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LOWER PERMIAN TERRESTRIAL PALEOCLIMATIC INDICATORS IN NEW MEXICO AND THEIR COMPARISON TO PALEOCLIMATE MODELS

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Abstract.—During Early Permian time, most of New Mexico occupied a position within ten degrees north of the equator in western Pangea. Wolfcampian paleoclimatic indicators, including paleosols, vertebrate fossils, plant fossils, and fluvial-channel architecture, suggest a warm, semi-arid to sub-humid paleoclimate characterized by seasonal precipitation. In contrast, widespread eolian sedimentation by northeasterly winds and evaporite precipitation during deposition of the Leonardian Yeso and Glorieta formations point to a more arid paleoclimate. Most numerical paleoclimatic models support the overall warm, seasonally dry paleoclimate, although some models predict greater precipitation in western equatorial Pangea than is indicated in the rocks.

The dry paleoclimate in western equatorial Pangea probably resulted from the breakdown in zonal circulation due to the large size of Pangea, as well as an orographic effect of the ancestral Rocky Mountains, although the latter is not viable during Leonardian time when the mountains in New Mexico were eroded and onlapped. The increase in aridity from Wolfcampian to Leonardian time may have been influenced by the northward shift of Pangea, melting of continental glaciers in Gondwana, and/or a greenhouse effect due to increasing concentration of carbon dioxide in the atmosphere.

INTRODUCTION

By Pennsylvanian and Early Permian time, most of the continents of the earth had combined into the supercontinent of Pangea (Fig. 1). There is considerable scientific interest in the climate that existed on Pangea, because its large size may have caused major disruptions of zonal circulation and because, like today, continental glaciers existed near the south pole early in the history of the supercontinent. There are two common approaches to the interpretation of paleoclimate, numerical modeling and paleoclimatic indicators. Paleoclimatic modeling involves applying the physics that controls modern climate to ancient geography and includes both energy balance and general circulation models (Crowley and North, 1991). Paleoclimatic indicators represent rock types or features within rocks that only develop under specific climatic conditions. Whenever possible, the two approaches should be used together to provide the most accurate interpretation of paleoclimate.

During Early Permian time, New Mexico was situated less than ten degrees north of the equator in western equatorial Pangea (Fig. 1). At this time, the northern and central parts of the state were occupied by nonmarine depositional systems, whose rocks are widely exposed and display several types of paleoclimatic indicators. The goals of this study are: (1) to describe and interpret Lower Permian terrestrial paleoclimatic indicators in New Mexico, (2) to compare the results with Permian paleoclimatic models, and (3) to discuss the variables that may have affected Pangean paleoclimate.

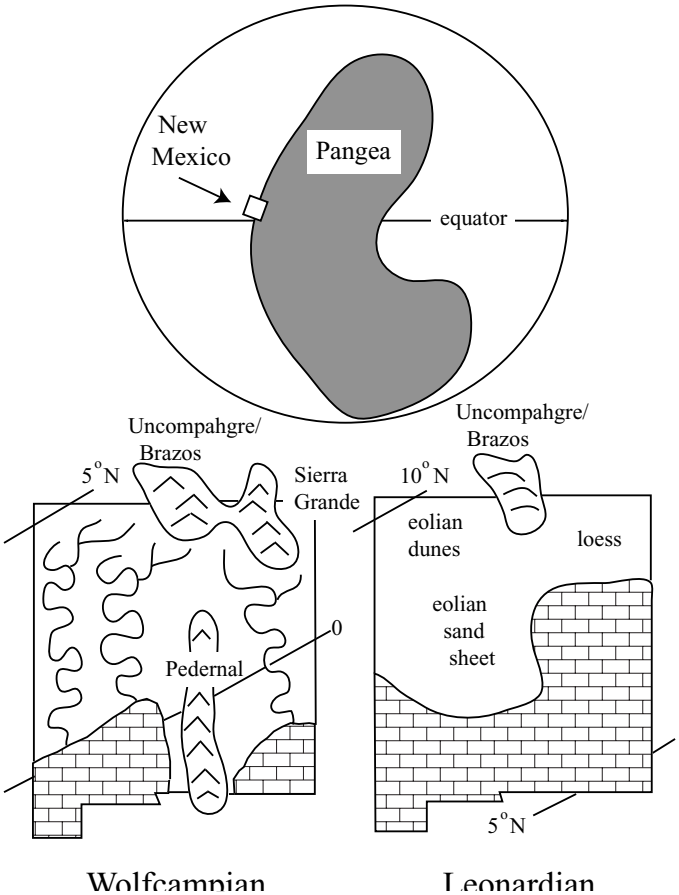

FIGURE 1. Paleogeography of New Mexico during Early Permian time, based on Baars (1962). Kottlowski (1963), Mack et al. (1995), Ziegler et al. (1997), and Dinterman (2001).

