RECOGNITION AND GEOLOGIC PRESERVATION OF ANCIENT CARBONATE EOLIANITES

DAVID B. LOOPE
University of Nebraska, Lincoln, Nebraska 68588, U.S.A.
AND
F. E. (RICK) ABEGG
Chevron USA Production Company, 935 Gravier St., New Orleans, Louisiana 70112, U.S.A.

ABSTRACT: Eolian dunes composed of calcium carbonate grains are today widespread along subtropical shorelines. The most definitive criterion for recognizing ancient dune deposits (regardless of original mineralogy) is inversely graded lamination produced by the migration and climb of wind ripples. Additional features useful for recognition of carbonate eolianites are rare (e.g., vertebrate trackways or raindrop imprints) or nondiagnostic, but provide supporting evidence. Eolianites typically lack clasts larger than 3 to 4 mm in diameter. Absence of large-scale cross stratification should not be used to disprove an eolian origin. Calcretes occur within and immediately below many eolianites, as indicated by scattered rhizoliths, alveolar texture, and vadose pendant cements. Depleted $\delta^{13}C$ whole-rock values in eolian strata largely result from concentration of ^{12}C in such vadose features.

Shorelines have high wind energy, and carbonate particles have been produced in great abundance throughout the Phanerozoic, but the pre-Quaternary record of carbonate dunes appears to be meager. Poor preservation potential of topographically high dunes would contribute to the paucity of ancient carbonate eolianites. Preservation may be enhanced by cementation of dunes or if dunes climb during migration, burying strata below interdune surfaces. If subsidence is sufficient, dune strata will escape ravinement during subsequent transgressions.

Many upper Paleozoic carbonate eolianites may not have been sourced by beaches but by deflation. Broad exposure of subtidal deposits resulting from rapid regression across flat platforms or ramps would allow deflation of carbonate sediments. Deflation may have been more widespread in the geologic past, inasmuch as rhizoliths suggest that plants may not have adapted to mobile dune substrates until the Cretaceous.

INTRODUCTION

Geologists have been studying coastal dunes composed of carbonate detritus for many years, but application of this work to the rock record has lagged. Wind energy in coastal areas today far exceeds that available in the deserts of continental interiors (Pye and Tsoar, 1990, p. 16); only a few tropical coasts today lack sufficient wind energy to develop dunes. Part of the problem could be that, until relatively recently, few sedimentologists had carried out research in both siliciclastic and carbonate systems and few sedimentologists have observed pre-Quaternary carbonate eolianites. Reliable criteria for differentiating eolian from high-energy shallow-marine sediments were not available until the late 1970s (Hunter, 1977). Recognition of carbonate eolianite is challenging because both eolian and high-energy subtidal carbonates may be cross-stratified (McKee and Ward, 1983) and eolianites contain grains formed in subaqueous environments. Many of the recognitional criteria rely on negative evidence (see Hunter, 1993; Dodd et al., 1993), further obscuring differences between eolian and subtidal carbonates. Identification of carbonate eolianites is also hindered by a subtidal bias introduced by numerous sedimentology textbooks and papers that state that carbonate sediment is autochthonous and is usually marine (e.g., Bathurst, 1975; James, 1984; Leeder, 1982; Sellwood, 1978; Moore, 1989). Given this subtidal bias and the degree of similarity between eolian and subtidal grainstones, it is not surprising that few ancient carbonate eolianites have been identified.

Despite continuing improvements in our ability to recognize eolian strata, it is quite possible that few ancient examples will ever be found. A major theme in carbonate sedimentology is the dominance of shallowing-upward packages capped by flooding surfaces; paleosols and other features produced during subaerial exposure are very common (Esteban and Klappa, 1983). Many Quaternary eolian carbonates are strongly lithified, and would seem to be resistant to reworking and hard to miss during stratigraphic analysis. The rarity of pre-Quaternary examples compared to the near ubiquity of Quaternary analogs suggests that geologists must improve our understanding of the processes that allow and prevent incorporation of carbonate eolian sediments into the stratigraphic record. The purpose of this paper is to review the recognitional criteria for carbonate eolianites, highlight some of the work on siliciclastic eolian sediments that can be usefully applied to recognition and interpretation of carbonate eolianites, and to discuss the preservation potential of these rocks.

This paper and this volume are focused primarily on sand-sized sediments that are carried by the wind in saltation or creep. The wind can also carry large amounts of finer-grained sediment in suspension. Although modern dust and Quaternary loess are primarily siliciclastic, in certain situations such sediment can have a large carbonate component. As with the coarser material, fine-grained, wind-transported carbonate detritus has rarely been recognized in the rock record, but it could have an important story to tell.

RECOGNITION CRITERIA

Many features are similar in eolian and subtidal carbonates (Table 1), thus recognition of carbonate eolianites can be difficult. Climbing translatent stratification (Hunter, 1977) is the only

Modern and Ancient Carbonate Eolianites: Sedimentology, Sequence Stratigraphy, and Diagenesis
SEPM Special Publication No. 71, Copyright © 2001
SEPM (Society for Sedimentary Geology), ISBN 1-56576-079-4, p. 3–16.

TABLE 1.—Contrasting features of eolian and subtidal carbonates (modified from Abegg, 1994; Loope et al., 1998).

EOLIAN	SUBTIDAL
Climbing translatent stratification	Subaqueous climbing ripples
Grainfall	Grainfall
Grainflow	Grainflow
Well to very well sorted	Moderate sorting
Typically very fine to medium sand grains > 4 mm extremely rare	Grains > 4 mm common
Well-rounded and abraded allochems	Rounding variable
Large-scale (> 1 m) cross strata common	Large-scale cross strata rare
Tangential foresets	Tangential foresets less common
Straight-crested, low-amplitude ripples (high ripple indices)	Sinuous, high-amplitude ripples (low ripple indices)
Trace fossil diversity low	Trace fossil diversity high
Adhesion ripples present	Adhesion ripples absent
Calcrete (scattered rhizoliths, alveolar texture, etc.) within or immediately below eolianites	Calcrete present only immediately beneath exposure surfaces
Vadose cements (scattered pendant, meniscus, etc.)	Vadose cement present below exposure surfaces

commonly occurring and completely trustworthy criterion for the recognition of ancient eolianites. Without such structures, multiple lines of evidence are required and an eolian interpretation is less certain. Table 1 compares and contrasts carbonate eolian and subtidal strata. We recommend that negative evidence, the absence of features, be used with caution.

Sedimentary Structures

Through the middle 1970s, sedimentologists lacked dependable, unambiguous criteria for identification of eolian deposits. Despite the large-scale of cross stratification within many thick, well-exposed sandstones, an eolian interpretation relied on the presence of rare features such as raindrop impressions or vertebrate trackways, and the absence of marine macrofossils (McKee, 1934; Walker and Harms, 1972). This situation was highlighted by the discussion spawned by Freeman and Visher's (1975) marine interpretation of the Navajo Sandstone (Steidtmann, 1977). Kocurek (1996) provides an excellent overview of eolian processes and deposits. The succinct, up-to-date review of criteria for recognition of eolian sandstones by Eriksson and Simpson (1998) is useful, as is Caputo's (1993, 1995) papers on structures and textures of Quaternary carbonate eolianites of San Salvador Island.

The distinctive geometric attributes of wind ripples relative to subaqueous ripples were recognized early (Bagnold, 1941). Hunter's (1977) work on coastal dunes jump-started a (post-Bagnold) renaissance in eolian sedimentology when he was able to show that the deposits of climbing wind ripples are quite distinctive. While grainflow and grainfall are important components of small dunes, only wind-ripple deposits are sufficiently distinct from their subaqueous analogs to serve as a definitive criterion for recognition of eolian deposits.

In fine-grained, well-sorted eolian deposits, the inverse grading in subcritically climbing translatent strata (the most voluminous of several types of wind-ripple lamination) is distinctive because very fine sand and coarse silt grains accumulate in ripple troughs (Fryberger and Schenk, 1988). These fine particles typically bear thicker, more continuous clay/hematite coatings than coarser grains, so the portions of laminae enriched in these grains are darker than adjacent coarser material. In many carbonate eolianites, the finer grains that accumulate in ripple troughs are enriched in detrital quartz. Fryberger and Schenk (1988) used the term "pinstripe lamination" to describe the even appearance of subcritically climbing translatent strata. In eolian strata that contain a greater variety of grain sizes, the grading is more clearly seen. The coarsest grains of the underlying stratum are juxtaposed against the finest grains of the succeeding stratum. Such stratification resembles the lateral growth of woody plants, in which the smallest-diameter cells in late wood are immediately succeeded by the largest cells produced in spring. For this reason, "wood-grain lamination" is an apt description of wind-ripple deposits that contain medium and coarse sand (Fig. 1). In eolian carbonates, coarse, low-density skeletal grains or ooids are darker than the subjacent finer siliciclastic particles, which, if beach derived, often lack clay/hematite coats. The inversely graded lamination is best seen in outcrops or cores in which the lamination is cut at a low angle, "stretching" the millimeter-scale laminae to centimeter scale (Fig. 1). Kindler and Davaud (this volume) point out, however, that wind-ripple strata are sometimes poorly defined in well-sorted carbonate eolianites that lack detrital quartz.

Sets of cross-strata meters to tens of meters thick are prominent in the best known ancient eolian sandstones and in many of the ancient carbonate eolianites that have so far been recognized. Thin sets of cross-strata, however, can also record the passage of large eolian bedforms. Dune fields at White Sands (New Mexico, U.S.A.) and Guerrero Negro (Baja California, Mexico) have dunes 10 to 15 m high that are leaving behind sets of cross-strata only a few decimeters thick with irregular upper bounding surfaces (Simpson and Loope, 1985; Fryberger et al., 1988). Such thin sets are also common in ancient eolian sandstones (Loope and Simpson, 1992; Trewin, 1993; Simpson and Eriksson, 1993).

