

Early Jurassic eolian dune field, Pomperaug basin, Connecticut and related synrift deposits: Stratigraphic framework and paleoclimatic context

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Abstract

The discovery of an extensive eolian sandstone in the Pomperaug basin, Connecticut is noteworthy because it is the most significant occurrence of eolian rocks in the continental rifts of the Newark Supergroup south of the Fundy basin, Canada. Climate-sensitive rocks provide important constraints for the influence of supercontinent landmass configurations on models of early Mesozoic Pangaean climate. The sedimentary structures and textures in the Pomperaug basin sandstone compare favorably with modern and ancient eolian sands. The eolian sandstone is traceable for at least 5 km and occupies a stratigraphic interval that is dominated by arid facies in the Pomperaug and Hartford basins, indicating that the eolian deposit is indicative of regional climate. The eolian sands were stabilized by a return to more humid conditions and subsequently buried beneath a thick, basin-wide basalt flow, preserving the dune field. Also described are related synrift eolian sandstones from the Hartford (Connecticut, USA), Fundy (Nova Scotia, Canada), and Argana (Morocco) basins. Using revised paleolatitude models for the Pangaean rifts, the distribution of eolian sandstones suggests that the Norian–Hettangian world had zonal climate belts with modified latitudinal gradients. © 2005 Elsevier B.V. All rights reserved.

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1. Introduction

This paper describes a basin-wide eolian dune field in Early Jurassic continental rocks of the Pomperaug basin, Connecticut and documents associated, recently recognized, eolian deposits in related Rhaetian–Hettangian synrift strata in the Hartford basin. The Pomperaug and Hartford basins are part of the early Mesozoic

Pangaean breakup rift system, known in North America as the Newark Supergroup (Fig. 1). Affiliated rifts, including the Argana basin, Morocco, discussed in this paper, are part of this circum-North Atlantic rift province. The Pomperaug basin dune field comprises the most extensive eolian sandstone in the Newark Supergroup found south of the Fundy basin (Hubert and Mertz, 1980, 1984; LeTourneau and Huber, 1997; Smoot, 1991a,b; Olsen, 1997), at less than about 25° paleolatitude (Kent and Olsen, 2000a; Olsen and Kent, 2000; Olsen et al., 2000; Kent and Tauxe, 2005). Eolian deposits are important paleoclimate indicators and, along with coals and evaporites, have been widely

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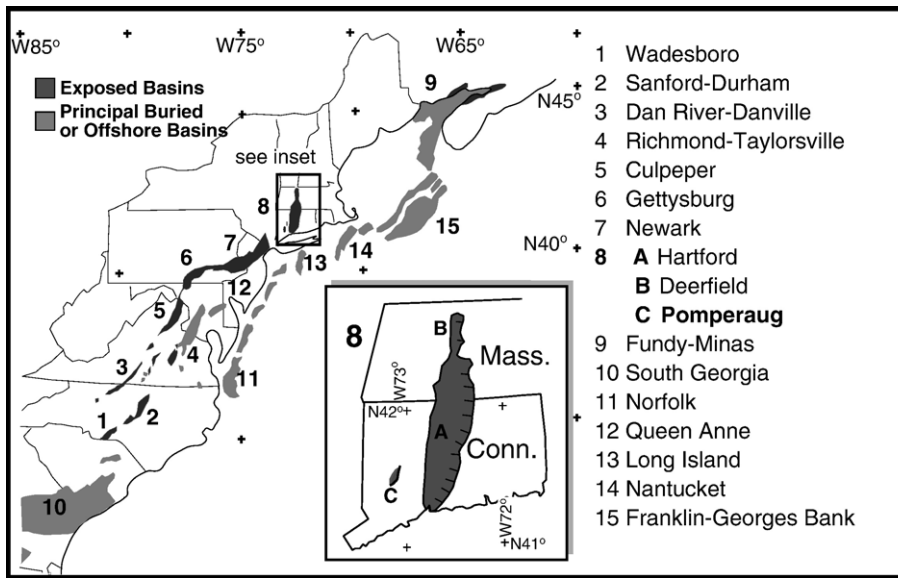


Fig. 1. Location of the Newark Supergroup rifts and the Pomperaug basin.

used to constrain Pangaean climate models (e.g., Hay et al., 1982; Chandler et al., 1992; Parrish, 1993; Hallam, 1994a,b; Wilson et al., 1994). Our identification of this basin-wide eolian dune field is important because it revises the distribution pattern of climate-sensitive rocks in the Newark rifts.

Eolian sandstones are, in general, uncommon within the Newark Supergroup rift basins (Fig. 2) but are common in Late Triassic and Early Jurassic age rocks of the Fundy basin, Canada, deposited at paleolatitudes rang-

ing from about 17°N (Carnian, Triassic) to about 25°N (Hettangian, Jurassic) (Hubert and Mertz, 1980, 1984; Nadon and Middleton, 1985; Olsen, 1997; Smoot, 1991a; Olsen, 1997; Kent and Olsen, 2000a; Olsen and Kent, 2000; Kent and Tauxe, 2005). In the Hartford basin, eolian sandstones have been recognized in the Late Triassic New Haven Arkose (Smoot, 1991a) and the Early Jurassic “brownstones” and “Longmeadow sandstone facies” of the Portland Formation (LeTourneau, 2001), both deposited at approximately 22°N (Kent and Olsen, 2000a; Olsen and Kent, 2000; Olsen et al., 2000; Kent and Tauxe, 2005). The Argana basin, Morocco, a North African affiliate of the Newark rifts, also contains noteworthy Norian age eolian strata of wide areal extent deposited at an approximate paleolatitude of 15°N, including the Tadrart Sandstone Member of the Bigoudine Formation (Tixeront, 1973; Olsen, 1997, Hofman et al., 2000; Olsen et al., 2000).

Paleoclimate reconstructions of the Late Triassic and Early Jurassic rely, in part, on identification of climate-dependent facies, including coals, evaporites, and eolian beds (e.g. Hay et al., 1982; Hallam, 1985, 1994a,b; Sellwood and Price, 1994; Wilson et al., 1994). Placing climate-sensitive strata in their paleogeographic and stratigraphic settings is necessary for constructing models of Pangaean climates, such as zonal (e.g., Kent and Olsen, 2000a; Olsen and Kent, 2000; Kent and Tauxe, 2005); modified zonal (e.g., Wilson et al., 1994), or non-zonal (e.g., Manspeizer, 1982; Parrish, 1993) atmospheric circulation hypotheses. It is particularly im-

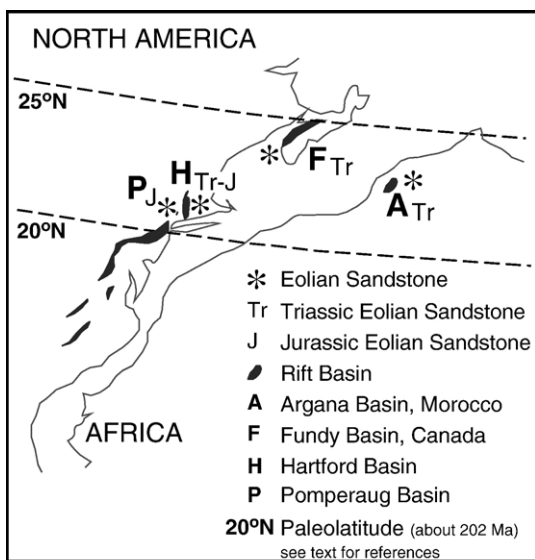


Fig. 2. Paleolatitudinal distribution of eolian sandstone in the circum-North Atlantic Pangaean rift system.

portant to constrain facies-dependent climate interpretations with high-resolution stratigraphy to discriminate paleogeographic, paleotopographic (Manspeizer, 1982), and paleolatitudinal (Ziegler et al., 1982) patterns from stratigraphic patterns produced by periodic climate variability (Olsen, 1986; Kent and Olsen, 2000a,b; Olsen and Kent, 2000). Mis-registration of climate-sensitive facies by as little as 20 ky in chronostratigraphic space (sensu Kent and Olsen, 2000b) may lead to flawed interpretations of regional paleoclimatic and paleogeographic trends.

