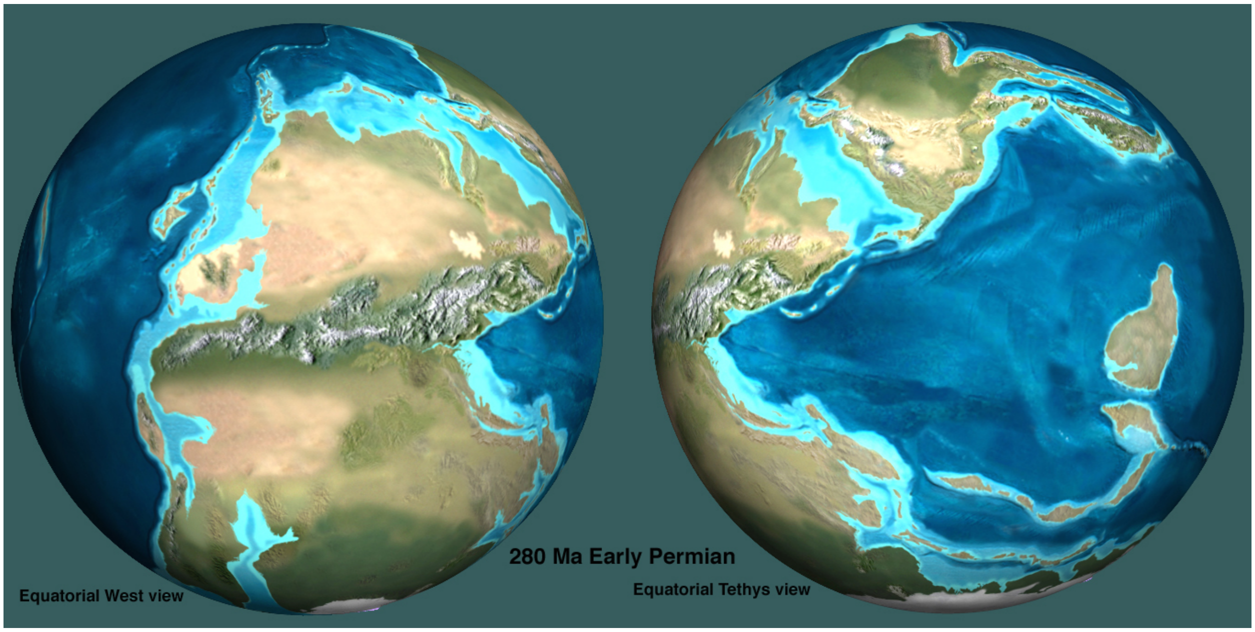
Pangean Paleoclimate



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GEO 387H
November 18, 2008

Abstract

The Pangean supercontinent existed for more than 100 million years and had a profound influence on Earth's climate and atmospheric circulation system. Proxy paleowind data from aeolian (wind-blown) deposits in the rock record and climate models indicate a monsoonal circulation system through the existence of Pangea. However, inconsistencies exist between studies and the exact reconstruction of the monsoonal system remains unclear.

1. Introduction

Wind is integral to the Earth’s climate system and a major component of atmospheric circulation. Historically, however, paleowind information has been under-utilized as input data for ancient climate models. Aeolian (wind-blown) sand dunes are the most direct proxies for paleowinds at the Earth’s surface because sand dunes form in direct response to the transport of surface sediment by wind. Aeolian sand dunes provide direct evidence of atmospheric circulation and the migration of dunes masks short-term climate variation and produces paleowind information at a scale similar to global climate models (Blumberg and Greeley, 1996). Where the study of dune fields is only feasible by remote and satellite images, aeolian systems have been used to interpret the wind directions on Earth (Kocurek and Ewing, 2005; Beveridge et al., 2006), Mars (Tsoar et al., 1979; Malin et al., 1998) and Titan (Lorenz et al., 2006). Aeolian deposits are common in the ancient rock record and have been used for decades to infer dune migration direction (e.g., Reiche, 1938; Curray, 1956; Poole, 1962; Peterson, 1988). More detailed reconstructions of dune morphology and behavior from cross-strata have been used to reconstruct wind regime (Rubin and Hunter, 1983; Kocurek et al., 1991; Crabaugh and Kocurek, 1993). Changes in wind directions within seasonal (e.g. monsoonal; Hunter and Rubin, 1983;

Chan and Archer, 1999; Loope et al., 2001) and daily cycles (Hunter and Richmond, 1988) have been distinguished from aeolian cross-strata.

2. Pangea

The supercontinent Pangea dominated our planet for over 100 million years of Earth's history, from the Late Pennslyvanian to the Jurassic, with maximum extent during the Triassic. This single continent stretched latitudinally across every part of the zonal atmospheric circulation, thereby producing an extraordinary effect on the global paleoclimate (Dubiel et al., 1991). The Permian-Triassic interval has been noted as a unique and extreme paleoclimate interval due to the global occurence of red beds and evaporite deposits in numerous locations world-wide (Dubiel et al., 1991; Glennie, 1987). During the Triassic the supercontinent was approximately symmetric about the equator (Parrish and Peterson, 1988).

