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Cyclic Eolian Stratification on the Jurassic Navajo Sandstone, Zion National Park: Periodicities and Implications for Paleoclimate

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ABSTRACT

Zion National Park and related areas of southern Utah contain exposures of the largest ancient wind-blown (eolian) dune system known in North America, preserved in the Jurassic Navajo Sandstone. Despite the common lack of absolute age constraints, ancient desert sand seas (ergs) and their erg margins can record valuable paleoclimatic proxies in the sedimentary record. The central erg portion of the Jurassic Navajo Sandstone of southwestern Utah contains nested cycles of eolian grainfall and wind-ripple laminae. These rhythmic alternations preserve random "snapshots" in time ranging from annual cycles to decadal climatic variations, influenced by periodic and quasi-periodic oscillators. Based on the established interpretation of annual cycles, nearly 300 of these high-frequency seasonal/annual cycles in the Navajo Sandstone of Zion National Park were measured in a continuous-thickness series of transverse dune foresets. Harmonic analysis reveals prominent periodicities of approximately 30 and 60 years and several other decadal periodicities. These long bedform cycles are interpreted as climatic oscillations/fluctuations of flow related to decadal periodicities that may be driven by solar variability and/or seasonal precipitation (moisture changes). This study demonstrates the utility of spectral analysis as a quantitative tool for interpreting periodic paleoclimatic oscillators in eolian environments.

INTRODUCTION

Ergs and erg margins are sensitive indicators of climatic changes and preserve potential paleoclimatic proxies within the sedimentologic and stratigraphic record. Large, shifting and migrating dunes deposit foresets at the front of the migrating dune. This foreset structure is called cross-bedding. The purpose of this study is to document the utility of harmonic and image analysis to evaluate periodicities within rhythmic and cyclic eolian cross-bedding of the Jurassic Navajo Sandstone of Zion National Park, southwestern Utah.

Rhythmic and cyclic eolian stratification is recognized as repeated variations within the structure and/or texture of cross-beds within a dune set. Cyclic cross-bedding in the Navajo Sandstone was originally recognized by Stokes (1964). Further study by Hunter and Rubin (1983) concluded that the prominent repetitions represent annual cycles based on regularity and cycle thickness (too thick to be daily cycles) as well as on comparisons to modern rates of dune movement. However, initial analyses presented here indicate the presence of additional bedform cycles (herein interpreted as climatic oscillations/fluctuations of flow) related to longer periodicities (for example, semiannual/seasonal to decadal-scale cycles). Drivers for these longer oscillations may be solar variability and/or seasonal changes.

Although daily cycles and winter-summer (annual) stratification changes are recognized in modern dunes of the Oregon coast and Padres Island, Texas (for example, Hunter and Richmond, 1988; Kocurek, 1996), there are currently no documented modern cyclicities with decadal-periodicities. Despite the fact that modern dune mechanics

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are well understood, it is generally either too difficult or too expensive to create the types of trenches that would be necessary to study long records of modern deposition. Thus, exposures of ancient eolian dunes can provide data that has not been studied in the modern record. Although decadal cycles may be present in modern dunes, eolian workers indicate that they haven't really looked for such cycles (N. Lancaster, verbal communication, 1997; G. Kocurek, verbal communication, 1998). "Reverse uniformitarianism, " the concept of the ancient as the key to the present or future, may prove fruitful for understanding the modern record.

Recognition of these cycles may be useful in paleoclimate modeling and examining parameters (such as paleogeography) that could have accentuated climate shifts. Cycles encoded in the Jurassic eolian rocks may show prominent periodicities of Mesozoic paleoclimates that can later be used to identify more subtle climatic signals in modern or Holocene analogs. Furthermore, identification of the magnitude and frequency of these well-preserved ancient cycles also help refine tools (image- and harmonic-analysis methodologies) to use in interpreting proxy paleoclimate signals.

GEOLOGIC SETTING AND STRATIGRAPHY

The Jurassic Navajo Sandstone and its related equivalents form the largest erg deposit in North America (Peterson and Turner-Peterson, 1989). This spectacular erg deposit is generally flat lying and well exposed in the Colorado Plateau. The Navajo Sandstone is the uppermost formation of the Glen Canyon Group (figure 1) that has been regionally traced over the Colorado Plateau (Pipiringos and O'Sullivan, 1978; Peterson and Pipringos, 1979). The Navajo Sandstone is underlain by the Kayenta Formation of the Glen Canyon Group, and overlain unconformably (J-1 surface) by the San Rafael Group. Previous work on this erg (for example, Blakey and others 1988; Peterson 1988; Verlander 1995; Blakey and others 1996; Kocurek 1999) provides the framework for the detailed examination of cyclic cross-beds presented here. Jurassic paleogeography and paleoclimatology is summarized in Kocurek and Dott (1983), Blakey and others (1988), Chandler and others (1992), Blakey (1994), Parrish and Peterson (1988), and Peterson (1994). In this study, a locality was chosen along State Highway 9, 2.4 kilometers west of the east gate in Zion National Park (figure 1) which provides a thick series of cyclic cross-beds for evaluation.

CYCLIC CROSS-BEDDING

Expression of Cyclic Eolian Stratification

Cyclic cross-beds are distinguished by alternations of eolian stratification types and fine internal structures originally delineated and defined by Hunter (1977, 1985).