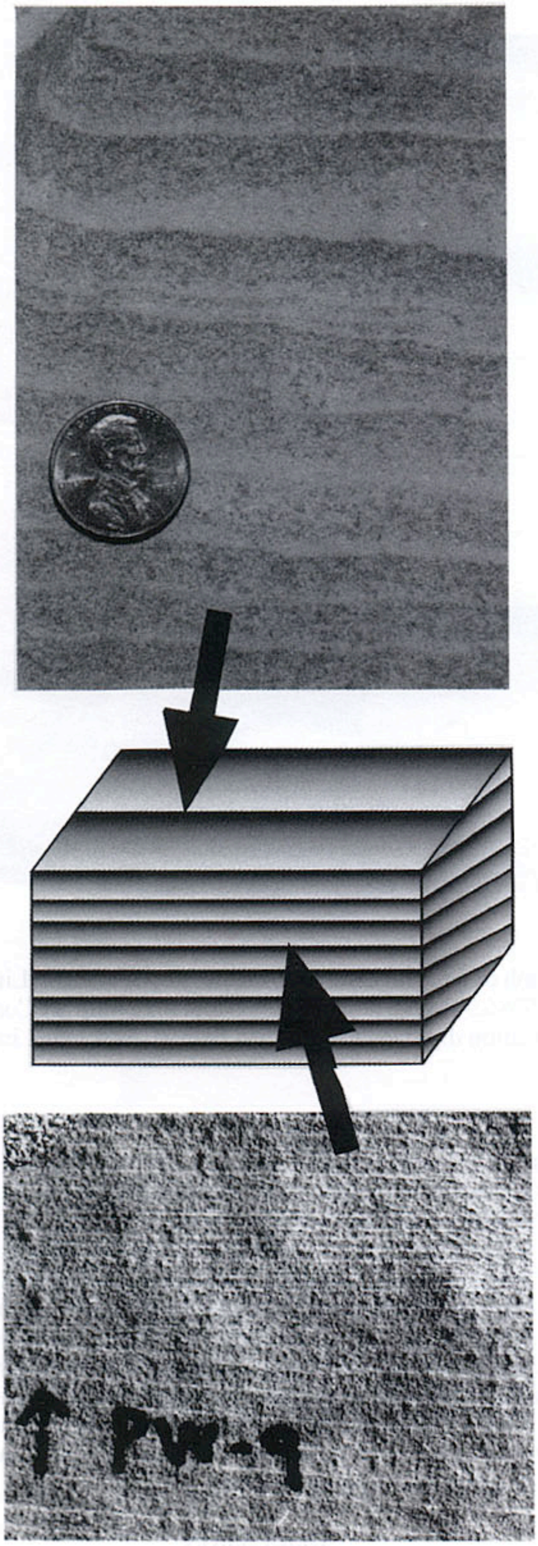

FIG. 1.—Wind-ripple laminations in ancient carbonate eolianites. Upper: Inversely graded "wood grain" wind-ripple lamination: Pennsylvanian Hermosa Formation, southern Utah; Lower: "Pinstripe" wind-ripple lamination, Upper Paleozoic Manakacha Formation, northwestern Arizona.

Not all eolian deposits contain sets of cross strata. Eolian sand sheets can develop in areas where high water table, coarse sediments, or abundant vegetation prevent dunes from forming (Kocurek and Nielsen, 1986). Wind-ripple laminae and granule ripples constitute the bulk of most sand sheets (Fryberger et al., 1979). Loope and Haverland (1988) recognized a carbonate-rich eolian sand sheet in Pennsylvanian rocks of southern Utah, and Upper Mississippian carbonate eolian sand sheets have also been recognized in the subsurface of southwestern Kansas (Handford and Francka, 1991; Abegg, 1992, 1994).

Adhesion ripples and warts are distinctive features that develop when saltating sand adheres to wet or damp substrates (Kocurek and Fielder, 1982). They are most commonly recognized on exposed bedding planes, but they also can be recognized in cross section, where they can be seen as indistinct strata that climb in an upwind direction. Kilibarda and Loope (1997) illustrated adhesion ripples from the base of a Jurassic eolian oolite in north-central Wyoming.

Other Recognition Criteria

Additional criteria for recognition (Table 1) are rare or nondiagnostic; thus, multiple lines of evidence are required to support an eolian interpretation. Subaerial exposure features can occur in both eolian and subtidal strata. Calcretes occur within and immediately below many eolianites, as indicated by scattered rhizoliths, alveolar texture, and vadose pendant cements (Fig. 2). Depleted $\delta^{13}C$ whole-rock values in eolian strata (Fig. 3, Table 2) result largely from concentration of ^{12}C in such vadose features (Abegg, 1992). The whole-rock isotopic method was originally developed to identify subaerial exposure surfaces (Allan and Matthews, 1982), but negative excursions in $\delta^{13}C$ relative to a marine baseline may indicate possible eolian intervals. Grainstone intervals with more negative $\delta^{13}C$ values should be examined more closely for evidence pointing to an eolian origin. Subtidal grainstones capped by paleosols, however, may produce similar isotopic signatures.

Recent studies suggest that the presence of fenestral pores cannot be used to disprove an eolian origin for the enclosing strata. Fenestral porosity has been reported within Quaternary carbonate eolianites, and the origin of such pores is attributed to wave splashing or rainfall action (Bain and Kindler, 1994; Hearty et al., 1998; Kindler and Strasser, 1999). Although generally an indicator of upper intertidal to supratidal deposition (Shinn, 1983), fenestral pores in Quaternary carbonate eolianites occur up to 40 m above present sea level in the Bahamas and Bermuda and are in close association with wind-ripple stratification, which indicates an eolian depositional environment (Kindler and Strasser, 1999).

SUBSURFACE RECOGNITION

Identification of small-scale sedimentary structures is key to the recognition of subsurface eolian rocks. Thus cores are required for an eolian interpretation. Sidewall cores will not suffice because they are too small to permit the identification of wind-ripple stratification. In an offset to a cored well, sidewall cores could allow recognition of lithologies similar to eolianites.

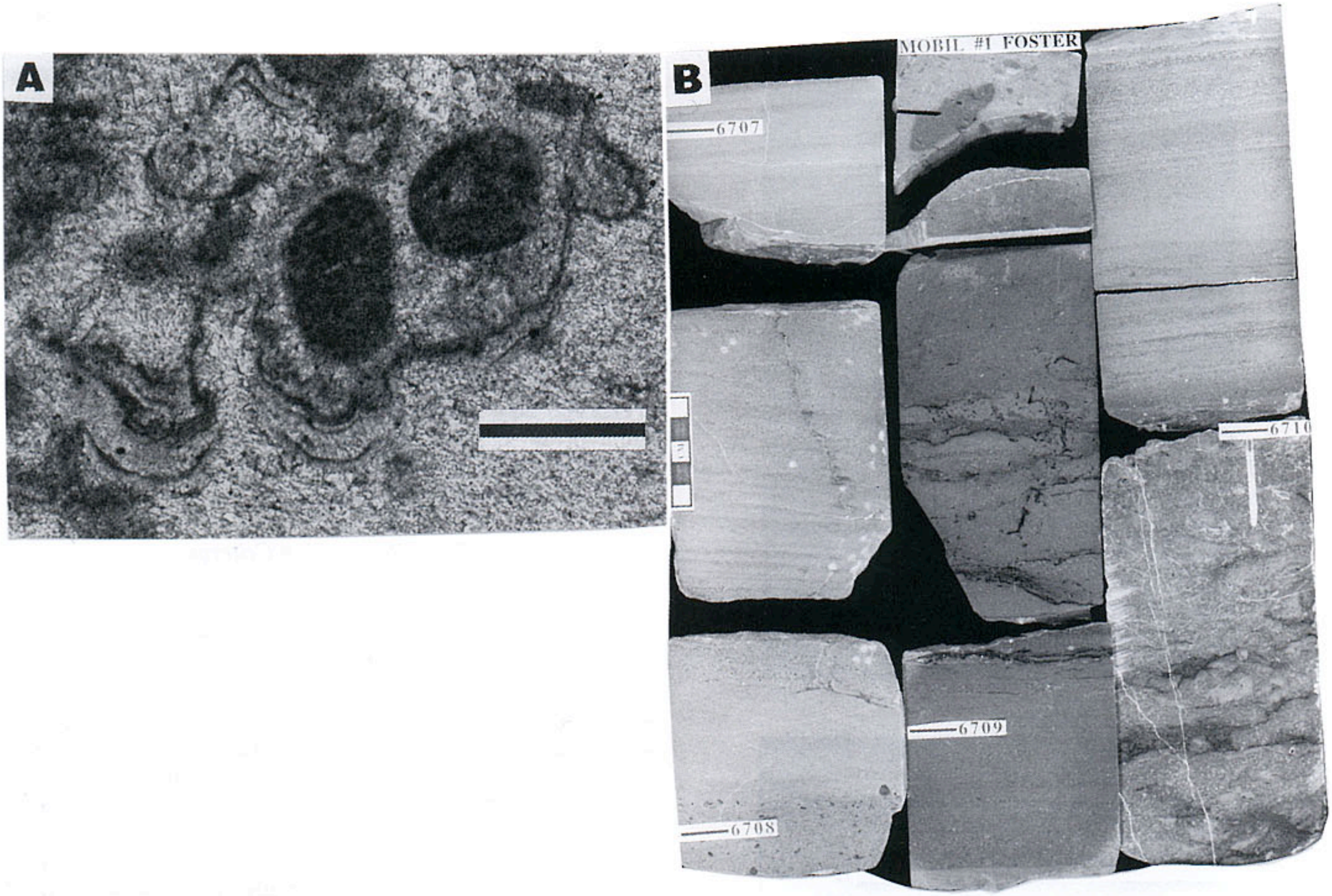

FIG. 2.—Meteoric diagenesis of carbonate eolianites. **A)** Photomicrograph of pendant cement from the Ste. Genevieve Limestone (Upper Mississippian), southwestern Kansas, Amoco #3 Cohen C, 5285.9 ft core depth. Scale bar is 0.25 mm. **B)** Core photo of calcrete in an eolian sand sheet with abundant wind-ripple stratification dipping at angles less than 7°, St. Louis Limestone, Mobil #1 A.W. Foster, 6706–6710 ft core depth.

Sedimentary Features

Wind-ripple stratification is easily recognized in core (Fig. 4). Acid etching of core samples commonly accentuates the greater concentration of finer-grained detrital quartz at the base of each lamination. Grainfall and grainflow are observable in the steeper-dipping upper parts of cross-stratification sets (Fig. 5) but are not diagnostic of eolian sedimentation.

Features such as vertebrate trackways or raindrop imprints generally require surfaces for observation, plus they are rare and unlikely to be sampled. Diagenetic features such as rhizoliths (Fig. 4) and vadose cements are easily observed in core but are not diagnostic of eolian sedimentation.