2. The Pomperaug basin

2.1. Setting

The Pomperaug basin is part of the suite of rifts located along the central Atlantic margin (CAM) in North America, North Africa, and western Europe that formed during the incipient breakup of Pangaea in the Late Triassic and Early Jurassic (Manspeizer, 1988; Olsen, 1997; LeTourneau and Olsen, 2003). The CAM rifts include onshore exposed basins, and onshore and offshore basins buried by Late Jurassic and younger passive margin deposits (Benson, 1992) (Fig. 1). The Pangaeon-breakup rifts of eastern North America are the best known of the Triassic–Jurassic age CAM basins and they contain the rocks of the Newark Supergroup (Olsen, 1997), including continental fluvial and lacustrine sedimentary rocks and, in some cases, extensive tholeiitic basalt flows and dikes. Collectively, the Newark rifts contain the geologic record of more than 30 million years of Late Triassic through Early Jurassic earth history and span more than 20° of paleolatitude from paleoequatorial to low mid-latitude regions (Olsen, 1997). Therefore the Newark rifts provide ideal opportunities to study the Pangaeon paleoclimate record as a function of both paleolatitude and astronomically forced climate cycles through an extensive period of geologic time (Olsen, 1986, 1997; Olsen and Kent, 2000; LeTourneau, 2003).

2.2. Note on stratigraphy and age of the Pomperaug basin

The Pomperaug basin is a small (~12 by ~4 km), Late Triassic to Early Jurassic age rift located about 20 km west of the Hartford basin and roughly centered near Southbury, Connecticut (Davis, 1888; Hobbs, 1901; Rodgers, 1985) (Fig. 1). The stratigraphy of the Pomperaug basin has been described by Davis (1888), Hovey (1890), Hobbs (1901), Scott (1974), and Rod-

gers (1985). Work by Davis (1888) and Hobbs (1901), and data from an early oil exploration well (Hovey, 1890), clearly reveals the presence of two basin-wide basalt flow units intercalated with fluvial and lacustrine strata, then believed to be of Late Triassic age.

Both Davis (1888) and Hobbs (1901) show, however, that the Pomperaug basin is structurally complex with several generations of post-depositional faulting. Some of the complexity in the basin structure is almost certainly due to the presence of inversion structures formed under post-extensional compression, similar to that recently defined for other rifts in the Newark Supergroup (Withjack et al., 1998; LeTourneau, 2003; Burton et al., 2005). This structural complexity, coupled with discontinuous exposures, has contributed to varied interpretations of basin stratigraphy. For example, although early workers (Davis, 1888; Hovey, 1890; Hobbs, 1901) document two separate basalt flow units, Krynine (1950), Scott (1974), Rodgers (1985), and more recently Philpotts (1998) suggest the presence of three basalt flow units based mainly on comparison with the neighboring Hartford basin. On-going work by the U.S. Geological Survey in the Pomperaug basin (Burton et al., 2005) also suggests the possibility of a third basalt flow, but, to date, the macroscopic and geochemical characteristics of the unit remain ambiguous. It is just as likely that the unit is in a faulted block of the Orenaug, or main, basalt. Advocates of the “broad-terrane” hypothesis cited the Pomperaug basin as evidence of the former connection of the Hartford and Newark basins (Russell, 1892; Hobbs, 1901; Barrell, 1915; Longwell, 1922). Influenced by the broad-terrane hypothesis, Krynine (1950) believed that the Pomperaug rift was merely an eroded “outlier” of the large neighboring Hartford Basin and he suggested that the stratigraphy of the two basins was the same. Modern interpretations of the Pomperaug stratigraphy by Scott (1974) and Rodgers (1985) adopted the Hartford basin terminology and considered the basin an “outlier” following Krynine’s (1950) hypothesis. It is interesting to note that of the writers who proposed stratigraphic schemes for the Pomperaug only Davis (1888), Hobbs (1901), and Scott (1974) actually conducted extensive field research in the basin. Scott (1974) was obviously led astray by the complex structure and glacial till cover when he proposed up to five or more intercalated sedimentary and basalt units within the lowest flow. Because the basalt flows provide important stratigraphic markers that are traceable throughout the basin, work to determine the distribution and character of the flows and their relationship to three intercalated sedimentary formations of

Late Triassic and Early Jurassic age is continuing (Burton et al., 2005).

We advocate the hypothesis that the Pomperaug basin was an isolated basin (Davis, 1888; Huber and McDonald, 1992; Burton et al., 2005) based on sedimentological evidence, especially paleocurrents and clast provenance that clearly show eastern and western source areas. Our reinterpretation of the Pomperaug stratigraphy is in general agreement with the early interpretations of Davis (1888) and Hobbs (1901) and the relatively unambiguous stratigraphy from exploratory oil well data reported by Hovey (1890). None of the previous workers in the Pomperaug basin formalized the stratigraphic nomenclature, either by the standards of their day (e.g., Davis, 1888; Hobbs, 1901) or in accordance with modern criteria, and there are no described type sections or reference sections for lithostratigraphic units.

Rodgers (1985) applied the stratigraphy of the nearby Hartford basin to the Pomperaug. However, Rodgers (1985) did not realize that most of the Hartford basin rock units he extended into the Pomperaug basin themselves lacked valid defined stratotypes, and that the Pomperaug rocks are composed of lithosome associations that are, by and large, distinct from their Hartford basin chronostratigraphic equivalents.

We have revised the stratigraphic nomenclature of the Pomperaug basin based on our stratigraphic and sedimentologic investigations (Burton et al., 2005), but until our work meets the publication criteria of the North American Commission on Stratigraphic Nomenclature (NACSN, 1983), the lithostratigraphic units named here should be considered informal, but accurate, descriptions of basin stratigraphy. Note, however, that the U.S. Geological Survey has adopted our stratigraphic nomenclature for Pomperaug basin strata and basalts (Burton et al., 2005; in prep.). We do not refer to the earliest stratigraphic nomenclature of Davis (1888) or Hobbs (1901) because their terminology is antiquated, cumbersome, and confusing (e.g., “anterior shale,” “posterior basalt,” “amygdaloid,” etc.). Nor do we refer to the earlier stratigraphic units of Rodgers (1985) or Scott (1974) because their interpretations are clearly in error as shown by simple field relationships and superposition of strata (Burton et al., 2005), and use of the incorrect stratigraphic scheme would serve only to further obfuscate the geologic relationships in the Pomperaug basin.

In our revised stratigraphy (Fig. 3) the coarse fluvial South Britain Formation (~250 m) of Late Triassic and Early Jurassic age forms the base of the Pomperaug basin section. The Triassic–Jurassic boundary is located

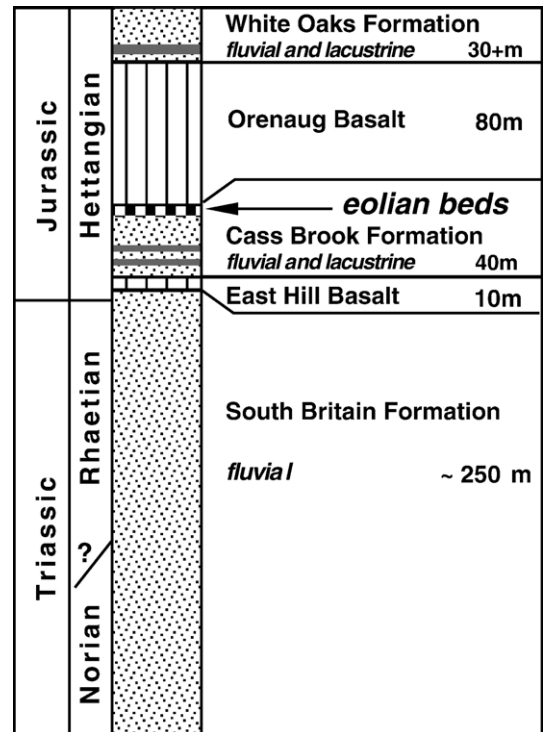


Fig. 3. Stratigraphic section of the Pomperaug basin.

in the uppermost portion of the South Britain Formation. The South Britain Formation is overlain by Early Jurassic strata (Huber and McDonald, 1992; Lucas and Huber, 1993) in the following vertical succession: the East Hill Basalt (10 m); the fluvial, eolian, and lacustrine Cass Formation (40 m); the Oreanug Basalt, 80 m; and the fluvial and lacustrine White Oaks Formation (30+ m). A possible third basalt unit is not shown in Fig. 3 because, at the time of this writing, its identity remains ambiguous. The eolian sandstone described in this paper comprises the upper several meters of the Cass Formation.