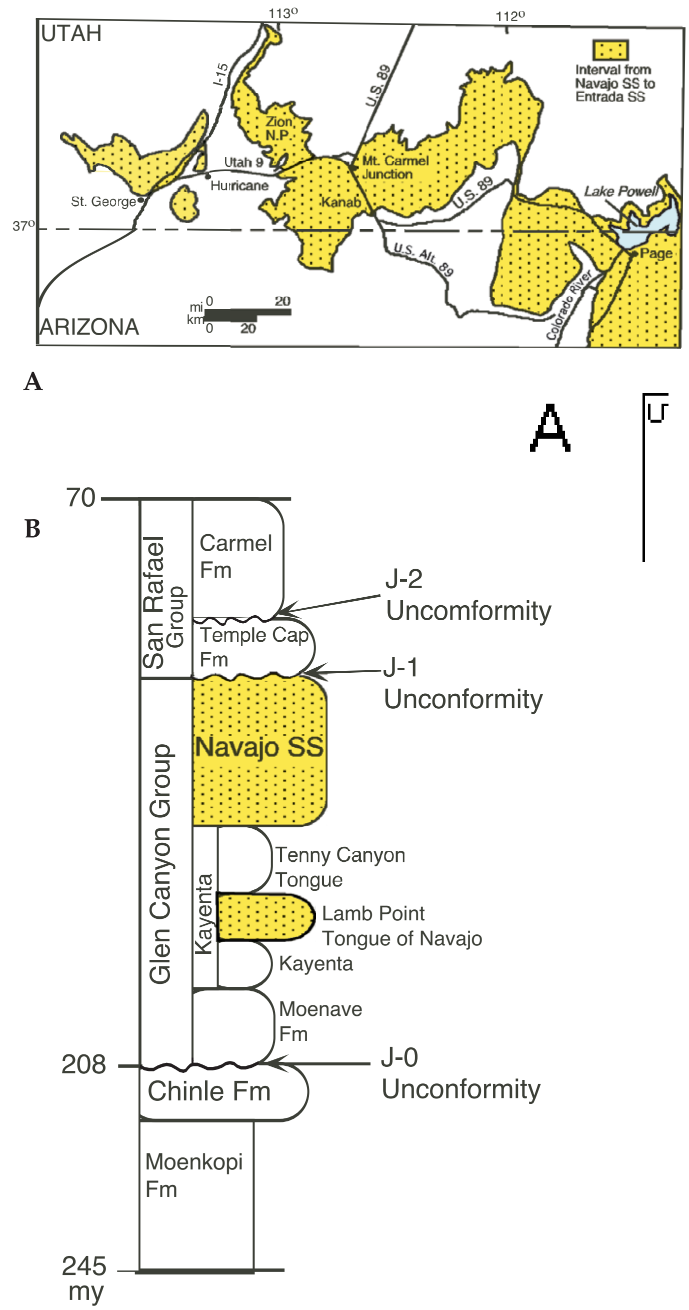


Figure 1. (A) Study area (modified from Rubin and Hunter, 1987) and (B) stratigraphic relationships of Jurassic Navajo Sandstone of the Zion National Park and Kanab areas. J-0 through J-2 indicate major unconformities of Pipiringos and O'Sullivan (1978). Stipple pattern indicates Navajo exposures containing cyclic cross-bedding. Measured locality is along State Highway 9, 2.4 kilometers west of the east gate in Zion National Park.

These lee-face stratification types and structures include: climbing-wind-ripple laminae, grainfall lamination, and grainflow/sandflow or avalanche tongues. In the lee face of dunes, wind ripples occur where tractional processes dominate. Both grainfall (from salting grains passively falling out of suspension) and grainflow (from grains that exceed the angle of repose and avalanche down the slipface) occur where gravitational processes dominate.

The arrangement of internal stratification types within the eolian foresets typically corresponds to how transverse, oblique, or longitudinal the airflow is, with respect to the incident angle of prevailing wind. The shifts in the incident angle appear to be seasonal wind patterns that are most commonly recognized by the variations of the internal stratification.

(1) Grainflow and grainfall strata. Grainflow deposits show a tapering wedge and occur from avalanching produced from the primary, transverse flow patterns of large dunes (for example, summer pattern). Large, modern dune crests typically build up and avalanche about six to ten times/year (G. Kocurek, verbal communication, 1996). Grainfall strata are indistinctly laminated and can also be deposited from primary, transverse flow patterns. These strata (either grainflow, grainfall, or both together) indicate the dominance of gravity-driven processes.

(2) Wind-ripple strata. Traction deposits may represent seasonal (for example,winter) patterns with an oblique incident angle of wind transport. Internally, the wind-ripple laminae are inversely graded (Hunter, 1977; Kocurek,1996). The bottom dune set is reworked to give a wind ripple plinth or apron at the base. This can be a seasonal shift in the wind direction, or could be the secondary (dune-modified) flow, where along-slope wind partly reworks bedforms and modifies the bottom set, producing the fluctuating asymmetry.

The differing stratification types in eolian deposits can be commonly "coded" with respect to color variations as well as weathering/cementation differences. The wind-ripple strata may additionally be better cemented having retained its pervasive initial cements (resulting in positive outcrop relief) in contrast to the more permeable grainflow deposits which were more commonly flushed with diagenetic waters (resulting in negative outcrop relief) (Chandler and others, 1989). These variations in cementation result in good delineation of the cyclic cross-beds in weathered outcrops. The grainflow deposits can be interspersed with grainfall deposits, and are likely to represent the long-term regional wind pattern established by summer winds. Stratification types can also be affected by position on the dune; grainfall is common when the lee face is close to the angle of repose and grainflows might start mid dune and extend to the toe of the dune. Secondary flow on the lee face (particularly developed towards the base) is likely to result in along-slope (or along-strike), traction transport (Kocurek, 1996), perhaps dominant during winter. Counts and analyses of individual events (grainfall vs. wind-ripple strata) within the annual cycles and examination of the primary (transverse) vs. secondary (oblique) wind patterns can provide information about frequency of changing energy flux on the scale of years and decades.

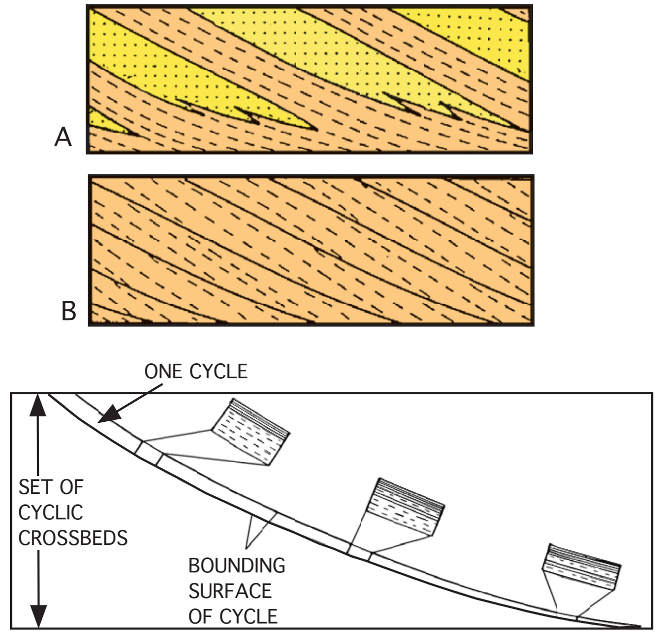
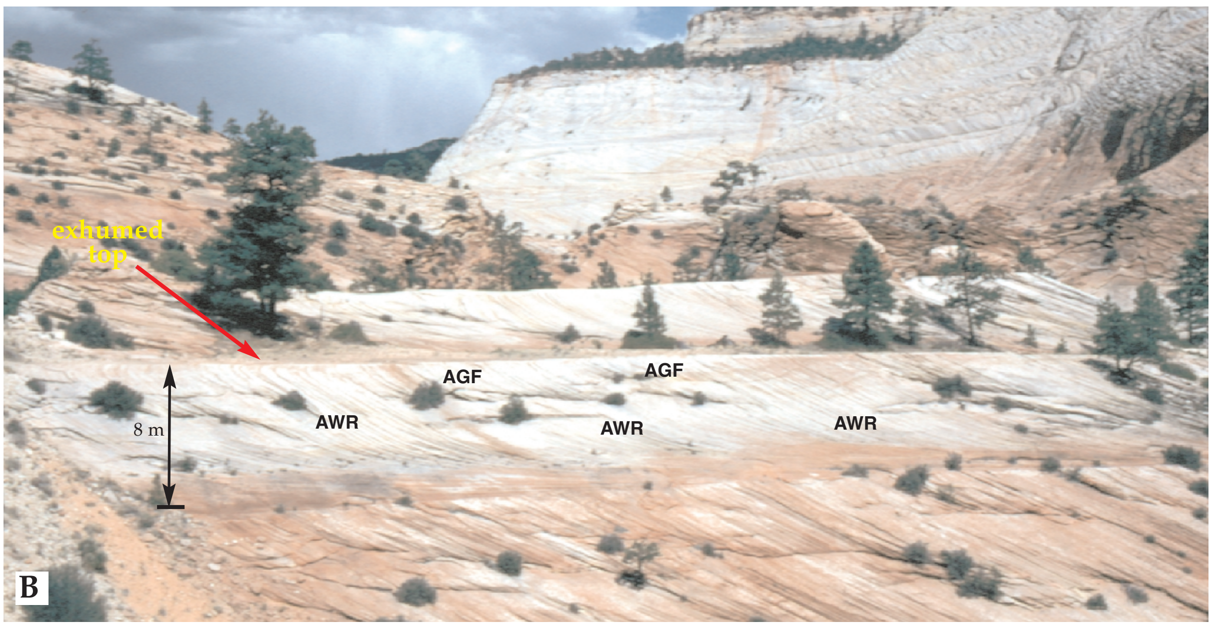