Approximately 2500m of aeolian-deposited sandstones accumulated in the south-western United States during the time of the Pangea supercontinent, the majority of deposits occurring on the Colorado Plateau (Blakey et al., 1988 (Figure 1). The Colorado Plateau is a modern highland centered at the Four Corners region, or the geographic point where the states of Arizona, New Mexico, Colorado and Utah meet. Peterson (1988) compiled paleowind data from cross-strata within these eolian units, creating a dataset of dune migration directions spanning the Late Pennsylvanian through Jurassic periods from which paleowind directions can be inferred. Peterson's (1988) dataset is the largest paleowind data set covering any region or time in Earth's history (Loope et al., 2004). Using this data set with reconstructed Pangean paleogeography, atmospheric circulation models can be used to predict the climate and atmospheric circulation during the Pangean supercontinent. Please note that in this paper, all descriptions of wind directions (e.g. north-westerly winds) refer to paleo-coordinates unless otherwise noted.

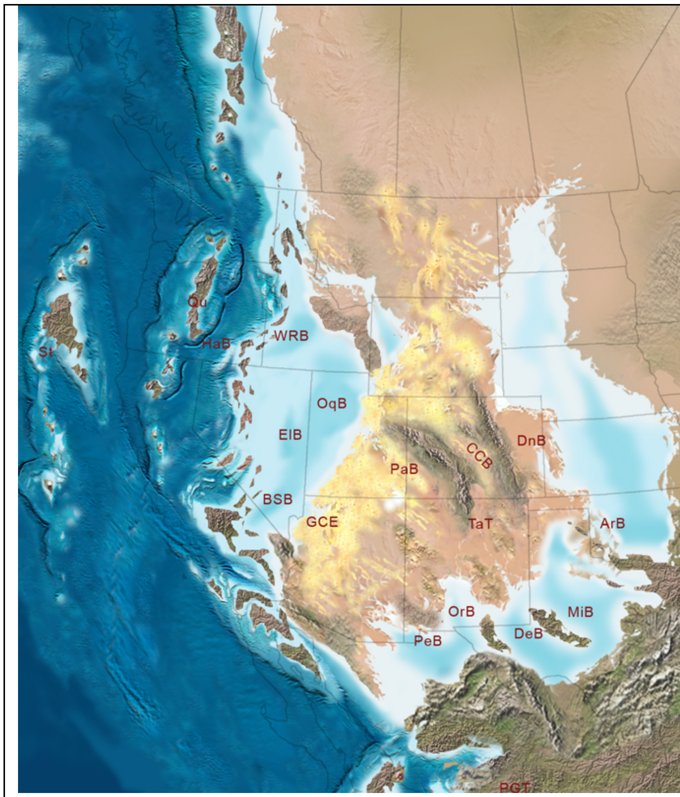

Figure 1. Paleogeographic map showing the Colorado Plateau and Four Corners region. Map by Ron Blakey. http://jan.ucc.nau.edu/~rcb7/

3. Paleomagnetism

The polarity of the Earth's magnetic field has repeatedly reversed orientations through time. These reversals are recorded by iron-bearing minerals in igneous rocks that magnetize parallel to the orientation of the Earth's current magnetic field. Rocks forming today (e.g. Atlantic Mid-Ocean Ridge basalts) contain magnetizations that match the current orientation of the Earth's magnetic field with magnetic north aligned with the North Pole. However, older rocks contain magnetizations that are opposite, or reversed, from today's orientation (Pitman and Heirtzler, 1966). Rocks forming today at different latitudes are concordant with the modern magnetic field. Likewise, Permian-aged rocks from various latitudes should all align with the

Permian magnetic field, as long as the continents are located in their correct paleogeographic position. The paleolatitudes of these rocks can be determined by rotating each continent from its current geographic position to one that aligns with the Permian magnetic field (Dott and Prothero, 1992) (Figure 2). Multiple samples from each continent are required to produce reasonable levels of accuracy, and the continent positions are adjusted until the paleo magnetic pole positions from multiple continents coincide in the same location (Dott and Prothero, 2002) (Figure 2).

