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HIGH-RESOLUTION SEQUENCE STRATIGRAPHIC SETTING OF MISSISSIPPIAN EOLIANITES, APPALACHIAN AND ILLINOIS BASINS

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ABSTRACT: Carbonate eolianites are abundant in the lower Chesterian (Upper Mississippian) succession in the Appalachian and Illinois Basins. The eolianites are quartz–peloid grainstones composed of well-rounded, very fine to fine sand-size peloids, whole ooids, broken ooids that have been re-rounded, skeletal fragments, and generally finer-grained subangular frosted quartz. Eolian deposits are 1 to 8 m thick and tens of meters to many kilometers wide. They have wedge sets of planar and tangential, sharply defined, inverse-graded laminae with dips of up to 20 degrees.

A high-resolution sequence stratigraphic framework was generated using the available biostratigraphy and closely spaced stratigraphic sections and core, and tracing regional disconformities marked by breccia, calcrete, and soil horizons between the sections. Eolianite units backstep within the transgressive part of the Chesterian supersequence and are absent from the highstand part, which is dominated by siliciclastics and likely formed in a more humid setting. Within third-order and fourth-order sequences, the eolianites occur updip in disconformity-bounded parasequences. In the transgressive and early highstand systems tracts of sequences, eolianites overlie exposure surfaces and are preserved in the transgressive parts of the parasequences. In the late highstand parts of sequences, eolianites are preserved in the regressive parts of parasequences and are capped by sequence-bounding disconformities marked by breccia and calcrete.

The abundance of carbonate eolianites in the Upper Mississippian is likely due to seasonal semiarid climate and moderate-amplitude fourth-order eustatic sea-level changes. The reservoir potential of the eolianites is limited by tight packing and calcite cementation. However, recognition of the eolianites is critical to understanding the vertical and lateral distribution of reservoir facies within the sequence stratigraphic framework because they indicate subaerial conditions and commonly mark subtle sequence boundaries.

INTRODUCTION

Quartzose carbonate eolianites are abundant in the Lower Chesterian (Upper Mississippian) Ste. Genevieve and Paoli Formations of the Illinois and western Appalachian Basins and the age-equivalent Denmar and Pickaway Formations of the eastern Appalachian Basin in West Virginia. Upper Mississippian carbonate eolianites were first described by Butts (1926) and Hickok and Moyer (1940) in their study of the Loyalhanna Limestone in the northern Appalachian Basin. The same quartz–peloid grainstones of the Loyalhanna Limestone were subsequently reinterpreted to be of marine origin (Flowers, 1956; Adams, 1970; Smosna and Koehler, 1993). In the Illinois Basin, the cross-bedded quartz–peloid grainstone deposits were also interpreted as marine (e.g., Choquette and Steinen, 1980). Hunter (1988, 1989, 1993), Merkely (1991), and Dodd et al. (1993) were the first to interpret the quartz–peloid grainstones of the Ste. Genevieve Formation of the Illinois Basin in southern Indiana as eolian in origin.

In subsequent regional sequence stratigraphic studies, Al-Tawil (1998), Smith (1996), and Smith and Read (1999) showed that the eolian facies are widespread in both the Ste. Genevieve and the overlying Paoli Formation and their equivalents in the Illinois and Appalachian Basins. The primary aims of this paper are to document the vertical and lateral position of these eolianites within a high-resolution sequence stratigraphic framework and discuss the conditions necessary to produce and preserve carbonate eolianites.

The high-resolution sequence stratigraphic framework was based on cross sections from outcrops and cores developed by Smith (1996) and Al-Tawil (1998) that document facies distribution and the extent of local and regional paleosols that mark sequence-bounding and parasequence-bounding disconformities. This data set was used to define the sequence stratigraphic significance of the eolianites, and their inferred relationships to systems tracts, sequence and parasequence boundaries, and marine sand bodies that could have acted as eolian sediment sources.

There has been considerable discussion in the past concerning whether coastal dune eolianites dominantly occur within the transgressive or regressive parts of sequences or both (Fairbridge and Teichert, 1953; Fairbridge, 1971; Ward, 1970, 1975; Carew and Mylroie, 1998, this volume). Our data sets show that in the most updip sections, eolianites typically overlie sequence-bounding and parasequence-bounding disconformities and are preserved in the transgressive parts of overlying sequences and parasequences. In the downdip sections, the eolianites are typically capped by sequence-bounding disconformities and are preserved in the late highstand parts of sequences.

GEOLOGICAL SETTING

Paleogeographic and Structural Setting

Mississippian carbonate eolianites of the Illinois and Appalachian Basins developed on a broad, shallow tropical ramp situ-

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ated between 5 and 15 degrees south of the Equator (Craig and Connor, 1979; McKerrow and Scotese, 1990). The ramp extended from the Appalachian foreland basin foreland of Kentucky and West Virginia across the Cincinnati Arch, across the Illinois Basin and farther to the west (Fig. 1). Subsidence rates increased in both the Illinois intracratonic basin and the Appalachian foreland basin in the Late Mississippian as a result of the collision between eastern North America and Gondwana (Heidlauf et al., 1986; Al-Tawil, 1998). The Cincinnati Arch, which separates the two basins, and the Waverly Arch to the east (Woodward, 1961; Ettensohn, 1980) were both structural highs that subsided at a much lower rate in the Mississippian. Most of the carbonate eolianite deposition occurred around these paleohighs.

The carbonate eolianites of the Illinois and Appalachian Basins are distributed over a much broader area than previously reported. Hunter (1988, 1989, 1993), Dodd et al. (1993), and Merkley (1991) described eolianites from southern Indiana and northernmost Kentucky. Similar carbonate eolianites also occur farther north in Indiana than previously reported and as far west as southwestern Illinois. In the Appalachian Basin, carbonate eolianites were previously described only in Pennsylvania and from a few sections in northern West Virginia (Butts, 1926; Hickok and Moyer, 1940; Berg, 1980; Ahlbrandt, 1996). Smith and Read (1999) and Al-Tawil (1998) show that the eolianites extend from northern Kentucky into southern and eastern Kentucky, and much farther south in West Virginia than previously reported. Similar carbonate eolianites occur in Upper Mississippian strata as far west as southwestern Kansas (Handford and Francka, 1991; Abegg, 1994; Abegg and Handford, 1998, this volume) and to the south in northeastern Tennessee.

Stratigraphic Distribution of Eolianite Facies

Carbonate eolianites were previously described in the Ste. Genevieve Formation of the eastern Illinois Basin (Hunter, 1988, 1989, 1993; Dodd et al., 1993; Merkley, 1991) and the Loyalhanna Formation of the northern Appalachian Basin (Butts, 1926; Hickok and Moyer, 1940; Berg, 1980; Ahlbrandt, 1996). This paper shows that in the Illinois Basin, eolianites occur in the (Lower Chesterian) Paoli Formation, the Spar Mountain and Rosiclare Members of the Aux Vases Formation, and the base of the Renault Formation as well as in the Ste. Genevieve. In the Appalachian Basin, eolianites occur in the Ste. Genevieve, Warix Run, and Paoli Formations in the western portion of the basin (Kentucky) and in the Hillsdale, Denmar, Pickaway, and Union Formations of the eastern Appalachian Basin in West Virginia (Fig. 2). Eolianites occur in both older and younger formations in the eastern portion of the Appalachian Basin than they do in the western Appalachian or Illinois Basins.

DESCRIPTION AND INTERPRETATION OF CARBONATE EOLIANITES AND ASSOCIATED FACIES

Common facies from the Illinois and Appalachian Basins are described in Table 1. The Chesterian carbonate eolianites of the Appalachian and Illinois Basins are associated with shallow-marine carbonates including skeletal grainstone and packstone, ooid grainstone, lime wackestone and mudstone (locally dolomitized), pelletal limestone, and various types of caliche paleosols (Dever, 1973; Ettensohn et al., 1988; Smith and Read, 1999; Al-Tawil, 1998). Marine siliciclastics occur in the western and central parts of the Illinois Basin near the top of the study interval (Smith and Read, 1999).