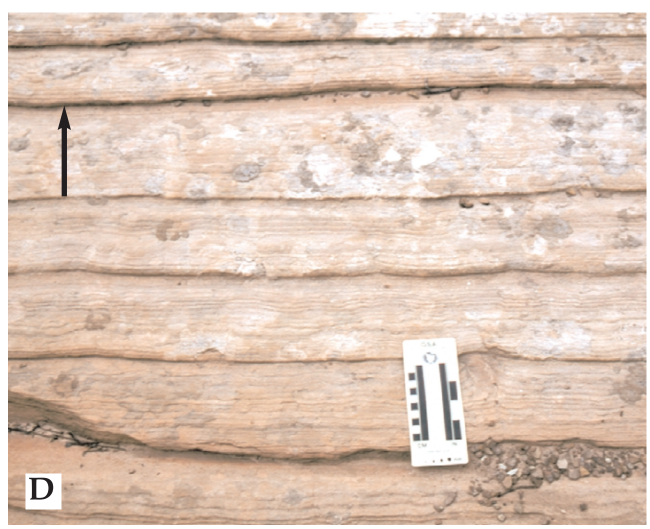
Figure 2. Cyclic cross-bedding from Hunter and Rubin (1983). (A) Concordant cyclic cross-beds (CCC), alternating stratification or grain sizes with parallel bounding surfaces. (B) Compound cross-beds (with foresets separated by erosional surfaces). (C) Amplification of concordant cyclic cross-beds (CCC, figure 2A) and alternating, internal eolian stratification types for the study locality. Dashed lines in bottom portion of inset boxes represent grainfall laminae; solid lines in top portion of inset boxes represent wind-ripple laminae.

The interpretations and relations to potential paleoclimate proxies in this study are based on the assumption that the cyclic grainfall and wind-ripple alternations are annual cycles. This yearly interpretation is based, in part, on the scale of the cycles, which are too thick to be related to diurnal wind-flow and directional changes. The annual cyclicity can be attributed to seasonal wind patterns and moisture changes that can produce various internal fine structures (figures 2 and 3). We feel this is a reasonable hypothesis from previous work of Hunter and Rubin (1983) in their examination of Navajo Sandstone cross-bedding, including a portion of this same study area. The concordant nature of the cyclic cross-beds argues for fluctuating flow, dictated by climate changes that could in turn affect migration speed and asymmetry, dune position, and/or shifting wind patterns.

Hunter and Rubin (1983) define two end members of cyclic cross-bedding: "concordant cyclic cross-bedding" (CCC) where lamination within cycles are parallel to the bounding surfaces of the cycle, or "compound cross-bedding" where the cross-beds composing a set are separated by surfaces of erosion and are internally cross-bedded (figure 2). The origins of the cyclic cross-bedding may be due to either superimposed bedforms or fluctuating-flow conditions, although there is not a one-to-one correlation be-

Figure 3. Measured annual cycles in the Jurassic Navajo Sandstone eolian stratification (figure 4A) in Zion National Park (1.5 miles or 2.4 kilometers west of east entrance station, Highway 9).
(A) View (looking east) of cyclic cross-bedding in canyon walls west of Checkboard Mesa. Specific area of study (B) is shown in the lower left of this photo.
(B) Cross sectional view of migrating dune set (bracketed). Some decadal cyclicity is indicated by packages of the thinner annual wind-ripple (AWR) dominated cycles towards the toes, alternating with thicker annual grainfall and grainflow (AGF) cycles. Surface of exhumed top is shown in (C).
(C) Exhumed top of the same migrating dune form in (B) showing repetitive annual cycles. Wind-ripple portions of the annual cycle marked at the tips of the arrow heads (center part of picture), alternate with thicker grainfall portions.
(D) Close view of annual cycles on exhumed top. Scale card = 16.5 centimeters tall, with cyclic packages ~ 10-15 centimeters thick (also shown by arrow length at left). Arrow indicates direction of dune migration.





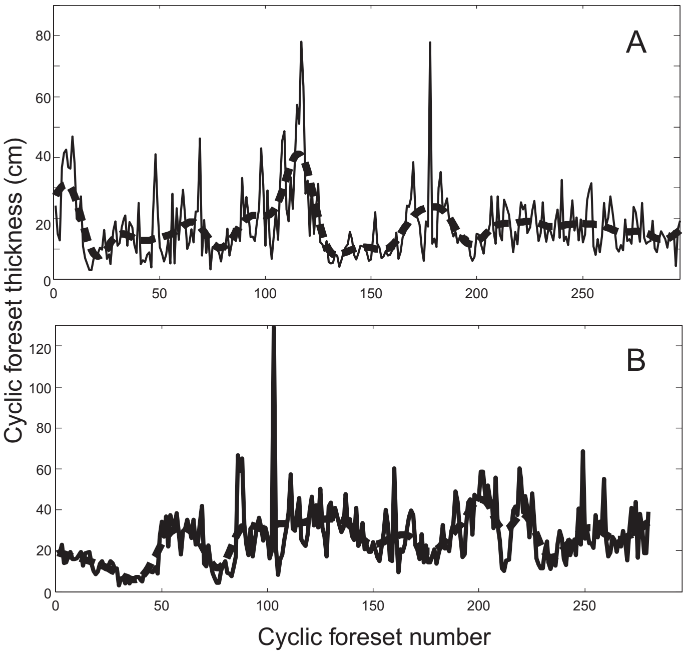


Figure 4. (A) Annual foreset-thickness data from outcrop measurements of exhumed top on concordant cycle cross-beds in the Navajo Sandstone. (B) Foreset thickness from a similar data set near locality of figure 3, obtained from digitizing graphic dune advance data of Hunter and Rubin (1983, p. 439).

