Field Trip to Colorado Plateau (southern Utah, northern Arizona, Permian-Triassic boundary)
Ge136c, Prof Joe Kirschvink
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The Lower Jurassic Navajo Sandstone: large-scale deposition and small-scale structures

Site: Glen Canyon Dam

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Introduction

The Lower Jurassic Navajo Sandstone is one of the signature outcrops of the Colorado Plateau. Stratigraphically it is situated above the upper member of the Kayenta Formation (pink sandstone and maroon siltstone, 500 m thick) and below the Temple Cap Formation (red siltstone and shale, 250 m thick). The Navajo Sandstone is perhaps most impressive in Zion National Park, where the towering cliffs reveal some 700 m of the spectacular red cross-bedding.

In this handout we review some basic aspects of cross-bedding to give an idea of how the various laminae formed and why they might have been preserved. In other words, we want to relate dune migration (e.g., Figure 3) to the cross-bedding in the rock record that we see all around us. We will also discuss the big-picture deposition of the Navajo Sandstone, and introduce some recent research on this formation.

Background references on cross-bedding and eolian facies[1] can be found in *Brookfield* (1992) and *Reineck and Singh* (1975); the deposition and preservation of the Navajo Sandstone is addressed in *Kocurek* (2003) and references therein; some recent research on the Navajo Sandstone is presented in *Chan and Archer* (2000); *Loope et al.* (2001); *Loope and Rowe* (2003); *Rahl et al.* (2003); *Eisenberg* (2003).

The Navajo Sand Sea in the Early Jurassic

As you gaze toward the massive walls of the Navajo Sandstone, try to place yourself at the time of deposition — the Early Jurassic (ca 190 Ma) — amongst towering sand dunes of almost pure quartz sand covering an area that dwarfs the modern Sahara, and situated on a world with one continent (Pangea) and one ocean (Figure 1). This Navajo Sand Sea covered a vast area of perhaps 625,000 km^2, an area 2.5 times larger than surface and subsurface extent of the Navajo Sandstone (Figure 2).

What is left for our enjoyment is probably only a small portion of the volume of sand that spent time in the Navajo Sand Sea. Nevertheless, the Navajo Sandstone constitutes the largest preserved eolian (wind-deposited) record on the globe. The volume of sand deposited by the Navajo Sand Sea is estimated at $60,000 - 140,000$ km^3; this corresponds to 6–14 million years of continuous deposition of sand from the modern Mississippi River at its delta, to put the numbers in perspective (*Kocurek*, 2003).

It is interesting to compare the ancient Navajo Sand Sea and the modern Sahara of Africa (*Kocurek*, 2003). The modern Sahara will leave little, if no, trace in the rock record, since it is effectively being blown into the Atlantic ocean and is not being supplied with a sediment influx. Indeed, 30% of the surface is exposed bedrock. Nevertheless, with extreme equatorial winds and a literal sea of sand stretching as far as the eye can reach, it provides a good starting point for

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[1] Definition to note: an *erg* is a highly technical term, defined as “a sand sea in a hot desert” (Oxford Dictionary of Earth Sciences).

envisioning what this area looked like some 190 million years ago. At Coral Pink Sand Dunes State Park we can observe modern dunes, where sand from the ancient Navajo Sandstone has erroded to form a new generation of dunes (Figure 3).

Cross-bedding: A record of sand dune migration

Cross-bedding can be observed in sedimentary rocks in the rock record or in cross-sections of sand pits where modern sand deposition is occurring. Cross-bedding is a record of the migration of dunes under the influence of a flowing fluid. If the fluid is air, then the process is called *eolian* or *subaerial*; if the fluid is water, then the process is called *marine* or *subaqueous*. In either case, the basic process of cross-bedding formation is the same and is shown in Figure 4A. We see from this illustration that the *paleohorizontal* is given by the bounding surfaces of the cross-sets; at the scale of 100 m, or with a slightly tilted base level, the planes in Figure 4A will appear horizontal. Figure 4B shows a slightly more complicated (and realistic) version, which results in *trough cross-bedding* in any plane oblique to the primary flow direction.

The properties of the fluid and granular medium are primary controls on the geometry of the dunes (we'll assume the velocity of the fluid is constant). It is clear from the photos in Figure 3 that it is possible to create very large eolian dunes from the Navajo sands. Furthermore, we know these dunes reached heights in excess of 20 m, the maximum observed height of the cross-bedding sets. It turns out that dunes this large are not generated in marine environments, and thus the sheer size of the dunes here is good evidence for eolian processes. Sedimentologists also note the presence of *adhesion structures* in the rocks, which are typical of eolian deposition. Furthermore, there are no conclusive marine features in the majority of the Navajo Sandstone, although there is good evidence of pluvial (=wet[2]) episodes (e.g., *Loope and Rowe*, 2003), whereby the troughs between dunes were filled with stagnant water for prolonged periods.