TECTONIC AND STRATIGRAPHIC SETTING

During Pennsylvanian and Early Permian time, New Mexico and adjacent states experienced the ancestral Rocky Mountains deformational event, which produced a series of Precambrian-basement-cored block uplifts and intermontane basins (Fig. 1; Kluth and Coney, 1981; Kluth, 1986; Ye et al., 1996; Baltz and Myers, 1999). Lower Permian sedimentary rocks are widely exposed throughout the state and generally exhibit a facies change from terrestrial redbeds in the north to shallow-marine carbonates and evaporites in the south (Fig. 2; Baars, 1962; Kottlowski, 1963). During Wolfcampian time, the Pedernal, Sierra Grande, and Brazos uplifts, the latter of which may have been the southern extension of the Uncompahgre uplift in Colorado, supplied coarse arkosic detritus to adjacent basins (Pray, 1961; Baars, 1962; Broadhead, 1997; Baltz and Myers, 1999). By early Leonardian time, the Sierra Grande and Pedernal uplifts were

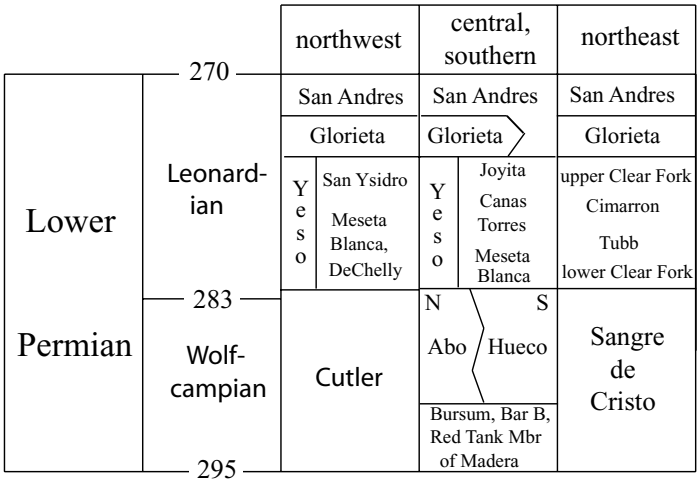

FIGURE 2. Lower Permian stratigraphy in New Mexico, adapted from Baars (1962), Kottlowski (1963), Roberts et al. (1976), Eberth and Berman (1993), and Tidwell et al. (1999).

onlapped by the Yeso Formation, although parts of the central Pedernal uplift remained topographically high during early Yeso deposition (Kelley, 1971; Kottlowski, 1985). The Brazos/Uncompahgre uplift probably continued to supply arkosic sediment during Yeso deposition, although it was much reduced in relief (Baltz and Myers, 1999).

Terrestrial paleoclimatic indicators in this report are from the Wolfcampian Bursum, Abo, Cutler, and Sangre de Cristo Formations, as well as from the Red Tanks Member of the Madera Formation. The marine Hueco Formation also contains petrified wood. Among the Leonardian formations, only the Yeso and Glorieta formations have terrestrial sedimentary rocks with paleoclimatic indicators (Fig. 2).

LOWER PERMIAN PALEOCLIMATIC INDICATORS IN NEW MEXICO

Wolfcampian Indicators

Four types of paleoclimatic indicators are present in Wolfcampian strata in New Mexico: (1) paleosols, (2) vertebrate fossils, (3) paleobotany, and (4) fluvial depositional systems. They provide evidence on temperature, precipitation, and their seasonality.

Paleosols

Mature, well-drained paleosols are well developed and widely exposed geographically and stratigraphically in the Cutler, Sangre de Cristo, and Abo formations, and have been described by Soegaard and Caldwell (1990), Mack et al. (1991, 1995, 2003) and Eberth and Miall (1991). The two pedogenic features most diagnostic of paleoclimate are pedogenic carbonate and vertic features. Pedogenic carbonate is most commonly developed in red, originally non-calcareous overbank mudstones, but also is present in the upper parts of crevasse-splay and channel sandstones and siltstones. The most common form of pedogenic carbonate is scattered nodules and tubules, corresponding to stage II morphology of Gile et al. (1966) (Fig. 3A), but it may also consist of massive beds of stage III or higher morphology. A soil origin for the carbonate is indicated by: (1) predominance of fine-grained, low-magnesium calcite (micrite), (2) association with peds and root traces, (3) position in lower part of paleosol profiles, and (4) rip-up clasts of soil carbonate at the base of fluvial channels.

