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SEASONAL PATTERNS OF WIND AND RAIN RECORDED BY THE NAVAJO SANDSTONE

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Introduction

Residents of the Colorado Plateau have been both repelled by and attracted to the great sandstone expanses they call slickrock. In the 19th century, the "holes, hills, and hollows" were always a trial and sometimes a life-threatening barrier to travelers. To modern-day backpackers, mountain bikers, and windshield tourists, the rocks are an inspiration, a challenge, or just an oddity. For a person with some interest in geology, though, the thick sandstones of the region are a window to a remarkable period in earth history. For about 150 million years—from the Pennsylvanian to the Middle Jurassic—southwestern North America lay near the western edge of the Supercontinent Pangea and was home to some of the largest dune fields the Earth has ever known.

The Navajo Sandstone is the thickest and most widely exposed of the wind-blown (eolian) strata of the Plateau. Nearly every particle in the Navajo is of sand size (between 1/16 and 2 mm in diameter), and this is a hint of the formation's origin: the wind is very good at sorting sediment particles by size. In modern deserts, the wind leaves gravel behind as a lag, and suspends silt, moving it to the desert margin as dust clouds. Sand, however, moves just above the desert floor by *saltation*—grains move at high velocity, splash down energetically, and eject other sand grains. This wind-driven sand very quickly heaps itself into ripples and dunes. As a dune migrates, sand comes to rest on the steep downwind (lee) side, generating *crossbedding* (layers of sediment that accumulate on a slope, rather than on a horizontal surface). The direction of slope coincides with the direction that the dune was migrating, and, usually (see below) with the direction of the dominant wind. In most of southern Utah and northern Arizona, the crossbeds in the Navajo (and many of the other, older sandstones) slope toward the modern-day southeast (Fig. 1).

Dunes, Winds, and the Positions of Ancient Continents

The dunes of modern deserts reflect the winds that shape them. Transverse and barchan dunes have crests that lie at a right angle to a single, dominant wind direction. In many modern deserts, however, no single, dominant wind direction is obvious; linear and star dunes are widespread in these settings. The diverse wind directions that drive saltating sand across linear and star dunes generate crossbedding that is much more complex than that in transverse dunes: crossbeds slope in many different directions. In light of the complexity of the dunes and wind regimes of most modern deserts, the simplicity shown in Figure 1 is difficult to understand: why do nearly all of the crossbeds slope toward the southeast? The apparent reason for the simple pattern is that the Navajo desert was dominated by transverse dunes that were pushed by a single dominant wind direction that persisted throughout the period of sand accumulation. What does this tell us about the atmospheric circulation over Pangea during the Early Jurassic?