Here we note a couple key terms; others are listed in Figure 3A. A *foreset* is a lamina of sediment that is deposited on the *slipface* of a dune, either via fallout from the air (or water) or via avalanching, after the slipface at the crest exceeds the angle of repose. Later in this handout we distinguish between primary and secondary foresets, since in many cases there is a hierarchy of lamina. *Cross-bedding* refers to the sedimentary record left by migrating dunes. A *cross-bedding set* or *cross-set* is the collection of foresets, bounded above and below by *bounding surfaces* and interpreted to represent an uninterrupted time interval of a single dune's migration. The *toesets* or *toes* refer to the lower reaches of the foresets, which typically run tangential to the lower bounding surface (see Figure 7A), giving a good indication of the paleohorizontal. It is important to distinguish terms describing dunes and dune migration from terms describing cross-bedding.

Some nice examples of computer simulations of cross-bedding formation, including comparisons with the Navajo Sandstone, can be found at the USGS bedform sedimentology site: http://walrus.wr.usgs.gov/seds/.

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[2] A *pluvial period* is defined as "a prolonged phase of markedly wetter climate that occurs in a normally dry or semi-arid area" (Oxford Dictionary of Earth Sciences).

What governs the preservation of these paleodunes?

Kocurek (2003) presents three possible mechanisms for preserving eolian deposits at the scale of the Navajo Sandstone (see Figure 5). Quoted directly, these are:

1. tectonic basins with pronounced sediment influx and high rates of subsidence
2. coastal regions that are marine transgressed with an associated inland rise of the water table
3. interior continental basins that experience a rise in the water table because of subsidence or climate

Furthermore, "extreme preservation is most likely to occur within a foreland basin or along a passive margin with a high subsidence rate, and in which the eolian system lies adjacent to a more basinal marine system that transgresses progressively inland through time" (p. 47). These features are illustrated in Figure 5B. Conditions for the deposition of the Navajo Sandstone are favored to be (1) above, with the massive sediment influx possibly coming from weathering of the Appalachian Mountains.

At a scale more relevant to field observations, we note that some bounding surfaces are probably caused by dunes migrating in succession over one another, similar to the example in Figure 4, while other bounding surfaces represent erosional discontinuities as a result of water table changes at a local scale. These concepts are illustrated in Figure 5A. It should also be noted that the dunes are more likely to be preserved in the rock record if they are migrating into a (local) topographic depression.

Recent research on the Navajo Sandstone

Rahl et al. (2003): Provenance of the Navajo sands

Rahl et al. (2003) collected zircon grains from the Navajo Sandstone, dated them using radiometric techniques, and compared these dates with source regions to infer the origin of the Navajo sands. As stated in *Rahl et al.* (2003): "Radioisotopic dating of detrital minerals in sedimentary rocks can constrain sediment sources (provenance), elucidate episodes and rates of ancient orogenesis, and give information on paleogeography and sediment-dispersal patterns" (p. 761). They conclude that the majority of the Navajo sands were derived from the Appalachian Mountains: "[W]e envision a system in which rivers with their headwaters in the Appalachians carried material to the Jurassic western shore of North America, flowing to the north of any residual topography associated with the Ancestral Rockies. From there, material was blown southward and incorporated into the Navajo-Aztec-Nugget erg" (*Rahl et al.*, 2003, p. 763).

Loope and Rowe (2003): Pluvial episodes

Loope and Rowe (2003) documented thick units of the Navajo that were "churned by insects and trampled by reptiles" (p. 223). They conclude that plant and animal life in wet interdune areas were sustained for thousands of years. Figure 6A shows a comparison between the arid and pluvial episodes; Figure 6B shows the relationship between the wet interdune areas and the preserved cross-bedding.

Eisenberg (2003): Giant stromatolites

Abstract from *Eisenberg* (2003): "At Capitol Reef National Park, Utah, 5-m-high stromatolites are present locally on interdune carbonate lenses in the Early Jurassic Navajo Sandstone.

The stromatolites display both finely laminated and fenestral internal fabrics, and grew along south-facing interdune margins. These stromatolites formed during a high-water-table episode engendered by a dune-dammed paleodrainage in a stabilized Navajo erg. These stromatolites, and the thick interdune section associated with them, suggest a hiatus in erg accumulation and the presence of a super bounding surface." *Eisenberg* (2003) defines *stromatolite* as "a convex-up, laminated growth structure of microbial origin" (p. 111).

Chan and Archer (2000): Paleoclimate forcing preserved in the cross-bedding

Figure 7A shows a particular cross-bedding set in Zion National Park, where *Chan and Archer* (2000) measured the thicknesses between the layers that stand out in this photo. Within these blatant layers (*primary foresets*), which are on the order of 20 cm in thickness, there are internal layers as well (*secondary foresets*). The key interpretation in the study of *Chan and Archer* (2000) is that *the primary foresets are the result of annual deposition*, whereby a seasonal climatic signal leads to a change in depositional pattern. The secondary foresets are interpreted to represent occasional (i.e., ∼6-10 per year) avalanches of sand, when the angle of the slipface at the crest of the dune exceeds the angle of repose for the sand. This number of avalanches per year is consistent with what is observed for modern eolian systems. (In general, more measurements of cross-bedding and avalanches in modern eolian dune systems would greatly assist studies and interpretations of ancient eolian dune migration.)