3. Eolian sandstones of the Pomperaug basin

3.1. Location and occurrence

The eolian sandstone is exposed in two quarries about 5 km apart near the towns of Southbury and Woodbury, Connecticut. In addition, talus and float blocks of eolian sandstone are abundant at the correlative stratigraphic interval of the Cass formation in several areas of the basin including Platt Farm Park near South Britain, and exposures along South Brook located about 1 km south of the northern (Woodbury) quarry (Fig. 4). The eolian sandstone rests on fluvial

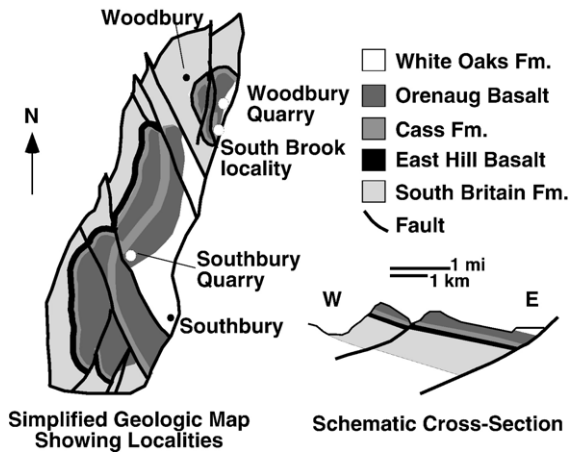


Fig. 4. Simplified geologic map of the Pomperaug basin.

conglomerate, sandstone, and siltstone and is overlain by the upper lava flow—the Orenaug basalt (Fig. 3). The base of the section containing the eolian sandstone consists of poorly sorted fluvial conglomerate containing clasts of high-grade metamorphic rocks, plutonic igneous rocks, and dolomitic marble. The coarse fluvial rocks are overlain by weakly bedded, red-brown, siltstone with deep root traces, in turn overlain by an extensive horizon of pedogenic carbonate nodules and calcareous rhizoconcretions found directly beneath the eolian sandstone (Fig. 5).

The eolian sandstone ranges from light tan to light yellow-brown and has secondary light to dark brown limonite and green malachite mineralization along coarse-grained, porous laminae. Individual eolian beds about 0.5- to 1-m thick combine to form a sandstone unit up to 3-m thick. Low-angle, planar to undulatory surfaces form the contacts between the beds, and cross-

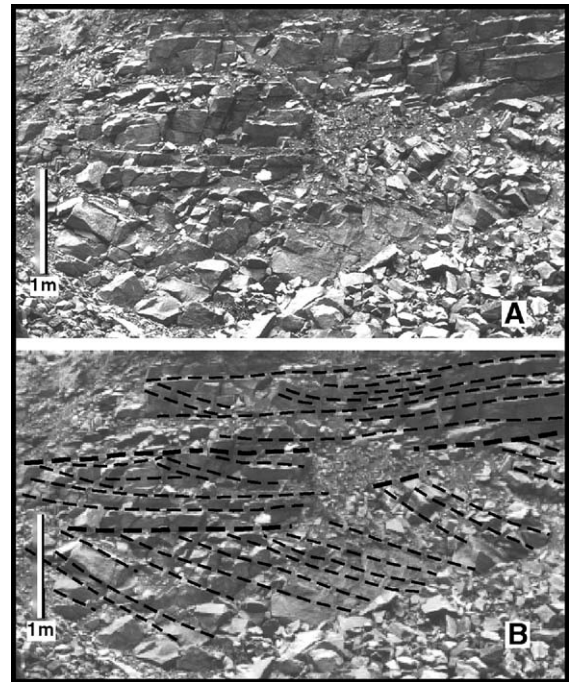


Fig. 6. (A) Eolian dune showing multiple truncation surfaces from dune migration and reactivation of slip faces. (B) Tracings of cross-bedding and surfaces.

bedding ranges from low- to high-angle as a function of apparent dip of the foresets and variable foreset inclinations (Fig. 6). The eolian beds are overlain by a 5- to 10-cm bed of well-sorted shallow lacustrine sandstone with planar lamination and oscillatory ripple cross-lamination (Fig. 7).

The section described above is capped by the 80-m thick Orenaug basalt that provides basin-wide stratigraphic control for correlation of exposures of the eolian sandstone. The eolian beds, including the undulatory surface

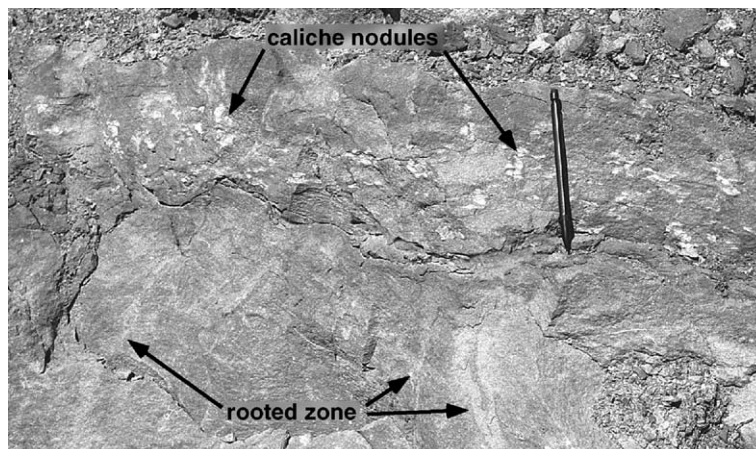


Fig. 5. Caliche paleosol and calcified roots traces in unit underlying eolian sandstone.

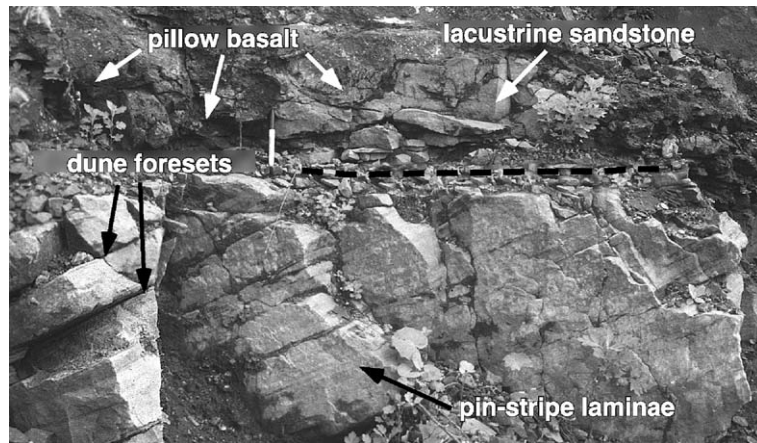


Fig. 7. Upper contact of the eolian sandstone. Bed immediately overlying the dune foresets is lacustrine re-worked eolian sand with planar lamination and oscillatory ripples in upper surface (not visible in this view). Topmost unit is basalt with pillow structures.

of the dune field, were apparently preserved by the overlying basin-wide basalt flow. Similar preservation of eolian sandstones by extensive lava flows has been described for Precambrian rocks in South Greenland (Clemmensen, 1988), and for Cretaceous deposits in Namibia (Mountjoy et al., 1999) and in Brazil (Scherer, 2000). Portions of the lower contact of the Orenaug lava flow contain vesicular pillow structures (Fig. 7) indicating that, in places, the flow encountered surface water. These observations support the sedimentological evidence that in some areas (inter-dune) the upper few centimeters of the eolian deposit were briefly reworked under sub-aqueous conditions, as discussed below.

3.2. Sedimentary structures

Diagnostic sedimentary structures observed in eolian sandstones of the Upper Cass Formation of the Pom-

peraug basin compare favorably with features observed in modern and ancient eolian sand deposits. Recognition of the inverse-graded strata formed by subcritically climbing high-index ripples and grainflow and grainfall cross-stratification is key to the identification of eolian sand deposits (Hunter, 1981; Kocurek and Dott, 1981; Fryberger and Schenk, 1988).

3.2.1. Pinstripe lamination

The Pomperaug basin eolian sandstone contains laterally continuous, inverse-graded horizontal and low-angle inclined laminae that repeat vertically to form a distinctive “pin-stripe” appearance (Figs. 7, 8). Although relatively scarce, isolated high-index ripples are also observed as millimeter-scale lenses within inverse- and normal-graded laminae in the Pomperaug basin sandstone. Inverse-graded pin-stripe lamination results from grain sorting in migrating high-index

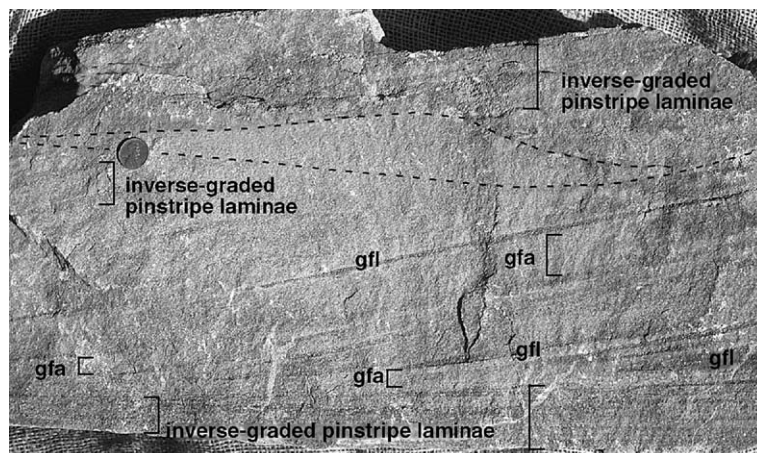


Fig. 8. Block of eolian sandstone showing diagnostic features. Gfa, grainfall layer; gfl, grainflow (mass flow) layer.

wind ripples, where finer grains are deposited in ripple troughs and coarser grains are deposited on the ripple crests and upper lee slopes (Hunter, 1977a; Fryberger and Schenk, 1988; Kocurek and Dott, 1981, Schenk, 1990). Fryberger and Schenk (1988) demonstrated the origin of inverse-graded lamination by wind ripples in laboratory experiments and field studies of modern and ancient eolian dunes.