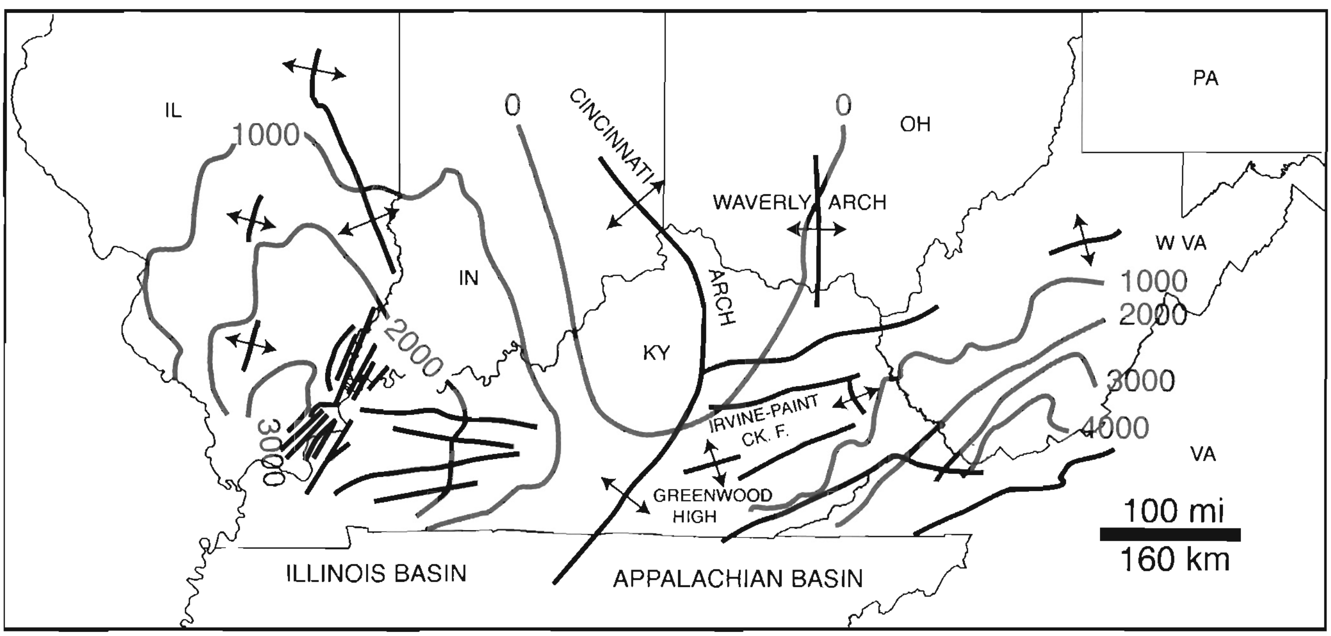


FIG. 1.—Regional structural setting of the Appalachian and Illinois basins during the Mississippian. The eolianites tend to be concentrated updip to the north against the cratonic shoreline, and flanking the Cincinnati Arch. Contours are total thickness of Mississippian System in feet (from Craig and Connor, 1979).

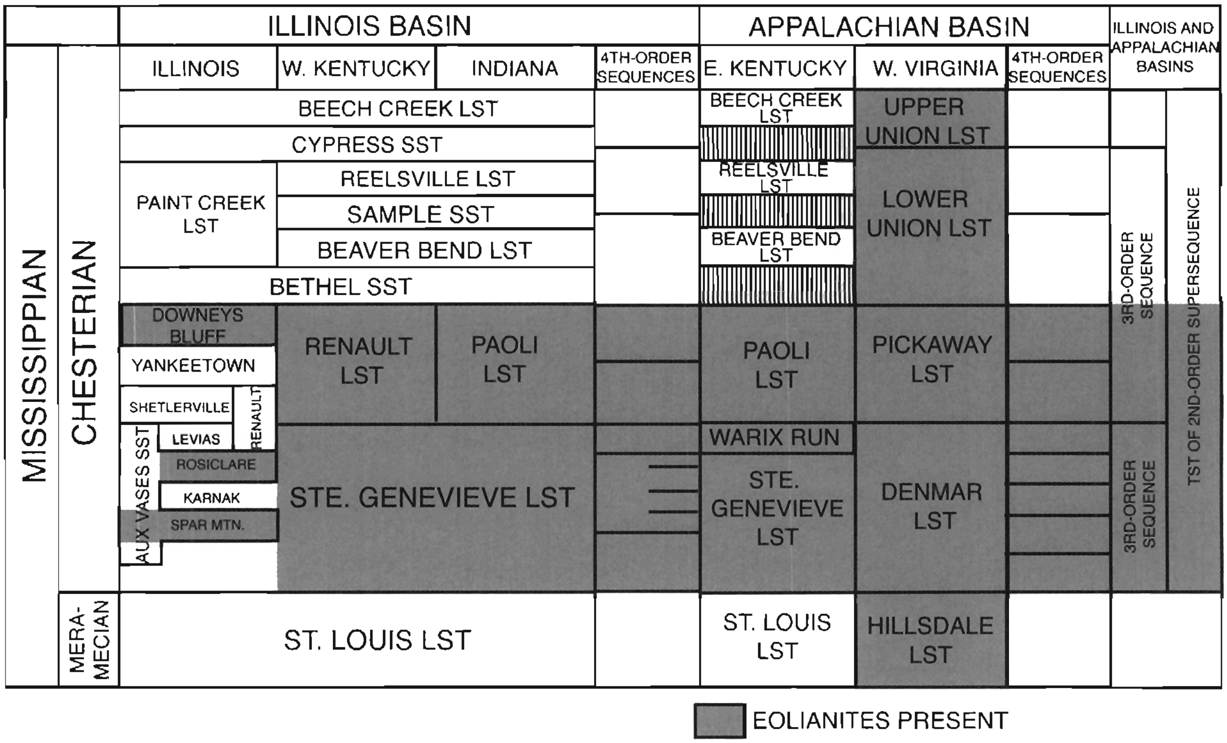


FIG. 2.—Formation names, sequences, and eolianite occurrences in Upper Mississippian strata of the Illinois and Appalachian basins. Fourth-order sequences or high-frequency sequences are dominant. Most of these sequences correlate from the Illinois Basin to the Appalachian Basin, with the exception of those in the Ste. Genevieve Formation, where only three sequences occur in the Illinois Basin compared to five in the Appalachian Basin. There are, however, numerous disconformity-bounded parasequences in the Illinois Basin, and these disconformities likely correlate to what are picked as sequence boundaries in the Appalachian Basin. The fourth-order sequences can be bundled into third-order sequences and the TST of a single second-order supersequence. Carbonate eolianites are abundant in the early TST of the supersequence.

Description of Eolianites

The eolianites from the Ste. Genevieve Formation have previously been described by Hunter (1988, 1989, 1993), Merkley (1991), and Dodd et al. (1993). The eolianite units are distinctively trough cross-bedded quartz–peloid grainstones (Fig. 3A) with sharply defined laminae that occur in beds from 0.5 to 8 m thick. They thicken, thin, and pinch out laterally, and range from less than a kilometer to many kilometers wide. The cross-beds have dips of up to 20 degrees (Fig. 3B). Rare exposures show anastomosing rhizoliths that form root mats on bedding planes (Fig. 3C) and well-preserved bedding-plane views of wind ripples and barchan dune crests (Fig. 3D). Some eolianites overlie or underlie beds with similar quartz and carbonate grains and abundant intraclasts (Fig. 3E).

The eolianites are dark gray-weathering quartz–peloid grainstones composed of well-rounded and abraded peloids, whole and abraded ooids, skeletal fragments, and generally finer-grained subangular quartz (Fig. 4). The quartz is medium silt to very fine sand size and the carbonate grains are medium silt to medium sand size. Grains are well sorted within laminae, may be inversely graded (with silt- and very fine-sand size quartz and carbonate grains passing up into fine- and medium-sand size carbonate grains producing the distinctive sharply defined laminations in weathered exposures; Figs. 3F, 4A). The grains are tightly packed and commonly show signs of pressure solution due to compaction and lack of early cementation. Burrowing is markedly absent, thus the cross laminae are extremely sharp, and the eolianites lack an *in situ* marine fauna.

Where the eolianites are capped by sequence boundaries, tops of eolianite units commonly grade into argillaceous, quartz–peloid packstone and conglomerate (Fig. 3E) which are interpreted as soil regoliths. This quartz–peloid packstone and conglomerate also occur at the base of some eolian deposits where they overlie disconformities. Thin, laminated calcrete crusts along with rhizoliths locally occur in upper parts of eolian units (Fig. 3D). Some tops of eolianites in Kentucky are intensely brecciated, and are draped by thin green lithoclastic mudrock.