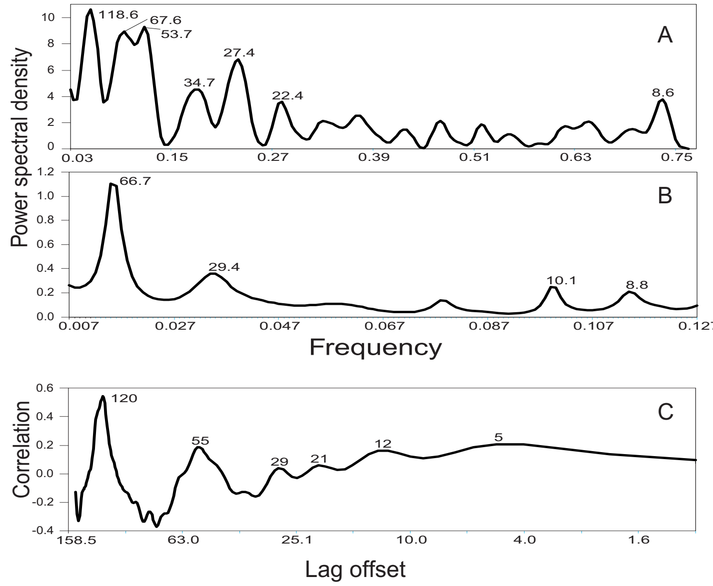


Figure 5. Comparative analyses of foreset-thickness data from both Navajo outcrop data sets as depicted in figure 4. Time-series analyses from both outcrops have been combined (stacked) in order to accentuate similarities of encoded periodicities.
(A) FFT (fast Fourier transform) power spectral density (PSD) exhibiting periodicities of 118.6, 67.6, 53.7, and 27.4 foresets.
(B) MEM (maximum entropy method) spectrum exhibiting well-developed periodicities of 66.7 and 29.4 foresets.
(C) Cross-correlation of foreset-thickness from data sets of figure 4. The strongest correlations, which occur at 120, 55, and 29 foresets are generally similar to both the FFT and MEM spectra.

tween the type of cyclic cross-bedding and the origin. Although both types of cyclic cross-bedding occur in the Navajo Sandstone, we focus on the best example of concordant cyclic cross-bedding formed by fluctuating flow (figure 2C). This type yields the best potential for climatic information because cyclicity is likely to be allocyclic (controlled by change in the total energy or material input to the system). In other words, there does not seem to be a change in dune shape, thus the differences in stratification are likely a function of climate parameters such as available sediment, and/or wind variations. In contrast, cyclic cross-bedding developed from superimposed bedforms (for example, Rubin, 1987) can be autocyclic (independent of energy or material input to the system) and thus may not yield useful proxy climate information.

Data Collection

For this analysis we measured continuous series of cyclic cross-beds within the Navajo Sandstone where an exhumed dune top and a side transverse section contain well-developed concordant cyclic cross-beds (CCC). Field relationships of stratification types, bounding surfaces, and interpreted airflow dynamics (see summary in Kocurek, 1996) are used in conjunction with the data gathered by image analysis of outcrops. This locality on the eastern boundary of Zion National Park (figures 1 and 3) was initially described by Hunter and Rubin (1983), and is conducive to study with the preferential weathering that distinguish grainfall and wind-ripple zones. The cycles here are parallel, relatively thin, concordant cyclic cross-beds in a long series. We could physically walk across the top of an exhumed set which showed no major reactivations nor shifts in the bedform geometry. From the strike of the cross-beds and bounding surfaces, we could determine that the cyclicity of the bedding was produced by cyclic fluctuating flows (cross-beds and bounding surfaces with the same strike), and not the result of superimposed bedforms where the cross-beds and bounding surfaces may have different strikes (Rubin 1987). Additionally, the long series showed that the cyclic eolian stratification appears to occur on a variety of scales; the annual cycles and then longer cyclicities composed of the annual cycles. These conditions enabled measurement of the thicknesses of the CCC.

The strike and dip of the foreset (295°, 24 to 26° south) indicates a south-southwesterly paleoflow of 200 to 210°. A continuous series consisting of 297 CCC (figure 3B) was measured and did not exhibit significant reactivations. The exhumed top allowed us to see our position along the straight 65-meter strike length of the dune foreset (with no visible major lateral migration of the dune). The geometry suggests this measured example is a transverse dune. Following the interpretation that each CCC represents the yearly migration of a dune, the series represents a large, relatively straight-crested dune that marched forward for some 297 annual seasonal (summer-winter) cycles (figures 4 and 5A). Thus, this series of measurements provides paleoclimatic proxy for a window of nearly 300 years during the early Mesozoic (late Triassic to early Jurassic).

Another set of similar data was obtained from Hunter and Rubin (1983). This second data set consists of a series of 281 sequential cyclic foresets (figure 4B), also measured in Zion National Park, but from a longitudinal section of a different dune set. This foreset-thickness series was reconstructed from the original data by digitizing the graphic depiction presented by Hunter and Rubin (1983, p. 439). Comparative harmonic analyses of these two sets of data (figure 4) are presented below and the extracted periodicities are compared to known, climatically significant oscillators.

Periodicities Within Cyclic Foresets

Several techniques were used to test for the presence of periods within the Navajo foreset-thickness series. The fast Fourier transform (FFT) algorithm of Horne and Baliunas (1986) was applied to both data sets. The resulting spectra for both data sets were subsequently averaged. This “stacking,” a standard geophysical technique, serves to reduce the more random components while accentuating any similar periodicities occurring in both data sets. The resultant spectrum (figure 5A) has a well-developed periodicity of 118.6 foresets as well as broad spectral peak suggesting a period ranging from about 68 to 54 foresets/cycle. Another significant period occurs at 27.4 foresets/cycle.

Maximum-entropy method (MEM) of spectral estimation was also applied to both data sets; this was based upon algorithms of Press and others (1988). The MEM approach presents a more averaged, less finely split spectrum. Similar to the FFT techniques described above, results for each set of data were “stacked” in order to produce a composite spectral estimate (figure 5B). This spectrum has peaks at 66.7 and 29.4 foresets/cycle. Both the MEM and FFT spectra indicate well-developed periodicities in the 50 to 60 and 30 foreset/cycle. The similarity of periodicities extracted using these disparate techniques and using data measured by different workers strongly suggests that some type of allogenic oscillator was operative during dune deposition. More data sets, however, are needed to verify the statistical significance of these periodicities.

As an additional test, the two data sets were cross-correlated using the algorithm described by Davis (1973). This technique (figure 5C) corroborates the long-term period of about 120 foresets/cycle also documented within the FFT spectrum. A somewhat weaker correlation occurs at a lag offset of 55 foresets; this apparently correlates to the 50-60 foreset cycles that are evident in both the FFT and MEM spectra. Higher frequency periods are not strongly expressed, but there is a weak correlation at an offset of 29 and this probably corresponds to the 27-30 foresets cycles evident in the FFT and MEM spectra.