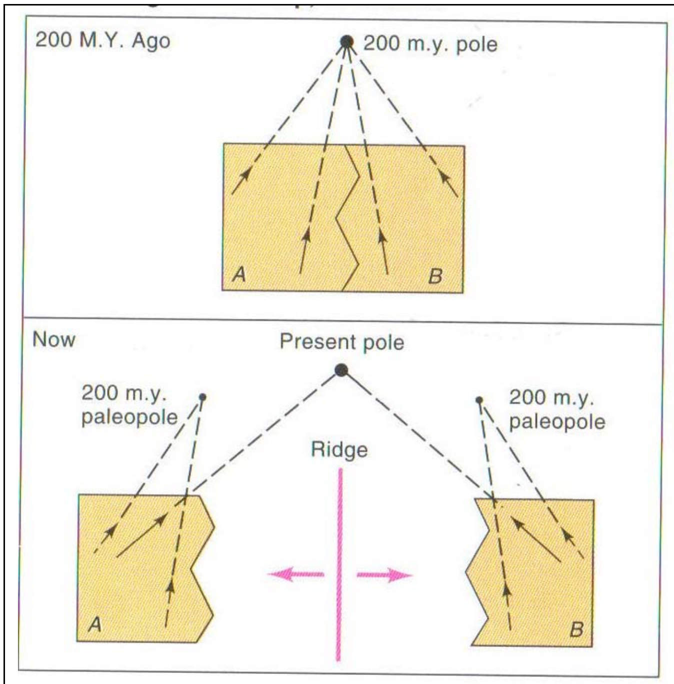

Figure 2. Diagram showing the method to calculate the paleo magnetic pole using multiple data points (same age) from different continents. From Dott and Prothero (2002).

Recently some scientists have adopted the method of using detrital hematite minerals from sedimentary rocks to determine the magnetization and paleolatitude of rocks (Steiner, 2003). However, the accuracy of these paleomagnetic reconstructions are limited due to the sediment compaction that detrital hematite grains experience during sediment burial and lithification. Comparisons of paleomagnetic data from sedimentary rocks (which undergo compaction) and from igneous rocks (which do not compact) indicate that sedimentary rocks will frequently yield paleolatitudes that are too low (Kent and Tauxe, 2005).

For Pangean paleogeographic reconstructions, traditional paleomagnetism methods have reconstructed a steady northward migration of the supercontinent from Permian (5°N) through Early Jurassic times (18°N) (Scotese, 1979 & 2003; Ziegler et al., 1997) (Figure 3). The total error in the paleomagnetic data for the position of Pangea is approximately a few degrees of latitude (Gibbs et al., 2002). Steiner (2003) used detrital hematite in Jurassic-age sedimentary rocks to define the movement of the supercontinent, which yielded low Pangean paleolatitudes (5-10°N) from the Early Permian through the Early Jurassic and migrating an additional 5°N during the Middle Jurassic.

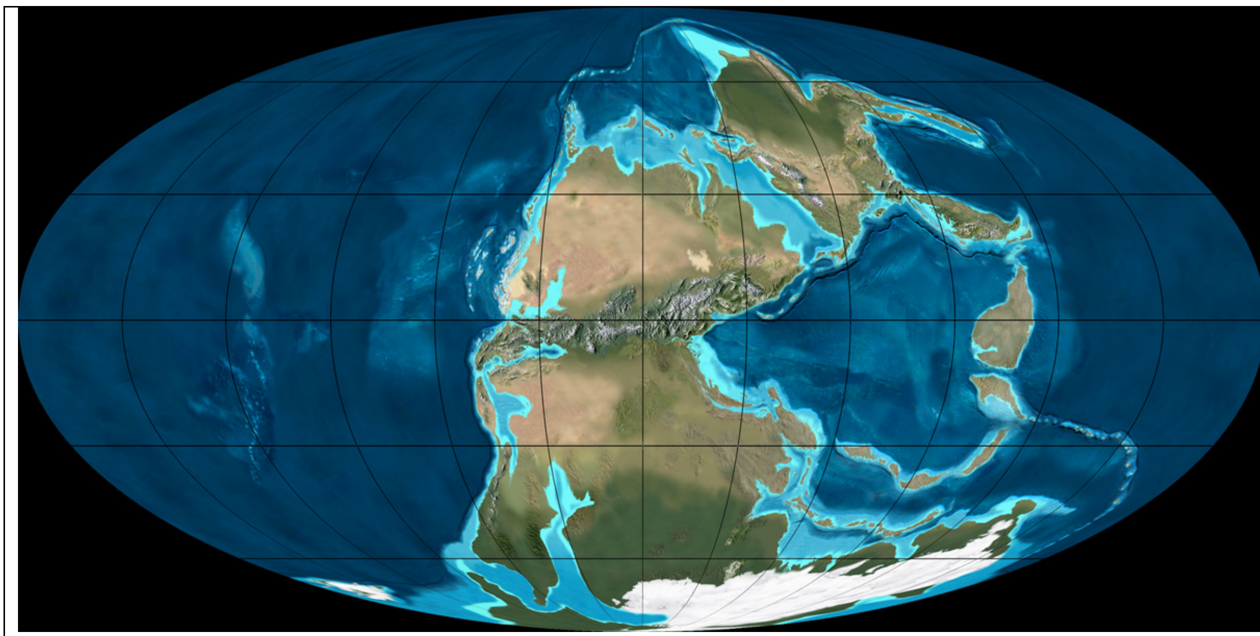

Figure 3. Paleogeographic map of Pangea. Note the unusual Eastern coastline and large embayment. Map by Ron Blakey. http://jan.ucc.nau.edu/~rcb7/