The eolian quartz–peloid grainstones differ significantly from the marine quartz–peloid grainstones and quartz sandstones in the Mississippian. The marine units are typically coarser grained, have less sharply defined laminae (Fig. 3A), contain larger marine fossils, and may have large intraclasts of detrital chert concentrated in layers.

TABLE 1.—Facies descriptions.

Lithology (Depositional Environment)	**Calcrete, breccia and blocky mudrock (paleosol)**	**Quartz–peloid grainstone (eolianite)**	**Muddy Carbonates (Lagoon and intershoal)**	**Ooid Grainstone (high-energy shoal)**	**Skeletal grainstone and packstone (bank, shoal)**	**Fossiliferous Shale (carbonate–clastic transition)**	**Quartz sandstone (tidal sand ridge, channel fill)**
Occurrence	Common throughout basin, better developed on shelves.	Dune-forms; units commonly thicken and thin over short distances; underlie and overlie subaerial exposure surfaces	Occurs on Southeastern Shelf in Beaver Bend and Beech Creek Formations	Most common on Eastern Shelf in Beaver Bend, Reelsville, and Haney Formations.	Common throughout basin in all limestone units. Forms sheet-like units at base of most regressive parasequences	Common throughout basin. Transition between siliciclastic and carbonate rock types.	Commonly fills incised valleys and forms in linear sand ridges
Color	Calcrete and breccia are brown, tan dark gray; mudrock paleosols are most commonly red or maroon.	Weathered: dark gray; Fresh: light to medium gray	Tan dolomite; Light gray-brown limestone	White to light gray	Light to medium to dark gray	Olive green and dark gray	White to light gray/green
Depositional texture and grain type	Calcrete is wispy to laminated micrite; breccia is composed of mm- to cm-scale angular clasts in micritic matrix; mudrock is blocky, slickensided clay.	Grainstone; medium silt to medium sand sized; composed primarily of peloids, subangular quartz, abraded ooids, and skeletal grains	Microcrystalline dolomite, lime mudstone/wacke-stone, pelletal limestone.	Grainstone with fine to medium grained ooids, echinoderms, and brachiopods	Grainstone and packstone with up to 15% shale. medium to very coarse grained.	Fissile shale with interbeds of wackestone and packstone; whole brachiopods and bryozoans.	Very fine- to medium-grained, subangular, well sorted; may have up to 15% shale
Bedding and sedimentary structures	Some calcrete is laminated; most paleosols have undulose top; rooting structures are common.	Millimeter-scale inversely graded laminae form cross beds that dip less than 20°	Massive, rare laminites; dolomite vuggy	Cross-bedded, thick-bedded, and massive	Thick-bedded, massive, and cross-bedded	Fissile, flat-bedded	Cross-bedded, flat-bedded, and massive bedded; flaser bedding common
Biota	None	Abraded rounded skeletal grains; coarse skeletal grains absent.	Gastropods, ostracodes, less common echinoderms, bryozoans, and brachiopods	Echinoderms and brachiopods	Abundant echinoderms, brachiopods, bryozoans, common mollusks, and foraminifera	Bryozoans, brachiopods, and echinoderms	Rare echinoderm fragments, could be transported or eroded from underlying limestone

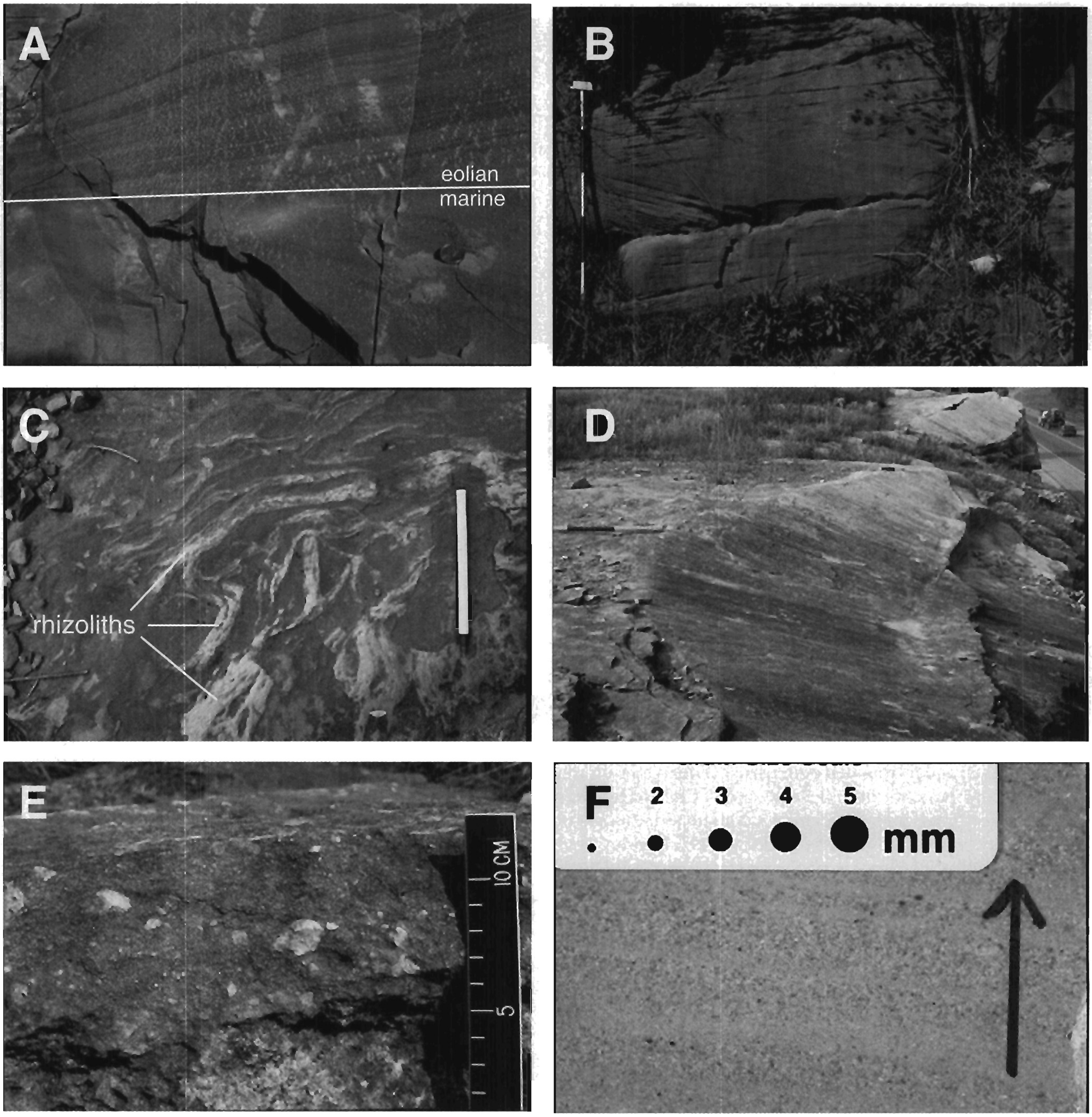


FIG. 3.—Mississippian carbonate eolianites of the Illinois and Appalachian Basins. **A)** Eolian facies with sharply defined laminae overlying cross-bedded marine sandstone with more diffuse laminae (Rosiclare Member of the Aux Vases Formation; Martin Marietta Stone Quarry, Cave-in-Rock, Illinois). **B)** Eolianite with cross-bedding from Canaan Valley, West Virginia. Scale in feet. **C)** Rhizoliths on top of eolianite (Ste. Genevieve Formation; Rte. 135 south of Corydon, Indiana). **D)** Eolian dune crest (Ste. Genevieve Formation; Rte. 135 south of Corydon, Indiana). **E)** Soil regolith composed of reworked windblown quartz and peloids with centimeter-scale lithoclasts (Paoli Formation, I-65 near Park City, Kentucky). **F)** Inverse grading in polished slab of eolianite (Canaan Valley, West Virginia).

