular siderite (5-20 cm) horizons noted 65 cm and 2.0 m above base; unit 1 progressively thickens to west, and is unconformably overlain by units 2 and 3; base of unit 1 begins at far northeast end of main cutbank cliff, about 1 m above river level. Total measured thickness 3.5 m.

STOP 5B: Garst-north section

Stop 5B is an exceptionally well-displayed and laterally-extensive exposure of Nishnabotna strata that occurs about a mile north of Stop 5A (Fig. 26). This exposure in the east wall of the Middle Raccoon River Valley was accentuated by road grading along the lower bluff a short distance above the Cretaceous-Pennsylvanian unconformity (Fig. 28). The resultant exposure face of lower strata portrays complex and mutually cross-cutting sandstone bodies over a horizontal distance in excess of 150 m (Fig. 29). The section is, in many respects, comparable to that seen at Stop 5A. The accessible portion of the main exposure face, based on relative position and elevation, probably equates with units 2 through 5 at Stop 5A, and the thickest mudstones at each locality (middle mudstone on Figure 28; unit 6 at Stop 5A) are likely correlatable. The upper bluff section at Stop 5B, which is poorly exposed in the wooded slope above the main exposure face, is a fine-grained sandstone interval comparable to the upper section at Stop 5A.

The stratigraphic section begins along saturated slopes of poorly-exposed Pennsylvanian shale below the road level. The basal part of the Nishnabotna Member is partially exposed above these soft shales, and includes iron-oxide-cemented ledges of coarse-grained and conglomeratic sandstone. By contrast, the exposure face above the road level is particularly well exposed.

The north half of the exposure face is the best portrayed and most instructive portion of Stop 5B. The unit that begins at road-grade level in this area is a planar-bedded to cross-stratified interval of medium- to coarse-grained sandstone, variably pebbly and conglomeratic. It displays regions of iron-oxide cementation. Of particular note, lateral changes in the direction and character of the cross-stratification are displayed along the extent of the exposure (Fig. 29). South-dipping crossbeds are seen at the north end, north-dipping crossbeds at the south end, and planar beds in the middle region. The dipping strata (inclined heterolithic stratification) are apparently lateral-accretion bedforms related to point-bar deposition in migrating river channels. Lateral accretion apparently occurred at different times on opposite sides of the channel, with horizontal bedforms characteristic of the central channel area.

The upper surface of this lower sandstone channel is erosionally beveled and crosscut by several different rock units of varying grain size (Fig. 29). A conglomeratic sandstone is identified at this position near the northern limits of the exposure, and a conglomerate lens (basal channel bedform) is preserved a short distance to the south (area B in Fig. 29). These coarse units and the underlying interval are, in turn, crosscut by a slightly finer grained sandstone channel (fine, medium, and coarse-grained sandstone with scattered granules and pebbles); this channel displays small-scale trough crossbeds in places. The northern margin of this channel sharply and steeply truncates the conglomeratic unit (see enlargements A and B, Fig. 29); abundant mudclasts are recognized near this margin. This sandstone channel is cut by an erosional surface southward; small swale-filling lenses of mudstone are seen along this surface (GR1, GR3 on Fig. 29) that are, in turn truncated by a massive sandstone channel.

A massive cliff-forming sandstone channel is found above the noted mudstone lenses, as best displayed in the central portion of the exposure face. This fine- to medium-grained sandstone shows a general decrease in average grain size over that observed below; pebbles are locally seen near the base of the channel. This large sandstone body shows small-scale trough crossbeds, and southward-dipping lateral accretion structures are seen near its northern extremity. A laterally extensive mudstone unit is seen in the upper part of the main exposure face, above this sandstone body. This mudstone is difficult to access. Fine-grained sandstones are exposed in the upper face and forested slope above the mudstone.