DISCUSSION

How can we be certain that cycles are allogenic and therefore climatically controlled? The continuous series of concordant cyclic cross-beds without any major lateral shifting of the dune suggests an allogenic origin. In a tectonically stable, non-marine regime of the Jurassic Navajo system, the overriding allogenic control on deposition would be climate. Although dunes are inherently complex, even if there were a systematic autogenic change in the migration of the dune every 30 or 60 years, it would likely be climatically induced (changing wind patterns to affect dune migration). If the cyclicity were a simple mechanical function of the way dunes form, perhaps building/migrating up to a point and then starting over, the cyclicity should be much more prevalent in dunes of all ages and detectable particularly in the modern record. The lack of the cyclicity in most dune deposits (either modern or ancient) seems to argue that well-preserved cyclicity must be caused by factors other than just bedform migration. The presence of strong cyclicity suggests climatic control, perhaps preserved only where there is strong seasonality and an abundant sand supply to record the climatic variability such as the Navajo erg. However, additional data sets are required before statistically significant conclusions can be made regarding the utility of such paleoclimatic proxies.

In comparing the decadal periodicities of cyclic cross-beds to known established decadal-scale climatic oscillators, there are a number of periodicities related to solar activity. The best documented sunspot cycles are at 11 years and 22 years (double sunspot, termed the Hale Cycle). These cycles (for example, Eddy, 1980) are supported by oxygen isotope ratios (δ18) from tree rings (Libby, 1983) and in several long-term fluvial hydrographs (Currie, 1994). There are no well-defined Navajo foreset periods in the range of the simple 10- to 11-year sunspot cycle, although there are weak, 8, 10, and 12-foreset periods. These weakly developed periodicities may relate to cycles of sunspot activity, which over the past several hundred years has been manifested as a quasi-periodic oscillator with a considerable range of variance.

In general, decadal-scale cycles are expressed within regional or local settings, but do not commonly seem to be hemispheric or global in scale (Mörner, 1984). Thus, such cycles are considerably different in geographic range than Milankovitch-scale orbital parameters. However, these decadal-scale cycles would contain important climatic information relevant to General Circulation Model (GCM)-scale modeling. Examples of decadal-scale climate change include droughts in the Sahel with a periodicity of approximately 30 years (Charney, 1975; Charney and others, 1977). Other modern studies of Kenya (Phillipson, 1975) suggest 5, 10, 40, and 50 year drought cycles, with the 50-year drought cycle being the most extreme. If these types of climate droughts occurred in the Jurassic, the response might be reflected in the cyclic eolian stratification by thicker grainfall and/or grainflow strata, and corresponding change in wind-ripple laminae thicknesses.

Although decadal-scale solar variability (Siscoe, 1980) and other longer-term periods have been discussed in the literature, they are controversial and typically rely upon the relatively subjective, historical records of sunspot or auroral activity. Many of the various solar periods are actually quasi-cyclic trends and might be developed only within parts of the longer-term records.

The various techniques of periodicity analyses all yielded cycles in the range of approximately 30 foresets/cycle, with values of 27.4, 29.4, and 29 for the FFT, MEM, and cross-correlation analyses, respectively. Thus, this appears to be one of the most consistently developed periodicities within the foreset series. The relationship of an approximately 30-year period to seasonal (for example, drought or precipitation) cycles might be significant in the understanding of fine-scale Jurassic climatic cyclicity.

A series of periodicities ranging from about 55 up through 67 were extracted in the FFT, MEM, and cross-correlational analyses. Although additional data is required in order to test the significance of these preliminary results, the analyses strongly suggest that periods of this magnitude were operative during the deposition of the Navajo dunes. Analysis of a long, evaporitic varve series from the Upper Jurassic Todilto Formation of New Mexico indicated a number of periods, including a 60-year cycle developed within parts of the sequence (Anderson and Kirkland, 1960). The development of these similar periodicities in a greatly different type of depositional system strongly suggests a well-developed, pervasive periodic oscillator that was affecting early Mesozoic climate in the Western Interior of the U.S.

PALEOCLIMATE IMPLICATIONS

In determining time constraints for interpreting paleoclimate, it is recognized that absolute ages are difficult to obtain from the non-marine rocks described herein. Although there is a lack of chronometric time control for individual bounding sets, there is good control of annual cycles. The rock record still provides random "snapshots" in time to tell us about decadal climatic variations. In principle, sequence stratigraphy and boundaries tied to eustasy could give additional time control, although the Jurassic Page Sandstone is one of the few erg units with that level of detailed stratigraphic analysis (for example, Blakey and others, 1996). The use of harmonic analyses can allow us to test different time periodicities to see conceptually whether or not the longer scales are coincident with observed stratification, and expected scales from interpretations and comparisons of modern eolian annual cycles.

During the deposition of the Early Jurassic eolian sandstones, the paleolatitude of the Navajo study example was close to 20° N, within the northeast trade winds belt (Parrish and Petersen, 1988; Chandler and others, 1992; Peterson, 1994) (figure 6). Resultant wind predictions and measured paleocurrent patterns show a shift from the Triassic to more northerly winds. This appears to correspond to predicted subtropical circulation as well as monsoonal circulation, most pronounced in eastern portions of Pangea (Parrish and Peterson, 1988; Kutzbach and Gallimore, 1989; Parrish, 1993). General circulation models (GCM) simulate warm surface-air temperatures and extreme continental aridity in the low and middle latitudes of western Pangea, as well as deep, low-pressure cells in summer alternating seasonally with winter high-pressure cells (Chandler and others, 1992). Initial results from this study suggest that this locality experienced decadal contrasts of wetter and drier periods during the Early Jurassic, possibly influenced by the one large ocean at this time, Panthalassa. This paleogeography could have had strong seasonal effects on precipitation, thus reflected in cyclic changes in eolian stratification. Outcrops of the Navajo set (figure 3B) show periodicities within groups of annual cycles (in other words, a group of thicker grainfall-dominated annual cycles, followed by a group of thinner wind-ripple-dominated annual cycles). These relationships suggest corroboration of seasonality interpretations for the Jurassic. Similarly, other workers (for example, Bell, 1986; Richmond and Morris, 1998) suggest potential Upper Jurassic Morrison Formation flood and drought cycles that affected shallow lakes and vertebrate populations in the Western Interior.

There are noted Jurassic trends of summer winds which were largely due south, and winter winds largely due west (from northeast winds). Dune crests are typically east-west with superimposed bedforms coming from approximately the northeast quadrant. More detailed paleoclimatic reconstructions for the Jurassic forthcoming by other workers may eventually allow distinction of monsoonal circulation (cyclicity) vs. subtropical flow patterns. Conversely, if future studies can elucidate more of the relationships between climate and dune cyclicity, the proxy information could be an important component for evaluating wind direction (for different seasons) and perhaps even relative wind strength/velocity. This in turn could serve as input for GCM models (for specific time periods, over certain areal extents).

Why does cyclic cross-bedding occur within the Navajo Sandstone? We have seen localized cyclic cross-bedding in a number of Permian through Jurassic erg deposits on the Colorado Plateau. However, cyclic cross-bedding appears to be most prominent within the Navajo Sandstone. This could be the result of several factors.

(1) The Navajo Sandstone may have had all the right conditions for a highly efficient system with a constant sand supply, large dune forms, extreme aridity, consistent wind patterns, perhaps the right continental configuration, and correspondingly the effect of a large ocean.