With the interpretation of 1 primary foreset = 1 year, the story of time is placed into the cross-bedding. The 300 primary foresets represent 300 Early Jurassic years, and the forcing cycles of 30 and 60 correspond to cycles with 30- and 60-year periods[3]. If the interpretation is correct, then what is the source of these cycles? *Chan and Archer* (2000) argue for a climatic forcing, which seems plausible. There is some evidence of drought periods on the order of decades in Africa in recent times, and at a global scale, the El Nino/Southern Oscillation (ENSO) exhibits a quasi-period on the order of decades as well. But because many of the climate cycles are influenced by the position of the continents (Figure 1, it is difficult to predict what the ancient climate periodicities would be. Global climate models would help in determining possible climatic cycles during the Early Jurassic. Similarly, there are countless other outcrops to measure — this would help determine the pervasiveness of the climatic forcing cycles within the Navajo Sandstone.

Loope et al. (2001): Annual monsoon rains recorded in the cross-bedding

Loope et al. (2001) analyzed sedimentary structures within the context of the foreset thickness patterns in outcrops at Coyote Buttes, Arizona. Abstract from *Loope et al.* (2001): "Here we analyze slump masses in the annual depositional cycles…Twenty-four slumps, which were generated by heavy rainfall, appear within one interval representing 36 years of dune migration. We interpret the positions of 20 of these masses to indicate slumping during monsoon rains, with the other four having been the result of winter storms. The slumped lee faces of these Jurassic dunes therefore represent a prehistoric record of yearly rain events." It is worth emphasizing that their findings depend heavily on two fundamental points:

1. the interpretation of an annual cycle within the cross-bedding thickness patterns, i.e., how time is "placed" onto the cross-bedding
2. the interpretation of heavy rainfall as the mechanism for the slump deposits

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[3] Note that these paleoclimate forcing cycles are orders of magnitude shorter in period than Milakovitch cycles, which haver periods on the order of 100,000 years.

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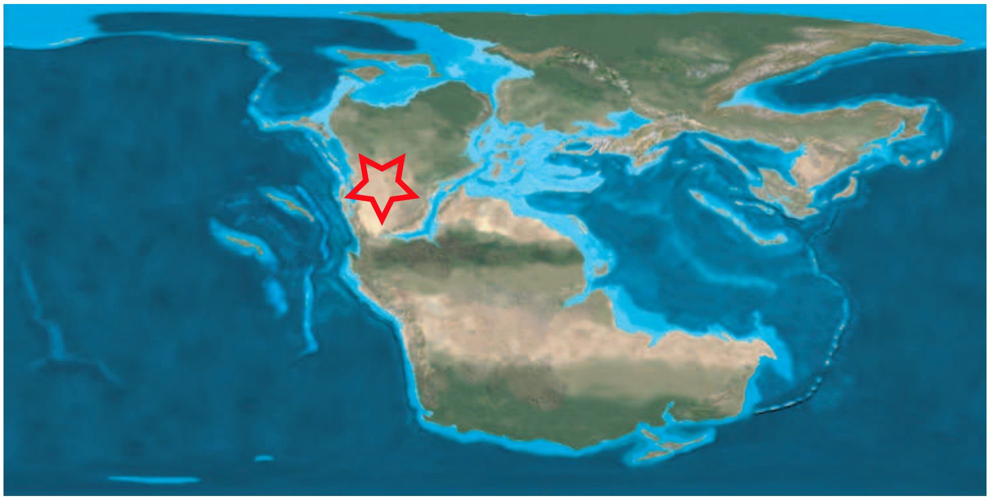

Figure 1: The configuration of the plates during the Early Jurassic (ca 190 Ma), at the time of deposition of the sands of the Navajo Sandstone. Star indicates approximate region of the Navajo Sand Sea. Note that this time period marks the breaking-up of Pangea. The single ocean is at this time is known as Panthalassa. Source: http://jan.ucc.nau.edu/~rcb7/globaltext2.html