The geometry of complex and mutually crosscutting fluvial facies in the lower Nishnabotna Member is better portrayed at Stops 5A and 5B than at any other locality in western Iowa. Even though the exposures are exceptionally good, the fluvial processes that were responsible for creating the displayed sedimentary structures and geometries remain open to interpretation. In general, the

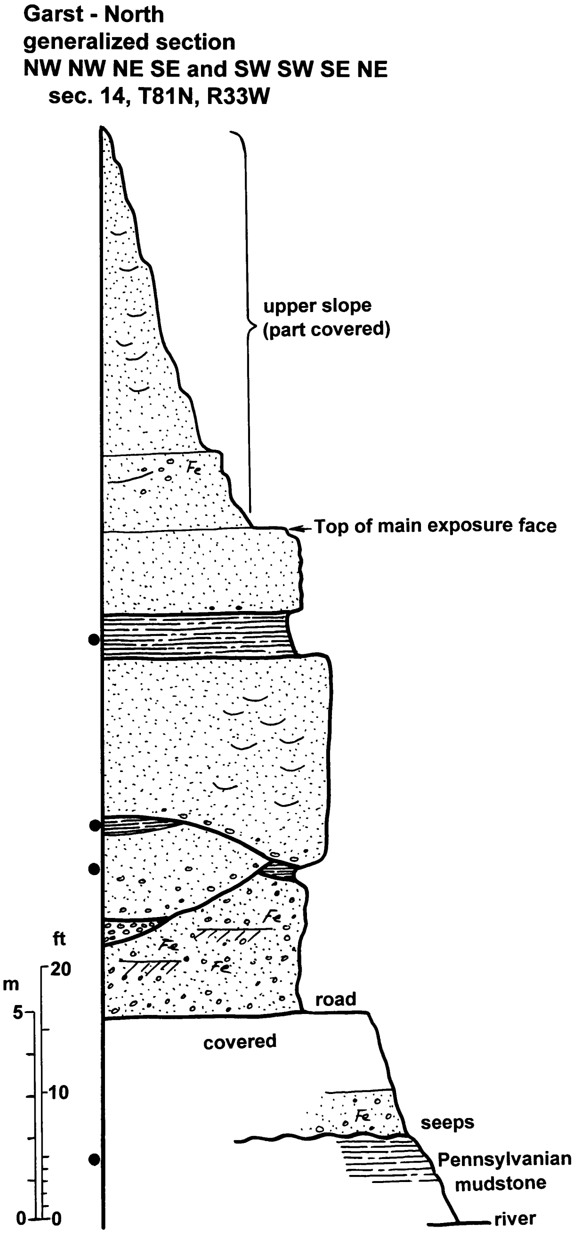


Figure 28. Generalized graphic section of Garst-North exposures, Stop 5B. Symbols as in Figure 17. Location of section shown on Figure 26.

lower Nishnabotna sediments exhibit features suggestive of braided fluvial deposition, including coarse grain size, poor sorting,, rare mudstone, and planar and horizontal stratification. The cross-cutting channel geometries indicate ongoing migration/avulsion of channels or braid systems during deposition. The finer-grained sandstone and smaller-scale sedimentary structures (especially trough crossbeds) of the upper Nishnabotna contrast markedly with the lower Nishnabotna, and different fluvial environments are indicated. A significant decrease in stream competency is indicated, which probably reflects changes in base level and a regional shift to distal braided and proximal meanderbelt fluvial sedimentation (Witzke and Ludvigson, 1994).

As the -field trip concludes, we hope that this brief look at a small segment of the Cretaceous outcrop belt in the Iowa region will serve to stimulate further study and foster a greater appreciation of the wealth of geologic information that can be found along the eastern-margin the great Western Interior Basin of North America. The ongoing accumulation of geologic data from this eastern region can serve to constrain and refine various paleoclimatic and paleogeographic models of the North American Western Interior, which, in turn, is needed to advance our understanding of the fascinating mid-Cretaceous “greenhouse world.”