Wireline Logs

Wireline log suites do not permit the identification of eolian rocks. Core control is critical to identify eolian rocks, and core lithologies can then be tied to log signatures. An increased quartz fraction and low gamma-ray values are typical but not diagnostic of carbonate eolianites (Fig. 6). Crossover of neutron-density logs or a subtle shift in the sonic log can indicate an increase in detrital quartz or authigenic chert (Fig. 6). Abegg (1992) used these log signatures to observe lateral continuity in eolianites in the Mississippian of southwest Kansas. Some subtidal sediments, however, also contain detrital quartz or authigenic chert which could produce log signatures similar to eolian strata. Carr and Lundgren (1994) used dipmeter logs to infer eolian transport direction in Mississippian strata of southwestern Kansas. They also used spectral gamma-ray logs to characterize uranium spikes associated with paleosols, but such paleosols can occur without eolian rocks being present.

DISCUSSION

Early Diagenesis and Original Mineralogy

Unlike their siliciclastic counterparts, carbonate sands can rapidly develop cements at grain contacts when placed in the vadose zone (Halley and Harris, 1979). Dravis (1996) showed

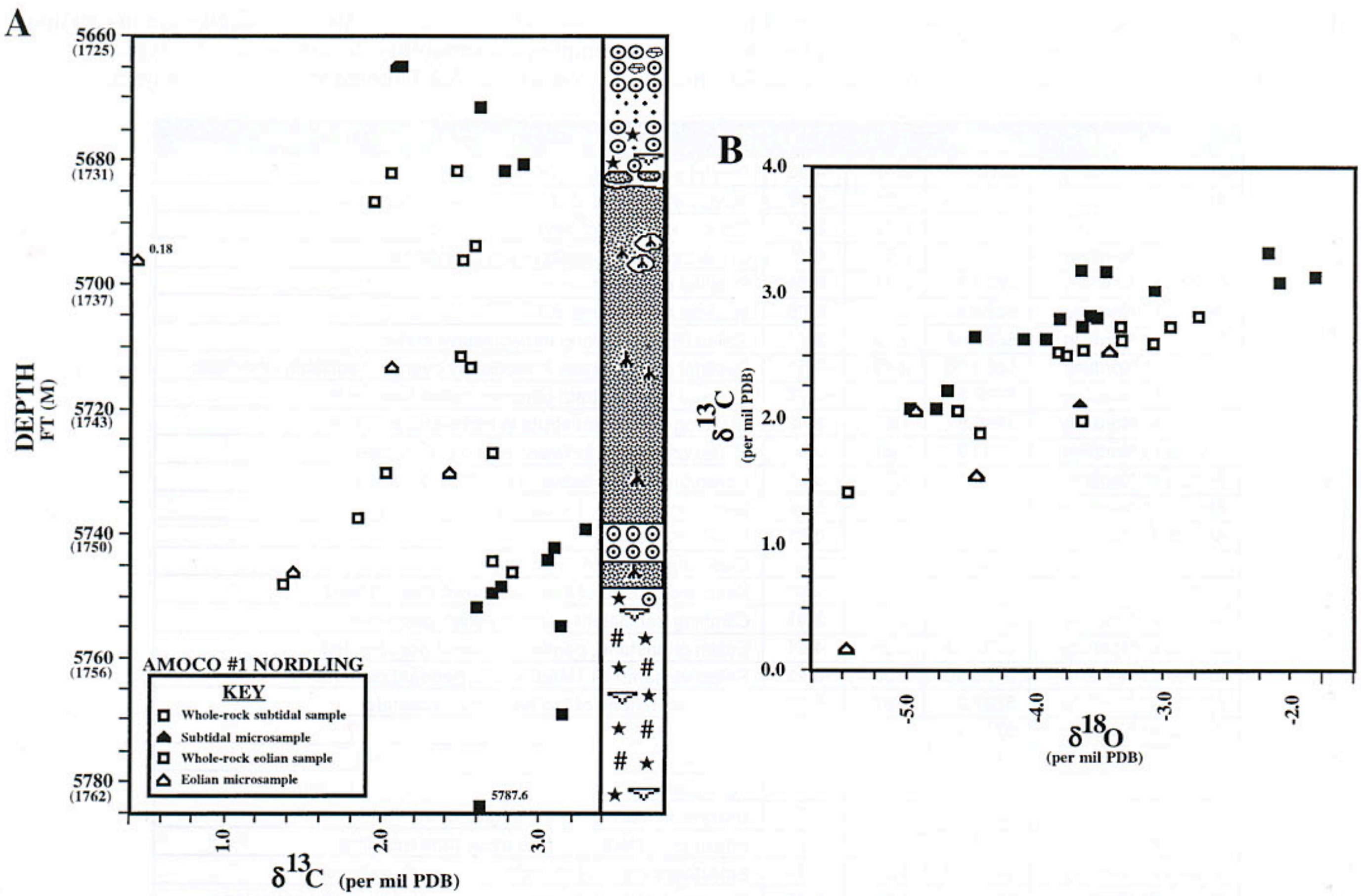

FIG. 3.—**A)** Stratigraphic section of intercalated eolian (stippled) and subtidal limestones with whole-rock $\delta^{13}C$ values from the upper St. Louis and Ste. Genevieve Limestones (Upper Mississippian), Amoco #1 Nordling, southwestern Kansas. Eolianites show a minor light carbon shift relative to adjacent subtidal values. Subtidal strata immediately below the eolianite also show a minor light carbon shift. Light carbon values at 5665.1 ft may correspond to subaerial exposure associated with the base of an eolian unit at 5655.5 ft. **B)** Cross plot of $\delta^{13}C$ and $\delta^{18}O$ whole-rock samples from the St. Louis and Ste. Genevieve Limestones, Amoco #1 Nordling, southwestern Kansas. Eolian samples are distinct from subtidal strata largely because eolian strata are slightly enriched in ^{12}C owing to localized vadose cements and such pedogenic features as rhizoliths. Some overlap occurs as subtidal strata immediately below eolianites experience meteoric diagenesis. See Table 2 for $\delta^{13}C$ values.

that aragonitic ooids on Eleuthera Island were stabilized by a centimeter-thick crust in only a few years. Cementation is preferentially developed parallel to cross-strata, cementing finer, more tightly packed laminae that hold meteoric water long after coarser layers have drained (Fryberger and Schenk, 1988; White and Curran, 1988; Caputo, 1993). Dune sand that is nearly isotropic when saturated with water may be strongly anisotropic when unsaturated. McCord et al. (1991) showed that in such a sand, unsaturated permeability parallel to bedding can be up to 20 times greater than permeability perpendicular to bedding. Preferentially cemented strata become prominent in weathered outcrops of carbonate eolianites. In heavily burrowed and rooted dune sands, steeply sloping, preferentially cemented zones may be the only remaining record of bedform migration—physical structures may be totally obliterated (Fig. 7; Loope et al., 1998).

Soft-sediment deformation is spectacularly developed in many eolian sandstones containing a high percentage of grainflow (avalanche) cross-strata (Hunter, 1981; Doe and Dott, 1980; Horowitz, 1982). Adjacent wind-ripple strata, which are more tightly packed upon deposition, typically remain undisturbed. Such deformation has not yet been reported from ancient eolian carbonates, probably precluded by the early, vadose lithification discussed above. Despite this observation and the fact that Quaternary carbonate eolianites are commonly strongly lithified (Williams and Walkden, this volume), the pre-Quaternary eolianites so far recognized show little evidence of lithification before deep burial. Most thin sections of late Paleozoic and middle Jurassic eolian limestones in western and Midcontinent United States reveal abundant interpenetrating framework grains and low cement volumes, indicating that any early-emplaced cements were insufficient to resist burial compaction (Rice and Loope, 1991; Abegg, 1992, 1994; Kilibarda and Loope, 1997). Where cross-strata of eolian oolite in the Jurassic Sundance Formation are directly overlain by wave-rippled marine strata, no

TABLE 2.—Whole-rock isotope values from samples of intercalated eolian and subtidal intervals. Core depths are in feet and isotopic values are in per mil. Duplicate samples taken to assess small-scale variability. Selective samples typically taken where vadose features are present to examine their effects on whole-rock isotopic values. See Figure 3.