The retention of carbonate in modern soils is primarily related to mean annual precipitation, although temperature, seasonality of precipitation, composition of parent material, and concentration of dissolved calcium ions in rainwater may play subordinate roles (Birkeland, 1999). Based on modern soils, pedogenic carbonate is rare in regions that receive above 80 cm/yr and is absent above 100 cm/yr precipitation in non-calcareous parent material (Retallack, 1994; Royer, 1999). A lower limit for annual precipitation is suggested by the paucity of gypsum in Abo, Cutler, and Sangre de Cristo paleosols. In modern soils, pedogenic gypsum only appears in areas receiving less than 25-30 cm/yr precipitation (Watson, 1992). Gypsum is rare in Abo paleosols (Mack et al., 1995), and where it is present, it commonly cross-cuts pedogenic features, suggesting it may be diagenetic rather than pedogenic.

Vertic features in Abo and Cutler paleosols, including wedge-shaped peds, slickensides, and deep desiccation cracks, are also reliable paleoclimatic indicators. Wedge-shaped peds consist of meter-scale, concave-upward fractures developed in red mudstones and argillaceous siltstones (Fig. 3B). Also present in these same parent rocks are slickensides, which exist as mm- to cm-scale striated patches within blocky mudstones, superimposed on thin coatings of manganese oxide, and on the undersides of wedge-shaped peds. Petrographically, slickensides display zones of oriented clay minerals (stress cutans). Less common are deep desiccation cracks that extend from 50 to 100 cm into pedogenically modified mudstones.

Vertic features develop as a result of alternating shrinking and swelling of expandable clays and are best developed in modern soils that experience a four to eight month dry season (Ahmad, 1983). Vertic features in paleosols have been used to suggest strongly seasonal precipitation in a variety of studies (Blodgett, 1988; Smith, 1990; Gustavson, 1991; Driese and Foreman, 1992; Marriott and Wright, 1993).

Vertebrate paleontology

Wolfcampian vertebrate fossils have been collected at nine major sites in New Mexico and comprise various species of fishes, amphibians, and reptiles, including the pelycosaurian reptiles informally referred to as mammal-like reptiles (Berman, 1993). In addition, amphibian and reptilian footprints are present in the Abo and Sangre de Cristo Formations (Hunt et al., 1990, 1995). Particularly diagnostic of paleoclimate are the large pelycosaurian reptiles *Ophiacodon*, *Dimetrodon*, and *Edaphosaurus*, which ranged from 1-3 m in length and probably weighed from 50-200 kg (Kemp, 1982; Cowen, 2000). These reptiles are generally considered to have been ectothermic (body temperature dependent on absorption of heat from the environment: Pough and Gans, 1982), because: (1) they are reptilian in morphology, and modern reptiles are ectothermic, (2) they have lamellar bone structure similar to modern ectothermic reptiles (Ricqles, 1974), (3) their populations feature a high predator-to-prey ratio characteristic of modern ectothermic populations (Bakker, 1975), and (4) *Dimetrodon* and