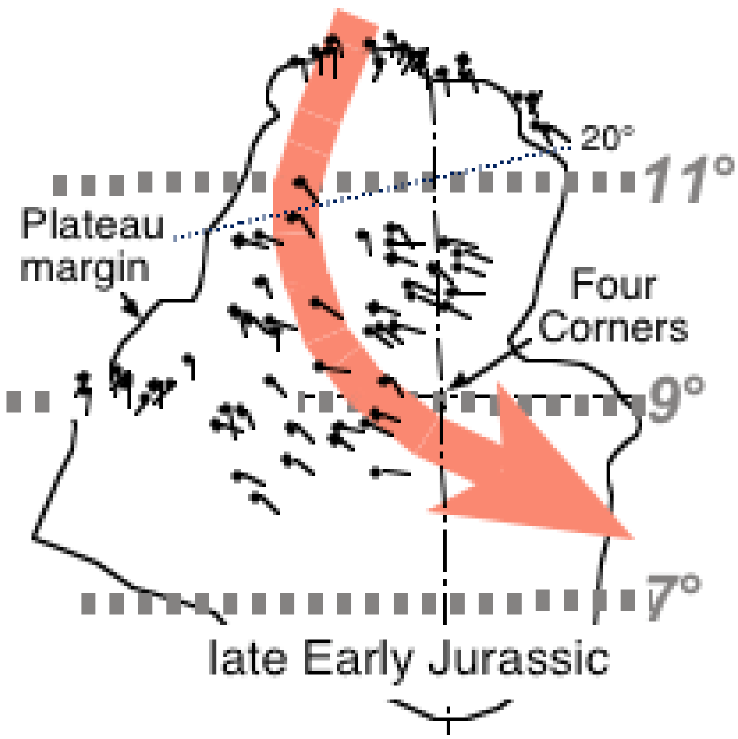

Figure 1. *Crossbed dip (down-slope) directions for the Navajo Sandstone. Tails of "tadpoles" point in the direction of dune migration. Irregular outline shows boundary of the Colorado Plateau; Four Corners is common point of Utah, Colorado, Arizona, and New Mexico. Bold lines (7°, 9°, 11°) show paleolatitude based on Steiner's work (Loope et al., 2004); dashed line (20°) is from Parrish and Peterson (1988). Bold arrow shows trade winds turning to become tropical westerlies.*

Since Alfred Wegener's pioneering work in the 1920's, and especially since the plate tectonics revolution of the 1960's, earth scientists have tried to show how the configuration of continents across Earth's surface has changed through geologic time. Paleomagnetists—scientists who study the magnetic properties of rocks-- have played a leading role in this work. Much of this work has been made accessible by the Paleomap Project (http://www.scotese.com/earth.htm) via a series of maps representing continental positions for more than a dozen time "slices". For the time period most closely representing the Early Jurassic (the time of Navajo Sandstone deposition), Paleomap shows the Four Corners (common point of UT, CO, NM, and AZ) at about 20°N. In the late 1980's, using the 20°N Early Jurassic position for the Four Corners, geologists interpreted the Navajo winds as mid-latitude westerlies (the same zonal winds that are familiar to residents of the temperate parts of North America). In our 2001 paper on the Navajo, even though we realized that mid-latitude westerlies rarely reach so close to the equator today, we followed this interpretation.

Shortly after publication of our paper, we became aware of several decades of work by Maureen Steiner (University of Wyoming) on the magnetic properties of Triassic and Jurassic rocks of the Colorado Plateau. Her studies placed the Plateau at a lower latitude during this time interval—she put the Four Corners at about 10°N in the

Early Jurassic. We also found a global reconstruction of continental positions for the Early Jurassic that placed the Four Corners at 10°N (Texas through Time-- http://www.ig.utexas.edu/research/projects/plates/plates.htm#recons). Because we knew it was completely unrealistic to bring mid-latitude westerlies all the way down to within 10° of the equator, these works caused us to rethink the Navajo paleowinds.

Given the uncertainty accompanying the diverse sources of paleomagnetic data, it is not surprising that there are discrepancies in the maps produced by different workers. And for many scientific purposes, a 10° difference in paleolatitude would be of little consequence. The direction and strength of winds, however, change abruptly with latitude, so if an earth scientist wants to understand ancient winds, knowing the paleolatitude of the area of interest with some precision is important. On the other hand, if two hypotheses for the position of the area are available, indicators of paleowind directions from the rocks might help to select the best map.

A Modern Analog for Navajo Winds

The positions of Earth's two largest continents--Asia and Africa—make tropical atmospheric circulation in the Eastern Hemisphere fundamentally different from that in the West. When sailing ships from Portugal, Spain, and England first plied the Atlantic and Pacific Oceans, sailors dreaded the doldrums—the area of weak winds near the equator where ships could be becalmed for weeks. In the Indian Ocean, however, Chinese and Arab traders knew the low latitudes as the home of the most reliable winds. The Arabs realized that the wind system reversed itself seasonally and named it the *mausim* (monsoon).

Summertime heating of large portions of Africa and Asia produces an extensive region of low pressure while cooling in the southern hemisphere (remember it's winter) enhances high pressure there. This results in a large pressure difference across the equator, causing winds to blow from the southern to the northern hemisphere. The Earth's rotation causes an apparent deflection of winds, relative to the Earlth's surface, known as the Coriolis effect. This is what causes air to spiral into low pressure areas as seen on satellite images of clouds circling around storms. However, the Coriolis effect is strongest at the poles and decreases to zero at the equator so that the air crossing the equator can move more directly toward the area of low pressure. As the air continues northward, the increasing Coriolis effect deflects the winds to the right, so that they arrive in India as *tropical westerlies* (Fig. 2). Six months later, during the winter monsoon (December-January-February), the flow across the equator is reversed because the intense heating (and attendant low pressure zone) shifts to the southern hemisphere (Fig. 2).