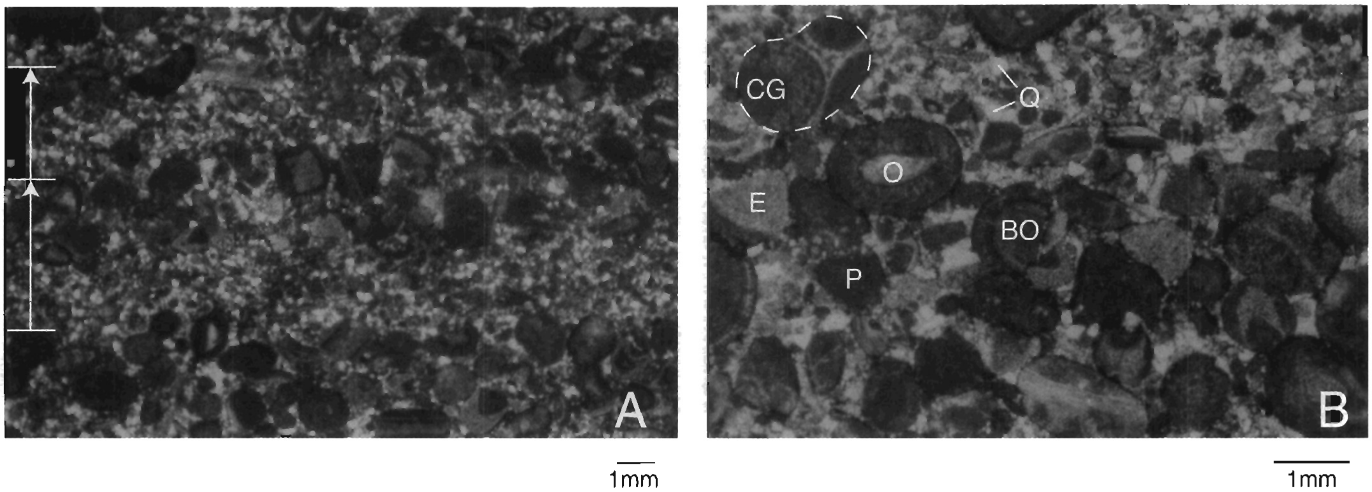


FIG. 4.—Thin-section photographs from quartz–peloid grainstone eolianite in northern Kentucky. **A)** Inversely graded laminae with very fine quartz and carbonate grains at base and fine to medium carbonate grains at top. **B)** Common grain types. CG = cemented grainstone clast that was ripped up and abraded; O = ooid; BO = broken ooid that was abraded and re-rounded; E = echinoderm fragment; P = peloid; Q = quartz silt.

Evidence of Eolian Origin

Characteristics of coastal eolianites are given in McKee and Ward (1983), Hunter (1993), and Carew and Mylroie (1998, this volume). Evidence that these Mississippian units were deposited in eolian settings is summarized in Dodd et al. (1993). Their lines of evidence include the very fine to fine sand size of the grains, the presence of inverse grading, the high degree of sorting within laminae, broken and re-rounded ooids, frosted quartz grains, the lack of marine burrows and skeletal grains, the presence of barchan dune forms, and association with subaerial exposure surfaces, paleosols, and rhizoliths (Merkley, 1991; Hunter, 1993; Dodd et al., 1993). The large-scale cross-stratification probably formed by grain-fall onto the leeward facies of dunes (Hunter, 1993). Inversely graded laminae were likely formed by climbing wind ripples, which are best preserved on the basal aprons of modern dunes and on gently sloping wind-rippled leeward-facing surfaces (Hunter, 1993).

Some subhorizontally laminated quartz–peloid grainstones at bases of the eolian deposits and above marine units may be beach facies, but the lack of coarse marine fossils suggests that they are more likely to be interdune or eolian sheet deposits.

Most cross-bedded quartz–peloid grainstones in the Illinois and Appalachian Basins that were examined for this study have been interpreted to be carbonate eolianites on the basis of the criteria for their recognition presented by Hunter (1993) and Dodd et al. (1993) (Smith and Read, 1999; Al-Tawil, 1998). Some far-updip quartz–peloid grainstone deposits with very coarse skeletal fragments and chert clasts occur near the Waverly Arch in the Appalachian Basin; these are clearly marine in origin, judging from high-angle tidal cross-bedding and the very coarse grain size. These deposits occur where the study interval is very thin because subsidence rates were very low on the Waverly Arch during the Mississippian. It may be that the farthest-updip eolianites are the most likely to be reworked in a marine setting because they were not immediately overlain by marine strata during subsequent transgressions.

SEQUENCE STRATIGRAPHIC SETTING OF CARBONATE EOLIANITES

Construction of Cross Sections

The high-resolution sequence stratigraphic framework was generated using detailed measured sections of more than one hundred closely spaced outcrops and cores (see Smith and Read, 1999, and Al-Tawil, 1998, for full descriptions of the sequence stratigraphy). Each section was measured bed by bed noting rock type, important macrofossils used for biostrati-graphy, and any evidence for subaerial exposure. Evidence of subaerial exposure such as paleosols, calcretes, breccias, teepee horizons, and eolianites were used to define sequence-bounding and parasequence-bounding disconformities at each section. Initial correlations between the sections were done using available biostratigraphy, the disconformities, and lithologic markers such as regional and semi-regional shale units. Internal facies were then correlated between the sections.

It should be understood that there are significant gaps between some of the sections and that the intervening stratigraphy it is unlikely to precisely match the cross sections as drawn. Despite this inaccuracy, the cross sections are still very good representations of the facies relationships present in the study interval and are more than adequate for determining the sequence stratigraphic distribution of carbonate eolianites. The relationships between the sequence boundaries, eolianites, and associated marine facies at each measured section have all been observed in the field. Unfortunately, the trend of the outcrop belts and the cross sections tended to be highly oblique to depositional dip (Figs. 5, 6), which inhibited the detailed reconstruction of facies relations between the eolian deposits and the immediately updip and coeval basinward and landward facies.

Sequence Stratigraphic Hierarchy

The Chesterian succession containing the eolianites is composed of up to six fourth-order high-frequency sequences (HFS), which are composed of numerous small-scale, higher-frequency parasequences (Fig. 2; Smith and Read, 1999; Al-Tawil, 1998). These HFSs were likely produced by fourth-order (~ 400 ky) glacio-eustatic sea-level fluctuations of 20 to 30 meters (Smith and Read, 1999; Smith and Read, 2000; Al-Tawil, 1998). The amplitude of sea-level fluctuations was calculated using the estimated sea-level rise needed to produce shallow marine conditions across the basin and the magnitude of sea-level fall required to produce the basin-wide exposure surfaces without significant erosion (Smith and Read, 1999).

The HFSs are bundled into subtle third-order sequences (termed composite sequences in Smith and Read, 1999). The ramp margin is outside of the outcrop belt of the Illinois Basin; thus the third-order sequence boundaries were defined more on the basis of evidence for longer periods of subaerial exposure such as thick breccia horizons, coincidence with multiple biostratigraphic zone boundaries, or significant erosion of underlying strata. In the Appalachian Basin, the third-order sequences can be defined on the basis of updip, late-highstand redbeds, and ramp-margin, lowstand marine clastic units.

The third-order sequences in turn are bundled into a larger-scale second-order supersequence. The base of the second-order supersequence is the post–St. Louis unconformity at the base of the Ste. Genevieve Formation, where there are coinciding conodont, coral, and foraminiferal zone boundaries (Maples and Waters, 1987). The maximum flooding surface for the supersequence lies within the Glen Dean Formation, which is a regional open-marine limestone that has deeper-water facies than any of the overlying or underlying strata (Al-Tawil, 1998). The upper supersequence boundary lies at the unconformity on top of the Mississippian Pennington–Mauch Chunk and equivalent siliciclastic units. The carbonate-prone study interval thus is all within the early transgressive portion of the supersequence.

Position of Carbonate Eolianites within Sequence Stratigraphic Hierarchy

Position within Parasequences.—

Carbonate eolianites occur as both transgressive and regressive deposits within parasequences (Fig. 7). Eolianites are interpreted to have been deposited during transgressions when they overlie surfaces with evidence for prolonged subaerial exposure and grade upward into overlying marine deposits (Fig. 7). Eolianites are interpreted to have been deposited during regressions, when they conformably overlie marine strata and are capped by subaerial exposure surfaces (Fig. 7). Some parasequences are composed entirely of eolianites, with exposure surfaces above and below them. Evidence for subaerial exposure is not preserved in all cases. In these cases, disconformities are interpreted to occur in the same stratigraphic position as in nearby sections where evidence for exposure is preserved.