Well Name	Depth	$\delta^{13}C$	$\delta^{18}O$	Description
Amoco #1 Nordling	5665.1A	2.07	-4.96	Porous subtidal ooid grainstone with lithoclasts
Amoco #1 Nordling	5665.1A	2.21	-4.67	Porous subtidal ooid grainstone with lithoclasts
Amoco #1 Nordling	5665.1B	2.12	-3.64	Selective sample of several lithoclasts
Amoco #1 Nordling	5671.7	2.64	-4.46	Cross-stratified subtidal peloid grainstone
Amoco #1 Nordling	5680.9	2.81	-3.56	Subtidal ooid grainstone
Amoco #1 Nordling	5680.9	3.01	-3.06	Subtidal ooid grainstone
Amoco #1 Nordling	5682.0A	2.49	-3.74	Eolian lithoclast along transgressive surface
Amoco #1 Nordling	5682.0B	2.79	-3.51	Subtidal marine strata immediately overlying eolianite lithoclasts
Amoco #1 Nordling	5682.3	2.07	-4.76	Subtidal marine strata between eolian lithoclasts
Amoco #1 Nordling	5686.8	1.97	-3.62	Climbing translatent strata in carbonate eolianite
Amoco #1 Nordling	5694.0	2.61	-3.31	Eolian grainstone between calcrete lithoclasts
Amoco #1 Nordling	5696.1A	2.53	-3.61	Eolian grainstone between calcrete lithoclasts
Amoco #1 Nordling	5696.1B	0.18	-5.46	Selective sample of rhizocretions in lithoclasts
Amoco #1 Nordling	5711.8	2.52	-3.81	Eolian grainstone
Amoco #1 Nordling	5713.5A	2.58	-3.07	Cross-stratified eolian grainstone
Amoco #1 Nordling	5713.5B	2.06	-4.92	Selective sample of thin light brown rhizocretions
Amoco #1 Nordling	5727.1	2.72	-3.31	Climbing translatent strata in eolian grainstone
Amoco #1 Nordling	5730.5A	2.05	-4.64	Eolian grainstone, pendant cements not sampled
Amoco #1 Nordling	5730.5B	2.53	-3.41	Selective sample of interval with pendant cements
Amoco #1 Nordling	5737.8	1.87	-4.42	Eolian grainstone at the base of an eolianite
Amoco #1 Nordling	5739.4	3.31	-2.17	Porous subtidal ooid grainstone
Amoco #1 Nordling	5742.3	3.12	-1.80	Subtidal ooid grainstone immediately below a hardground
Amoco #1 Nordling	5744.3	3.07	-2.08	Tight subtidal ooid grainstone (with calcrete? clasts)
Amoco #1 Nordling	5744.5	2.72	-2.93	Uppermost part of an eolian grainstone
Amoco #1 Nordling	5746.3A	2.85	-2.72	Eolian grainstone sampled away from rhizoliths
Amoco #1 Nordling	5746.3B	1.54	-4.44	Selective sample of stylolitized brown rhizocretions
Amoco #1 Nordling	5748.3	1.40	-5.45	Climbing translatent strata at the base of an eolian grainstone
Amoco #1 Nordling	5748.6	2.78	-3.80	Subtidal packstone immediately below eolian lithoclast lag
Amoco #1 Nordling	5749.8	2.72	-3.62	Subtidal skeletal packstone
Amoco #1 Nordling	5752.0	2.62	-3.90	Subtidal skeletal packstone
Amoco #1 Nordling	5755.0	3.16	-3.43	Subtidal skeletal packstone
Amoco #1 Nordling	5769.2	3.17	-3.63	Subtidal skeletal packstone
Amoco #1 Nordling	5787.6	2.62	-4.08	Subtidal skeletal mud-poor packstone
Amoco #3 Cohen C	5285.9A	1.53	-3.24	Eolian grainstone in lithoclast with no rhizoliths
Amoco #3 Cohen C	5285.9B	1.66	-4.15	Selective sample of rhizolith-rich area
Amoco #3 Cohen C	5286.1	2.29	-1.50	Eolian grainstone with possible pendant cements
Amoco #3 Cohen C	5286.8A	1.96	-2.67	Eolian grainstone sampled away from rhizoliths
Amoco #3 Cohen C	5286.8A	2.19	-2.84	Eolian grainstone sampled away from rhizoliths
Amoco #3 Cohen C	5286.8B	1.58	-4.71	Selective sample of rhizolith-rich area
Amoco #3 Cohen C	5295.4	2.39	-3.63	Climbing translatent strata in eolian grainstone
Amoco #3 Cohen C	5297.8	2.79	-4.08	Subtidal skeletal wackestone
Amoco #3 Cohen C	5301.1	2.41	-3.13	Subtidal skeletal wackestone
Amoco #3 Cohen C	5305.8	3.01	-1.52	Subtidal skeletal packstone
Amoco #3 Cohen C	5311.3	2.79	-2.89	Porous subtidal ooid grainstone
Amoco #3 Cohen C	5315.7	2.74	-3.89	Porous subtidal ooid grainstone
Amoco #3 Cohen C	5319.0	2.71	-3.40	Porous subtidal ooid grainstone
Amoco #3 Cohen C	5319.0	2.79	-3.45	Porous subtidal ooid grainstone
Amoco #3 Cohen C	5321.6	2.84	-3.77	Top part of an eolian? grainstone
Amoco #3 Cohen C	5322.2A	2.87	-2.69	Subtidal ooid packstone, calcrete not sampled
Amoco #3 Cohen C	5322.2A	2.80	-2.94	Subtidal ooid packstone, calcrete not sampled
Amoco #3 Cohen C	5322.2B	1.92	-4.33	Calcrete lithoclast at the top of a subtidal interval
Amoco #3 Cohen C	5323.0	3.16	-3.70	Subtidal skeletal packstone
Amoco #3 Cohen C	5324.0	2.37	-3.44	Subtidal skeletal packstone
Amoco #3 Cohen C	5328.0	2.00	-4.66	Subtidal skeletal packstone
Amoco #3 Cohen C	5347.1	3.03	-3.30	Subtidal skeletal grainstone
Amoco #3 Cohen C	5364.7	3.44	-3.34	Subtidal peloid skeletal packstone

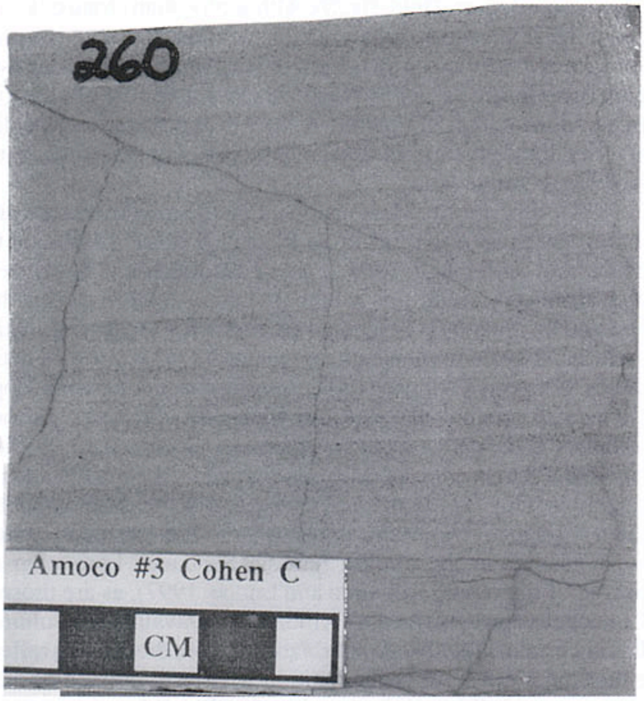

FIG. 4.—Climbing translatent stratification, dipping at approximately 6°, from an eolian sand sheet. The arrow marks a vertical rhizolith. These wind-ripple strata are unusually thick (up to 9 mm), inversely graded, and contain exceptionally well-developed ripple-foreset lamination. Direction of ripple migration is to the right. Mobil #1 A.W. Foster, 6707 ft core depth.

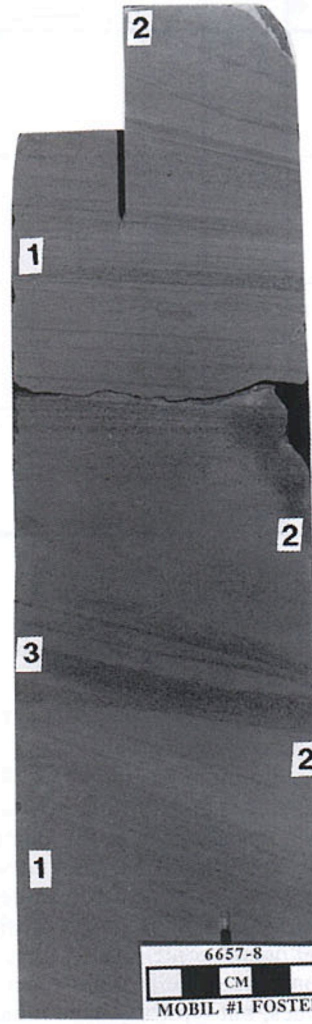

FIG. 5.—Cross stratification in eolian limestones commonly contains abundant wind-ripple stratification (1) in the lower parts of sets. Wind-ripple stratification is intercalated with indistinctly bedded grainfall (2) and rare grainflow toes (3) in the upper parts of sets. Dip of grainflow toes is an apparent dip; true dip is slightly greater than 20°. Mobil #1 A.W. Foster, 6657–6658 ft core depth.

cemented blocks or sediment-filled fissures are apparent. The tabular form of rhizolithic material within some Paleozoic carbonate eolianites (Fig. 8) indicates an origin within fractures, which requires cementation of the sand matrix before burial. Cemented blocks lacking paleosol features are present at the top of one Mississippian eolianite in a core from southwestern Kansas (Abegg, 1992) but represent the exception rather than the rule. The relatively few late Paleozoic carbonate eolianites with copious intergranular cement and open fabrics contain abundant micrite envelopes, suggesting that their early lithification was linked to a relatively high proportion of aragonitic detrital grains (Rice and Loope, 1991, their fig. 9a).

The presence of chert nodules in Paleozoic carbonate eolianites (Fig. 9) indicates that opaline skeletal material was another abundant component of some ancient dunes. From the Silurian to the Cretaceous, siliceous sponges were important sediment producers in the warm, clear, shallow-water environments that are now accumulating only carbonates (Maliva et al., 1989). Chert nodules grew during diagenesis when biogenic opal was preferentially dissolved and reprecipitated as quartz. Cenozoic shallow marine and eolian carbonates lack these nodules because the Cretaceous radiation of diatoms restricted later chert deposition to the deep sea (Maliva et al., 1989).

Evidence of Dune Vegetation

Although a large part of today's continental surfaces are underlain by unconsolidated materials, only along shorelines and in deserts are these materials readily available for eolian transport. Since the Silurian, vascular plants have become adapted to life in a broad variety of environments. Surely, eolian processes were active over a much larger area of the landscape in pre-Silurian time than now. Arguing against the simplistic view that eolian strata should be more abundant in progressively more ancient strata, Trewin (1993) pointed out that reworking by unconfined (pre-Silurian) rivers would have decreased the preservation potential of dune deposits.

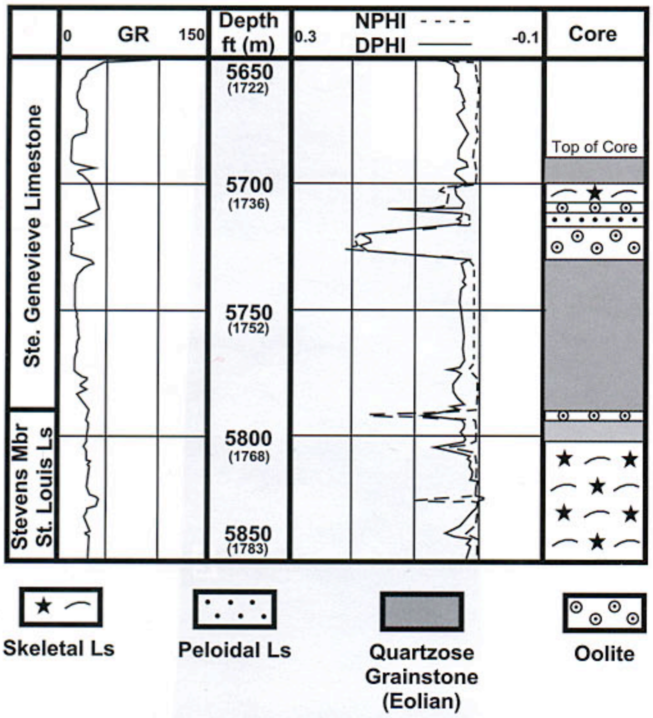

FIG. 6.—Gamma-ray and neutron-density log from the Amoco #1 McPherson & Citizen, St. Louis and Ste. Genevieve Limestones, southwestern Kansas (28-T29S-R39W). This well offsets the Amoco #1 Nordling, whose lithologies are shown in the depth track, where carbonate eolianites are indicated by the stippled pattern. Eolianites are marked by low gamma-ray values, a slight neutron-density crossover ("shaded" where neutron reads lower porosity than density) due to a detrital quartz content of 5–30%, and little or no porosity. In contrast, subtidal grainstones also have low gamma-ray values, but typically have minor neutron-density crossover due to a low detrital quartz content, and have variable porosity (typically < 20%).