(2) With the conditions previously stated in (1) above,

the Navajo Sandstone may have thus been sensitive to climate oscillators.

(3) Given the nature of the Navajo erg, there was good preservation potential to capture these snapshots of time.

POTENTIAL FOR FUTURE WORK

This study focussed primarily on one Jurassic Navajo example that is well exposed and contains a long record. Future work can take a number of different approaches to refine the interpretations of cyclic stratification, including a comparison of the exhumed dune top counts (figure 3C) of this Zion locality with an independent evaluation of the 2-D side view cross sectional cross-bedding at the same locality (figure 3B). In the field, it is generally rare to find an exhumed top, thus if the side two-dimensional (2-D) cross-sectional data (that was cross checked with the exhumed top data) could be reliably correlated, then it might be possible to analyze and interpret counts where only 2-D cross-sectional data is available. Following this comparison, it would also prove useful if mathematical relationships and projections can be determined for relatively short 2-D sections where the number of annual cycles may be only half or less as long as the Zion example of this paper.

More data sets of different types, sizes, and forms of cyclic cross-bedding could help distinguish new and/or recurring periodicities, using both modern and ancient examples. A variety of 2-D cross sections of eolian cross-bedding exist within more exposures of the Navajo Sandstone (figure 7) and the Permian DeChelly Sandstone (figure 8). Some of these would require more detailed examination in order to determine the bedform geometry and whether these are annual cycles also, or a larger, longer periodicity. A comparison of different-aged periodicities (for example, Permian vs. Jurassic) might be able to distinguish paleoclimate proxies, and perhaps ultimate controls of dune sizes and wind transport capacity, sand supply, and sediment availability.

Continued studies of air flow, as well as dune and bedform mechanics (for example, Werner and Kocurek, 1997, 1999) may also help further elucidate on the importance of

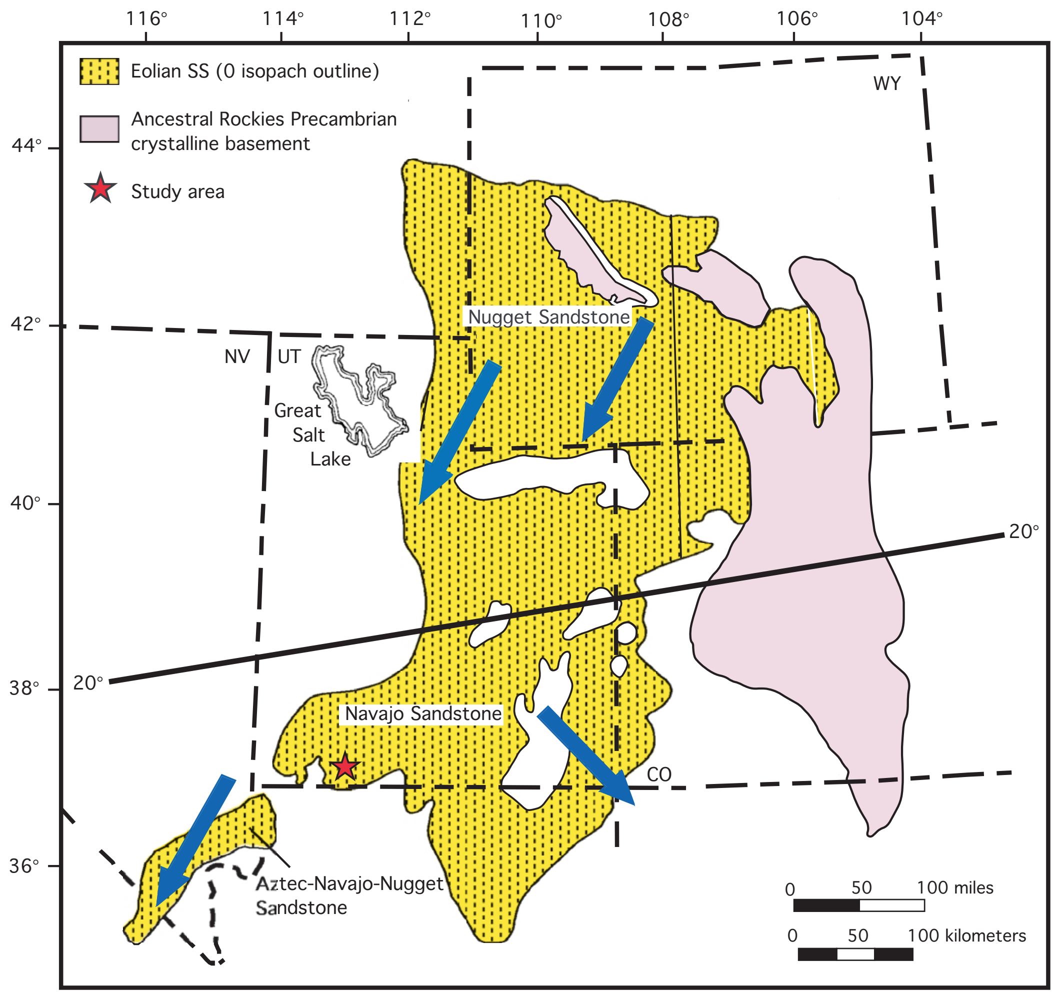


Figure 6. Paleolatitude and predicted wind patterns (large arrows) from Early Jurassic eolian sandstones, after Peterson (1988) and Parrish and Peterson (1988).