3.2.2. Grainfall deposits

Other distinctive eolian features of the Pomperaug basin beds are well-sorted, non-graded cross-laminae that form sheet-like asymmetric wedges that thicken abruptly toward foreset toes and thin gradually toward the upper slipface (Figs. 8, 9). These fine-to-medium-grained layers interfinger with coarse-grained, wedge-shaped, cross-strata (described below), and truncate against basal, low-angle and horizontal surfaces comprised of wind ripple laminae. These clinofom-shape layers are interpreted as grainfall deposits that form by direct fall-out of sand in the zone of airflow separation in the leeward side of dunes (Hunter, 1977a, 1981; Fryberger and Schenk, 1988; Kocurek and Dott, 1981; Schenk, 1990). The interfingering of grainfall layers with grainflow and wind ripple laminae suggests that the upper Cass Formation dunes were relatively small, meter-scale bedforms (Kocurek and Dott, 1981; Kocurek, 1996).

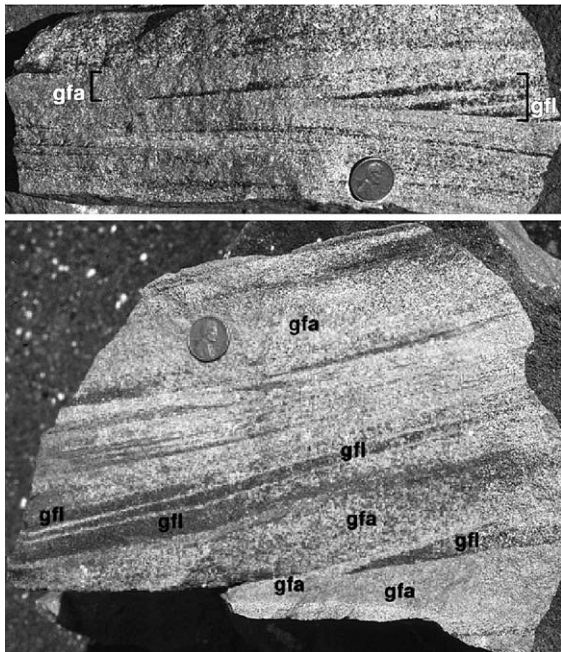


Fig. 9. Blocks of eolian sandstone showing diagnostic features. Gfa, grainfall layer; gfl, grainflow (mass flow) layer.

3.2.3. Grainflow deposits

The eolian origin of the sandstone is also indicated by layers of medium to coarse sand that interfinger with grainfall and wind ripple laminae (Figs. 8, 9). These distinct sedimentary structures variably referred to as grainflow (Kocurek and Dott, 1981; Kocurek, 1996), sandflow (Hunter, 1977a), or avalanche (McKee, 1979; Schenk, 1990) cross-beds. The Cass Formation grainflow cross-beds are massive (non-graded) to inverse-graded and form asymmetrical clinofoms that thin abruptly toward the lower slipface, and taper gradually toward the upper slipface (Figs. 8, 9). Strike-parallel views of the Pomperaug grainflow layers reveal narrow (decimeter-scale), thin (centimeter-scale) coarse-grained lenses with rounded tops and flat bottoms. The grainflow layers recognized in the Pomperaug basin sandstones are similar in geometry and grain size to grainflow tongues observed in small modern eolian dunes (Hunter, 1977a; Kocurek and Dott, 1981).

3.3. Bedding

The meter-scale cross-bedding in the sandstone ranges from low- to high-angle with a maximum dip of approximately 30° (tilt corrected) (Figs. 6, 7). Cross-stratification is predominantly wedge-planar and sets taper to low-angle tangential contacts at the lower bounding surfaces. Internally, the laminae comprising the cross-stratification have varied textures ranging from inverse-graded to normal-graded to massive (non-graded) in wind ripple, grainfall, and grainflow laminae. Contacts between cross-laminae range from parallel and continuous to irregular and discontinuous to lenticular. Most of the eolian beds observed in the Pomperaug basin contain dune-form cross-stratification bounded by low-angle planar to undulating surfaces. Low-angle inclined planar stratification is less common, which suggests that the Pomperaug eolian environment was dominated by dunes rather than low-angle sand sheets or extensive interdune areas (Ahlbrandt and Fryberger, 1981).

Migration of dunes and repetitive aggradation and erosion of dune flanks modify depositional bedding patterns and commonly create a hierarchy of bounding surfaces that reflect the interplay between sand deposition and erosion on several temporal and spatial scales (Brookfield, 1977; Fryberger, 1990a,b; Kocurek, 1986, 1988, 1996). The sandstone beds in the Pomperaug basin contain a hierarchy of bounding surfaces separating compound cross-bed sets. Second-order surfaces (sensu Fryberger, 1990b) created by dune migration form prominent surfaces truncate the

eolian cross-beds at low angles (Fig. 6), and the third-order reactivation surfaces form angular discordances between cross-beds (Fig. 8) as a result of local reworking and reactivation of dune slip faces (Fryberger, 1990a; Fryberger et al., 1979; Kocurek, 1996). The upper part of the eolian sandstone bed is in places truncated by the overlying basalt flow and locally by a thin layer of eolian sand reworked by shallow lacustrine processes.

3.4. Texture

The Pomperaug basin sandstone consists of moderately well-sorted, fine to coarse sand. The layers possess a bimodal segregation of medium and coarse sand in distinct layers and lenses, but highly sorted continuous and discontinuous laminae are common as a result of sub-aerial grain sorting processes (Fryberger and Schenk, 1988). Sand grains range from sub-rounded to well-rounded and consist of mostly of quartz with subordinate quantities of feldspar and lithic fragments; mica flakes are notably absent. Laboratory measurements of porosity and liquid and gas permeability support high porosities observed in hand sample. Porosities range from 14% to 21%, and gas and liquid permeabilities (in millidarcies, mD) reach values as high as 395 and 368 mD, respectively. In addition, certain beds or layers observed in outcrop contain prominent malachite grain coatings and pore fillings. The malachite is the result of secondary hydrothermal mineralization that preferentially penetrated high porosity eolian sandstones and fractures in sedimentary and igneous rocks in the Pomperaug basin. The high porosity and permeability of the eolian sandstone, coupled with the fact that it is capped by a thick, less permeable, basalt flow unit, suggest that it has a very good potential to be a significant aquifer.

Although textural characteristics are not entirely reliable indicators of eolian sand (Ahlbrandt, 1979), modern dune sands are commonly well-sorted with well-rounded individual grains (Ahlbrandt and Fryberger, 1982). In addition, the general absence of mica in the Pomperaug sandstone beds, in contrast with the highly micaceous siltstones and arkosic sandstones that form most of the basin section, suggests that mica flakes were effectively winnowed during subaerial transport.

3.5. Paleocurrents

Measurements of dune-scale cross stratification indicate a mean sand transport azimuth direction of 016°

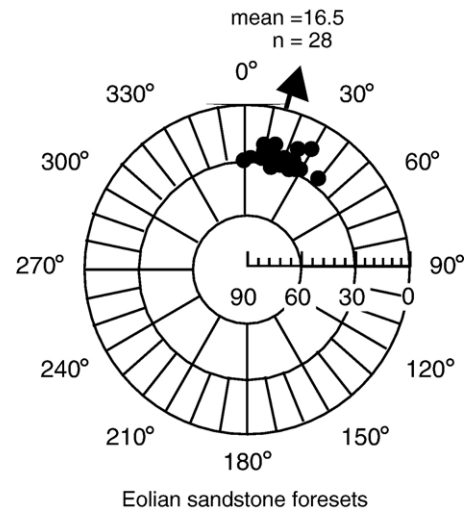


Fig. 10. Paleocurrent direction derived from eolian foresets.

(north–northeast) (Fig. 10). Dispersion of foreset dip directions is low, perhaps due to the relatively small number of measurements ($n=28$) obtained from five cross-bed sets, or a fairly well organized set of straight- to slightly sinuous-crested dunes. Limited three-dimensional exposures revealed mainly transverse dune forms with straight crested to broadly barchanoid or sinuous dune morphologies. The paleocurrent directions indicate that sand was transported north and east, roughly parallel to the long axis of the rift (Fig. 4).