4. Monsoonal Circulation

The Pangean climate has been described as “seasonal” since Daugherty (1941) and “monsoonal” since Robinson (1973). An important feature of monsoonal circulation is cross-equatorial flow, a product of the thermal and pressure contrast between the winter and summer hemispheres (Dubiel et al., 1991). The modern Asian monsoon shows a 180° reversal of wind directions between the winter and summer months (as defined for the northern hemisphere). During the summer months southern hemisphere south-easterly trade winds blow over the Indian and eastern Atlantic oceans, but as they reach the equator these winds turn abruptly and flow south-westerly into low-pressure zones over India and West Africa (Loope et al., 2004) (Figure 4). During the winter months these winds are reversed, flowing north-easterly from Asia over the Indian Ocean, turning abruptly to north-westerly winds as they reach the equator (Loope et al., 2004) (Figure 4). The weakening of the Coriolis force at the equator allows this reversal of wind directions to occur (Loope et al., 2004; Parrish and Peterson, 1988).

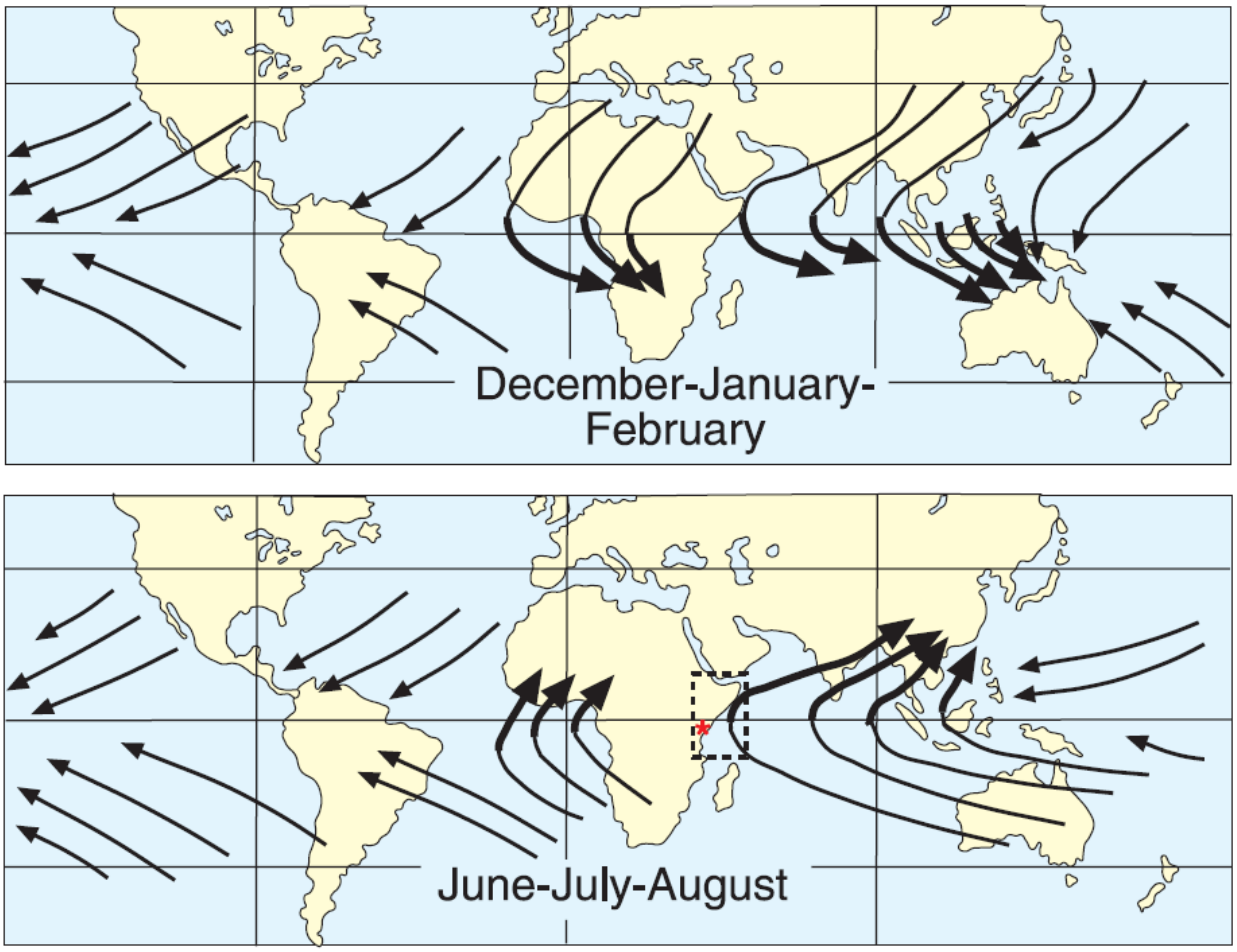

Figure 4. Diagram of the modern Asian monsoon, showing the cross-equatorial flow characteristic of all monsoonal circulation systems. Bold arrows are westerly winds. Note that in some locations, trade winds are reoriented to westerlies before crossing the equator. From Loope et al. (2004).