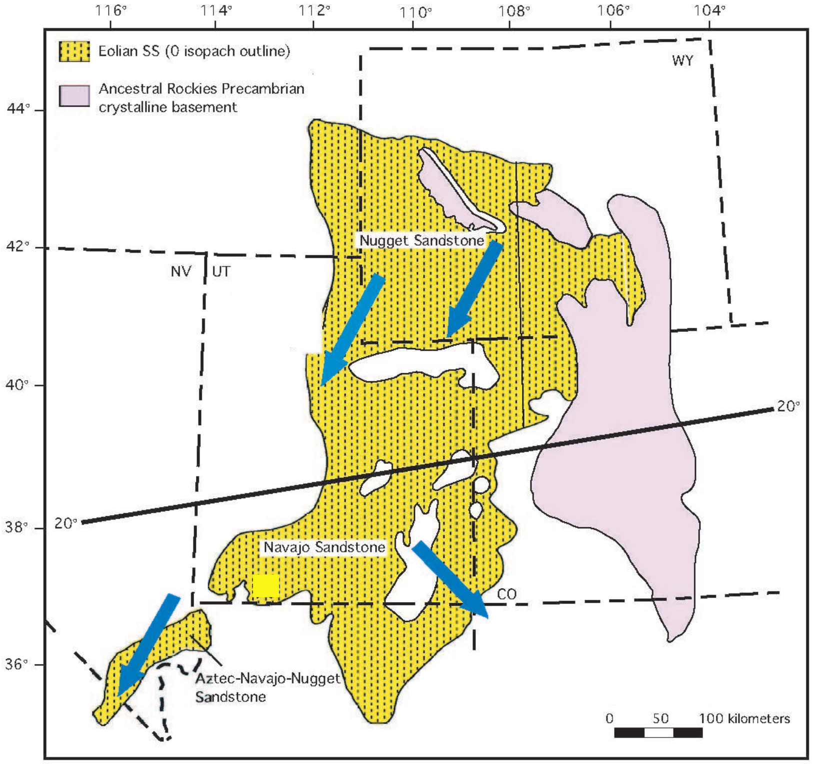

Figure 2: The extent of the Navajo Sandstone in the southwestern U.S., covering an area of approximately 250,000 km^2. The extent of the Navajo Sand Sea is predicted to be 2.5 times this area! Arrows indicate the regional paleoflow direction for the Navajo. Bold line indicates the 20° paleolatitude line at the time of deposition. Figure from *Chan and Archer* (2000).