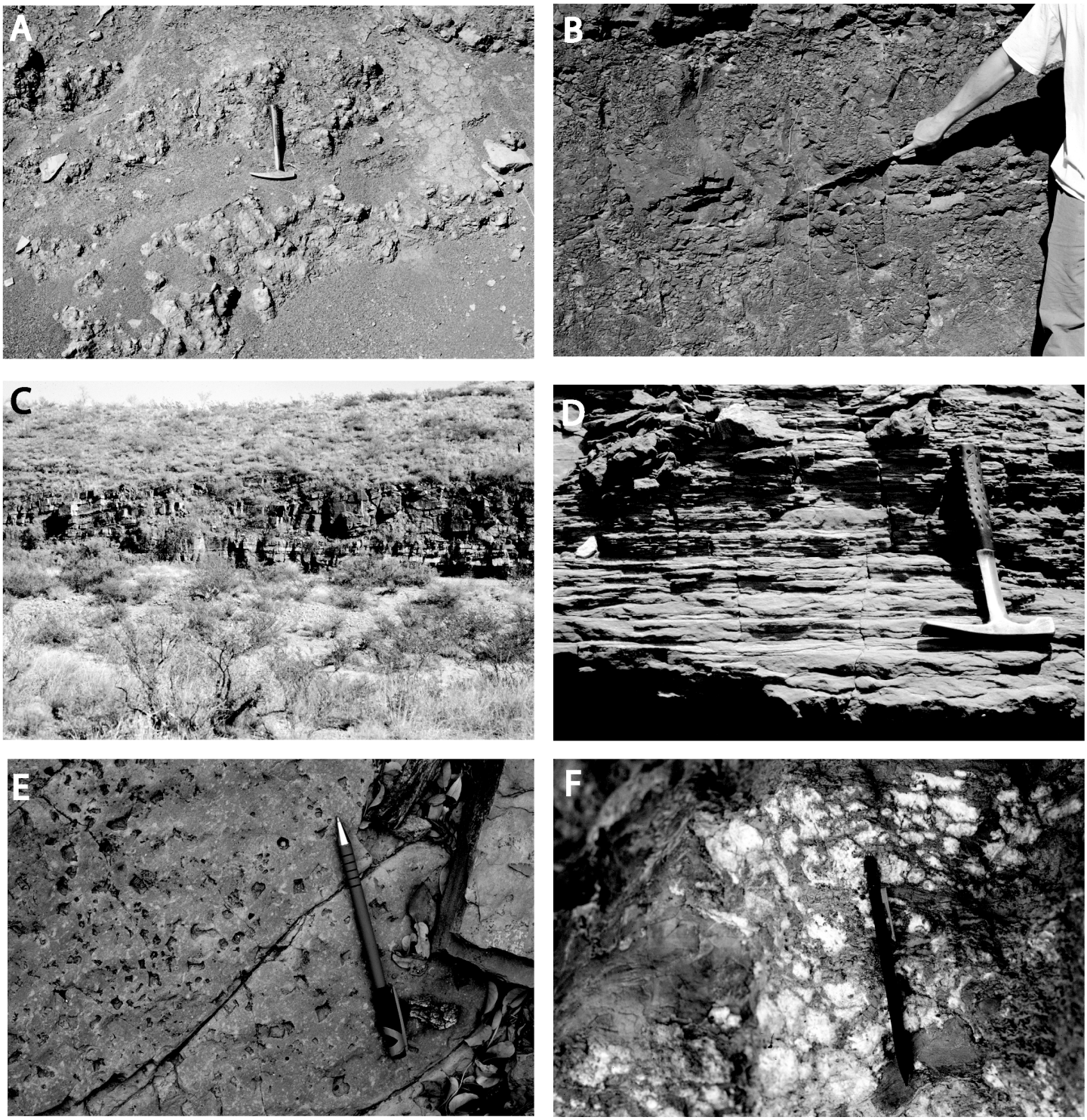

FIGURE 3. Lower Permian paleoclimatic indicators in New Mexico. A. Calcic nodules and tubules in a paleosol of the Wolfcampian Abo Formation; hammer is 25 cm long. B. Wedge-shaped peds in a paleosol of the Wolfcampian Abo Formation. C. Lateral accretion sets in a fluvial channel of the Wolfcampian Abo Formation; outcrop is 7 m high. D. Eolian wind-ripple cross-laminae in the lower Leonardian Meseta Blanca Member of the Yeso Formation; hammer is 25 cm long. E. Halite casts in the lower Leonardian Meseta Blanca Member of the Yeso Formation; pen is 10 cm long. F. Pedogenic gypsum in the lower Leonardian Yeso Formation; pen is 10 cm long.

Edaphosaurus had dorsal sails that were probably used for thermoregulation (Bramwell and Fellgett, 1973; Bennett, 1996).

The geographic distribution of viable populations of modern large, ectothermic reptiles is limited by temperature. Because of large volume-to-surface area ratio, large ectotherms heat up and cool down more slowly than small ectotherms. Moreover, behavioral processes, such as basking or rapid motion, are less effective strategies of thermoregulation for large ectotherms than for small

ones. As a consequence, modern large ectotherms tend to live in tropical and subtropical regions with mild temperature and little daily or seasonal temperature fluctuation (Cowen, 2000). Indices of reptilian body temperature that are particularly useful climate indicators are: (1) activity temperature, which is the range of body temperatures of the active animal, (2) critical thermal minimum, the temperature at and below which narcosis occurs, which effectively prevents locomotion and the righting reflex, (3) critical thermal maximum, the temperature above which locomotary activity becomes disorganized and the animal loses its ability to escape lethal conditions, and (4) lethal temperature, the temperature at or above which the animal dies (Pough and Gans, 1982). Because ectotherms have body temperatures at or very close to the temperature of their surroundings, the various body temperature indicators listed above are reasonable proxies for the air temperatures at which the animals function.

The largest reptiles living today are alligators, crocodiles, and the varanid lizards, which include the goannas of Australia and the Komodo Dragon of Indonesia. The North American alligator, *A. mississippiensis*, which may have a mass in excess of 180 kg, has a minimum critical temperature of 4 to 5° C (Brisbin et al., 1982), an activity range of 26-37° C, and a lethal temperature of 38-39° C (Avery, 1982). Similar values characterize the largest of the modern varanid lizards. *V. giganteus*, which is up to 2 m long, has an activity temperature of 27-40° C, *V. komodoensis*, which attains a length up to 3 m long and a mass of 100 kg, has an activity temperature of 25-41° C and a critical maximum temperature of 43° C, and *V. varius* (2 kg mass) has an activity temperature of 33-37°C, a critical maximum temperature of 43-45° C, and a critical minimum temperature of 5° C (Spellenberg, 1972; McNab and Auffenberg, 1976; Auffenberg, 1981; Heatwole and Taylor, 1987; Green et al., 1991; King and Green, 1993).