Today, tropical westerlies originate very near the equator (Fig. 2), but global climate models show that if the pressure difference across the equator is strong enough, the trade winds can turn before they reach the equator. In a climate model for early

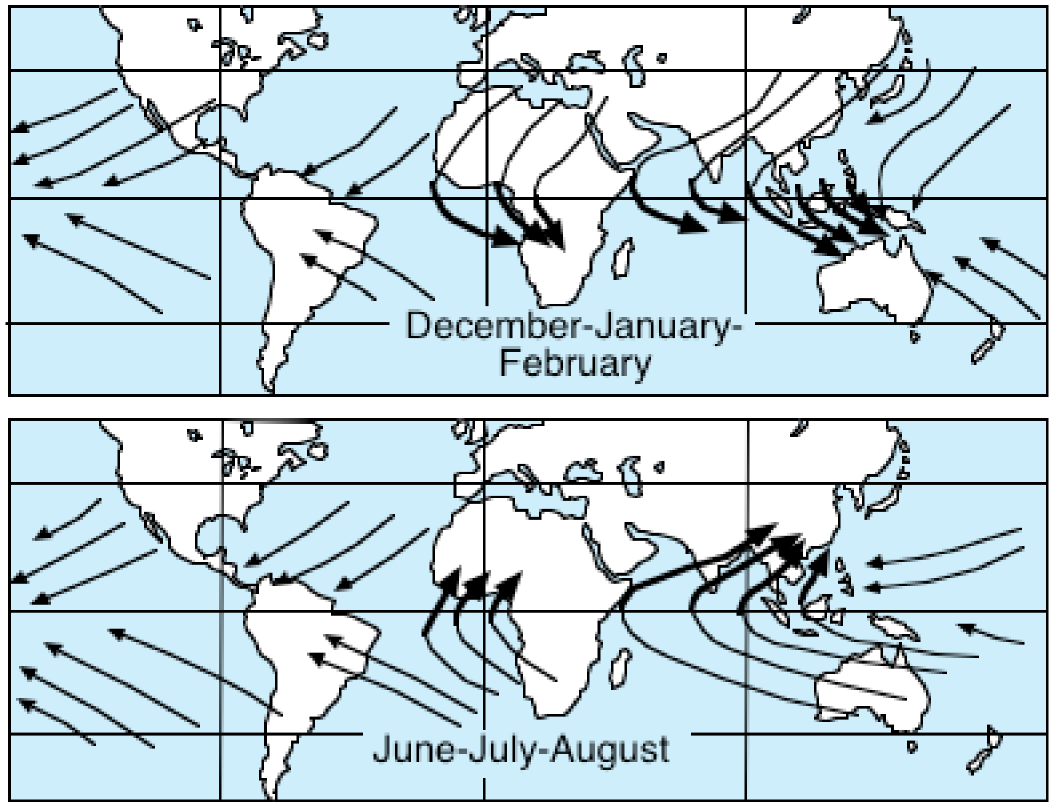

Figure 2. *Modern winter and summer atmospheric circulation. Note prominence of tropical westerlies in the Eastern Hemisphere (from Webster, 1987).*

Jurassic Pangea contructed by Mark Chandler and his colleagues at Columbia University in the early 1990's, the Trades turn to become tropical westerlies more than 10° from the equator (Fig. 3). During the Jurassic, most of Pangea lay south of the equator, so the winter monsoon (December-January-February) was the dominant circulation. After we became aware of the evidence supporting lower latitudes for the Colorado Plateau during the Jurassic, all that remained for us to do was to "connect the dots": the northwesterly flow of air recorded by the crossbeds of the Navajo Sandstone was unrelated to the mid-latitude circulation, but instead was the direct result of north-to-south monsoonal flow over Pangea during Northern Hemisphere winter (December-January-February).