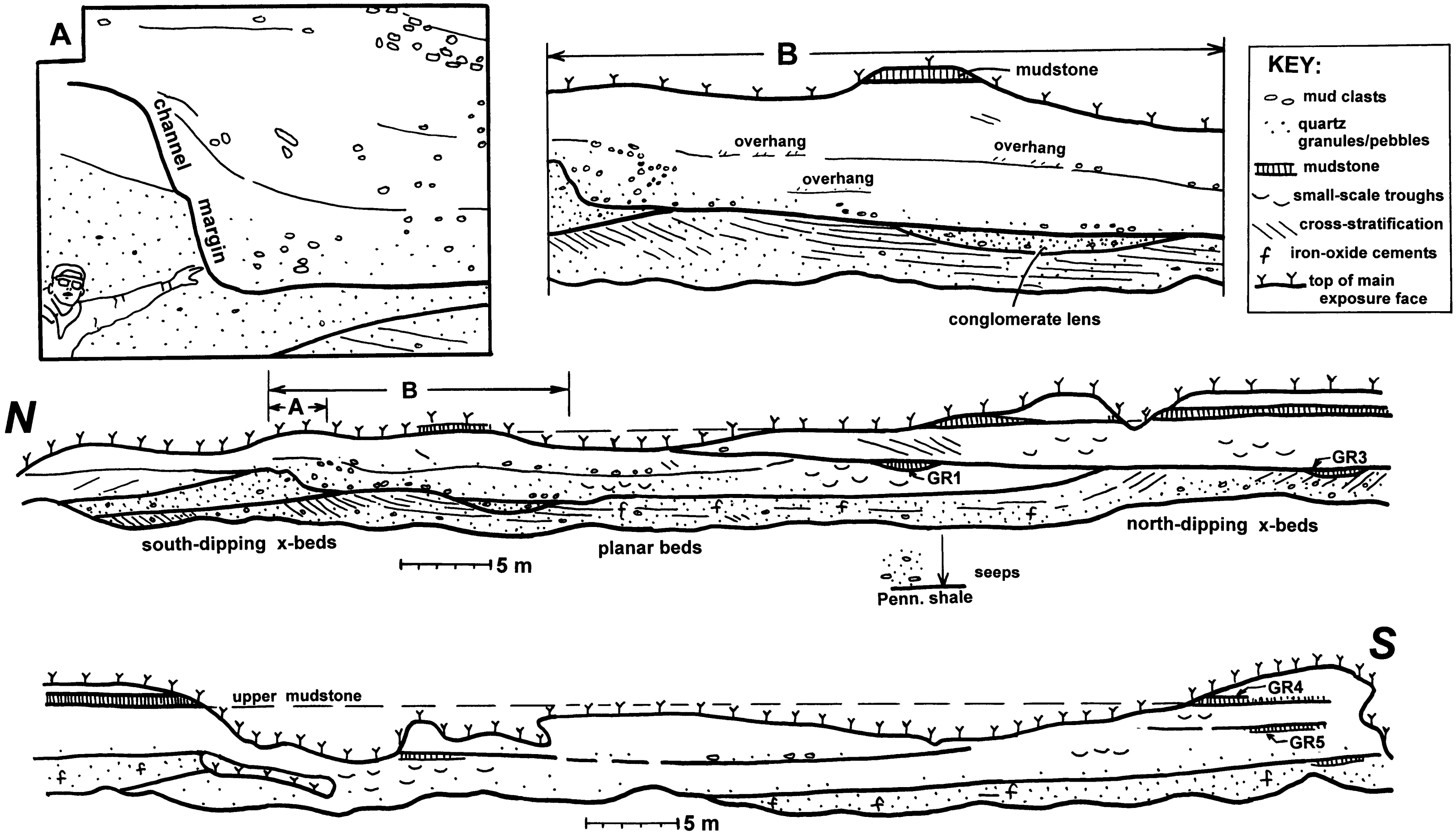


Figure 29. General north-south cross section of exposure face of Nishnabotna strata at Stop 5B (Garst-North section). Section based on tracing of photo-mosaic; simplified to reflect general cross-cutting geometries of sandstone and mudstone bodies. The vertical scale approximates the horizontal scale, but due to vertical compression created by the wide-angle lens, the upper half of the exposure face shows slight horizontal exaggeration. Areas A and B (bracketed at north end of main exposure) are enlarged to show greater detail of channel geometries. See Figure 28 for general stratigraphic position of portrayed section. GR1, GR3, GR4, GR5 are location of mudstone samples for palynology.