Assuming the large Lower Permian ectotherms of New Mexico were similar to the largest reptiles on the earth today, then it is possible to estimate the temperature conditions during Early Permian time in New Mexico. Daytime temperatures all through the year probably averaged between 25 and 41° C, and the minimum temperature probably was no lower than 5° C for any significant length of time. A maximum temperature is more difficult to estimate, because reptiles can shelter themselves during the hottest part of the day, so that the air temperature may rise above the critical maximum and lethal temperatures of the animals without killing them. It seems unlikely, however, that the large Wolfcampian ectotherms could have survived sustained temperatures in excess of 45° C. Although these temperature estimates for the Early Permian of New Mexico are reasonable given its equatorial paleolatitudinal position, this type of uniformitarian approach is not without its detractors, who argue that extinct organisms need not have been like their closest living relatives (Ostrom, 1970).

Another Lower Permian fossil vertebrate in New Mexico with paleoclimatic implications is the dipnoan (lungfish) *Gnathorhiza* (Berman, 1976, 1979). Like its modern counterpart, *Gnathorhiza* presumably survived the dry season by aestivating in a burrow. In addition to finding bones of *Gnathorhiza* in the Abo Formation near Socorro, including one site where the fish fossil was still in its burrow, lungfish burrows without bones have been found in the Sangre de Cristo Formation (Vaughn, 1964) and in the Abo Formation (Bailey, 2000). The presence of *Gnathorhiza* and lungfish burrows in New Mexico argues for seasonal precipitation.

Paleobotany

Despite being found at dozens of locations in the state, including a new site discovered by the author in Lucero arroyo near Las Cruces (SE1/4, NE1/4, SE1/4, Sec 6, T21S, R1E), Wolfcampian leaf fossils are relatively rare and largely restricted to impressions in siltstones and sandstones. The paleoflora is dominated by conifers, particularly *Walchia*, seed ferns, and cordaites, which are generally considered to have been adapted to dry (xerophytic) conditions (Read and Mamay, 1964; Ash and Tidwell, 1982; Hunt, 1983; Tidwell et al., 1999). DiMichele and Aronson (1992) argue that these and other xerophytic plants began to dominate the basinal lowlands of the American Southwest as the climate became drier and more seasonal during Early Permian time.

A dissenting paleoclimatic interpretation comes from Tidwell and Munzing (1995), who examined one species of gingko and two species of conifer wood from the middle member of the Hueco Formation in south-central New Mexico. The wood either lacked or had broad growth rings, which Tidwell and Munzing (1995) interpreted to indicate a warm, humid climate without seasons. However, the provenance of the specimens of petrified wood is not known, because they are not in growth position and they are located in marine shale. Thus, the wood may have been transported large distances from somewhere other than New Mexico. Moreover, an abrupt change from broad earlywood to very narrow latewood, which appears in the two conifer samples of Tidwell and Munzing (1995), has been interpreted in Jurassic woods of England (Francis (1984) and Mongolia (Keller and Hendrix, 1997) to indicate seasonal precipitation.

Fluvial depositional systems

Throughout Wolfcampian time, most of the northern and central part of the state of New Mexico was occupied by rivers that flowed generally southward before emptying into a shallow sea (Fig. 1). Proximal to the Brazos/Uncompahgre uplift, the gravel- and sand-bed rivers were braided or anastomosing in character (Soegaard and Caldwell, 1990; Eberth and Miall, 1991). Southward, the rivers that deposited the Abo Formation consisted of very fine sand- and silt-bed, high-sinuosity channels with depths up to 8 m and widths up to 50 m (Mack et al., 1995, 2003). Point-bar deposition in the distal channels is indicated by lateral accretion sets (Fig. 3C), whose surfaces display desiccation cracks from their upper to lower reaches (Mack et al., 1995, 2003).

The size of the distal rivers of the Abo Formation argues for sufficient discharge to maintain flow for hundreds of kilometers from the headwaters in northern New Mexico and southern Colorado to the sea in southern New Mexico. Although much of the precipitation that fed the rivers may have fallen in the northern mountains, it is unlikely the rivers could have maintained flow in relatively deep, broad channels over such distances across a hyperarid alluvial plain. The relatively large Abo rivers are consistent with the semi-arid to sub-humid conditions suggested by calcic paleosols that developed on the adjacent floodplains.

The presence of desiccation cracks on the lateral accretion surfaces indicates that discharge in the distal rivers fluctuated dramatically. This feature of Abo channels is consistent with strongly seasonal precipitation, in which the point bars migrated laterally during the rainy season and then were partially or wholly exposed during the dry season. However, it is not possible to prove that each lateral accretion set represents annual growth of the point bar, and it is possible that growth and exposure of the point bars occurred on a longer time scale, perhaps associated with decadal droughts.