3.6. Interpretation

The sedimentary structures and features described above compare favorably to those observed in modern dune sands and in ancient sandstones interpreted as eolian deposits. In particular, the presence of repetitive inverse-graded pinstripe laminae with interbedded grainfall and grainflow laminae are considered diagnostic of eolian sedimentation (Hunter, 1977a, 1981; Kocurek and Dott, 1981; Fryberger and Schenk, 1988; Kocurek, 1996). Other more ambiguous sedimentary features support an eolian interpretation when found with the above-mentioned fabrics include good sorting, high primary porosity and permeability, types of hierarchical bounding surfaces, meter-scale cross-bedding, and slump sheets (e.g., Hunter, 1977a,b, 1981; Fryberger et al., 1979; McKee, 1979; Kocurek and Dott, 1981; Schenk, 1990).

Based on the thickness of the cross-bed sets and the minimum 5 km lateral extent of the eolian sandstone, the Pomperaug eolian beds evidently formed a thin field

of small dunes with amplitudes up to several meters. The grainfall and grainflow wedges at the foreset toes, coupled with the scale of some of the sedimentary structures (Fig. 9), suggest that the dunes were small (G. Kocurek, pers. comm.) in comparison to those found in coeval rifts such as the Fundy and Argana

basins (see below). A modern analogy for the Pomperaug dune field may be the dune field at Stovepipe Wells in Death Valley, California (Fig. 11E, F), where a relatively thin layer of eolian sand overlies playa-lake beds and the height of the dunes averages about 2–3 m, reaching a maximum of about 7–10 m.

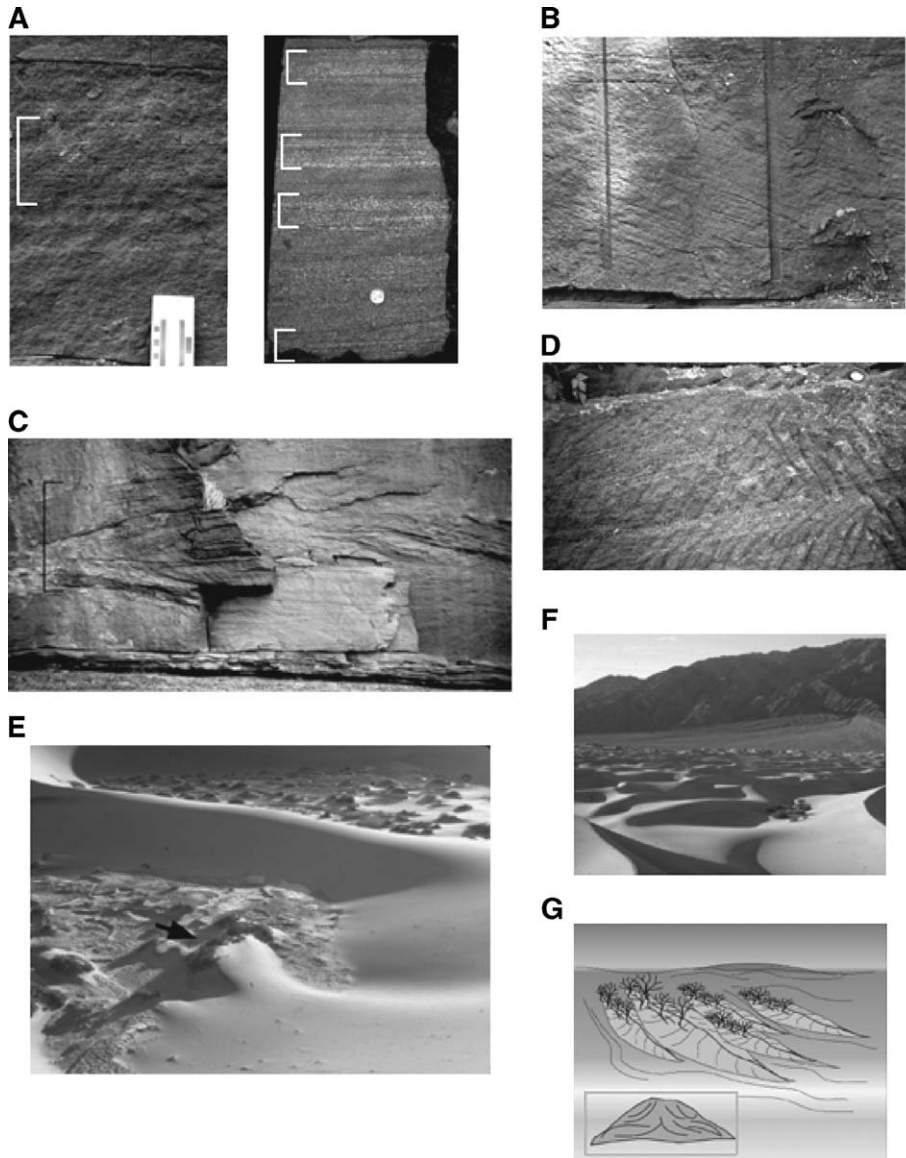


Fig. 11. Eolian sandstone from the Portland brownstone quarry, Portland Formation, Portland, Connecticut and modern dune field and coppice dunes, Stovepipe Wells, Death Valley, California. (A) Outcrop (left) and cut slab (right) of Portland brownstone showing inverse-graded wind ripple laminae (selected examples shown in brackets) and normal-graded layers. (B) Eolian dune foresets with inverse-graded wind ripple laminae and grainfall and grainflow toesets. (C) Coppice dune (bracketed), view is sub-parallel to flow direction. (D) Cross-cutting sets of inverse-graded wind ripple laminae. Thick striations on surface are chisel marks on surface of worked quarry block. (E) Coppice dune (arrow), Stovepipe Wells, Death Valley, California. Numerous coppice dunes are shown at top right. (F) View south and west across Stovepipe Wells dune field, Death Valley, California. Average thickness of eolian sand overlying carbonate and saline playa beds, and alluvial fan deposits (background) is about 3 m with largest dunes reaching about 10 m. (G) Cartoon of coppice dunes and their internal structure (inset).

3.7. Preservation of the Pomperaug eolian dune field

Our observations lead us to conclude that the Pomperaug eolian dune field was ultimately preserved by the overlying basin-wide Orenaug basalt flow (Fig. 7). As the lava flow filled the Pomperaug rift surface waters were displaced and the upper several centimeters of the eolian deposit were reworked by shallow and temporary lake waters. The presence of ponded water in the brief interval between dune deposition and preservation by the lava flow is also indicated by well-developed, oscillatory ripples at the top of the Cass Formation and pervasive vesicular pillow structures at the base of the overlying Orenaug basalt at all localities where the eolian sandstone–basalt contact is observed. The source of the displaced surface water in the hypothesized arid to semi-arid interval was likely a playa lake ponded near the footwall margin of the rift, or perhaps from fluvial watersheds and channels whose drainage was disrupted by the westward advance of the Orenaug Basalt from source areas located more than 20 km away in, and near, the Hartford basin. Regardless, the occurrence of extensive dune fields and playa lakes within a single depositional basin is common in many modern arid to semi-arid extensional valleys, including those of the U.S. basin and range province.

An alternative hypothesis for the preservation of the dune field that cannot be entirely discounted requires a return to humid climatic conditions that stabilized the eolian sand by raising the regional water table (e.g., Stokes, 1968; Clemmensen and Dam, 1993; Crabaugh and Kocurek, 1993; Kocurek and Havholm, 1993; Benan and Kocurek, 2000) and submerging the dunes beneath shallow lacustrine waters. This hypothesis is appealing, but the lack of fluvial deposits and the apparently slight reworking of the upper layers of eolian sand would require a very rapid rise in lake level. The short-term astronomically forced climate cycles are approximately 21 ky long with the transition from maximum wet to maximum dry conditions taking about 10 ky which we feel would have likely caused greater reworking or destruction of the eolian sand layers. Based on our analysis of the foreset structures, the Pomperaug dunes were in the meter-scale range, although some amalgamated dunes may have reached up to 3–5 m, and therefore the relatively thin dune field may have been particularly susceptible to reworking under a more humid climatic regime. However, the original thickness of the eolian deposits, and the amount of possible erosion are unknown. Furthermore, the occurrence of the lava flow nearly coincident with

the shallow lacustrine conditions seems to us unrealistically fortuitous.

4. Discussion

4.1. Eolian sandstones in related Pangean rift basins

Eolian sandstones occur in Newark Supergroup rift strata in the Fundy and Hartford basins, and the Argana (Morocco) rift basin. In the Hartford basin, LeTourneau (2002) recognized eolian sandstones in the Hettangian Portland Formation at the Portland “brownstone” quarry, Portland, Connecticut, as well as in samples of the Portland Formation from dimension stone quarries at Longmeadow, Massachusetts.