In order to better understand the distribution of eolianites, the number of occurrences of eolianites occurring above and below parasequence boundaries were counted. The majority (58%) of the eolianites occupy a transgressive position within parasequences in the Illinois Basin. Some of these transgressive eolianites appear to pass downdip into a disconformity surface, but the oblique orientation of the cross sections limits the true downdip tracing of units. Only about 40% of the eolianites occupy a regressive position, and rare eolianites cannot be classified as either transgressive or regressive within parasequences. Parasequences with transgressive eolianites are most common in the updip, landward parts of the basin and parasequences with regressive eolianites are more common in the downdip parts of the basin. Parasequences composed entirely of eolianites with evidence for prolonged subaerial exposure above and below them are most common in the far updip sections, where the least amount of accumulation and preservation space was created.

In our studies in the western portion of the Appalachian Basin, parasequences are rarely traceable for any distance, but where developed, the eolianites occur in both transgressive and regressive positions within local parasequences.

Position within High-Frequency Sequences.—

In the Illinois basin, over 50% of the eolianites occur in the lower, transgressive parts of HFSs, and just over a third occur in the upper highstand parts, the rest occurring in the middle, indeterminate parts of the sequences. In the Appalachian Basin HFSs, the eolianites are equally distributed between the transgressive and regressive parts of HFSs. Overall in both basins, the eolianites seem to be dominantly transgressive updip and dominantly regressive downdip within the high-frequency sequences.

Position within the Chesterian Supersequence.—

The carbonate eolianites all occur within the early transgressive portion of the Chesterian second-order supersequence (Ste. Genevieve to Paoli interval; Al-Tawil, 1998). There are no eolianites in the later transgressive or highstand parts of the supersequence, which are dominated by much more open-marine facies and greater amounts of siliciclastics (Fig. 2).

CONTROLS ON DEVELOPMENT AND PRESERVATION OF THE MISSISSIPPIAN CARBONATE EOLIANITES

Climatic Control on Eolianite Development

The presence of abundant dolomite, calcrete, and ooids, along with the eolianites, suggests a semiarid setting for the eolianite-bearing Ste. Genevieve and Paoli units of the Upper Mississippian in the Appalachian and Illinois Basin (Smith and Read, 1999). The lack of evaporites in this part of the section, which are common in the underlying St. Louis Formation, suggests that the climate was not entirely arid. Pangean tropical climates likely were dominated by the Pangean mega-monsoons, which allowed development of low-latitude deserts (Parish, 1993).

This semiarid climate promoted the development of eolianites by preventing newly emergent coastal sandbodies from becom-

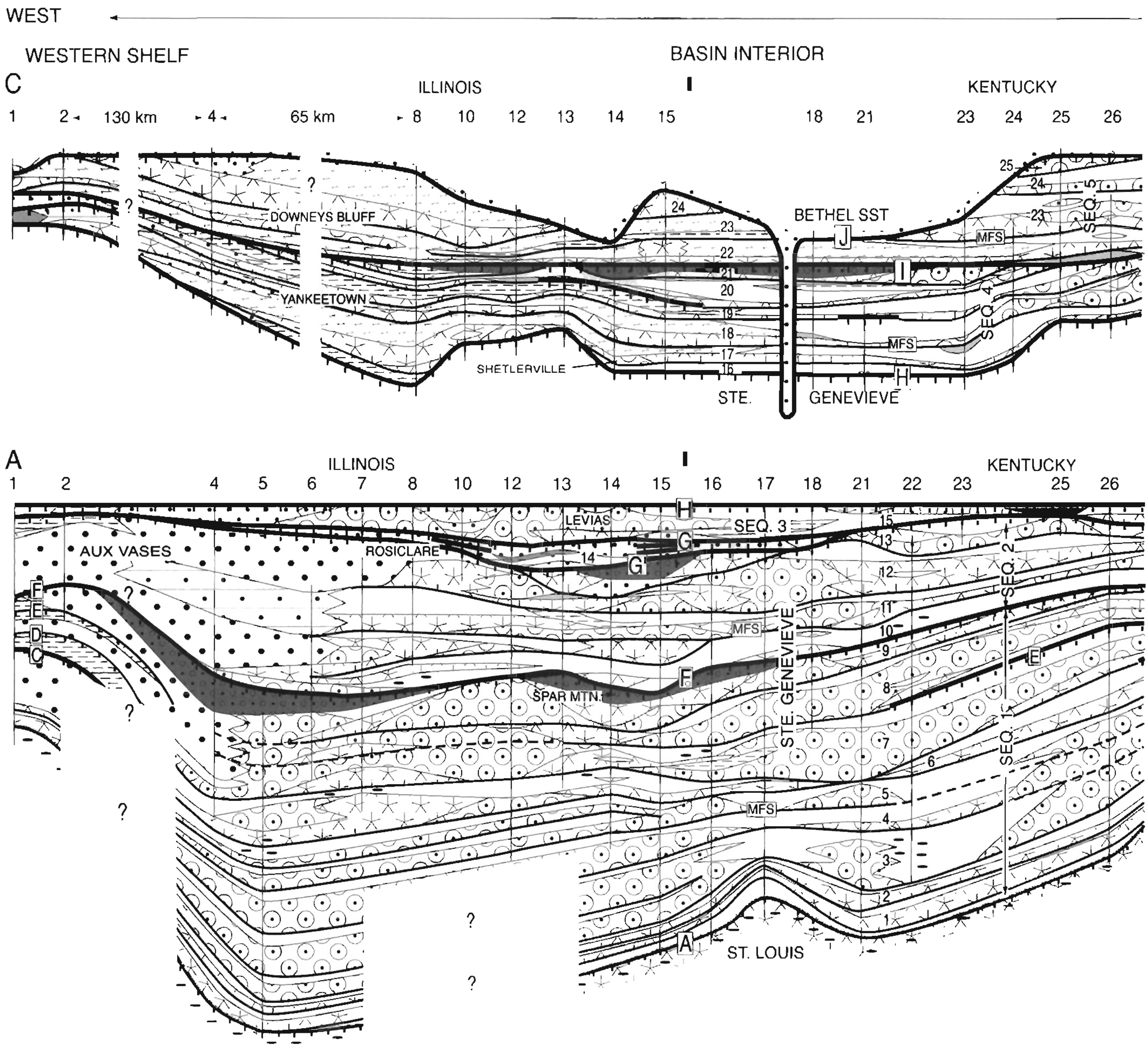
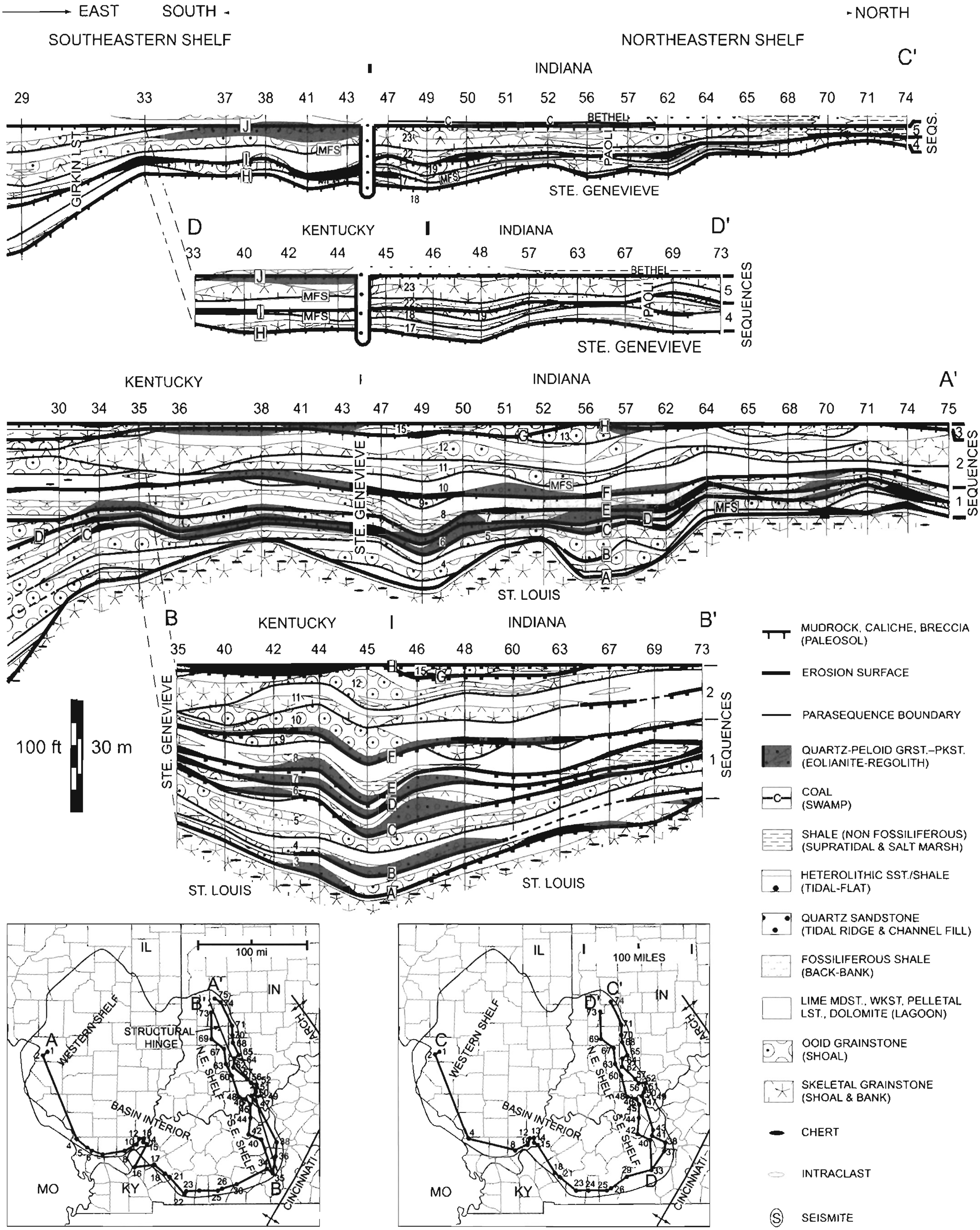