Summary of Wolfcampian paleoclimate

The data cited above suggest that during Wolfcampian time New Mexico experienced a warm, semi-arid to sub-humid paleoclimate (Fig. 4). Daytime temperatures were probably in the range of 25-41° C, and winter temperature probably did not drop below 5° C for any significant length of time. Precipitation most likely ranged between 30 and 100 cm/yr, which falls in the semi-arid to sub-humid range in modern climatic classifications (cf. Strahler and Strahler, 1983). Although precipitation was probably strongly seasonal, there are no data to indicate whether the paleoclimate was summer-wet or winter-wet. However, modern equatorial, seasonal climates are summer-wet (cf. Strahler and Strahler, 1983).

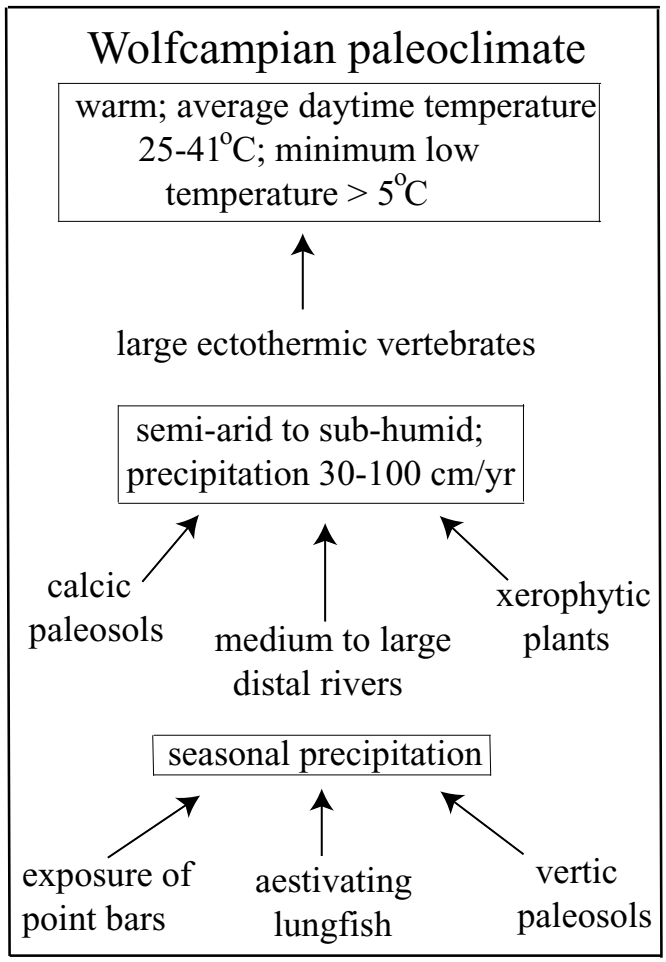

FIGURE 4. Summary of the interpretation of Wolfcampian paleoclimate in New Mexico based on terrestrial paleoclimatic indicators.

Leonardian Indicators

Paleoclimatic indicators in the Leonardian Yeso and Glorieta formations are largely restricted to depositional systems, which differ markedly from those in Wolfcampian strata. Vertebrate paleontology and paleobotany play a minor role in the interpretation of Leonardian paleoclimate because of the scarcity of fossils.

Paleontology

Easily identifiable vertebrate fossils have not been found in the Yeso and Glorieta Formations in New Mexico. However, large ectothermic amphibians and reptiles and the lungfish *Gnathorhiza* have been recovered from rocks in north-central Texas that are probably coeval to the Yeso and Glorieta formations and that were located at about the same paleolatitude as southern New Mexico. These vertebrates suggest that the paleoclimate in north-central Texas, and by inference in southern New Mexico, in Leonardian time was warm and had seasonal precipitation (Kemp, 1982; Eberth and Berman, 1993).

Charles B. Read (personal commun. in King, 1942) collected a *Supaia* flora from central New Mexico from what he considered to be the uppermost Abo Formation, but which Kottlowski (1963) assigned to the Meseta Blanca Member of the Yeso Formation. Because of stratigraphic uncertainty and because no individual taxa were listed, these possible Leonardian plant fossils are of little use in paleoclimate interpretation. However, xerophytic plant fossils collected from Leonardian rocks in north Texas are consistent with a dry paleoclimate characterized by seasonal precipitation (DiMichele et al., 2001).