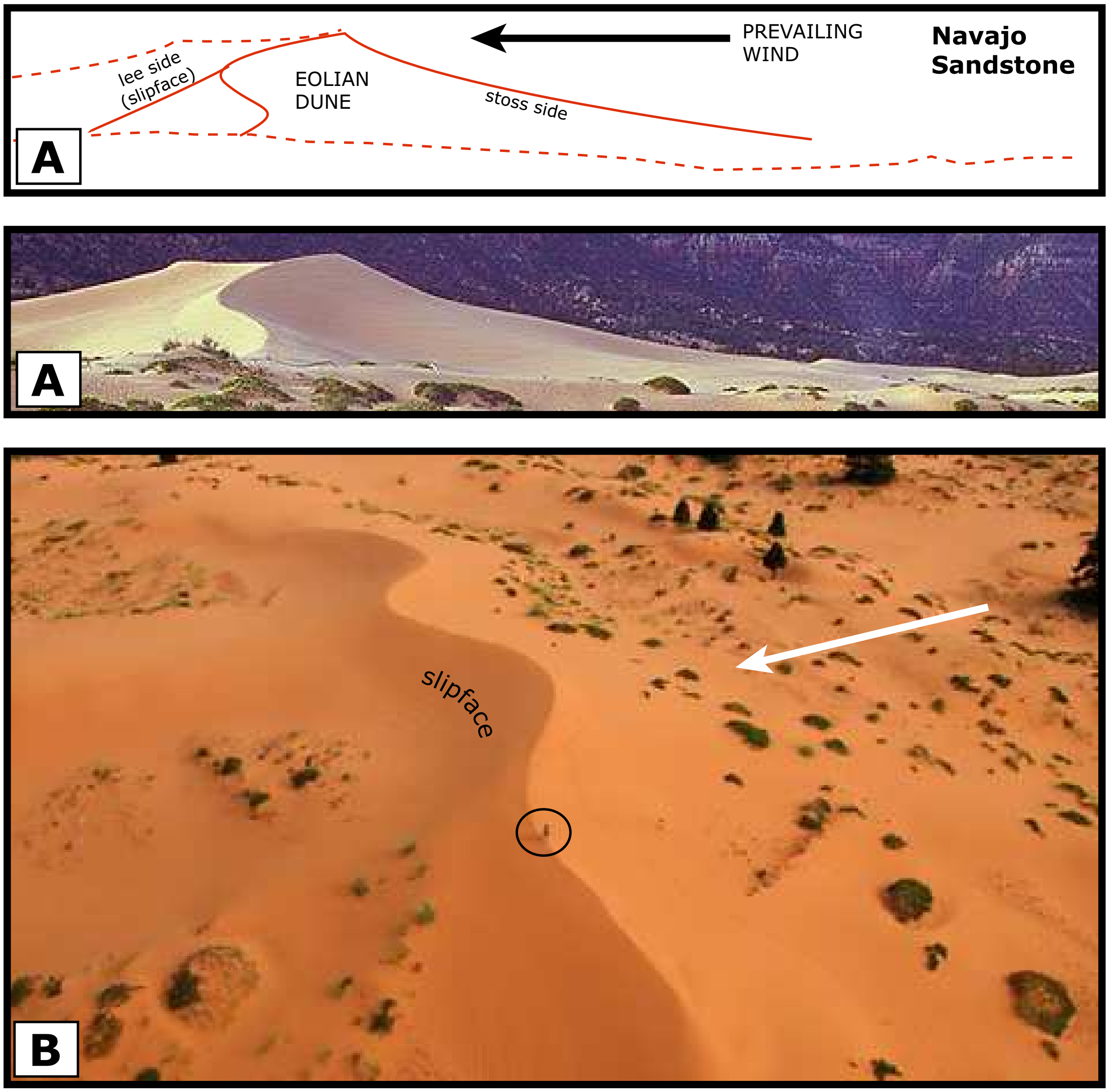

Figure 3: Modern eolian dunes being formed at Coral Pink Sand Dunes State Park, not far from the east entrance to Zion National Park. Here the ancient sands of the Navajo Sandstone (ca 190 Ma) have eroded, and new dunes are being formed in the windy stretch between two bluffs of sandstone. In essence, these sands are forming a second generation of eolian dunes, separated by about 200 million years. **A.** Sketch with photo showing a typical profile of a dune, which exhibits an asymmetry (lee side steeper than stoss side) due to a prevailing wind direction. Note the cliffs of the Navajo Sandstone in the background. The height of this dune at the crest is approximately 25 m. **B.** View from above, showing the crest of one of these dunes. Note the circled person for scale. (This photo was taken by a camera attached to this person's kite, which was tied to a nearby tree.) Also note that plants, which stabilize the dune, were probably only present during the wetter climatic periods during the time of the Navajo Sand Sea.