FIG. 5.—Interpretive cross sections of sequences 1 through 5 in the Ste. Genevieve to Paoli interval. Eolianites are colored gray. Note occurrence of eolianites updip in the transgressive parts of sequences and downdip in the late highstand parts of sequences. Measured sections are equally spaced except where there are major gaps between sections (see location maps for actual horizontal spacing). Disconformities are lettered from A to J, and parasequences are numbered from 1 to 25. The Bethel Channel is not drawn to scale; its actual depth is 75 m (Friberg et al., 1969). Color version of these cross sections in Smith and Read (1999). Cross section A–A' includes the Ste. Genevieve and trends west to east from location 1 to location 35 and south to north from location 35 to location 75. Cross section B–B' shares location 35 and trends south to north parallel to and downdip of section A–A'. Cross section C–C' trends west to east from location 1 to location 33 and south to north from location 33 to location 74. Cross section D–D' shares location 33 and trends south to north parallel to and downdip of cross section C–C'. MFS = maximum flooding surface, PKST = packstone, MDST = mudstone, WKST = wackestone, and LST = limestone.


EAST
SOUTH
NORTH
SOUTHEASTERN SHELF
NORTHEASTERN SHELF
C'
INDIANA
BETHEL
PAOLI
STE. GENEVIEVE
GIRKIN LST.
SEQS.
D
D'
KENTUCKY
INDIANA
SEQUENCES
KENTUCKY
INDIANA
A'
ST. LOUIS
B
B'
100 ft
30 m
MFS
MUDROCK, CALICHE, BRECCIA (PALEOSOL)
EROSION SURFACE
PARASEQUENCE BOUNDARY
QUARTZ-PELOID GRST.–PKST. (EOLIANITE-REGOLITH)
COAL (SWAMP)
SHALE (NON FOSSILIFEROUS) (SUPRATIDAL & SALT MARSH)
HETEROLITHIC SST./SHALE (TIDAL-FLAT)
QUARTZ SANDSTONE (TIDAL RIDGE & CHANNEL FILL)
FOSSILIFEROUS SHALE (BACK-BANK)
LIME MDST., WKST, PELLETAL LST., DOLOMITE (LAGOON)
OOID GRAINSTONE (SHOAL)
SKELETAL GRAINSTONE (SHOAL & BANK)
CHERT
INTRACLAST
SEISMITE
IL
IN
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KY
100 mi
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WESTERN SHELF
STRUCTURAL HINGE
N.E. SHELF
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BASIN INTERIOR
CINCINNATI ARCH

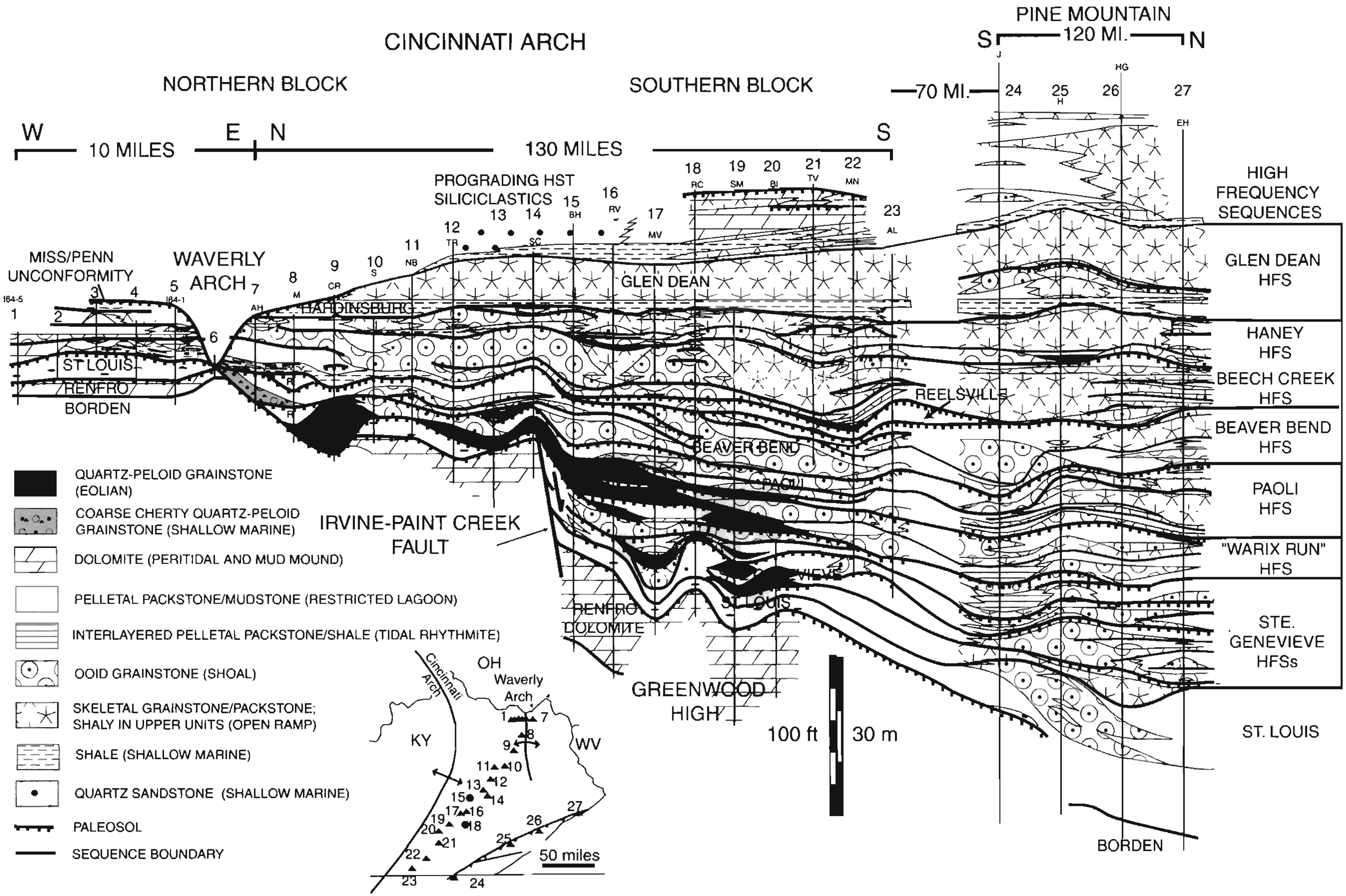

FIG. 6.—Regional strike cross section through eastern Kentucky, from the Waverly Arch in the north, extending southwest to the Tennessee line, and then continuing in the Pine Mountain Belt, from southwest to northeast. Note that the eolianites are well developed on the downthrown side of the Irvine–Paint Creek Fault, especially in the Warix Run Formation. Marine quartz–peloid grainstones occur adjacent to the Waverly Arch where the section is the thinnest. These may be reworked eolianites.