Annual Cycles of Jurassic Winds and Rains

In parts of southern Utah and northern Arizona, the crossbeds of the Navajo Sandstone show distinct depositional cycles (Fig. 4). In the early 1980's, Ralph Hunter and David Rubin of the U.S. Geological Survey argued that there are only two strong rhythms in nature that could produce such distinct structures: *daily* or *annual* shifts in the wind direction and speed. They then showed that daily shifts would have too been too brief for the large Navajo dunes to have migrated sufficient distances to produce the cycles. Annual shifts in wind direction or speed are common in modern dune fields, and Hunter and Rubin made a strong case that the Navajo crossbeds record such changes. Their study fits perfectly with the new interpretation of the wind regime described above: under the dominant winter winds, the dunes moved about one meter toward the southeast

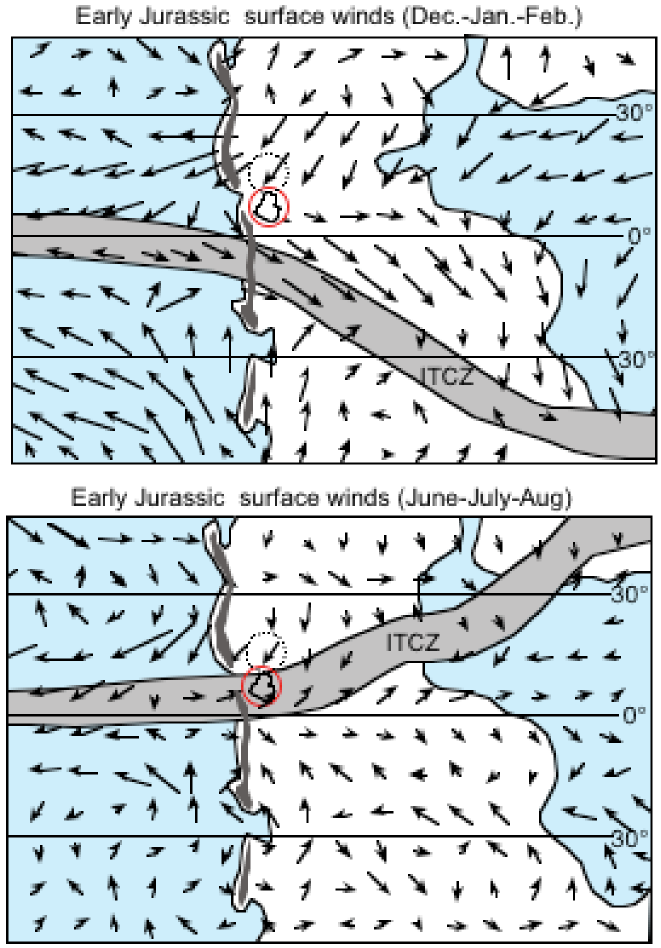

Figure 3. *Jurassic surface winds over Pangea (from global climate model of Chandler et al., 1992). Colorado Plateau (circled) is displaced southward to about 10°N (based on Steiner's paleomagnetic data (Loope et al., 2004). Note turning of trade winds to become tropical westerlies at about 10°N. Intertropical convergence zone (ITCZ) migrates northward over site of Plateau in summer, bringing enhanced rainfall.*

by repeated avalanching of the slipface (Fig. 5). During the rest of the year, winds from other directions pushed wind-ripple deposits up against the slipface. The wind-ripples were buried the following winter by more avalanches. Because they moved large dunes a meter per year, the Jurassic monsoon winds were apparently stronger than any modern-day tropical westerlies. Such wind strength was probably the result of a greater difference in barometric pressure across Pangea's equator than exists for any modern location. With a supercontinent straddling the equator, the Jurassic world was better-suited than the modern one for strong cross-equatorial flow.

Heavy rain falling on the steep slopes of sand dunes can induce slumping (Fig. 6). Along the western edge of the Paria Plateau on the Arizona-Utah border, there are numerous slumps encased within Navajo crossbeds. At one site where there is a continuous exposure of 36 depositional cycles, slumps are present in 24 of the cycles.