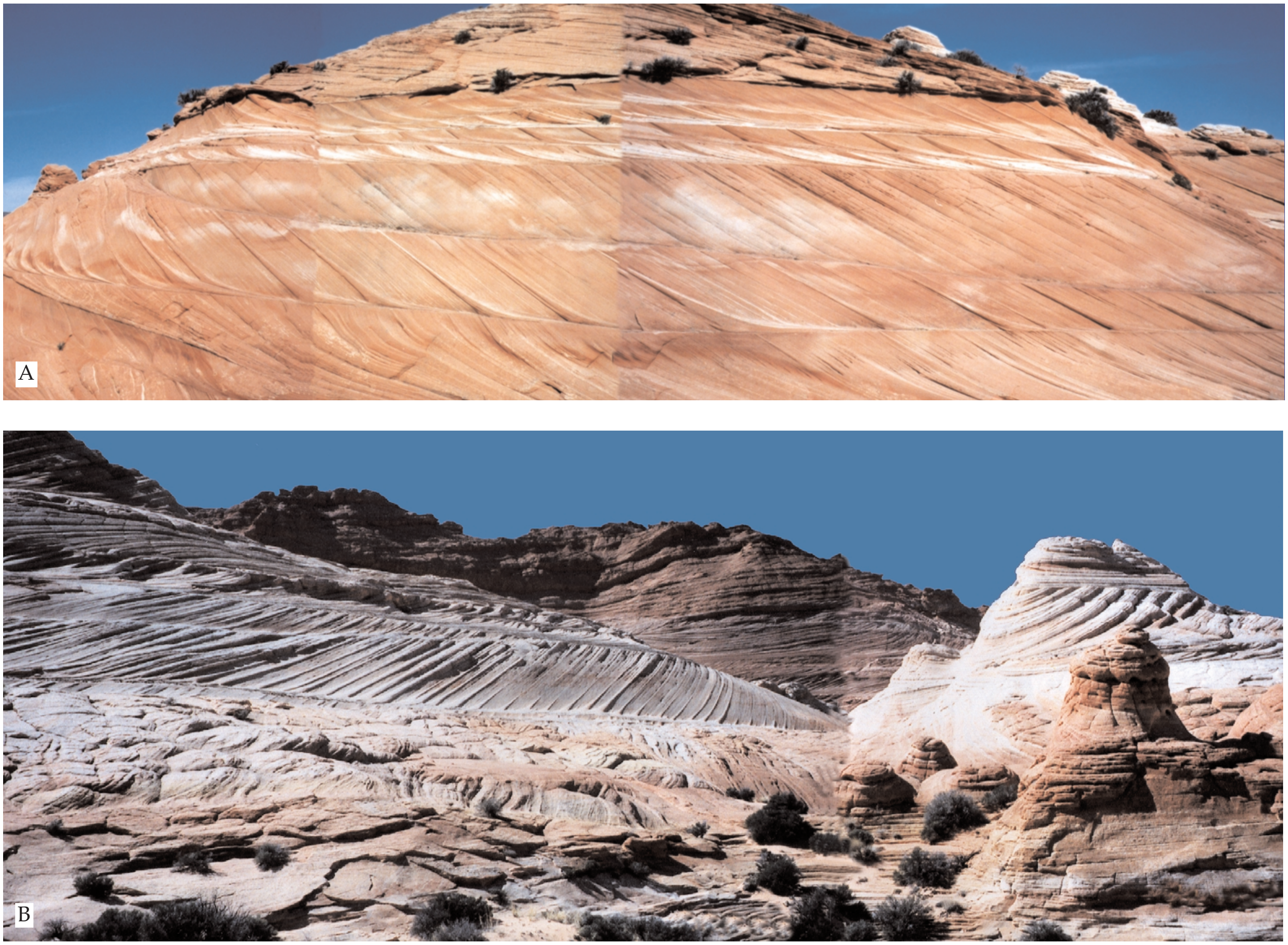


Figure 7. Spectacular sections of thick cyclic cross-bedding in the Jurassic Navajo Sandstone of the Coyote Buttes area, Paria Wilderness, Utah-Arizona border, east of Kanab, Utah. All cross-bedding is dipping towards the southwest. The thickest parts of the cycles represent the grainflow and grainfall portions, separated by the thinner, better-cemented basal plinths of wind-ripple laminae. (A) In the dead-center portion of this Navajo Sandstone panel, an indivdual cross-bed set is approximately 4 meters thick. (B) The central cyclic set of this photo panel is estimated at 10 meters thick. Location in GPS coordinates: 36° 59' 42 N, 112° 0' 22 W.

Figure 8. Cyclic cross-bedding in the Permian DeChelly Sandstone near Oljeto, Utah (far southeast corner of Utah). Thick alternating grainflow deposits are separated from thin, better-cemented wind-ripple laminae (wind-ripple laminae shown at arrows). Foresets ~ 2 meters high. The stacked sets at the right show truncations and reactivations, that warrant further study to interpret flow dynamics.

autocyclic vs. allocyclic effects on cyclic cross-bedding. As more is known about the bedform mechanics, these may help explain the variability in size, and thicknesses of cyclic cross-bedding.

Collaborative work with paleoclimate modelers who can perform detailed comparisons of GCM wind and rainfall results will help refine the relationships of eolian cyclicity with different geologic ages and predicted climate regimes. This type of data can have strong predictive capabilities in both ancient and modern dune settings. As the earth sciences are looking towards the integrative field of global climate change, extraction of numerical values from the ancient stratigraphic record will be important in interpreting Quaternary paleoclimates and in evaluating predictive climatic models.

SUMMARY

Eolian dune seas are particularly sensitive indicators of climatic change and provide good proxy sedimentologic and stratigraphic evidence of paleoclimate. This study focuses on a section of Jurassic Navajo Sandstone in the eastern portion of Zion National Park where there is excellent three-dimensional exposure of cyclic cross-bedding in the dune deposits. Image- and harmonic-analysis are useful methodologies to distinguish and numerically evaluate cyclicity within eolian cross-stratification. These methods show distinction of individual small-scale and stacked larger scale periodicities (particularly those at 30 and 60 years in this example) reflecting annual to seasonal to decadal and longer oscillators that are interpreted to be signals of solar variability and/or seasonality. It is rare to be able to find much control on time in non-marine deposits, however these rhythmic "snapshots" in time can provide important paleoclimate information to help us unlock secrets of the past, and may also provide new keys to search for in the modern record.

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REFERENCES

Anderson, R.Y., and Kirkland, D.W., 1960, Origin, varves, and cycles of Jurassic Todilto Formation, New Mexico: American Association of Petroleum Geologists Bulletin, v. 44, p. 37-52.

Bell, T.E., 1986, Deposition and diagenesis of the Brushy Basin Member and upper part of the Westwater Canyon Member of the Morrison Formation, San Juan Basin, New Mexico, *in* Turner-Peterson, C.E., Santos E.S., and Fishman, N.S., editors, A basin analysis case study; the Morrison Formation, Grants uranium region, New Mexico: American Association of Petroleum Geologists Studies in Geology 22, p. 77-91.

Blakey, R.C., 1994, Paleogeographic and tectonic controls on some Lower and Middle Jurassic erg deposits, *in* Caputo, M.V., Peterson, J. A., and Franczyk, K.J., editors, Mesozoic systems of the Rocky Mountain region, USA, Colorado Plateau: Denver, Colorado, Rocky Mountain Society for Sedimentary Geology, p. 273-298.

Blakey, R.C., Peterson, F., and Kocurek, G., 1988, Synthesis of late Paleozoic and Mesozoic eolian deposits of the western interior of the United States: Sedimentary Geology, v. 56, p. 3-125.

Blakey, R.C., Havholm, K.G., and Jones, L.S., 1996, Stratigraphic analysis of eolian interactions with marine and fluvial deposits, Middle Jurassic Page Sandstone and Carmel Formation, Colorado Plateau, U.S.A.: Journal of Sedimentary Research, v. 66, p. 324-342.

Chan, M.A., and Archer, A.W., 1999, Spectral analysis of eolian foreset periodicities -- implications for Jurassic decadal-scale paleoclimatic oscillators: Palaeoclimates, v. 3, no. 4, p. 239-255.

Chandler M., Kocurek G., Goggin D.J., and Lake, L.W., 1989, Effects of stratigraphic heterogeneity on permeability in eolian sandstone sequence, Page Sandstone, northern Arizona: American Association of Petroleum Geologists Bulletin, v. 7, p. 658-668.

Chandler, M., Rind, D., and Ruedy, R., 1992, Pangaean climate during the Early Jurassic- GCM simulations and the sedimentary record of paleoclimate: Geological Society of America Bulletin, v. 104, p. 543-559.