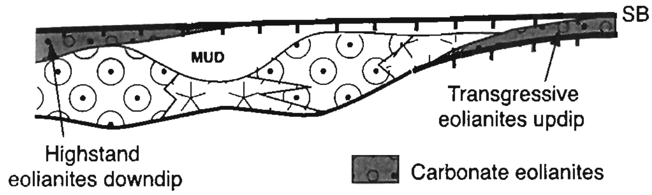

FIG. 7.—Schematic showing the sequence stratigraphic distribution of Upper Mississippian eolianites of the Illinois and Appalachian basins. Downdip, eolianites are typically preserved in the late highstand parts of sequences. Updip, eolianites are commonly preserved in the transgressive parts of sequences and parasequences. In the farthest updip sections, entire sequences and parasequences may be composed of disconformity-bounded eolianites.

ing heavily vegetated or cemented by meteoric cements. Widespread meteoric calcite cementation did not occur in the Mississippian sediments until after the bulk of the Chesterian carbonates had been deposited and the climate had become more humid (Niemann and Read, 1988). Prior to this, early meteoric calcite cements rarely were formed in Ste. Genevieve and Paoli during periods of exposure because the semiarid climate inhibited the development of meteoric aquifers and ground water was likely to be relatively saline.

Additionally, Mississippian ooids have distinctive radial fabrics typical of primary calcite mineralogies, and so the scarcity of easily dissolved aragonite inhibited early meteoric calcite cementation. Many skeletal and oolitic grains became peloids when they were micritized shortly after deposition. These micritized grains were much less likely to be cemented than their unmicritized counterparts because of the very small nucleation surfaces. Thus, the primary components of the eolianites (peloids, quartz grains, and ooids) were largely uncemented, which allowed them to be moved by eolian processes during periods of subaerial exposure.

The direction of the prevailing winds during the Mississippian could have influenced the development of the eolianites. Many modern coastal eolianites appear to be best developed where onshore winds are common (McKee and Ward, 1983) as well as where winds blow parallel to the shoreline (Lomando, 1999). Given that the ancestral Appalachian Mountains and the Illinois Basin lay south of the equator in the early Pangean desert belt, with the Appalachians trending roughly west-southwest in terms of Mississippian paleogeography, summer low-pressure areas likely were localized on the emergent shield area (Golonka et al., 1994). This low-pressure zone would have migrated north or south of the equator with the northern and southern summer, respectively, thus influencing the seasonal wind patterns (Golonka et al., 1994). Low-pressure zones are typically associated with wet climates, but there was probably an orographic effect caused by the mountains to the east. Moist air from the seaway between Gondwana and North America likely was forced to rise and cool over the mountains, leading to precipitation on the eastern side of the mountains and relatively dry air in the Illinois and Appalachian Basins during the early Chesterian.

The paleoclimate maps of Golonka et al. (1994) suggest that during northern summer the winds probably blew from the southeast, toward the southern margin (Appalachian Basin side) of the Cincinnati Arch, and parallel to the cratonic shoreline (Fig. 8). In southern summer, the winds from the southeast still blew toward the southern side of the arch and parallel to the cratonic coastline. Hunter (1993) published a rose diagram of the orientation of eolian cross-beds in southern Indiana (Fig. 8) that shows a spread from southwest to due north. This suggests that the eolianites on the Illinois Basin side of the Cincinnati Arch may also have been sourced from the Appalachian Basin. Judging by that rose diagram, the prevailing winds in the Illinois Basin ranged from south to north to northeast to southwest. Daily, strong onshore winds normal to the cratonic shoreline also could have been set up as sea-breeze systems during late afternoon, as a result of strong summer heating of the emergent land. Winds blowing onshore and parallel to the shore would have favored development of the extensive Mississippian coastal eolianites.

The quartz sand in the eolianites could have been blown into the coastal environments during dust storms (cf. Shinn, 1973) or transported to the coast by runoff during flash floods. Possible sources for quartz sand to the basins are the Appalachians to the east and northeast, the Canadian Shield to the north, and the Transcontinental Arch to the west. Eolian deposits tend to be progressively richer in quartz from the east to the west in the Appalachian Basin, suggesting that the source of the quartz may have been the Transcontinental Arch. In the Appalachian Basin, fluvial–deltaic siliciclastics to the north and east were the likely source of the detrital quartz.

Moderate-Amplitude Fourth- and Fifth-Order Eustasy

The frequent, moderate-amplitude sea-level changes during the Late Mississippian transition to global ice-house climate were clearly important in the widespread formation and preservation of carbonate eolianites. The third- and fourth-order sequences likely were produced by 20 to 30 meter sea-level changes and the higher-frequency fifth-order parasequences by sea-level changes of roughly 10 m (Smith, 1996; Al-Tawil, 1998; Smith and Read, 1999). The moderate-amplitude eustasy in the Mississippian caused frequent lateral migration of the shoreline and incorporation of marine sediment grains into coastal dunes. Moderate-amplitude sea-level changes favored the development of widespread high-energy subtidal oolitic and peloidal deposits that ultimately covered large areas of the ramp, because each marine transgression tended to flood the ramp to 10 m or less. As sea level fell, much of the platform was exposed, leaving extensive grain-rich units to be blown into eolian deposits.

Moderate-amplitude sea-level changes also helped to create accumulation and preservation space (*sensu* Kocurek and Havholm, 1993). Relatively rapid moderate-amplitude sea-level falls left unfilled topography between marine ooid shoals that were ideal for eolian deposition and preservation in the late highstand parts of sequences and parasequences. Relatively rapid sea-level rises helped to increase preservation space for eolian deposits that initially accumulated above sea level on the shelves during transgression.

It appears that carbonate eolianites are most likely to be preserved during periods of moderate- to high-amplitude sea-