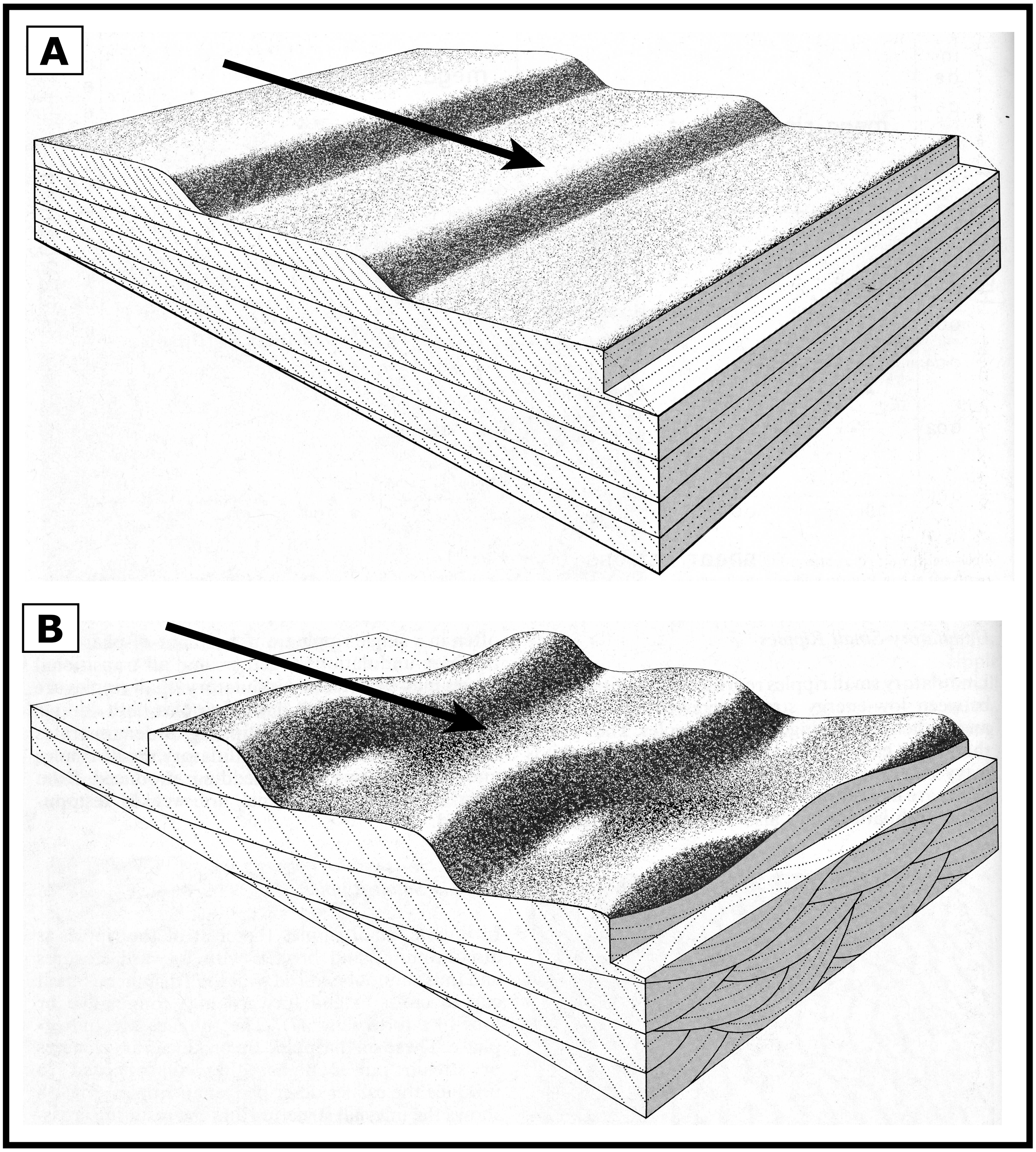

Figure 4: The relationship between dune migration and cross-bedding, with arrow indicating direction of (air) flow. What is seen at the outcrop will clearly depend on the angle of the outcrop face with respect to the dune's migration. Figures from *Reineck and Singh* (1975). **A.** Simplest scenario for dune migration. With large distances between dunes, the bounding surfaces of the cross-bedding sets are approximately horizontal. **B.** A slightly more complicated depiction. Compare with the modern eolian dune pictured in Figure 3.

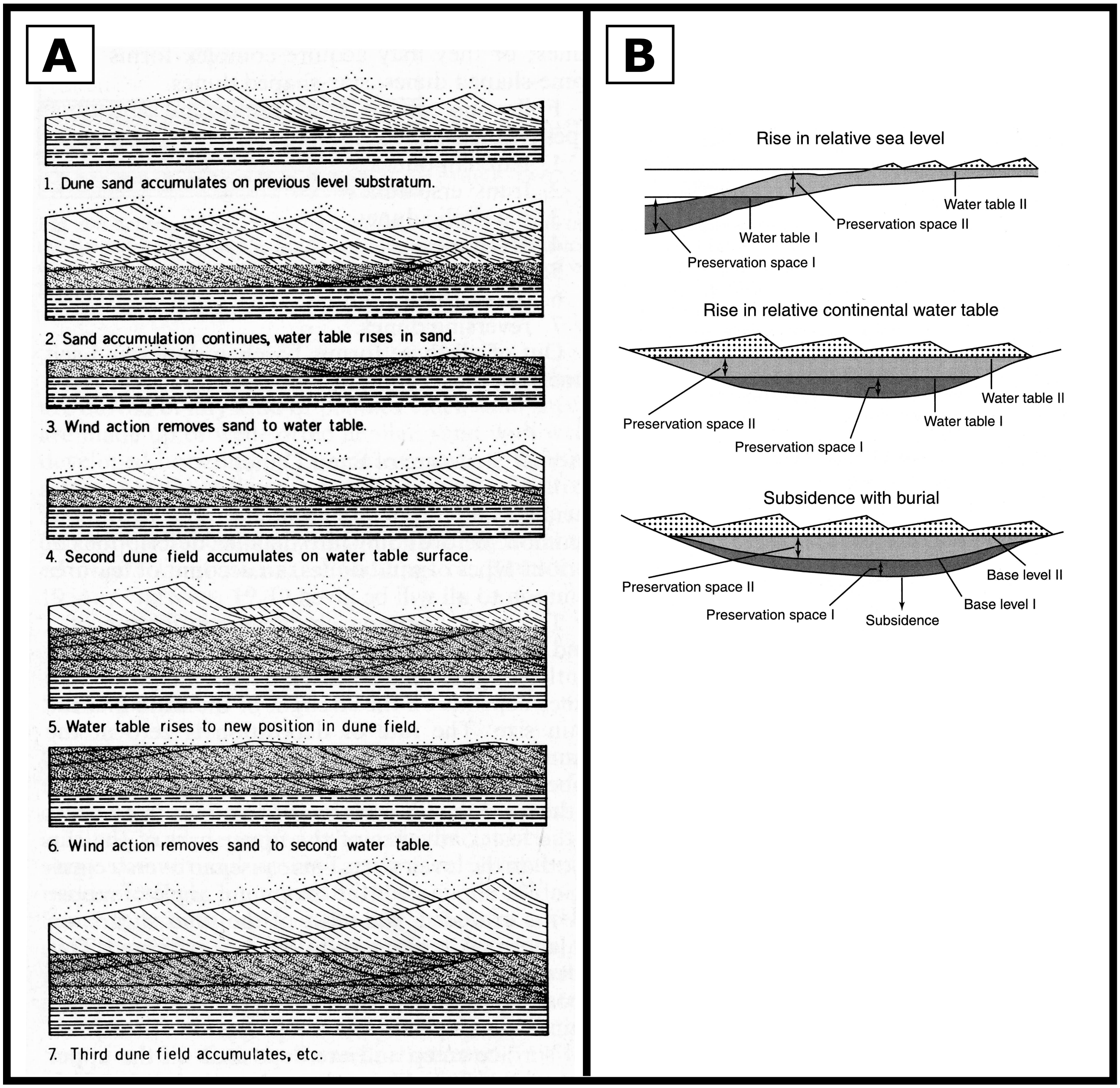

Figure 5: The preservation of the Navajo Sand Sea into the rock record. The level of the water table plays a crucial role in the preservation of eolian dunes. **A.** Schematic process of the formation of cross-bedding similar to what is seen within the Navajo Sandstone. The level of the water table determines the base (i.e., bounding surface) of the subsequent cross-bedding set. Figure from *Reineck and Singh* (1975). **B.** Three possible modes of preservation of an eolian system. The preferred mechanism for the Navajo Sandstone is in lower model, whereby sand dune deposits subside into the water table and are eventually lithified into the rock record (and are then uplifted to the surface). Figure from *Kocurek* (2003).