Vertical circulation cells driven by sensible heating are key features of monsoons, and are created by the thermal differences between oceans and continents. During early summer the continents heat up more quickly than ocean waters, causing convection of warm air above the continent. Humid, dense air over the cooler ocean water flows towards the area of low pressure above the continent. Latent heat release plays an important role in maintaining the convection of the monsoonal system (Dubiel et al., 1991).

Two dominant features of monsoonal circulation are 1) abundant, yet seasonal rainfall, concentrated in the summer months, and 2) small annual temperature fluctuations (Dubiel et al., 1991). A large indentation existed at the equator along the eastern side of Pangea (Figure 3), setting up the ocean/land interface necessary for monsoonal climates. During the early stages of Pangea development in the Late Carboniferous, a large mountain chain formed on the equator as the result of continental collision. These mountains and the associated interior plateau may have enhanced the monsoonal circulation, much as the Himalayas and the Tibetan Plateau influence the modern Asian monsoon (Dubiel et al., 1991). However, due to their position on the equator, these mountains may have hindered the monsoonal circulation (Rowley et al., 1985). If this was indeed the case, full monsoonal circulation still would have been established in both hemispheres by the Triassic, when Pangea had moved north and the mountains had begun to erode (Parrish and Peterson, 1988).

5. Pangean Climate Models

Pangean atmospheric circulation models by Parrish and Peterson (1988) predict the presence of a subtropical high-pressure cells off the northwest coast of Pangea and a monsoonal low-pressure cell to the east of the supercontinent. The subtropical high-pressure cells are a stable and long-lived component of atmospheric circulation that form as a result of land-sea temperature differentials. Parrish and Peterson (1988) believe the summer winds were stronger and more important than the winter winds for aeolian dune-field development, representing the southeastern limb of a subtropical high-pressure (Parrish and Peterson, 1988). Larger summer temperature differences produce stronger summer winds, which explains why the measured wind directions of Peterson (1988) correspond best to the predicted summer winds as opposed to winter winds (see next section) (Parrish and Peterson, 1988). It is possible that dune fields located in the south-eastern portion of Pangea may have been influenced by summer monsoonal circulation, particularly the Cedar Mesa Sandstone. Patzkowsky et al. (1991) modeled easterly winter winds and northerly/northwesterly (summer monsoonal) winds for the Colorado Plateau during the Early Permian.

Loope et al. (2004) cite several models of Pangean atmospheric circulation which predict semi-arid equatorial zones and tropical westerlies (Gibbs et al., 2002; Chandler et al., 1992), including a shift from subtropical north-easterlies to tropical north-westerlies at approximately 10°N of the equator. However, Chandler et al. (2002) caution that these monsoonal systems are not the "megamonsoons" described by other authors (e.g., Dubiel et al., 1991), but instead are associated with localized mid-latitude pressure cells located near the coast that are influenced by topography and coastal geography. The monsoonal circulation patterns likely allowed the development of semi-arid deserts at low latitudes, differing from the modern distribution of semi-arid deserts located between 30°N and 30°S (Dubiel et al., 1991; Chandler et al., 2002). Similarly, the modern African Sahara desert is located at low latitudes and is influenced by the Asian monsoon (Loope et al., 2004).

Rowe et al. (2007) performed Early Jurassic climate simulations using the latest version of the Community Climate System Model from the National Center for Atmospheric Research. Simulations were performed using two paleogeography configurations: 1) the Colorado Plateau is located at approximately 20°N, and 2) the Colorado Plateau is shifted to approximately 10°S of the equator. This second configuration is used to fit with the conceptual monsoonal climate model that Rowe et al. (2007) have proposed for Pangea (see Section 8).

6. Early Permian Wind Data, Colorado Plateau

The direction of Early Permian sediment transport in south-eastern Utah, derived from aeolian cross-strata, indicates winds generally blew towards the southeast (present coordinates) (Peterson, 1988). Throughout the Pennsylvanian-Middle Jurassic the winds on the Colorado Plateau generally blew towards the southwest, south, or southeast (present coordinates) (Peterson, 1988; Dubiel et al., 1991; Loope et al., 2001). These measured winds correspond with the predicted summer subtropical circulation from circulation models, except during the Triassic when monsoon circulation was at a maximum and influenced wind patterns in the south-eastern portion of western Pangea and the southern Colorado Plateau (Parrish and Peterson, 1988). The winds shifted during the Late Jurassic and blew towards the northeast (present coordinates) (Peterson, 1988). This counterclockwise shift in wind patterns likely records the northward migration of western Pangea out of the subtropical circulation and into the belt of westerlies (Peterson, 1988; Parrish and Peterson, 1988).