The strata of the Portland brownstone quarry are of both fluvial and eolian origin (Fig. 11). The eolian strata (LeTourneau, 2002) include: sand sheet deposits dominated by inverse-graded wind ripple laminae (pinstripe lamination) (Fig. 11A); small-scale dune forms with pinstripe laminae and grainfall and grainflow toesets (Fig. 11B, D); and unusual “coppice” dunes deposited around clumps of vegetation (Fig. 11C, E, G).

The porosity and permeability of the Portland eolian sandstones are lower than either the Pomperaug or Longmeadow eolian sandstones. Porosity of the Portland brownstone measured about 10% and gas and liquid permeability measured 5 and 7 mD, respectively (LeTourneau and Olsen, unpublished data). The Longmeadow samples have 21% porosity-comparable to the porosity of the Pomperaug samples, and permeabilities of 78 mD (gas) and 73 mD (liquid) (LeTourneau and Olsen, unpublished data).

We identify here for the first time eolian sandstones in outcrop and quarry blocks at the Newgate Prison State Park, Granby, Connecticut (Fig. 12). Due to an unconformity which cuts out the Talcott basalt, an important stratigraphic marker, it is uncertain if the Newgate eolian beds are part of the Rhaetian upper New Haven Formation or Hettangian lower Shuttle Meadow Formation. We believe that the beds are in the Rhaetian part of the upper New Haven Formation and may be lateral equivalents of the thin eolian sand sheets described by Smoot (1991a) (see below).

The Newgate eolian sandstone is formed mainly of sand sheet beds containing pinstripe laminae (Fig. 12, top) and isolated high index ripples. Other eolian features including reactivation surfaces that cross-cut low-angle, inverse-graded, dune foresets (Fig. 12, middle), and grainfall and grainflow toesets (Fig. 12, bottom) are observed at the Newgate site. Interestingly, the New-

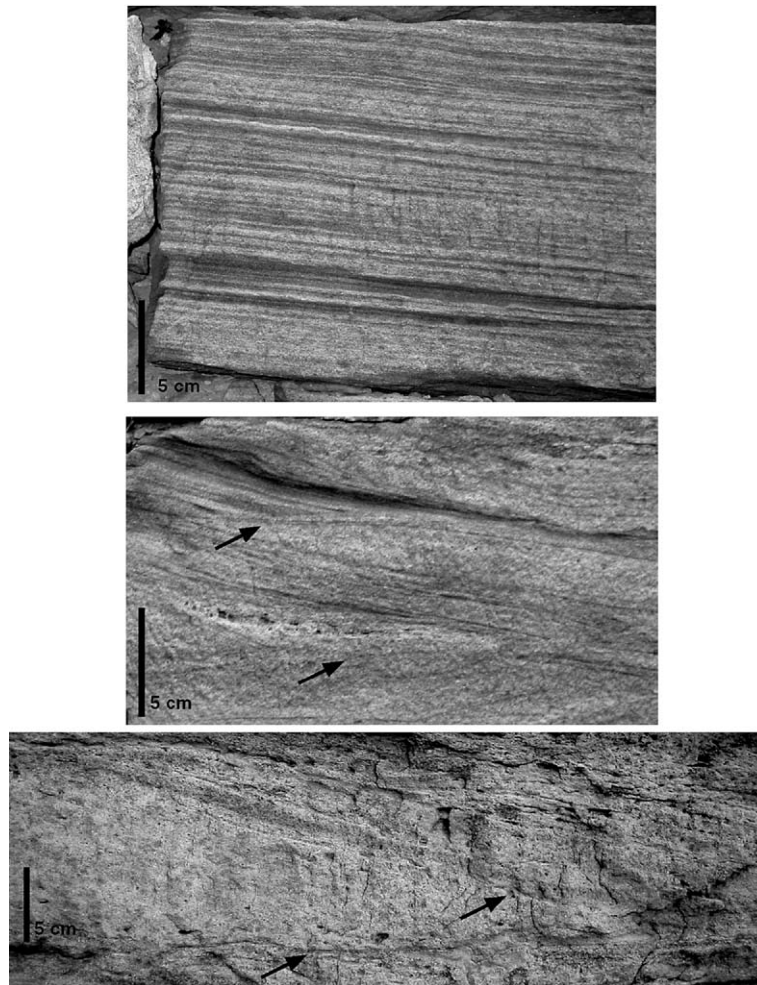


Fig. 12. Eolian sandstone, Newgate Prison State Park, Granby, Connecticut (Late Triassic New Haven Formation, Hartford basin). All photos are quarry blocks from copper mine and adjacent quarry. (top) Inverse-graded wind ripple laminae. (middle) Cross-cutting sets of inverse-graded wind ripple laminae and small dune foresets. Arrows mark reactivation surfaces. (bottom) Foresets of small dune showing grainfall (upper arrow) and grainflow laminae (lower arrow). Lower arrow at bounding surface.

gate sandstones were mined during the American Colonial Period for copper, which occurs as malachite pore fillings, similar to, but in higher concentrations than the malachite pore fillings observed in the Pomperaug eolian sandstone. The porosity of a sample obtained from an outcrop near Newgate (we were not allowed to sample the historic stone walls containing some of the best eolian beds) was about 10% and the permeability was negligible (LeTourneau and Olsen, unpublished data), perhaps as a result of the copper and silicate mineralization. In the Newgate Prison and Pomperaug mineralizations the copper-bearing hydrothermal fluids preferentially flowed through the high porosity eolian sandstones.

Smoot (1991a) described an eolian sand sheet from the upper part of the Late Triassic New Haven Forma-

tion in the Hartford basin, Connecticut (Fig. 13). This deposit, located in road cuts on I-691 in Meriden, Connecticut, is 1–2 m thick and consists mainly of low-angle inclined planar stratification with pinstripe laminae and a small dune about 1 m high. The well-sorted medium to fine sandstone did not contain visible mica, which is abundant and characteristic of the fluvial beds that enclose the eolian sand sheet (Smoot, 1991a).

Hubert and Mertz (1980, 1984) and Nadon and Middleton (1985) described eolian sandstones, the Red Head beds, of the Fundy basin associated with alluvial-fan and fluvial deposits. Hubert and Mertz (1980, 1984) identified diagnostic eolian features including; a hierarchy of bounding surfaces; sedimentary structures including grainflow, grainfall, and wind-ripple pinstripe laminae; large scale cross-strata; bimodal



Fig. 13. Eolian dune deposits, upper New Haven Formation, Meriden, Connecticut. First described by Smoot (1991a,b) this outcrop shows large scale dune foresets with grainfall and grainflow foresets, and inverse-graded wind ripple laminae (pinstripe laminae). Scale bar is 1 m.

grain size distribution; and presence of ventifacts. The Red Head dunes are much larger than the dunes observed in the Pomperaug basin, and the entire eolian sequence there is measured in dekameters compared to 1–3 m for the Pomperaug. Paleocurrent directions obtained from cross-beds indicates sand transport toward the west–southwest by easterly to northeasterly paleowinds in the Fundy basin. Nadon and Middleton (1985) recognized similar eolian features and sand transport directions in the Fundy basin, but also observed features interpreted as wet interdune deposits, including mud drapes and burrowed horizons.

An eolian sandstone (Fig. 14) approximately 20 m thick and at least 50 km in lateral extent occurs in the Tadrart Sandstone Member of the Bigoudine Formation, Late Triassic (Unit t6 of Tixeront, 1973), in the Argana basin, Morocco (see also Hofman et al., 2000; Olsen et al., 2000, Et-Touhami and Olsen, 2003). The Argana eolian sandstone contains high and low angle tabular, wedge-planar, and trough cross strata in well-sorted sandstone and characteristically shows a bimodal grain size distribution between adjacent wind-ripple laminae. Typical eolian features such as high-index ripples oriented perpendicular to the dip of the dune slipface in exhumed straight-crested dunes were also observed. Porosity and permeability of the Tadrart eolian sandstone are low, 7% and <1 mD (LeTourneau and Olsen, unpublished data), respectively, due in large part to secondary mineralization of a high porosity sandstone.