Marzolf (1988) suggested that the same evolutionary events that according to Schumm (1968) have altered fluvial systems have also greatly restricted the geographic range of eolian processes: the rise and diversification of angiosperms in the Cretaceous and of grasses in the Oligocene and Miocene. Another factor, however, makes dunes a harsher habitat for plant growth today than they may have been in some earlier time intervals. Today, the low water retention of dune sand poses a difficulty for plants, but any elevation of atmospheric pCO_2 above the present value should act to ease this effect. If plants can capture the CO_2 needed for photosynthesis without losing as much water through their stomata, their soil moisture requirements are diminished. McElwain and Chaloner (1995) showed that the stomatal density and stomatal index of fossil leaves increased from the Early Devonian through the Permian. Their data corresponds very well with pCO_2 estimates based on global carbon modeling (Berner, 1998) and on carbon isotopes from paleosols (Mora et al., 1991) that show diminishing CO_2 levels during this time interval. During the late Paleozoic, atmospheric pCO_2 was low (comparable to today's levels), but it was much higher during the Mesozoic (Berner, 1998, fig. 5). Although eolian strata of Cretaceous age appear to be rather rare (as would be expected if sandy substrates were then more hospitable to plants), those of Jurassic and Triassic age are widespread. The possible role of changing pCO_2 in the extent of upland vegetation and therefore of eolian activity through time is difficult to assess at this time but is worthy of further study.

Rhizoliths are abundant in upper Paleozoic eolian sandstones and limestones of the Colorado Plateau (Loope, 1988) and the Midcontinent (Abegg, 1994; Carr and Lundgren, 1994; Abegg and Handford, 1998, this volume). Loope (1988) argued that, because the rhizoliths he studied are restricted to planar deflation surfaces, they do not indicate that plants were growing on active dunes. Loope and Dingus (1999) described rhizoliths from Upper Cretaceous eolian sandstones from Mongolia and interpreted them as traces of the oldest dune vegetation yet documented. Because carbonate dunes are especially conducive to the preservation of rhizoliths, they should be our best record of the development of dune vegetation. Despite an abundance of vadose cement, carbonate eolianites in the middle Jurassic Sundance Formation are devoid of rhizoliths (Kilibarda and Loope, 1997), as are those of Cretaceous age described by Kindler and Davaud (this volume). It is uncertain if the absence of rhizoliths from these rocks reflects either the absence of roots due to a hyperarid climate or other factors, or conditions inappropriate for rhizolith preservation.

Preserving Carbonate Eolianites in the Rock Record

Cemented, aragonite-rich Quaternary dunes form coastal dune ridges along the northeast coast of the Yucatan Peninsula of Mexico (e.g., Loucks and Ward, this volume). Such dunes would seem to have better preservation potential than those that were originally composed of calcite because aragonitic dunes are more likely to be cemented before they are transgressed. Using only information based on the Yucatan coast, a logical prediction would be that, if carbonate eolianites are rare in the stratigraphic record, the preserved examples should show evidence of having been aragonite-dominated, early cemented dune ridges that cap shallowing-up successions. As outlined above, the known ancient examples of carbonate eolianites appear to have originally been calcite-dominated. If the original mineralogy of the known ancient carbonate eolianites was indeed dominated by calcite, this fact would at least partially explain the sheet geometry of these rocks: the low reactivity of calcitic sands to meteoric water allowed them to migrate farther from their source. Williams and Walkden (this volume), however, show that aragonite-rich Quaternary dunes can migrate far inland in hyperarid settings. For carbonate eolianites sourced from beaches, the mineralogy of the sand influences only the geometry (not the volume) of the resulting eolian deposit. If early lithification is not the key to preservation, then what other factors are involved?

In the middle 1970s the claim was made that eolian sands are unlikely to be preserved in the rock record because they would be reworked during marine transgressions. We can now say with confidence that upper Paleozoic through Jurassic eolian sandstones of the Colorado Plateau reach an aggregate thickness of more than 3500 m (Kocurek, 1988, 1999) and that many of these rocks intertongue with marine rocks to the west. We also know, however, that conditions required for incorporating siliciclastic eolian sediments into the rock record are not widespread today,

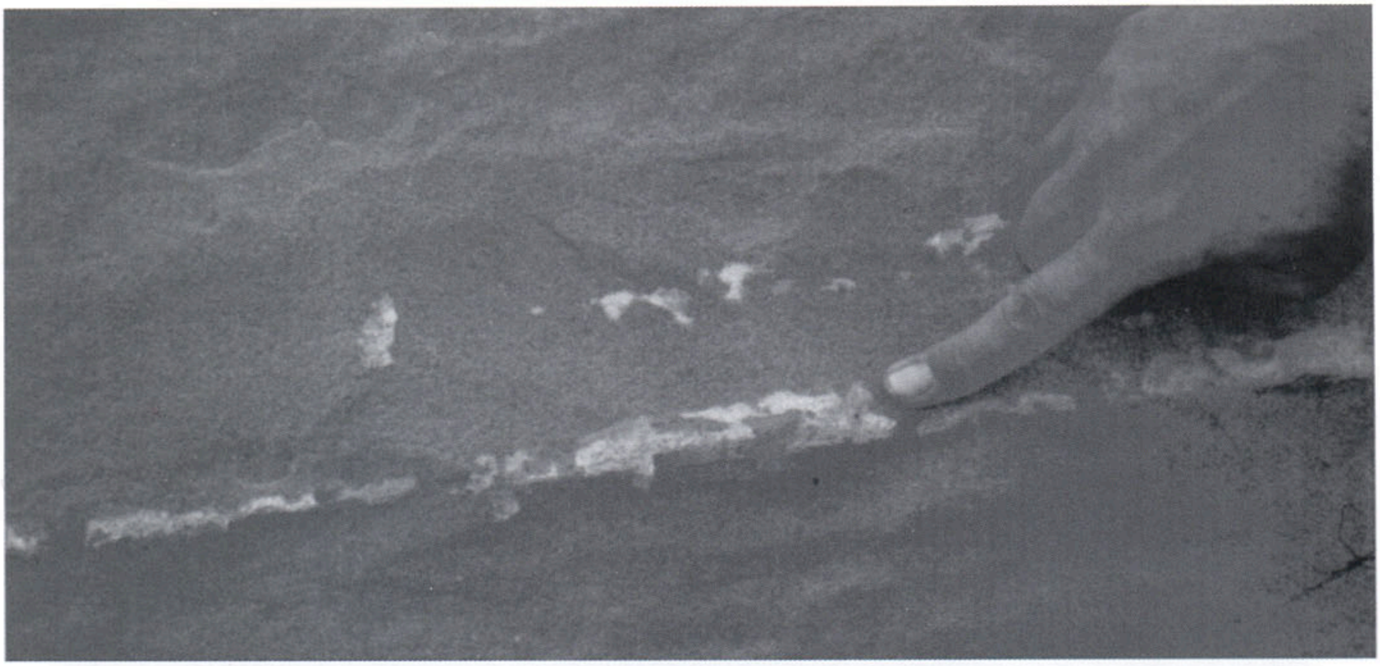

FIG. 7.— Structureless sand with calcite-cemented zone that is cut by burrows (Djadokhta Sandstone, southern Mongolia; Loope et al., 1998). Calcite-cemented zone dips at 25 degrees and is interpreted as pedogenic calcite that formed beneath a dune lee slope. Primary depositional structures have been destroyed by rooting and burrowing, and burrowing continued after cementation.

FIG. 8.—Carbonate eolianite cut by near-vertical fissures that are filled with rhizoliths (see the "root rock" of Perkins, 1977). Fissures indicate that sand matrix was lithified before burial. Pennsylvanian Hermosa Formation, southern Utah.

even though dunefields are widespread. Kocurek (1999) notes that of all the dunes in North Africa, the only eolian strata likely be preserved are those that have already been transgressed off the Atlantic coast and those that are immediately adjacent to the coast and below the water table. The sand in the dunes farther east is likely to be cycled between ergs many times. Some of this sand may eventually reach geologic storage as eolian strata if it gets below the water table, but much of it may be buried in fluvial systems. The key point for preservation of eolian carbonates, however, is that nearly all eolian sediments (cemented or uncemented) deposited since the last highstand that have not subsided below the level of ravinement are destined to be reworked (Fig. 10). Allen et al. (2000) argue that, for preservation of the thick eolian deposits of the Colorado Plateau, flexural subsidence linked to Jurassic crustal shortening events provided not only a high rate of subsidence but also a rain shadow that helped maintain an arid paleoclimate.

As long as uncemented eolian sand resides strictly within bedforms, it will be above the water table and extremely vulnerable to reworking by both wind and water. Kocurek (1999) stresses the importance to long-term preservation of the transfer of sand from bedforms to storage space below the interdune surface, and that this transfer can take place as wind power

FIG. 9.—Chert nodules (arrows) in a late Paleozoic carbonate eolianite, Manakacha Formation, northwestern Arizona. Opaline skeletons were likely transported along with calcareous material before suffering dissolution and reprecipitation as microcrystalline quartz.

decreases over time. If the rate of sediment delivery to a coastal dune field increases during falling sea level, and if air flow decelerates with increasing distance from the shoreline, accumulation of preservable eolian carbonates seems likely as regression proceeds.