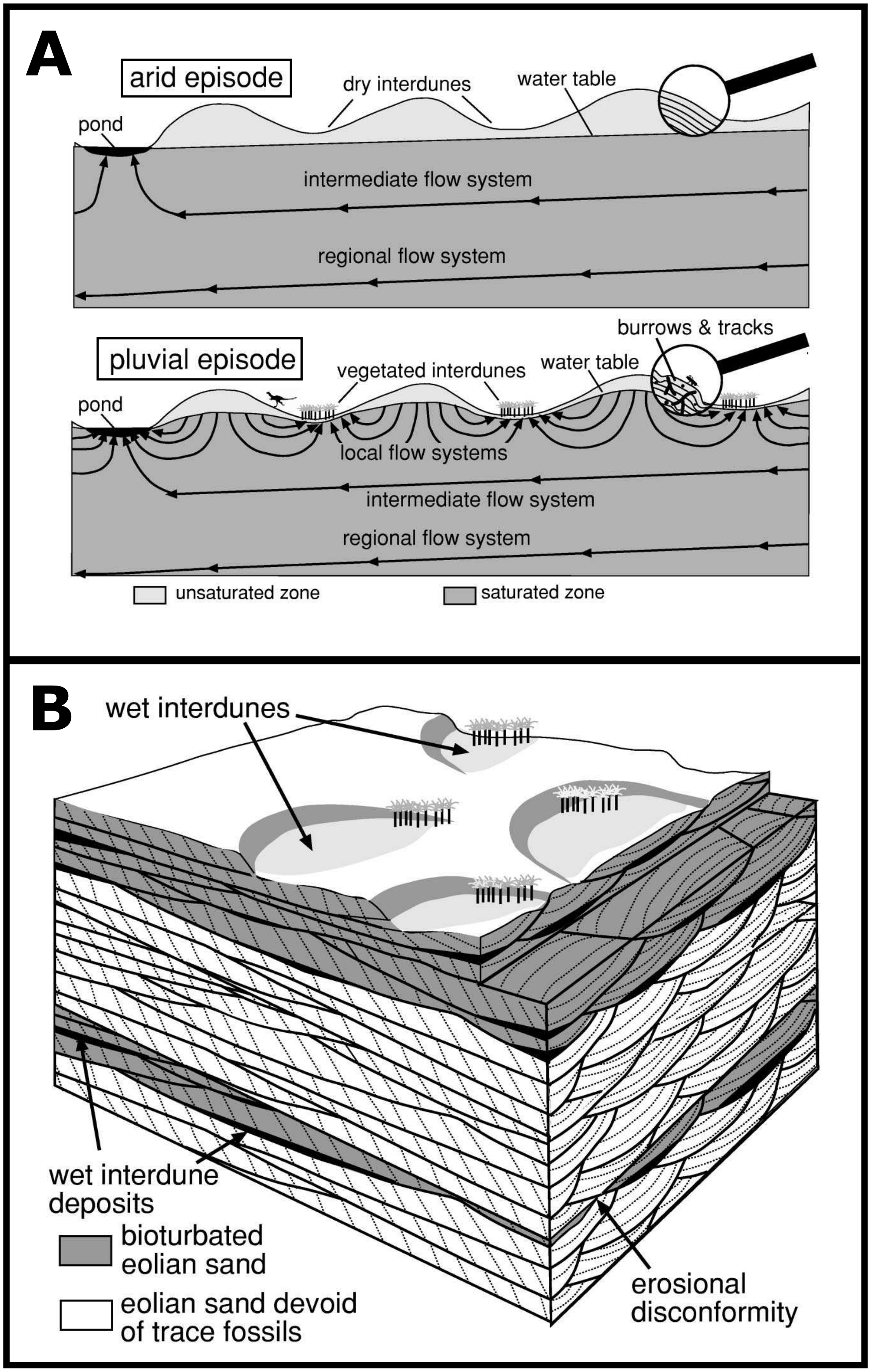

Figure 6: Pluvial episodes recoded in the Navajo Sandstone. Figures from *Loope and Rowe* (2003). **A.** Change in hydrologic regime during deposition of the Navajo Sandstone. During arid episodes, the water table is nearly flat; during pluvial episodes, the water table rises and “becomes mounded beneath dunes”. **B.** Model for the recording of pluvial and arid episodes in the Navajo Sandstone. The top of the lower bioturbated zone is marked by an erosional disconformity caused by a fall in the water table. See also Figure 4.