Eolian dust, or loess deposits, can serve as proxy indicators of aridity and wind direction, although they lack information about wind intensity and velocity due to the small size and density of the particles (Soreghan, 1992). Loess commonly records high-resolution evidence of terrestrial climate and climate change (Soreghan et al., 2002a). Pye (1987) documented modern loess deposits that occur as a result of dry winds associated with either 1) depressions and cold fronts, or 2) monsoonal circulation, specifically circulation downwind of moist monsoon systems.

Soreghan et al. (2002b) inferred Early Permian (Wolfcampian) paleowinds by using U-Pb detrital-zircon geochronology and determining the provenance (i.e. source location) of detrital zircons from loess deposits in New Mexico and south-eastern Utah. The New Mexico samples contain zircons derived from the Ancestral Rocky Mountains to the west, and zircons derived from the Appalachian-Ouachita-Marathon Uplift to the east. The Utah samples contain zircons derived from the western Mojave terrane located near present-day California and Arizona border (Soreghan et al., 2002b). Results indicate that New Mexico experienced both westerly and easterly paleowinds. Meanwhile, results indicate that Utah experienced unidirectional westerly winds. It is likely that the high topography of the Ancestral Rocky Mountains acted as a wind block, sheltering south-eastern Utah from the easterly winds recorded in New Mexico (Soreghan et al., 2002b). These results are consistent with the predictions from Pangean climate models and paleowind data from aeolian deposits.

The Cedar Mesa Sandstone is an Early Permian (Wolfcampian) succession of wind-blown, eolian strata exposed in south-eastern Utah (Figure 5). The Cedar Mesa Sandstone is a member of the Cutler Group and the distal, arid component of a fluvial system draining the Uncompahgre Uplift (Mountney, 2006) (Figure 6). Peterson (1988) indicates that northwesterly winds were responsible for development of the Cedar Mesa Dune Field. The Cedar Mesa Sandstone consists of vertically-stacked sequences of eolian deposits, each separated by an erosional surface. Loope (1985) proposed that these cycles of deposition and erosion (i.e. arid and humid times) were caused by regionally-extensive cyclical changes in climate, possibly driven by a glacio-eustatic mechanism. The Cedar Mesa Sandstone contains very few deposits of evaporite minerals, indicating that the prevailing paleoclimate was relatively humid and rates of surface evaporation did not exceed rates of ground water recharge via precipitation or local fluvial input (Mountney, 2006).

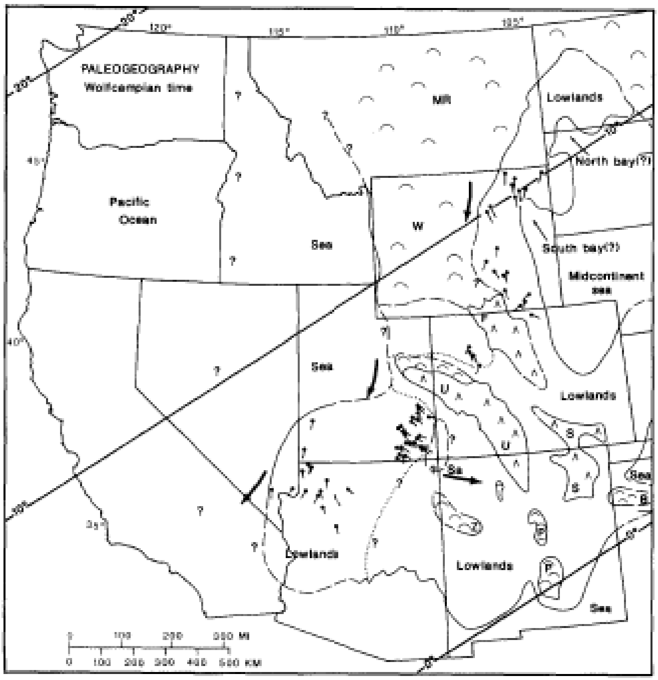

Figure 5. Paleogeographic map for Early Permian (Wolfcampian) showing dune migration "tadpoles", where the tail points downwind. The large arrows indicate wind patterns predicted from the climate model of Parrish and Peterson (1988). From Peterson (1988).