Charney, J.G., 1975, Dynamics of deserts and drought in the Sahel: Quarterly Journal of the Royal Meteorlogical Society, v. 101, p. 193-202.

Charney, J.G., Quirk, W.J., Chow, S.H., and Kornfield, J., 1977, A comparative study of the effects of albedo change on drought in semi-arid regions: Journal of Atmospheric Science, v. 34, p. 1366-1385.

Currie, R.G., 1994, Variance contribution of luni-solar and solar cycle signals in the St. Lawrence and Nile River records: International Journal of Climatology , v. 14, p. 843-852.

Davis, J.C., 1973, Statistics and data analysis in geology: New York, John Wiley, p. 245-246.

Eddy, J.A., 1980, The historical record of solar activity, *in* Pepin, R.O., Eddy, J.A., and Merrill, R.B., editors, The ancient sun -- fossil record in the Earth, moon, and meteorites: New York, Permagon Press, p. 119-134.

Horne, J.H., and Baliunas, S.L., 1986, A prescription for period analysis of unevenly sampled time series: Astrophysical Journal, v. 302, p. 757-763.

Hunter, R.E., 1977, Terminology of cross-stratified sedimentary layers and climbing-ripple structures: Journal of Sedimentary Petrology, v. 47, p. 697-706.

Hunter, R.E., 1985, Subaqueous sand-flow cross-strata:

Journal of Sedimentary Petrology, v. 55, p. 886-894.

Hunter, R.E., and Richmond, B.M., 1988, Daily cycles in coastal dunes: Sedimentary Geology, v. 55, p. 43-67.

Hunter, R.E., and Rubin, D.M., 1983, Interpreting cyclic cross bedding, with an example from the Navajo Sandstone, *in* Brookfield, M.E., and Ahlbrandt, T.S., editors, Eolian sediments and processes: International Association of Sedimentologists Developments in Sedimentology, v. 38, New York, Elsevier, p. 429-454.

Kocurek, G., 1996, Desert aeolian systems, Chapter 5, *in* Reading, H.G., editor, Sedimentary environments-processes, facies and stratigraphy (3rd edition): Oxford, England, Blackwell Science, p. 125-153.

—1999, The aeolian rock record, yes, Virginia, it exists, but it really is rather special to create one, *in* Goudie, A.S., Livingstone, I., and Stokes, S., editors, Aeolian environments, sediments and landforms: New York, John Wiley & Sons, Ltd., p. 239-259.

Kocurek, G., and Dott, R.H., Jr., 1983, Jurassic paleogeography and paleoclimate of the central and southern Rocky Mountain region, *in* Reynolds, M.W., and Dolly, E.D., editors, Mesozoic paleogeography of the west-central U.S: Denver, Colorado, Society of Economic Paleontologists and Mineralogists Rocky Mountain Section, Rocky Mountain Paleogeography Symposium, p. 101-116.

Kutzbach, J.E., and Gallimore, R.G., 1989, Pangean climates- megamonsoons of the megacontinent: Journal of Geophysical Research, v. 94, p. 3341-3357.

Libby, L.M., 1983, Past climates- tree thermometers, commodities, and people: Austin, Texas, University of Texas Press, 143 p.

Mörner, N.A., 1984, Climatic changes on a yearly to millennial basis, an introduction, *in* Mörner, N.A., and Karlén, W., editors, Climatic changes on a yearly to millennial basis: Dordrecht, Holland, D. Reidel, p. 1-13.

Parrish, J.T., 1993, Climate of the supercontinent Pangea: Journal of Geology, v. 101, p. 215-233.

Parrish, J.T., and Peterson, F., 1988, Wind directions predicted from global circulation models and wind directions determined from eolian sandstones of the western United States -- a comparison: Sedimentary Geology, v. 56, p. 261-282.

Peterson, F., 1988, Pennsylvanian to Jurassic eolian transportation systems in the western United States: Sedimentary Geology, v. 56, p. 207-260.

—1994, Sand dunes, sabkhas, streams, and shallow seas -- Jurassic paleogeography in the southern part of the Western Interior basin, *in* Caputo, M.V., Peterson, J. A., and Franczyk, K.J., editors, Mesozoic systems of the Rocky Mountain region, USA, Colorado Plateau: Denver, Colorado, Rocky Mountain Society for Sedimentary Geology, p. 233- 272.

Peterson, F., and Pipiringos, G., 1979, Stratigraphic relations of the Navajo Sandstone to Middle Jurassic formations, southern Utah and northern Arizona: U.S. Geological Survey Professional Paper 1035-B, 43 p.

Peterson, F., and Turner-Peterson, C., 1989, Geology of the Colorado Plateau, 28th International Geological Congress Field Trip Guidebook T130: American Geophysical Union, 65 p.

Peterson, J.A., 1972, Jurassic system, *in* Mallory, W.W., editor, Geologic atlas of the Rocky Mountain region: U.S.A.: Rocky Mountain Association of Geologists, p. 177-189.

Pipiringos, G.N., and O'Sullivan, R.G., 1978, Principle unconformities in Triassic and Jurassic rocks, Western Interior U.S. -- a preliminary report: U.S. Geological Survey Professional Paper 1035-A, 29 p.

Phillipson, J., 1975, Rainfall, primary production and "carry capacity" of Tsavo National Park, Kenya: East African Wildlife Journal, v. 13, p. 171-201.

Press, W.H., Flannery, B.P., Teukolsky, S.A., and Vetterling, W.T., 1988, Numerical recipes in C, the art of scientific computing: New York, Cambridge University Press, 735 p.

Richmond, D.R., and Morris, T.H., 1998, Stratigraphy and cataclysmic deposition of the Dry Mesa Dinosaur Quarry, Mesa County, Colorado: Modern Geology, v. 22, p. 121-143.

Rubin, D.M., 1987, Cross-bedding, bedforms, and paleocurrents: Society of Economic Paleontologists and Mineralogists Concepts in Sedimentology and Paleontology, v. 1, 187 p.

Rubin, D.M., and Hunter, R.E., 1987, Field guide to sedimentary structures in the Navajo and Entrada Sandstones in southern Utah and northern Arizona, *in* Davis, G.H., and Vanden Dolder, E.M., editors, Geologic diversity of Arizona and its margins -- excursions to choice areas: Geological Society of America 100th Annual Meeting Phoenix Arizona guidebook, Arizona Bureau of Geology and Mineral Technology Geological Survey Branch Special Paper 5, p. 126-139.

Siscoe, G.L., 1980, Evidence in the auroral record for secular solar variability: Reviews of Geophysics and Space Physics, v. 18, p. 647-658.

Stokes, W.L., 1964, Eolian varving in the Colorado Plateau: Journal Sedimentary Petrology, v. 34, p. 429-432.

Werner, B.T., and Kocurek, G., 1997, Bedform dynamics-does the tail wag the dog?: Geology, v. 25, p. 771-774.

—1999, Bedform spacing from defect dynamics: Geology, v. 27, p. 727-730.

Verlander, J.E., 1995, Basin-scale stratigraphy of the Navajo Sandstone -- southern Utah, USA: University of Oxford, Ph.D. dissertation, 159 p.