Of the eolian sandstones discussed here, those found in the Fundy and Argana basins are the most extensive and contain large-scale dune forms (Fig. 14). Reconstructions of Late Triassic Pangaea show that the Norian-age eolian beds were deposited when the Fundy and Argana rifts were located at paleolatitudes of approximately 17° and 15°, respectively (Kent and Olsen, 2000a,b; Kent and Tauxe, 2005). The extensive eolian sandstones found in the Fundy and Argana rifts are

likely indicative of arid to semi-arid, regional, if not hemispheric, paleoclimates at sub-tropical paleolatitudes (Olsen et al., 2000). Examination of Pangaeon rifts from southerly paleolatitudes reveals that eolian sandstones become progressively scarce with only three distinct occurrences noted in the Hartford basin, one in the Pomperaug basins, and one in the Newark basin. No eolian occurrences of any age have been noted in the

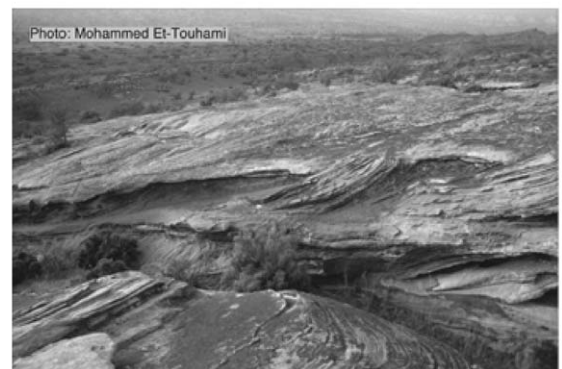
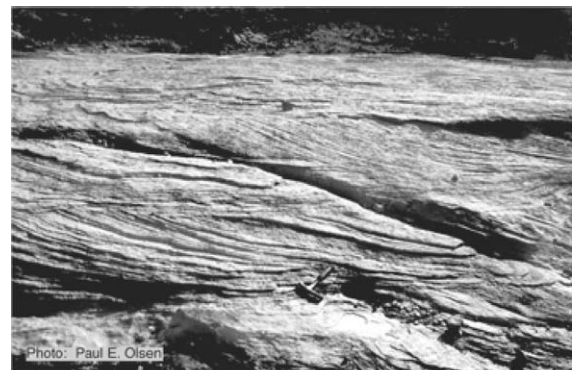


Fig. 14. Eolian dunes of the lower Bigoudine formation, Late Triassic, Argana basin, Morocco. (top) Meter-scale dune foresets enclosed in second-order bounding surfaces. Photo: Paul E. Olsen, Columbia University (bottom). View of the Bigoudine dune field north of Argana, Morocco. Photo: Mohammed Et-Touhami, LGVBS, Université Mohamed Premier, Oujda, Morocco.

Newark rifts at paleolatitudes less than $\sim 15^\circ$ by previous workers (Olsen, 1997; Smoot, 1991a,b; Smoot and Olsen, 1994; LeTourneau, 2003; Kent and Tauxe, 2005).

4.2. Paleoclimate considerations

The Late Triassic and Early Jurassic Pangaeon world apparently represent an important end-member state with a maximum of continental aggregation and a global climate dominated by a strong land–sea contrast (Chandler et al., 1992; Parrish, 1993). In the Late Triassic and Early Jurassic the Pangaeon landmass spanned from about 85°N to 90°S (Ziegler et al., 1982) and was arranged nearly symmetrically about the equator (Chandler et al., 1992). Furthermore, during the Late Triassic and Early Jurassic the polar latitudes of Pangaeon were likely ice-free (Frakes and Francis, 1988) and atmospheric CO_2 may have approached four times present values (Bernier, 1990, 1991). In concert with elevated global temperatures, the presence of a large Pangaeon landmass may have promoted a strongly seasonal “megamonsoon” climate dominated by a persistent summer low pressure system over the vast continental interior (Kutzbach and Gallimore, 1989; Parrish, 1993). Parrish (1993) further suggests that the monsoonal climate would have completely disrupted zonal climate belts in the Late Triassic and Early Jurassic.

The modern moisture balance model (MMBM) of Crowley and North (1991) allows predictions about the depositional environments expected at various latitudes (and paleolatitudes) (Fig. 15). If paleolatitudes of climate-sensitive rocks are known with some certainty, their plotted position on the MMBM should show rough agreement with expected facies. Furthermore, the MMBM suggests a possible range of response to astronomical climate forcing (Fig. 16). Depositional environments in basins located at latitudes near the humid or arid maxima should show little variability because only extreme astronomical forcing could cause the necessary deviation from the mean expected precipitation (Zones 1 and 3, Fig. 16). Sediment deposited at latitudes located near the zero-crossing points of the MMBM should show a high degree of variability because astronomical forcing will cause periodic alternations between “humid” and “arid” modes (Zone 2, Fig. 16). Lastly, the validity of the zonal climate belts predicted by the MMBM are testable over geologic time by comparing data from ancient sedimentary deposits with the range of expected facies.

The Fundy basin is located within the arid zone maximum predicted by the MMBM and indeed it does contain abundant evidence of arid to semi-arid depositional environments, with few excursions into wetter paleoclimates in the Early Jurassic (Hubert and Mertz, 1980, 1984; Nadon and Middleton, 1985; de

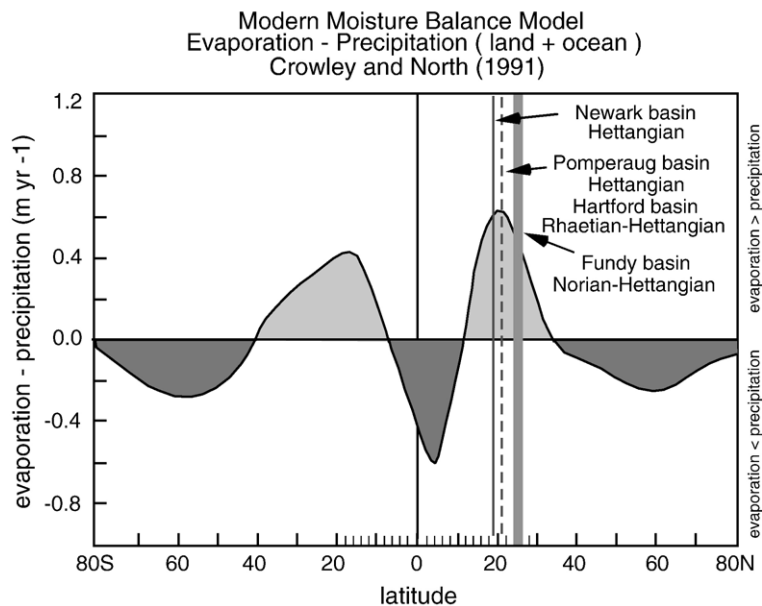


Fig. 15. Modern moisture balance model of Crowley and North (1991) showing latitudinal distribution of climate belts. Location of basins discussed in text shown for reference.

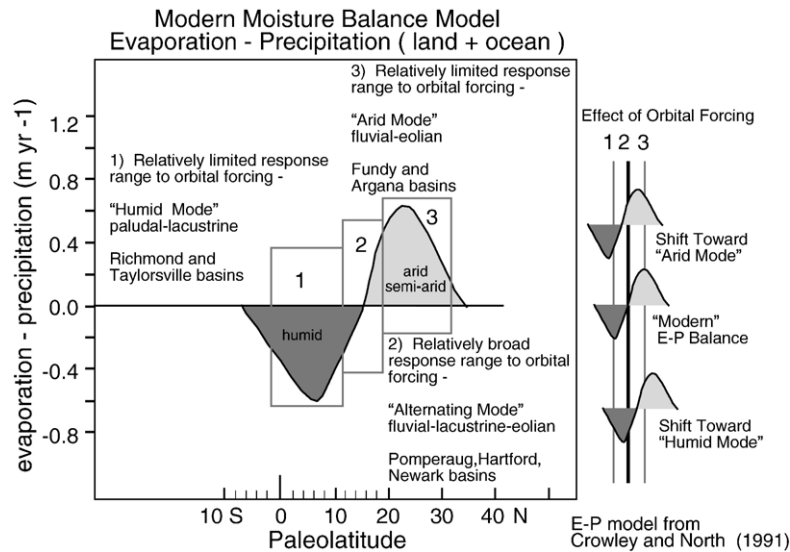


Fig. 16. Our model of sensitivity of basin environments based on position within climate belts. Sediments deposited in basins located near edges of climate belts have greater sensitivity to orbitally forced variability and show alternations of humid and arid facies. Basins located toward central portions of climate belts are less sensitive and tend to contain either predominately arid or predominately humid facies.

Wet and Hubert, 1989; Olsen, 1997; Smoot, 1991a; Tanner, 2003). Most of the Fundy basin stratigraphic section is dominated by eolian and fluvial-reworked eolian sand, while organic-rich, deep-water lacustrine are absent and shallow lake or palustrine beds are scarce (Tanner and Hubert, 1992; Olsen, 1997). Apparently, the Fundy basin was located favorably within the central part of the evaporation-dominated envelope of the MMBM and only rarely did orbitally forced climatic fluctuations cause a shift into precipitation-dominated paleoclimates (Fig. 16). As North America continued to drift north in the Early Jurassic, the Fundy basin drifted away from the arid maxima and closer to the zero-crossing point on the MMBM, allowing a greater range of depositional climates due to astronomical forcing, and indeed the Early Jurassic rocks show evidence of increased precipitation (de Wet and Hubert, 1989; Olsen, 1997; Tanner, 2003). The Argana basin, Morocco, located a little south of the Fundy basin in the Late Triassic, is also dominated by arid and semi-arid facies, but does include a few perennial lacustrine beds (Olsen, 1997; Olsen et al., 2003).