A large part of the carbonate rock record consists of shallowing-upward cycles produced during shoreline progradation following base-level rise (James, 1984). Development of shallowing-upward successions with thick eolian carbonates resting directly upon beach facies would require a very high sediment production rate. None of the sand driven from the beach to the dunes contributes to prograding the shoreline because it does not fill sub-sea-level space. Oolitic dunes capping beach sand can be seen on the east shore of West Caicos Island (Wanless and Tedesco, 1993) where Holocene progradation has produced a dune–beach ridge complex that is 7 km long, 0.5 km wide, and up to 10 m high. Such a vertical sequence of facies is yet to be described from pre-Quaternary carbonate eolianites. Does this indicate that shallow-water carbonate production rates were rarely high enough to sustain progradation while simultaneously generating extensive, thick dune deposits?

Loope and Haverland (1988), Rice and Loope (1991), and Atchley and Loope (1993) argued that the late Paleozoic carbonate eolianites that they studied were not directly sourced by beaches but instead by deflation of subtidal sediments that were broadly exposed during rapid regressions across low-gradient carbonate platforms. Mud-rich allochems, many of which had been dolomitized before transport (Fig. 11), and echinoderm grains with abraded overgrowths are present in these rocks and in the carbonate eolianites of southwestern Kansas (Abegg and Handford, this volume). The grains that record diagenetic events prior to eolian transport may have been delivered to beaches by storm events, or, after rapid regression and broad exposure, could have been deflated directly from their site of origin. Because the marine-sourced sediment for these eolianites was calcite-dominated, it may have escaped rapid lithification by meteoric water upon exposure, and may therefore have remained available for eolian transport while above the water table. One carbonate eolianite in southern Utah overlies a mud-rich subtidal marine limestone that contains five-meter-deep desiccation fissures filled by calcareous eolian sand of the overlying unit (Fig. 12; Loope and Haverland, 1988). Arid climatic conditions could have contributed to the origin of this eolianite in two ways: by delaying cementation of its marine source sediments and by keeping the water table low so that this material could be deflated. The pedogenic features within the upper Paleozoic carbonate eolianites of the Colorado Plateau and southwestern Kansas indicate deposition in an arid to semiarid setting. To our knowledge, karst features or other indicators of a positive paleo–water budget have not yet been found associated with this facies.

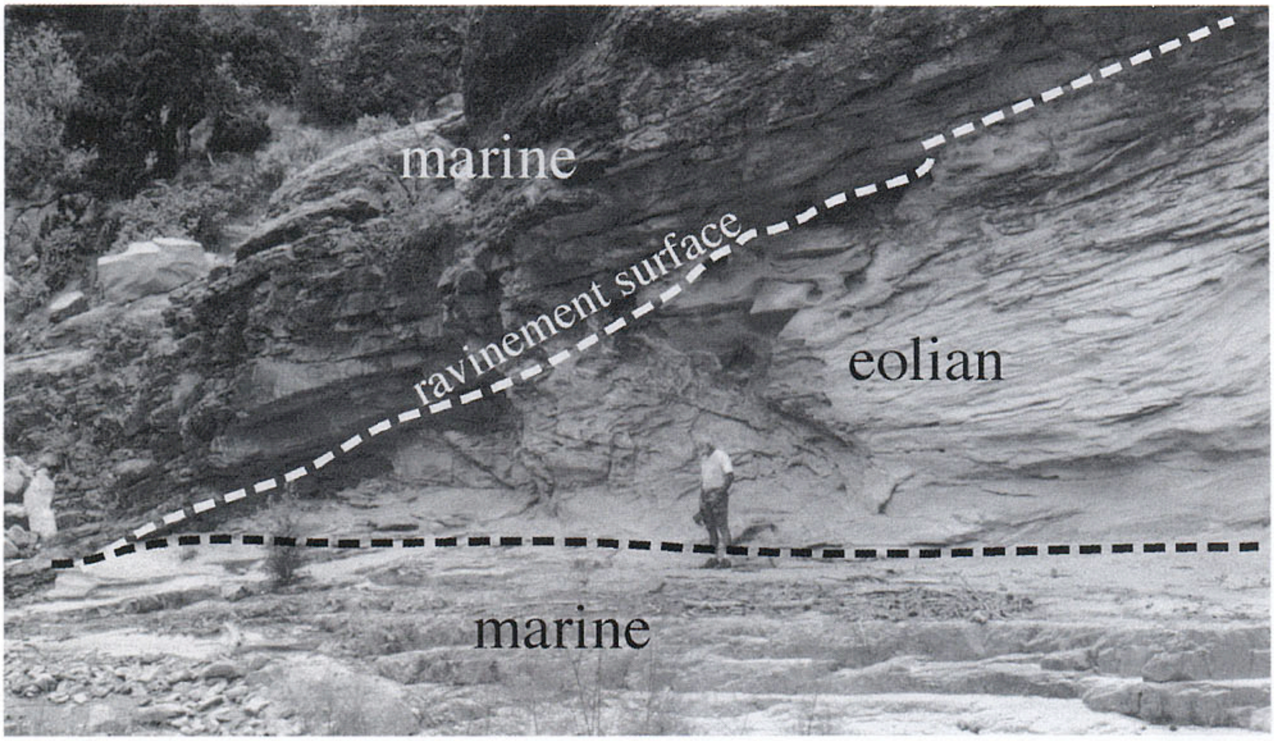

FIG. 10.—Scour into cross-stratified calcareous eolian strata filled by marine calcarenite. High-energy transgression locally removed eolian strata, but dune material below the ravinement surface was preserved. Eolianites overlie flat-bedded marine carbonates. Pennsylvanian Hermosa Formation, southern Utah.

As opposed to beach-sourced dunes, the generation of deflation-sourced carbonate eolianites does not require onshore winds. The Pennsylvanian–Permian eolian limestones within the Manakacha Formation (Supai Group) of northwestern Arizona and southern Nevada accumulated on the eastern side of the Cordilleran trough. The winds that transported the calcareous material were out of the north (McKee, 1982, p. 221; Rice and Loope, 1991, their fig. 12), and depending on the details of paleogeography, may have been onshore (Blakey, 1990, fig. 13) or shore-parallel (McKee, 1982, p. 53).

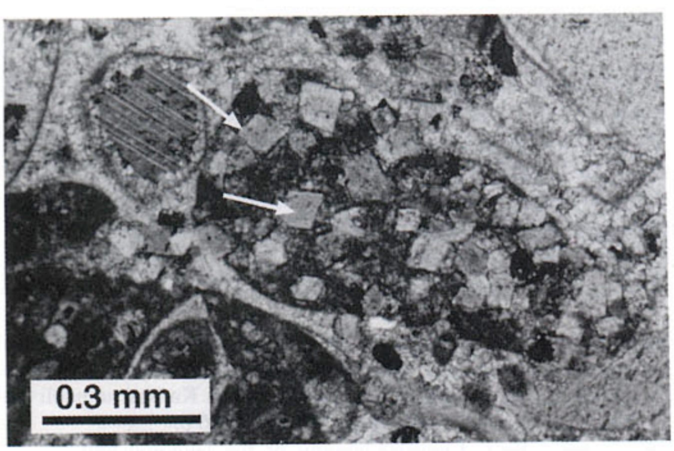

FIG. 11.—Dolomite rhombs (arrows) are truncated in mud-rich grain that is interpreted to have been dolomitized prior to eolian transport, Late Paleozoic Callville Limestone, southern Nevada.

Calcareous Dust in the Stratigraphic Record

Dust in general, and carbonate dust in particular, makes major contributions to Quaternary soils (Pye, 1987). Carbonate dust can even fall in sufficient amounts to become a major detrital constituent of thick, widespread stratigraphic units (Pye, 1983). In the Illinois River Valley, U.S.A., late Quaternary loess contains up to 30% detrital dolomite (Grimley et al., 1998).

Calcareous paleosols are well developed in the upper Paleozoic siliciclastic deposits that surrounded the Ancestral Rockies uplifts of western United States (Loope and Schmitt, 1980; Mack and Rasmussen, 1984) and may owe their origin to dust derived from coeval carbonate deposits. Because of the high energy of impacts during saltation, some carbonate dust should be generated when carbonate sand is driven inland from beaches. If, however, subtidal carbonates were to become subaerially exposed under arid conditions, as called for by the deflation model for deposition of carbonate eolianites, a much larger amount of fine-grained material would become available for transport in suspension. If copious saltating grains were available for "sandblasting," the amount of dust that could have been raised would have been greatly enhanced (see Shao et al., 1993, Mason et al., 1999). Calcareous siltstones and quartzose calcisiltites with abundant detrital dolomite are interbedded with the upper Paleo-

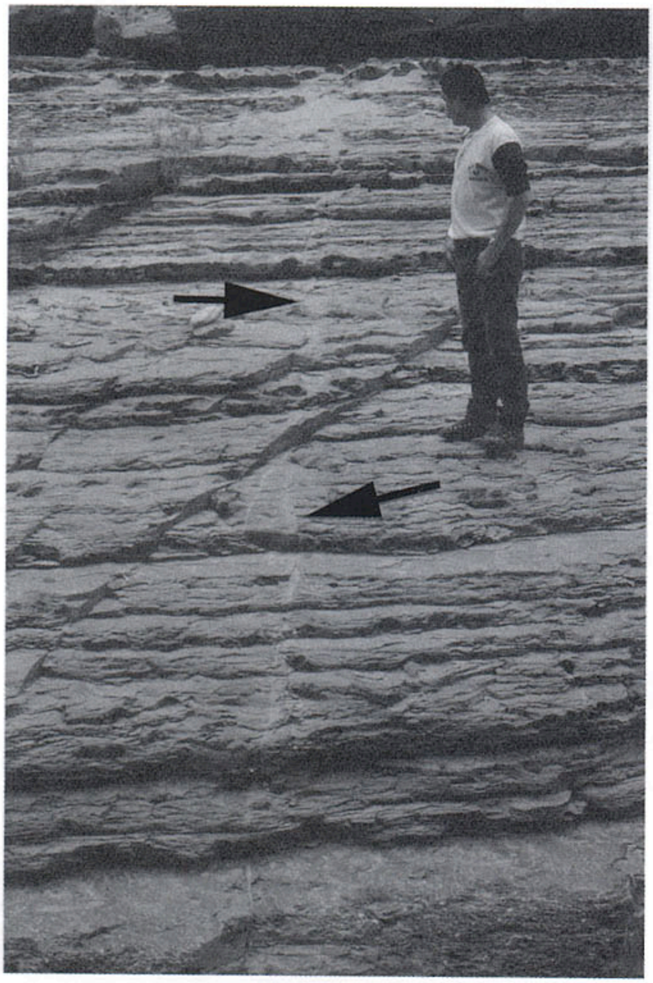

FIG. 12.—Desiccation fissure in subtidal marine limestone that is filled by calcareous eolian sand. Pennsylvanian Hermosa Formation, southern Utah.