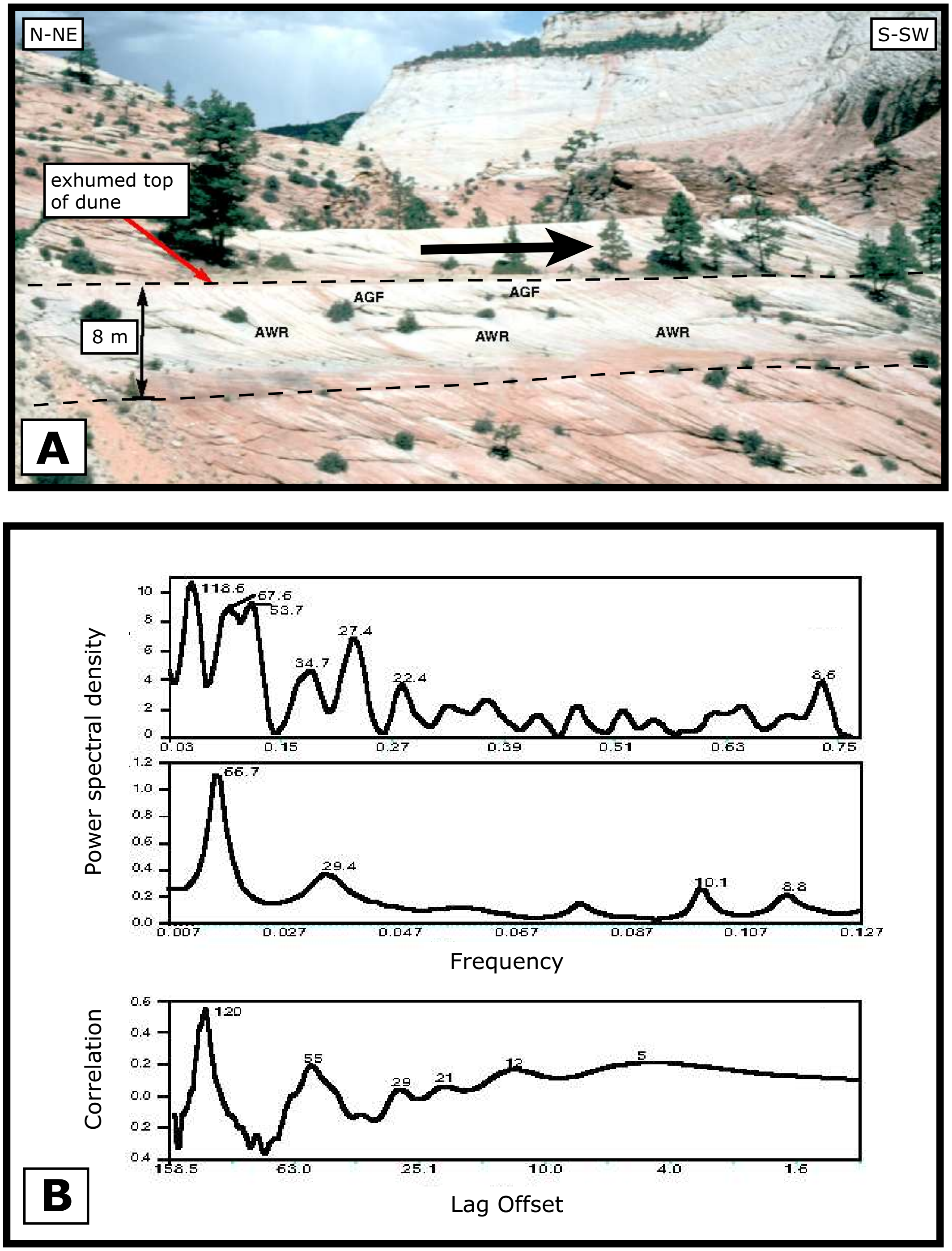

Figure 7: The cross-bedding set analyzed by *Chan and Archer* (2000). It is in Zion National Park, approximately 2.4 km west of the east entrance station on Highway 9. Figures from *Chan and Archer* (2000). **A.** Cross-bedding set delineated by bounding surfaces (dashed lines). Arrow indicates a paleoflow direction to the S-SW. AWR (annual wind-ripple) indicates intervals of (thinner) primary foresets; AGF (annual grainfall and grainflow) indicates intervals of thicker foresets. **B.** Frequency analysis of the primary foreset thickness data of the cross-bedding set shown in A, as well as for an additional cross-bedding set nearby. The main point here is that there are dominant periods of about 60 and 30 primary foresets. (The peaks >100 are probably not well-resolved, given the length of the data set, which is about 300 primary foresets.) The forcing periods are interpreted to represent decade-scale climate cycles.