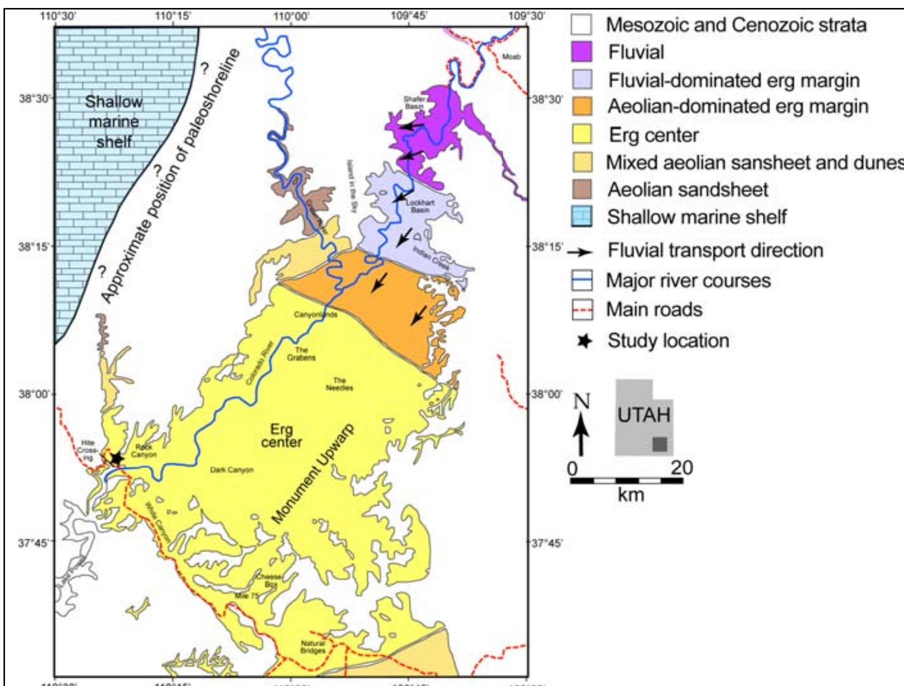

Figure 6. Location of Early Permian Cedar Mesa Sandstone outcrops, arrows represent inferred direction of paleowind from aeolian cross-strata. Modified from Mountney (2006).

Soreghan et al. (2002a) identified paleosols and loessites in the Early Permian (Wolfcampian) Lower Cutler beds from the south-western Paradox Basin that record a long-term transition from semiarid conditions during the Late Pennsylvanian to seasonally wet conditions during the Early Permian. Soreghan et al. (2002a) believe this climate transition represents intensification of the Pangean monsoonal circulation, with the moisture increase resulting from the seasonal presence of westerly winds. The vertical succession of paleosols and loessites record high-frequency fluctuations between dry glacial periods and wet interglacial periods, with increased sediment transport by wind during the glacial periods.

7. Pangean Paleoclimate Interpretations

Parrish and Peterson (1988) used the paleogeography results obtained from Scotese (1979) and the paleowind data from Peterson (1988) to interpret the dominant western equatorial Pangean winds as mid-latitude northern hemisphere anticyclones. Loope et al. (2004) used the detrital hematite paleomagnetism from Steiner (2003) and paleolatitudes inferred from aeolian cross-strata in Peterson (1988) to interpret the dominant winds in the Pangean Colorado Plateau as tropical north-westerlies that seasonally blew across the equator, rather than the subtropical anti-cyclones interpreted by Parrish and Peterson (1988), Dubiel et al., (1991), Loope et al., (2001).

Rowe et al. (2007) interpreted the aeolian cross-strata from Peterson (1988) as representing two different circulation belts within Pangea's monsoonal system. The northern portion of the Colorado Plateau records northeasterly trade winds, while the southern portion of the Colorado Plateau rocks show northwesterly winds, or a belt of tropical westerlies located equator-ward of the trade winds (Figure 7) (Rowe et al., 2007). Rowe et al. (2007) recognize that the detrital hematite paleomagnetism methods used in Loope et al. (2004) are incorrect, while the traditional paleomagnetism methods are correct. This means that western equatorial Pangea and the Colorado Plateau were located near/at the equator during the Permian, and migrated steadily northward to approximately 20°N by the Early Jurassic (Peterson, 1988; Scotese, 1979 & 2003).