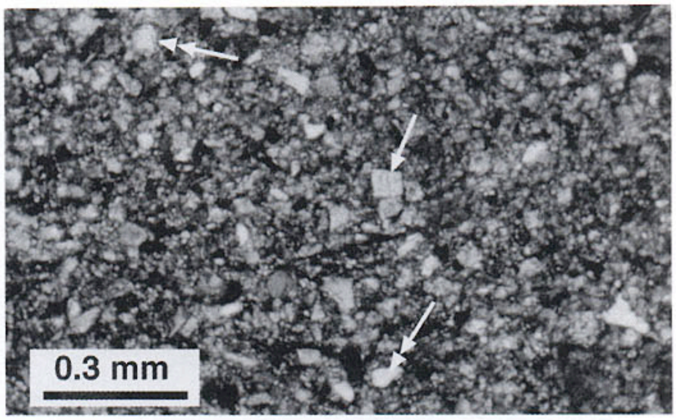

FIG. 13.—Quartzose calcisiltite interpreted as a calcareous loessite (unit 2e of Loope and Haverland, 1988, their fig. 2). Pennsylvanian Hermosa Formation, southern Utah. Note good sorting of both detrital dolomite rhombs (arrow) and quartz (double-headed arrows).

zoic carbonate eolianites of the Colorado Plateau and may be dustfall deposits (Fig. 13; Loope and Haverland, 1988). It is possible that some of the micrite in Mississippian calcretes may also be wind-blown calcareous dust. Additional research is needed to test these hypotheses.

CONCLUSIONS

1. Ancient carbonate eolianites are best recognized by the presence of inversely graded lamination produced by the migration and climb of wind ripples. Additional criteria are rare or nondiagnostic and provide supporting evidence.
2. Although strongly cemented calcareous dune deposits are today widespread along subtropical shorelines, pre-Quaternary analogs show little evidence of early lithification.
3. Rhizoliths record ancient plant habitats, and suggest that plants many not have adapted to mobile dune substrates until the Cretaceous. Higher atmospheric pCO_2 during the Mesozoic should have decreased the water requirements of land plants, and may have allowed plants to curtail eolian sediment transport in arid settings where it had been active during the late Paleozoic and is active in the Cenozoic.
4. Topographically high materials are likely to be reworked during transgression. Preservation is most likely if bedform climb has placed dune strata below the water table and if subsidence lowers them below the wave base of subsequent transgressions.
5. Some ancient carbonate eolianites may not have been beach-derived, but were instead generated when rapid regression exposed subtidal, calcite-dominated sediment to deflation.
6. Calcareous dust contributes to modern soil-forming processes and can accumulate (with associated siliciclastics) to form loess. Analogs should be sought in association with ancient carbonate dune deposits.

ACKNOWLEDGMENTS

Research was supported by the donors of the Petroleum Research Fund, administered by the American Chemical Society, and by National Science Foundation Grants EAR-8816222 and EAR-9709742. Reviews by Ron Blakey, Mitch Harris, and Ed Simpson greatly improved the manuscript. The authors thank Chevron for permission to publish this paper.

REFERENCES

ABEGG, F.E., 1992, Lithostratigraphy, depositional environments, and sequence stratigraphy of the St. Louis and Ste. Genevieve Limestones (Upper Mississippian), southwestern Kansas: unpublished Ph.D. dissertation, University of Kansas, 206 p.

ABEGG, F.E., 1994, Lithostratigraphy of the Hugoton and Stevens Members of the St. Louis Limestone and the Ste. Genevieve Limestone (Upper Mississippian), southwestern Kansas, *in* Baars, D.L., ed., Revision of Stratigraphic Nomenclature in Kansas: Kansas Geological Survey, Bulletin 230, p. 39–66.

Abegg, F.E., and Handford, C.R., 1998, Lowstand deflation origin of Mississippian carbonate eolianites of southwestern Kansas: American Association of Petroleum Geologists, Annual Convention, Extended Abstracts, v. 1, no. A2, 4 p.

Allan, J.R., and Matthews, R.K., 1982, Isotopic signatures associated with early meteoric diagenesis: Sedimentology, v. 29, p. 797–817.

Allen, P.A., Verlander, J.E., Burgess, P.M., and Audet, D.M., 2000, Jurassic giant erg deposits, flexure of the United States continental interior, and timing of the onset of Cordilleran shortening: Geology, v. 28, p. 159–162.

Atchley, S.C., and Loope, D.B., 1993, Low-stand influence on stratigraphic completeness: upper member of the Hermosa Formation (latest Carboniferous), southeast Utah, USA, *in* Pye, K., and Lancaster, N., eds., Aeolian Sediments: Ancient and Modern: International Association of Sedimentologists, Special Publication 16, p. 127–149.

Bagnold, R.A., 1941, The Physics of Blown Sand and Desert Dunes: London, Methuen & Company, Ltd., 265 p.

Bain, R.J., and Kindler, P., 1994, Irregular fenestrate in Bahamian eolianites: a rainstorm-induced origin: Journal of Sedimentary Research, v. A64, p. 140–146.

Bathurst, R.G.C., 1975, Carbonate Sediments and Their Diagenesis, 2nd Edition: New York, Elsevier, Developments in Sedimentology 12, 658 p.

Berner, R.A., 1998, The carbon cycle and CO_2 over Phanerozoic time: the role of land plants: Royal Society [London], Philosophical Transactions, Ser. B, v. 353, p. 75–82.

Blakey, R.C., 1990, Supai Group and Hermit Formation, *in* Beus, S.S., and Morales, M., eds., Grand Canyon Geology: New York, Oxford University Press, p. 147–182

Caputo, M.V., 1993, Eolian structures and textures in oolitic–skeletal calcarenites from the Quaternary of San Salvador Island, Bahamas: A new perspective on eolian limestones, *in* Keith, B.D., and Zuppann, C.W., eds., Mississippian Oolites and Modern Analogs: American Association of Petroleum Geologists, Studies in Geology 35, p. 243–259.

Caputo, M.V., 1995, Sedimentary architecture of Pleistocene eolian calcarenites, San Salvador Island, Bahamas, *in* Curran, H.A., and White, B., eds., Terrestrial and Shallow Marine Geology of the Bahamas and Bermuda: Geological Society of America, Special Paper 300, p. 63–77.

Carr, T.R., and Lundgren, C.E., 1994, Use of gamma ray spectral log to recognize exposure surfaces at the reservoir scale; Big Bow Field (St. Louis Limestone), Kansas, *in* Dolson, J.C., Hendricks, M.L., and Wescott, W.A., eds., Unconformity-Related Hydrocarbons in Sedimentary Sequences; Guidebook for Petroleum Exploration and Exploitation in Clastic and Carbonate Sediments: Rocky Mountain Association of Geologists, Denver, Colorado, p. 79–88.

Dodd, J.R., Zuppann, C.W., Harris, C.D., Leonard, K.W., and Brown, T.W., 1993, Petrologic method for distinguishing eolian and marine grainstones, Ste. Genevieve Limestone (Mississippian) of Indiana, *in* Keith B.D., and Zuppann, C.W., eds., Mississippian Oolites and Modern Analogs: American Association of Petroleum Geologists, Studies in Geology, no. 35, p. 31–48.

Doe, T.W., and Dott, R.H., Jr., 1980, Genetic significance of deformed cross-bedding—with examples from the Navajo and Weber Sandstones of Utah: Journal of Sedimentary Petrology, v. 50, p. 793–812.

Dravis, J.J., 1996, Rapidity of freshwater calcite cementation—implications for carbonate diagenesis and sequence stratigraphy: Sedimentary Geology, v. 107, p. 1–10.

Eriksson, K.A., and Simpson, E.L., 1998, Controls on spatial and temporal distribution of Precambrian eolianites: Sedimentary Geology, v. 120, p. 275–294.

Esteban, M., and Klappa, C.F., 1983, Subaerial exposure environment, *in* Scholle, P.A., Bebout, D.G., and Moore, C.H., eds., Carbonate Depositional Environments: American Association of Petroleum Geologists, Memoir 33, p. 1–54.

Freeman, W.E., and Visher, G.S., 1975, Stratigraphic analysis of the Navajo Sandstone: Journal of Sedimentary Petrology, v. 45, p. 651–658.

Fryberger, S.G., Ahlbrandt, T.S., and Andrews, S., 1979, Origin, sedimentary features, and significance of low-angle eolian "sand sheet" deposits, Great Sand Dunes National Monument and vicinity, Colorado: Journal of Sedimentary Petrology, v. 49, p. 733–746.

Fryberger, S.G., and Schenk, C.J., 1988, Pinstripe lamination: a distinctive feature of modern and ancient eolian sediments: Sedimentary Geology, v. 55, p. 1–15.

Fryberger, S.G., Schenk, C.J., and Krystinik, L.F., 1988, Stokes surfaces and the effects of near-surface groundwater-table on aeolian deposition: Sedimentology, v. 35, p. 21–41.

Grimley, D.A., Follmer, L.R., and McKay, E.D., 1998, Magnetic susceptibility and mineral zonations controlled by provenance in loess along the Illinois and central Mississippi Valleys: Quaternary Research, v. 49, p. 24–36.

Halley, R.B., and Harris, P.M., 1979, Fresh-water cement of a 1,000-year-old oolite: Journal of Sedimentary Petrology, v. 49, p. 969–988.

Handford, C.R., and Francka, B.J., 1991, Mississippian carbonate siliciclastic eolianites in southwestern Kansas, *in* Lomando, A.J., and Harris, P.M., eds., Mixed Carbonate–Siliciclastic Sequences: SEPM, Core Workshop 15, p. 205–243.

Hearty, P.J., Neumann, A.C., and Kaufman, D.S., 1998, Chevron ridges and runup deposits in the Bahamas from storms late in oxygen-isotope substage 5e: Quaternary Research, v. 50, p. 309–322.