Figure 4. *Depositional cycles in the Navajo Sandstone on the Utah-Arizona border, west edge of Paria Plateau. Upward-thinning wedges of wind-ripple strata (shadowed at their bases) divide avalanche deposits into distinct packages. See Fig. 5 for further interpretation.*

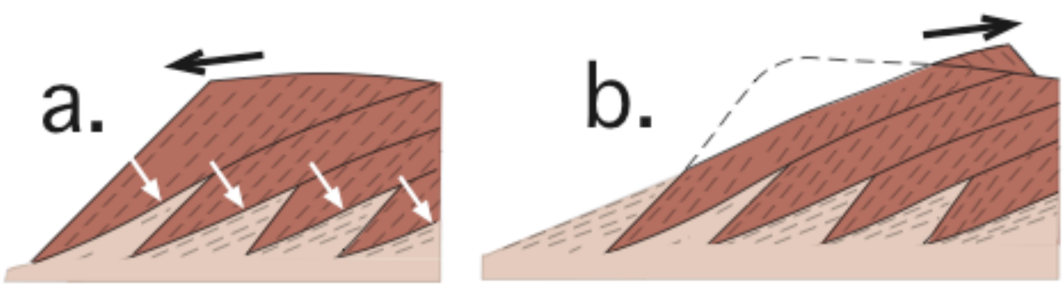

Figure 5. *Paleoclimatic interpretation of depositional cycles:* ***A:*** *Under the dominant (winter) tropical westerly winds, dunes migrate southeastward by avalanching on their downwind slopes. Light arrows show where dunes have buried wind-ripple strata.* ***B:*** *During the remaining months of the year, wind-ripple strata are pushed up against the steep avalanche face by subordinate winds. These strata are buried when winter winds return.*

The slumps are defined by compressional folds and faults (Fig. 7) and breccia sheets, and are buried by undisturbed crossbeds. These characteristics differentiate the slumps (which form on the slopes of active dunes) from other forms of soft-sediment deformation, most of which originate after the dune deposits have been buried below the water table.

Figure 6. *Slump on a steep dune slope after a heavy rainstorm. Northern Mexico; photo by Nick Lancaster.*

Figure 7. *Ancient rain-triggered slump, Navajo Sandstone. Folded and faulted mass of sediment slid down the lee face of a dune and was buried by undisturbed crossbeds when dune migration continued.*

In the tropics, rainfall is most abundant in the Intertropical Convergence Zone—a low pressure trough that moves north and south as direct solar radiation shifts with the seasons. In the northern hemisphere, the heaviest rainfall comes in summer (June-July-August). The positions of the slumps within annual depositional cycles of the Navajo fit well with the monsoonal interpretation of the crossbeds. The slumps don't "split" the avalanche (winter) portion of the cycle. Instead, they lie within or are adjacent to the wind-ripple wedges that define the edges of the avalanche portions and record the "non-winter" part of the annual cycle.

Conclusions

Like the other Paleozoic and Mesozoic eolian sandstones of the Colorado Plateau, the Navajo accumulated on the Supercontinent Pangea. The winds that swept Pangea were much more similar to winds of the modern Eastern Hemisphere than to those of the Western Hemisphere. Our recent work indicates that the Navajo dunes were driven by strong monsoon winds that blew across the equator toward a zone of low air pressure that developed each December when the portion of Pangea south of the equator was receiving the sun's direct radiation. Although the crossbeds within the Permian Cedar Mesa Sandstone of Utah's Canyonlands record dunes nearly 100 million years older than those that deposited the Navajo, these crossbeds, like those in the Navajo, also slope toward the modern southeast. We interpret this to mean that the Colorado Plateau lay near enough to the equator for this entire time interval to have been dominated by tropical westerly winds. Pangea lay mostly to the south of the equator during this time, so north-to-south winds were far stronger than south-to-north winds. Although rainfall events may have been rare during much of this time span, when rain came, it came in the summer months.

Acknowledgements

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