Eolian and fluvial environments

The most common type of terrestrial sediment in the Yeso Formation is eolian sandstone (Mack and Suguio, 1991; Dinterman, 2001; Mack and Dinterman, 2002). During deposition of the Meseta Blanca Member of the Yeso Formation, the northwestern part of New Mexico was occupied by eolian dunes, represented by well-sorted sandstones with cross-beds up to 5 m thick. The Meseta Blanca Member in the central and southern parts of the state, along with the San Ysidro Member in northwestern New Mexico, was deposited on a broad eolian sand sheet characterized by eolian wind ripples (Fig. 3D). The Torres and Joyita Members also contain wind-rippled sandstones, and the Tubb Sandstone in northeastern New Mexico, which correlates with the upper part of the Meseta Blanca Member, has massive siltstones interpreted by Kessler et al. (2001) to be loessites. Most of the Glorieta Formation in northwestern New Mexico and the lower part in north-central New Mexico is eolian in origin (Dinterman, 2001). The majority of Glorieta beds were deposited as wind ripples, although a few cross-beds up to 4 m thick indicate the local existence of eolian dunes.

Fluvial sediments in the Yeso Formation consist of small sandstone channels and overbank red mudstones (Dinterman, 2001; Mack and Dinterman, 2002). The fluvial channels generally are less than 1 m thick and 10 m wide, and consist primarily of climbing current-ripple cross-laminae and numerous desiccation cracks. Fluvial sediment is very rare in the Yeso Formation and is largely restricted to the northern part of the state. Fluvial sedi-

ment has not been identified in the Glorieta Formation.

Widespread eolian sedimentation during deposition of the Yeso and Glorieta Formations suggests an arid paleoclimate. Although eolian sediment on the modern earth is not restricted to arid climates, the vast areas covered by eolian sediment during Yeso and Glorieta deposition are analogous to modern dune fields and sand sheets occupying regions of arid climate. Moreover, rare, small ephemeral fluvial channels in the Yeso and their absence in the Glorieta argue for an arid paleoclimate that was unable to maintain medium or large rivers among the dune fields or on the sand sheet, which contrasts with the moderately large rivers that flowed across most of the state into the southern sea during Abo deposition.

Yeso and Glorieta eolian cross-beds provide evidence of regional wind patterns. Southwest-directed paleocurrent data from the Meseta Blanca Member of the Yeso Formation and from the Glorieta Formation indicate prevailing northeasterly winds (Dinterman, 2001; Mack and Dinterman, 2002). Northeasterly winds are consistent with the expected direction of Early Permian trade winds in the region of the ancestral Rocky Mountains (Peterson, 1988).

Coastal salinas and sabkha environments

Interbedded with wind-rippled sandstone in southern exposures of the Meseta Blanca Member of the Yeso Formation are thin beds of green sandstone or intercalated sandstone and shale with wave oscillation ripples and displacive halite casts interpreted to represent coastal salinas (Fig. 3E; Dinterman, 2001; Mack and Dinterman, 2002). The upper members of the Yeso Formation also contain dolostones with fenestral fabric, cryptalgal laminae, brecciation, and secondary gypsum interpreted to have been deposited in intertidal and supratidal environments (Dinterman, 2001; Mack and Dinterman, 2002). The gypsum exists as displacive nodules or displays chickenwire texture, both of which indicate precipitation in the vadose zone of a soil (Fig. 3F; Watson, 1992). Growth of displacive halite in shallow brine pools and precipitation of pedogenic gypsum take place on modern sabkhas under arid climatic conditions (Butler, 1969; Shinn, 1983). Pedogenic gypsum generally occurs today in areas receiving less than 25-30 cm/yr of precipitation (Watson, 1992).

Summary of Leonardian paleoclimate

The Leonardian Yeso and Glorieta formations in New Mexico were deposited under arid paleoclimatic conditions, which promoted widespread eolian deposition and evaporite precipitation near and at the shoreline (Fig. 5). The dominant winds were northeasterly trade winds, which is consistent with a paleolatitudinal position less than ten degrees north of the equator. Despite little direct evidence from the Yeso and Glorieta formations, large ectothermic reptiles, xerophytic plants, and lungfish in north-central Texas suggest the paleoclimate was warm, and precipitation may have been seasonal.