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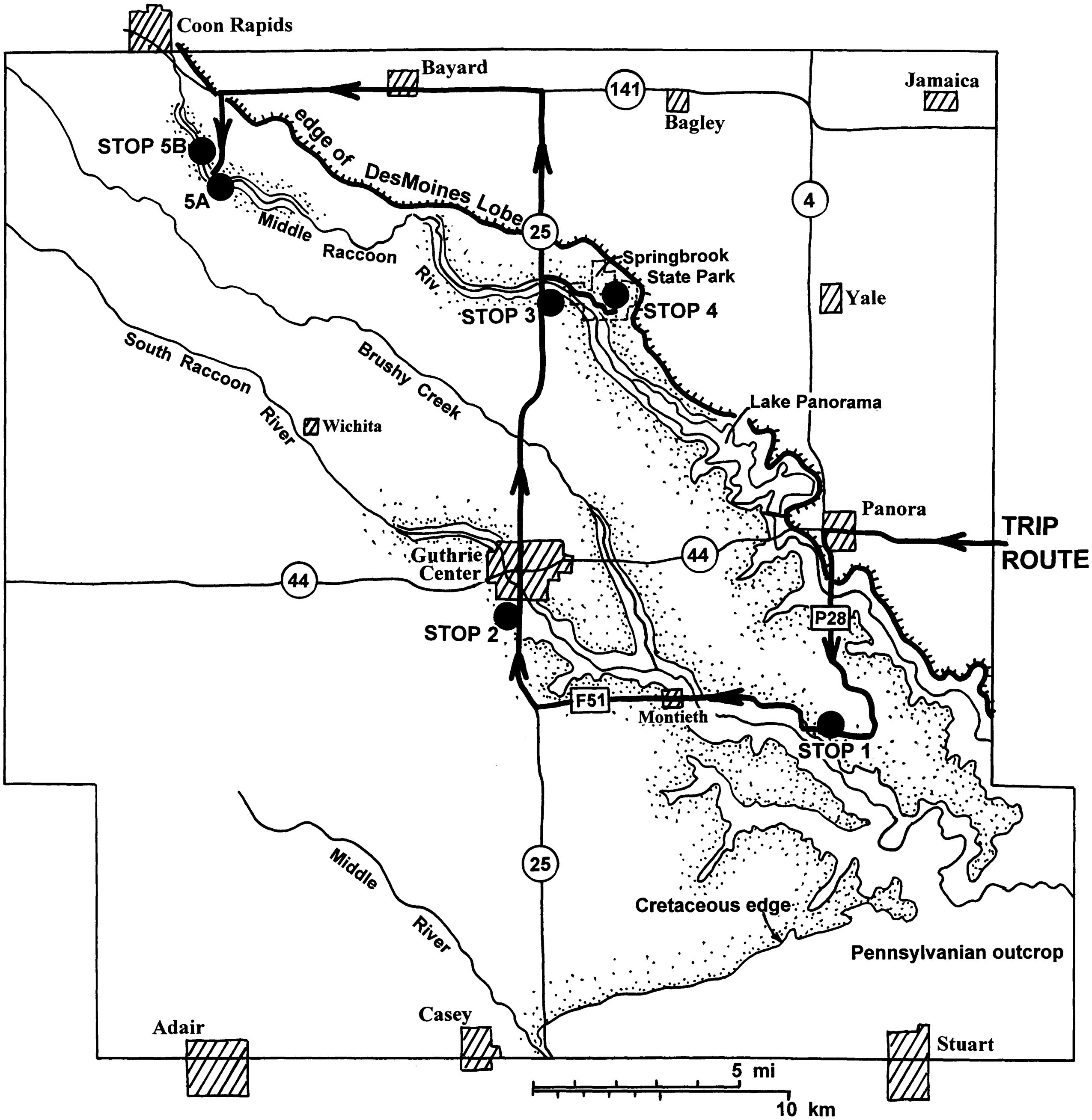

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