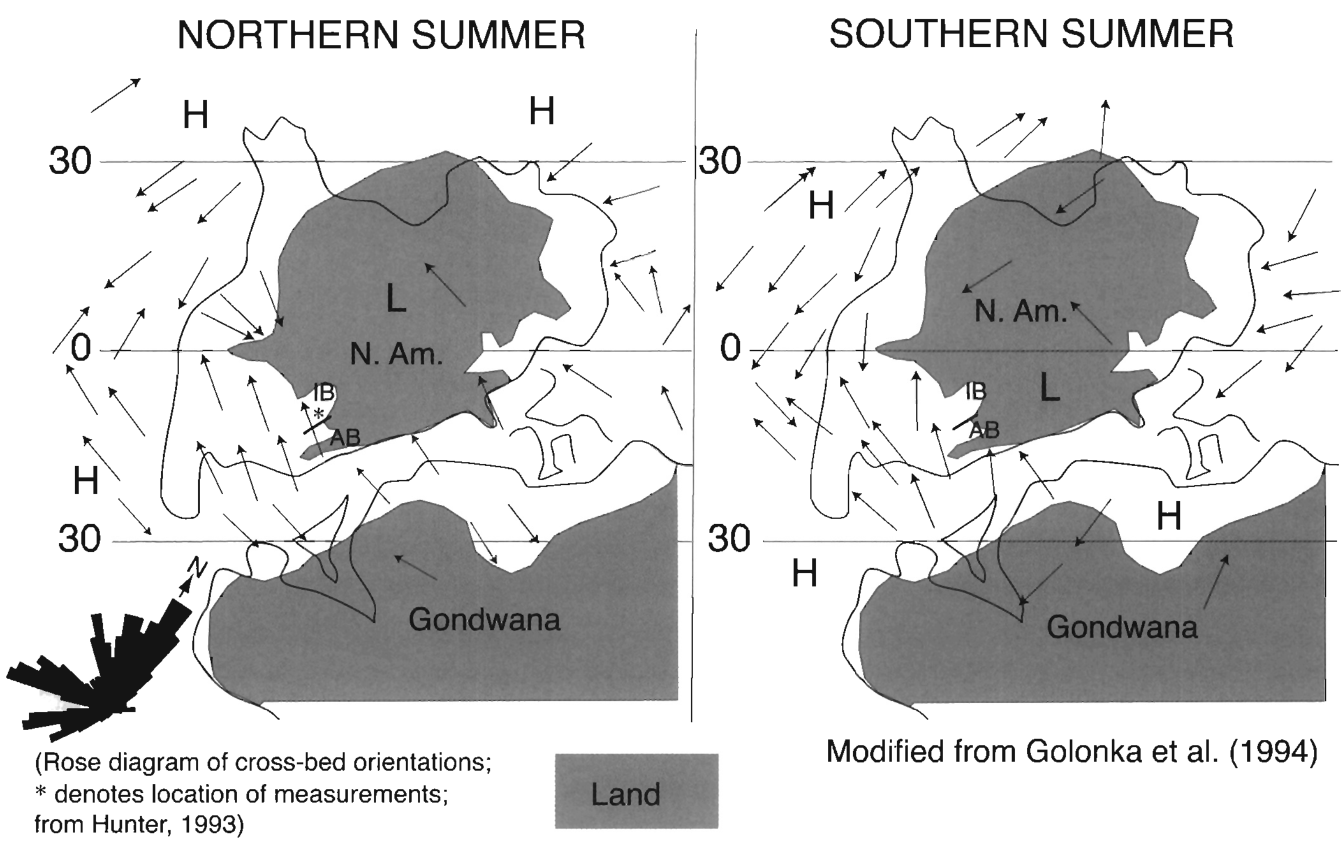

FIG. 8.—Inferred wind patterns for North America during the Visean (modified from Golonka et al., 1994) and rose diagram with the orientation of eolian cross-bedding in southern Indiana (from Hunter, 1993). Land is shaded; Illinois Basin and Appalachian Basin are labeled IB and AB, respectively; Cincinnati Arch is shown by short dark line separating basins. Prevailing winds are shown by arrows. Left shows pattern in northern summer with low pressure centered on North America, and the winds blowing to the northwest, across the Cincinnati Arch. In southern summer, the low is centered farther toward the Appalachians, and the winds here blow toward the northwest onto the southern (Appalachian Basin) side of the Arch. The modeled atmospheric circulation is supported by the rose diagram of Hunter (1993), which was constructed using a weighted moving average of 84 eolian cross-bed orientations. Note the lack of any component of west-to-east cross bedding.

level changes (20 m to 100 m or more), as evidenced by the widespread distribution of Mississippian and Pleistocene carbonate eolianites (McKee and Ward, 1983; Abegg et al., this volume). Low-amplitude, high-frequency sea-level changes (a few meters) typical of greenhouse times do not generally submerge ramps to depths sufficient to generate widespread high-energy deposits (Read, 1995). Shorelines typically do not migrate distances sufficient to expose the grainy facies that are concentrated along the seaward edges of greenhouse platforms, which would provide the source for the eolianites. Additionally, on aggraded greenhouse ramps, marine carbonate sandbodies commonly are capped by peritidal muds and tidal-flat facies, which inhibits the marine grainstones from being incorporated into coastal dune systems during the ensuing transgression.

Transgressive versus Regressive Eolianites

Eolianites have been considered to form either during both transgressive and regressive events (Fairbridge and Teichert, 1953; Carew and Mylroie, 1995, 1998, this volume) or mainly during regressive events (Fairbridge, 1971; Ward, 1970, 1975). This study shows that both transgressive and regressive eolianites occur in the Mississippian.

Within the transgressive parts of the HFSs updip, the eolianites are localized in transgressive parts of disconformity-bounded parasequences. The abundance of transgressive eolianites in updip parts of parasequences and HFSs indicates that sea-level rise and shoreline migration favored eolian deposition. Landward shoreline migration generated dunes fed from transgressive oolitic units immediately offshore, or from wave and wind erosion of emergent, uncemented oolitic bodies at the top of the underlying parasequence. As the shoreline advanced landward, sediments were fed into dunes that tended to migrate landward. Rising sea level created preservation space, and the transgressive eolianites were preserved and buried beneath marine strata.

Fourth-order regressions also favored eolian deposition, but the common downdip occurrence of regressive eolianites in HFSs suggests that they formed toward the end of fourth-order seaward migration of the shoreline. These downdip regressive coastal eolianites formed landward of prograding subtidal marine oolitic units that continually fed the dune system. Regressive eolianites may have been more likely to be preserved downdip because they filled tectonic or depositional lows in areas of higher subsidence and were less likely to be eroded.

Structural and Tectonic Controls

The distribution of many modern eolianites may be influenced by subtle folding and faulting of the subjacent beds (Lomando, 1999). Although gentle tectonic deformation (faulting and flexure) was occurring during the Mississippian in the Appalachian and Illinois basins, it is not clear how much this influenced the localization of the eolianite units. Resolution of this would require much denser data sets than were used in the sequence stratigraphic reconstructions. Many of the eolianites in Kentucky tended to accumulate updip, however, abutting against the fault-bounded, positive, northern block adjacent to the Cincinnati Arch. Similarly, in the Illinois Basin the eolianites tended to flank the western margin of the Cincinnati Arch.

Sequence Stratigraphic Importance and Reservoir Potential

Recognition of carbonate eolianites is critical in developing the sequence stratigraphic framework because they indicate subaerial conditions in much the same way as the disconformities that bound the sequences and parasequences. Misidentification of the eolianite units as subtidal and tidal-inlet deposits within what are dominantly shallow-water successions results in the numerous subaerial emergence events being overlooked.

The eolianites tend to have very low porosity and permeability because of compaction and close packing of grains. A few samples contain fine equant cements that may have kept the grain framework open during burial, but the great majority have little to no early cement. The calcite cements in the eolianites likely are meteoric phreatic calcite cements, which developed during more humid phases in the later Mississippian and early Pennsylvanian (Neimann and Read, 1988), along with some shallow-burial calcite cement. Thus the quartzose–carbonate eolianites have limited potential as reservoirs. The relatively arid setting, the calcitic primary mineralogies of the radial ooids (Wilkinson, 1979), and the lack of aragonitic skeletal grains probably limited the formation of secondary porosity. Perhaps in more humid settings during times of aragonitic ooid precipitation, more secondary porosity might be expected.

CONCLUSIONS

1. Eolianites are widespread in Mississippian (Chesterian) Ste. Genevieve and Paoli carbonates of the Appalachian and the Illinois Basins. The eolianite units are 0.5 to 8 m thick and less than a kilometer to several kilometers wide. The eolianite units are characterized by large-scale cross-bedding, sharply defined lamination, inverse grading, and very fine to fine quartz–peloid grainstone lithologies. They lack burrow structures or coarse skeletal debris.

2. Both transgressive and regressive eolianites occur within parasequences and fourth-order high-frequency sequences. Updip, eolianites are typically preserved in the transgressive parts of sequences where they overlie sequence-bounding and parasequence-bounding disconformities and are overlain by marine strata. Downdip, regressive eolianites overlie marine units and are capped by sequence-bounding disconformities.

3. Moderate-amplitude (10 to 30 m) eustasy, semiarid climate, and perhaps onshore to shore-parallel winds, were the main controls on the development of the eolianites. Moderate-amplitude eustasy led to the prolonged exposure of subtidal shallow marine grainstone shoals that fed coastal dune systems during fourth- and fifth-order transgressions or regressions. There was little early meteoric cement or binding vegetation because of the semiarid paleoclimate, which further enabled grains to be transported by eolian processes. The eolianites are most common near structurally positive features such as the Cincinnati Arch, and adjacent to the cratonic shoreline, except for eolianites in the late highstands of some sequences, which formed thin regressive units downdip.

4. The Mississippian eolianites typically have very low porosity and permeability and appear to have low reservoir potential. A paucity of early marine or meteoric cementation led to tight compaction of the grains. However, the eolianites are important sequence stratigraphic markers indicating subaerial emergence within these lithologically complex successions and may help to better understand the vertical and lateral distribution of oolitic reservoir facies within the study interval.

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