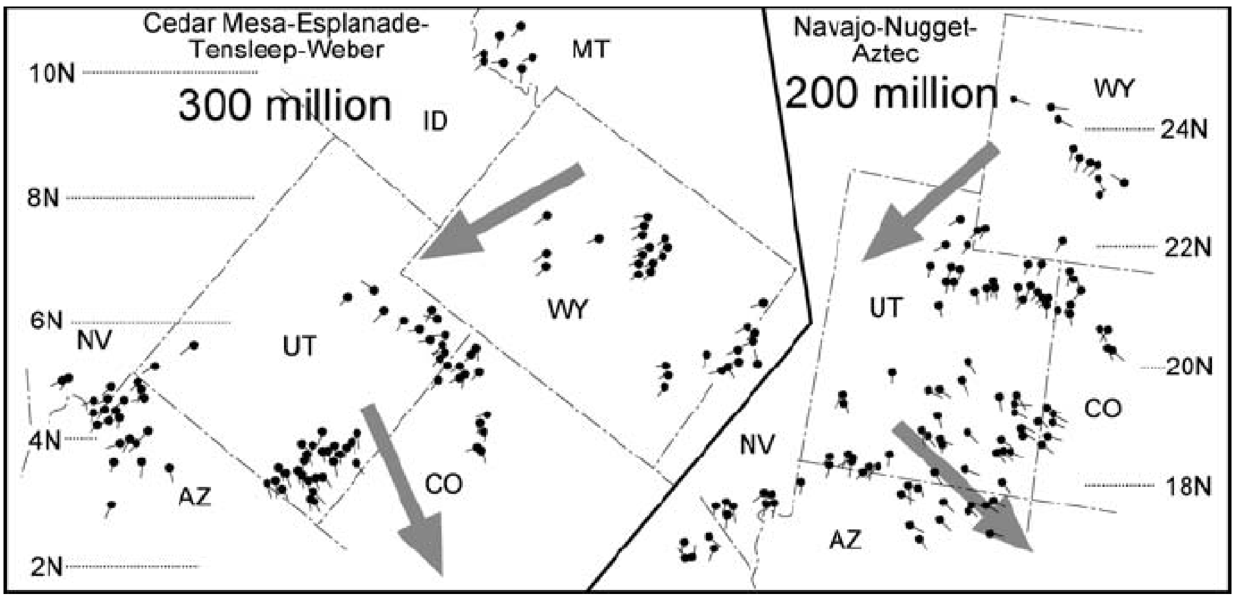

Figure 7. Dune dip directions for Early Permian (left) and Early Jurassic (right) aeolian sandstones. Each "tadpole" represents at least 20 dune dip measurements, and the tails point downwind. The large gray arrows show the flow of trade winds (upper arrows) and tropical westerlies (bottom arrows). From Rowe et al. (2007).

Rowe et al. (2007) recognize that their interpretation of two circulation belts (trade winds and tropical westerlies) could not have occurred at 20°N. They reason that in order for their climactic belt interpretation to be plausible, western equatorial Pangea must been located at or just south of the equator, where the northwesterly winds inferred from aeolian cross-strata in the southern Colorado Plateau represent cross-equatorial flow induced by strong summer monsoonal circulation in the southern hemisphere (Rowe et al., 2007). Rowe et al. (2007) cite "basic qualitative concepts of climate" and climate model results as evidence that the Colorado Plateau must have been situated on or south of the equator between Permian and Jurassic times, despite long-standing paleomagnetism data that states otherwise. Rowe et al. (2007) present results of the climate simulations that show a low pressure cell in the summer hemisphere and a high pressure cell in the winter hemisphere, regardless of the paleolatitude configuration used. Rowe et al. (2007) state that the simulations which place the Colorado Plateau in the southern hemisphere are the only simulations which produce northeasterly trade winds in the northern hemisphere that turn and become northwesterly winds south of the equator. Rowe et al. (2007) conclude by making the assumption that the wind patterns inferred from the aeolian cross-strata is correct and stating that one of the three following possibilities must be true: 1) the paleomagnetism-based paleolatitude reconstruction that show northward migration of the Colorado Plateau from the equator (Permian) to 20°N (Early Jurassic) is incorrect, 2) Early Jurassic circulation models that simulate a pattern of northeasterly winds north of the equator turning abruptly to northwesterly winds just south of the equator as a result of monsoonal circulation are incorrect, or 3) the circulation pattern recorded by aeolian cross-strata within the Pangean supercontinent represent an extreme climatic state that is far removed from anything we have experienced or previously reconstructed from historical proxy data.

8. Discussion

Rowe et al. (2007) make the assumption that their interpretation of the paleowinds and inferred dune migration directions from aeolian cross-strata is correct. However, Peterson (1988) warns that "random measurements throughout all or part of the eolian formation are what is mostly available in the literature, and a reevaluation based on more involved studies must, perforce, await future work" (p. 209). Peterson (1988) also cautions that "that statistical treatment of the [wind direction] data by rose diagrams and summary resultants may be an oversimplification that can be misleading" (p. 210). Perhaps the paleomagnetism data is not incorrect as Rowe et al. (2007) seem to suggest, but in fact, the interpretations of wind directions from Peterson's (1988) data set have been oversimplified and do not accurately represent the complexities in the ancient wind regimes.

9. Conclusions

Wind is an integral component of atmospheric circulation and overall climate. Proxy paleowind data can be inferred from aeolian deposits in the ancient rock record and used to reconstruct the climate of the supercontinent Pangea. Pangea existed for over 100 million years, from the Late Pennsylvanian through Jurassic, and the distribution of continents as one large landmass had a profound effect on the climate. Pangean climate models and deposits from the ancient rock record indicate a monsoonal circulation, yet inconsistencies exist between studies and the exact reconstruction of the circulation system remains uncertain. A more detailed examination of aeolian cross-strata is needed to correctly infer the Pangean paleowinds; the orientation of dunes needs to be taken into account when measuring the dune dip direction.

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