In contrast, the “southern” Newark rifts, including Carnian-age rocks of the Richmond and Taylorsville basins in Virginia (Fig. 1), are dominated by organic-rich lacustrine and palustrine deposits, including coal beds and seams, and fluvial sequences, deposited near the paleoequator. Plotting those basins on the MMBM shows that they were located within a precipitation-

dominated envelope of the model and only rarely could astronomically forced climatic fluctuations cause a shift into evaporation-dominated paleoclimates (Kent and Olsen, 2000a; LeTourneau, 2003; Olsen and Kent, 2000; Olsen et al., 2000). As the Taylorsville basin drifted north away from the paleoequator and toward the northern edge of the humid paleoequatorial zone its rocks show a broader range of climate-sensitive facies and a shift from lacustrine, deltaic, and coal deposits to intercalated and alternating shallow lacustrine and fluvial deposits with well-developed carbonate paleosols.

Basins located at paleolatitudes sensitive to small fluctuations in the E–P balance should show wide paleoenvironmental variations in deposition, ranging from deep lake organic-rich black shale (lacustrine and palustrine), to perennial and ephemeral streams and rivers, to eolian deposits. The Newark, Hartford, and Pomperaug basins do show a wide range of depositional environments but the Pomperaug and Hartford basins are located near the modern arid maximum (Fig. 15). If the MMBM holds in the Late Triassic and Early Jurassic, those basins should contain a record of mainly arid depositional environments. While arid indicators such as caliche paleosols (Hubert, 1978), halite crystal molds (Parnell, 1983), and eolian sandstones (Smoot, 1991a) may be found in certain stratigraphic intervals, organic-rich deep lake shales (Olsen, 1986, 1997) and perennial fluvial deposits (Hubert et al., 1978) are common and occur

with cyclic regularity within the basin section (Olsen, 1984).

Comparison of the paleolatitudinal distribution of eolian sandstones in the Newark rift with the MMBM of Crowley and North (1991) shows that the deposits formed within the central part of the evaporation-dominated climate zone, ranging from about 15°N to 25°N during the Norian–Hettangian. What is surprising, however, is that there are no eolian deposits recognized at lower paleolatitudes within the Newark rifts, closer to the 11°N zero-crossing of Crowley and North's (1991) moisture balance model.

There are, however, sedimentary indicators of arid conditions at lower paleolatitudes. Abundant, well-developed Norian-age carbonate paleosols that formed between 9° and 11°N are found in the Leedstown Formation of the Taylorsville basin, Virginia (LeTourneau, 2003), and Coffey and Textoris (2003) describe Norian carbonate paleosols formed about 3–5°N from the Durham sub-basin of the Deep River basin, North Carolina. There is also evidence of Norian-age evaporite mineral formation at 10–12°N in the Newark basin (Olsen, 1997; Olsen and Kent, 2000; Kent and Tauxe, 2005).

The MMBM of Crowley and North (1991) (Fig. 15) indicates that precipitation exceeds evaporation below 11°N latitude and evaporation exceeds precipitation in the sub-tropical zone from about 11° to 35°N latitude. The Pangaean rift eolian sandstones of the Newark Supergroup are at paleolatitudes within descending air-mass ("trade wind") zones based on modern atmospheric circulation patterns (e.g., Glennie, 1987; Kocurek, 1996), supporting the hypothesis (contra Parish, 1993) that zonal circulation patterns prevailed during the Late Triassic and Early Jurassic on Pangea (Kent and Olsen, 2000b; Kent and Tauxe, 2005). Although zonal paleoclimate patterns may have prevailed, they were likely modified from modern patterns. Furthermore, the paleogeographic patterns of Newark eolian sandstones and their correspondence with the modern negative moisture balance zone argue against the hypothesis that orography strongly controlled climate in the Pangaean breakup rifts (Manspeizer, 1982).

The Pomperaug basin eolian sand beds overlie a well-developed caliche paleosol indicative of arid to semi-arid conditions (Fig. 5). Pedogenic carbonates form optimally in strongly seasonal climates with mean annual precipitation estimated as less than 1000 mm by Blodgett (1988) and less than 760 mm by Royer (1999). Correlation of the eolian unit over a minimum extent of 5 km shows that the Pomperaug basin eolian sandstone is a nearly basin-wide deposit

that formed during an arid to semi-arid interval, rather than a local deposit of wind-blown sand. This hypothesis is supported by the regional correlation of the Pomperaug eolian sandstone with an arid interval in the Hartford (LeTourneau, 2002) and the Newark basins (Olsen and Kent, 1996; Olsen et al., 1996). Thus, the Pomperaug eolian sandstone formed at paleolatitudes where evaporation exceeded precipitation in an arid to semi-arid climatic interval that promoted the development of eolian dunes. The Cass Formation (Fig. 3) also contains organic-rich lacustrine beds with abundant fossil fish, indicating that the climate within the Pomperaug rift alternated between arid to semi-arid and humid intervals similar to periodic paleoclimate patterns observed throughout the Newark Supergroup (e.g., Olsen, 1986; Olsen, 1997). The association of humid depositional facies alternating with arid facies in the Pomperaug, Hartford, and Newark basins suggests that the latitudinal distribution of climate zones defined by the modern moisture balance model of Crowley and North (1991) may, in fact, have differed in the Late Triassic and Early Jurassic.

The wide range of alternating humid to arid depositional environments in the Pomperaug, Hartford and Newark basins suggest that the zonal climate belts delineated by the MMBM were modified in the Late Triassic and Early Jurassic (Fig. 17). Accommodation

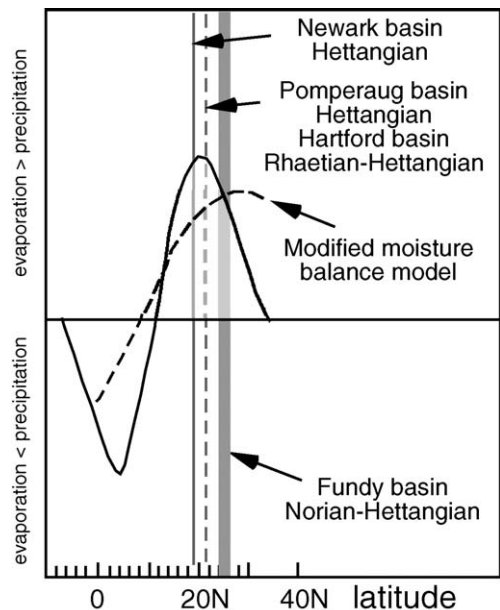


Fig. 17. Possible configuration of early Mesozoic low latitude, northern hemisphere climate belts based on distribution of Pangaean rift eolian sandstones. Note that the transition between zones is attenuated and the arid zone is shifted south in comparison to modern zones.

of both low latitude carbonate paleosols in the Taylorsville and Deep River basins and alternating humid and arid conditions in the Pomperaug, Hartford, and Newark basins (Zone 2, Fig. 16) is accomplished by attenuating the gradient between the equatorial humid and sub-tropical zones and by shifting the sub-tropical arid belt southward (Fig. 17).

The next challenge in assessing early Mesozoic paleoclimates of the Pangaeian rift system is to apply quantitative methods, using known precipitation values for climate sensitive rocks and compare those values with calculated precipitation variability expected from orbital forcing, to further constrain and define the distribution of atmospheric patterns in the supercontinent-dominated Late Triassic and Early Jurassic.

5. Conclusions

The laterally extensive eolian sandstones in the Early Jurassic (Hettangian) Pomperaug and Hartford rift basins are evidence for paleolatitudinal distribution of arid to semi-arid environments. Previously, large scale eolian deposits were recognized in Norian–Hettangian strata in the Fundy basin, Canada, Norian rocks of the Argana basin, Morocco, and a few limited occurrences in Rhaetian–Hettangian rocks of the Newark and Hartford basins. The Pomperaug basin sandstone is one of the most southerly Early Jurassic eolian deposits within the Newark Supergroup rifts, providing a constraint for the distribution of climate-sensitive rocks in the early Mesozoic. In the Pomperaug basin, eolian sedimentation was favored by paleolatitudinal position and deposition during an arid to semi-arid climatic interval. Furthermore, the paleogeographic distribution of eolian sandstone and other arid facies suggest that although the climate zones predicted by the modern moisture balance model of Crowley and North (1991) are recognizable in the early Mesozoic, the zones were likely modified.

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