Horowitz, D.H., 1982, Geometry and origin of large-scale deformation structures in some ancient wind-blown sand deposits: Sedimentology, v. 35, p. 155–180.

Hunter, R.E., 1977, Basic types of stratification in small eolian dunes: Sedimentology, v. 24, p. 361–387.

Hunter, R.E., 1981, Stratification styles in eolian sandstones: some Pennsylvanian to Jurassic examples from the Western Interior, U.S.A., *in* Ethridge, F.G., and Flores, R.M., eds., Recent and Ancient Non-Marine Depositional Environments: Models for Exploration: Society of Economic Mineralogists and Paleontologists, Special Publication 31, p. 315–329.

Hunter, R.E., 1993, An eolian facies in the Ste. Genevieve Limestone of southern Indiana, *in* Keith, B.D., and Zuppann, eds., Mississippian Oolites and Modern Analogs: American Association of Petroleum Geologists, Studies in Geology 35, p. 31–47.

James, N.P., 1984, Introduction to carbonate facies models, *in* Walker, R.G., ed., Facies Models, 2nd Edition: Geoscience Canada, Reprint Series 1, p. 209–228.

Kilibarda, Z., and Loope, D.B., 1997, Jurassic eolian oolite on a paleohigh in the Sundance Sea, Bighorn Basin, Wyoming: Sedimentology, v. 44, p. 391–404.

Kindler, P., and Strasser, A., 1999, Paleoclimatic significance of co-occurring wind- and water-induced sedimentary structures in the last-interglacial coastal deposits from Bermuda and the Bahamas: Sedimentary Geology, v. 131, p. 1–7.

Kocurek, G., ed., 1988, Late Paleozoic and Mesozoic Eolian Deposits of the Western Interior of the United States: Sedimentary Geology, v. 56, 314 p.

Kocurek, G., 1996, Desert aeolian systems, *in* Reading, H.G., ed., Sedimentary Environments: Processes, Facies and Stratigraphy, 3rd edition: Oxford, U.K., Blackwell Science, Ltd., p. 125–153.

Kocurek, G., 1999, The aeolian rock record (yes, Virginia, there really is an aeolian rock record, but it really is rather special to create one), *in* Goudie, A.S., Livingstone, I., and Stokes, S., eds., Aeolian Environments, Sediments and Landforms: London, John Wiley & Sons, Ltd., p. 239–259.

KOCUREK, G., AND FIELDER, G., 1982, Adhesion structures: Journal of Sedimentary Petrology, v. 52, p. 1229–1241.

KOCUREK, G., AND NIELSON, J., 1986, Conditions favorable for the formation of warm-climate aeolian sand sheets: Sedimentology, v. 33, p. 795–816.

LEEDER, M.R., 1982, Sedimentology; Processes and Product: London, George Allen & Unwin, 344 p.

LOOPE, D.B., 1988, Rhizoliths in ancient eolianites, *in* Kocurek, G., ed., Late Paleozoic and Mesozoic Eolian Deposits of the Western Interior of the United States: Sedimentary Geology, v. 56, p. 301–314.

LOOPE, D.B., ABEGG, F.E., and HARRIS, P.M., 1998, Recognizing ancient carbonate eolianites (abstract): American Association of Petroleum Geologists, Annual Convention, Salt Lake City, Utah, Extended abstract no. A412.

LOOPE, D.B., AND DINGUS, L., 1999, Mud-filled *Ophiomorpha* from Upper Cretaceous continental redbeds of Southern Mongolia: An ichnologic clue to the origin of detrital, grain-coating clays: Palaios, v. 14, p. 452–459.

LOOPE, D.B., DINGUS, L., SWISHER, C.C., III, AND MINJIN, C., 1998, Life and death in a Late Cretaceous dune field, Nemegt Basin, Mongolia: Geology, v. 26, p. 27–30.

LOOPE, D.B., AND HAVERLAND, Z.E., 1988, Giant desiccation fissures filled with calcareous eolian sand, Hermosa Formation (Pennsylvanian), SE Utah, *in* Kocurek, G., ed., Late Paleozoic and Mesozoic Eolian Sediments of the Western Interior of the United States: Sedimentary Geology, v. 56, p. 403–413.

LOOPE, D.B., AND SCHMITT, J.G., 1980, Caliche in the late Paleozoic Fountain Formation; rediscovery and implications [abstract]: Geological Society of America, Abstracts with Programs, v. 12, no. 7, p. 413.

LOOPE, D.B., AND SIMPSON, E.L., 1992, Significance of thin sets of eolian cross-strata: Journal of Sedimentary Petrology, v. 62, p. 849–859.

MACK, G.H., AND RASMUSSEN, K.A, 1984, Alluvial-fan sedimentation of the Cutler Formation (Permo-Pennsylvanian) near Gateway, Colorado: Geological Society of America, Bulletin, v. 95, p. 109–116.

MALIVA, R.G., KNOLL, A.H., AND SIEVER, R., 1989, Secular change in chert distribution: a reflection of evolving biological participation in the silica cycle: Palaios, v. 4, p. 519–532.

MARZOLF, J.E., 1988, Controls on late Paleozoic and early Mesozoic eolian deposition of the western United States, *in* Kocurek, G., ed., Late Paleozoic and Mesozoic Eolian Sediments of the Western Interior of the United States: Sedimentary Geology, v. 56, p. 167–191.

MASON, J.A., NATER, E.A., ZANNER, C.W., AND BELL, J.C., 1999, A new model of topographic effects on the distribution of loess: Geomorphology, v. 28, p. 223–236.

MCCORD, J.T., STEPHENS, D.B., AND WILSON, J.L., 1991, Hysteresis and state-dependent anisotropy in modeling unsaturated hillslope hydrologic processes: Water Resources Research, v. 27, p. 1501–1518.

MCELWAIN, J.C., and CHALONER, W.G., 1995, Stomatal density and index of fossil plants track atmospheric carbon dioxide in the Paleozoic: Annals of Botany, v. 76, p. 389–395.

MCKEE, E.D., 1934, The Coconino Sandstone—its history and origin: Washington, D.C., Carnegie Institute, Publication 440, p. 78–115.

MCKEE, E.D., 1982, The Supai Group of Grand Canyon: U.S. Geological Survey, Professional Paper 1173, 504 p.

MCKEE, E.D., AND WARD, W.C., 1983, Eolian environment, *in* Scholle, P.A., Bebout, D.B., and Moore, C.H., eds., Carbonate Depositional Environments: American Association of Petroleum Geologists, Memoir 33, p. 131–170.

MOORE, C.H., 1989, Carbonate Diagenesis and Porosity: New York, Elsevier, Developments in Sedimentology 46, 338 p.

MORA, C.I., DRIESE, S.G., AND SEAGER, P.G., 1991, Carbon dioxide in the Paleozoic atmosphere: evidence from carbon-isotope composition of pedogenic carbonate: Geology, v. 19, p. 1017–1020.

PERKINS, R.D., 1977, Depositional framework of Pleistocene rocks of South Florida, *in* Enos, P., and Perkins, R.D., Quaternary Sedimentation in South Florida: Geological Society of America, Memoir 147, p. 131–198.

PYE, K., 1983, Grain surface textures and carbonate content of late Pleistocene loess from West Germany and Poland: Journal of Sedimentary Petrology, v. 53, p. 973–980.

PYE, K., 1987, Aeolian Dust and Dust Deposits: London, Unwin Hyman, 396 p.

PYE, K., AND TSOAR, H., 1990, Aeolian Sand and Sand Dunes: London, Unwin Hyman, 396 p.

RICE, J.A., AND LOOPE, D.B., 1991, Wind-reworked carbonates, Permo-Pennsylvanian of Arizona and Nevada: Geological Society of America, Bulletin, v. 103, p. 254–267.

SCHUMM, S.A., 1968, Speculation concerning paleohydrologic controls of terrestrial sedimentation: Geological Society of America, Bulletin, v. 79, p. 1573–1588.

SELLWOOD, B.W., 1978, Shallow-water carbonate environments, *in* Reading, H.G., ed., Sedimentary Environments and Facies: New York, Elsevier, p. 259–313.

SHAO, Y., RAUPACH, M.R., AND FINDLATER, P.A., 1993, Effect of saltation bombardment on the entrainment of dust by the wind: Journal of Geophysical Research, v. 98, p. 12,719–12,726.

SHINN, E.A., 1983, Tidal flat environment, *in* Scholle, P.A., Bebout, D.G., and Moore, C.H., eds., Carbonate Depositional Environments: American Association of Petroleum Geologists, Memoir 33, p. 172–210.

SIMPSON, E.L., AND ERIKSSON, K., 1993, Thin eolianites interbedded within a fluvial and marine succession: early Proterozoic Whitworth Formation, Mount Isa Inlier, Australia: Sedimentary Geology, v. 87, p. 39–62.

SIMPSON, E.L., AND LOOPE, D.B., 1985, Amalgamated interdune deposits, White Sands, New Mexico: Journal of Sedimentary Petrology, v. 55, p. 361–365.

STEIDTMANN, J.R., 1977, Stratigraphic analysis of the Navajo Sandstone: A discussion: Journal of Sedimentary Petrology, v. 47, p. 484–489.

TREWIN, N.G., 1993, Mixed aeolian sandsheet and fluvial deposits in the Tumblagooda Sandstone, Western Australia, *in* North, C.P., and Prosser, D.J., eds., Characterization of Fluvial and Aeolian Reservoirs: Geological Society of London, Special Publication 73, p. 219–230.

WALKER, T.R., AND HARMS, J.C., 1972, Eolian origin of flagstone beds, Lyons Sandstone (Permian) type area, Boulder County, Colorado: The Mountain Geologist, v. 9, p. 279–288.

WANLESS, H.R., AND TEDESCO, L.P., 1993, Comparison of oolitic sand bodies generated by tidal vs. wind-wave agitation, *in* Keith, B.D., and Zuppann, C.W., eds., Mississippian Oolites and Modern Analogs: American Association of Petroleum Geologists, Studies in Geology 35, p. 199–225.

WHITE, B., AND CURRAN, H.A., 1988, Mesoscale physical sedimentary structures and trace fossils in Holocene carbonate eolianites from San Salvador Island, Bahamas: Sedimentary Geology, v. 55, p. 163–184.