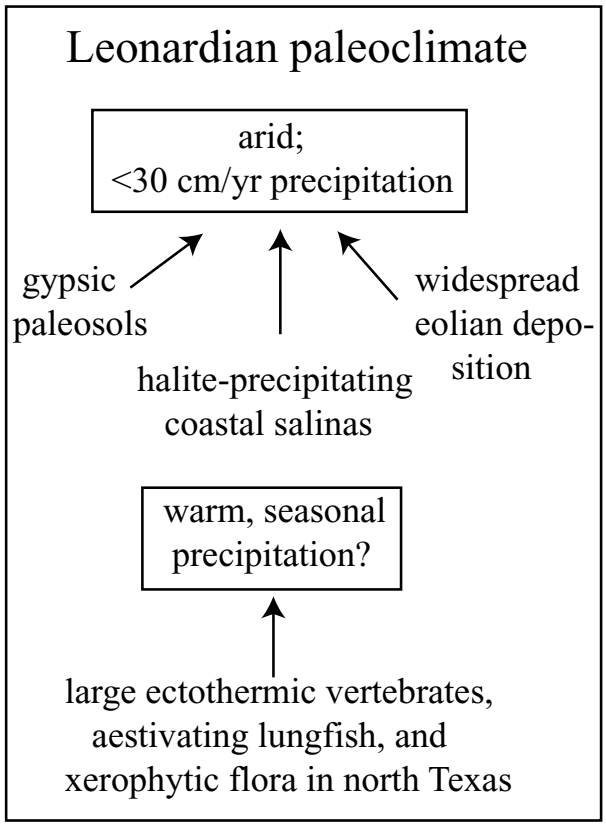

FIGURE 5. Summary of early Leonardian paleoclimate in New Mexico based on terrestrial paleoclimatic indicators.

PERMIAN PALEOCLIMATIC MODELS

Numerical models have been constructed using Pangean paleogeography from the Middle Permian Kazanian age, which post-dates the Leonardian (Kutzbach and Gallimore, 1989; Crowley et al., 1989; Kutzbach and Ziegler, 1993; Fawcett et al., 1994; Rees et al., 1999). These models are considered pertinent to this study, because Kazanian paleogeography is not substantially different than that of Wolfcampian and Leonardian times (Ziegler et al., 1997). In addition, the numerical model of Kutzbach (1994) was constructed for an "idealized" Pangea, but provides insight into Permian paleoclimate because the "idealized" Pangea is similar to that which existed in Early Permian time. The area of the models highlighted in this study is western equatorial Pangea between five and ten degrees north latitude, which corresponds to New Mexico in Early Permian time.

The models generally agree that western equatorial Pangea was warm and equable, with average temperatures between 25 and 35° C and a yearly range of temperature less than 5° C (Crowley et al., 1989; Kutzbach and Gallimore, 1989; Kutzbach and Ziegler, 1993; Kutzbach, 1994; Fawcett et al., 1994). These temperature calculations are consistent with the presence of large ectothermic reptiles in Wolfcampian strata of New Mexico and in Leonardian strata of north Texas.

There is less agreement among the models regarding precipitation in western equatorial Pangea. Model estimates of annual precipitation range from about 73 cm to 146 cm (Kutzbach and Gallimore, 1989; Kutzbach and Ziegler, 1993; Fawcett et al., 1994). The lower value is consistent with, but the upper value is too high for the retention of calcite in Wolfcampian paleosols, and even the lower value is too high for the retention of gypsum in early Leonardian paleosols. Kutzbach and Gallimore (1989) show an annual

moisture deficit (precipitation minus evaporation) in western equatorial Pangea, although the value may have been near zero in the Spring and Summer. A moisture deficit is essential to precipitation of carbonate and evaporites in soils. The model of Rees et al. (1999) predicts a tropical-summerwet climate for western equatorial Pangea, which is consistent with paleoclimatic indicators in Lower Permian rocks, but the model does not provide absolute values of precipitation. The model of Kutzbach (1994) predicts a tropical climate with year-round precipitation (Af climate in the Koppen system), which is at odds with the paleoclimate indicators in both Wolfcampian and Leonardian strata.

The direction and relative strength of winds have been calculated in the models of Kutzbach and Gallimore (1989), Kutzbach and Ziegler (1993) and Kutzbach (1994), which indicate strong northeasterly winds in the Winter, milder northeasterly winds in Spring and Fall, and weak northwesterly winds in the Summer. This suggests that eolian cross-beds in the Yeso and Glorieta Formations were created during the Winter, Spring, and Fall.

DISCUSSION

Origin of Equatorial Aridity

The dry paleoclimate of New Mexico in Early Permian time, based on paleoclimate indicators and most numerical models, is anomalous given a paleolatitudinal position within five to ten degrees north of the paleoequator. On the earth's surface today, equatorial regions are characterized by abundant precipitation (>100-250+ cm) equally distributed throughout the year, although seasonality of precipitation increases steadily away from the equator (Strahler and Strahler, 1983). It has been argued that the large size of Pangea and its nearly symmetrical distribution with respect to the equator would have disrupted normal zonal circulation, resulting in unusually dry and seasonal paleoclimate, particularly at mid to high paleolatitudes (Kutzbach and Gallimore, 1989; Parrish, 1993). A scenario that may explain the overall aridity, seasonality of precipitation, and seasonal winds in New Mexico during Early Permian time is illustrated in Figure 6. During the Summer, a low pressure cell may have developed over the northern part of Pangea, deflecting the band of high precipitation (intertropical convergence zone: ITZ) northward, providing less precipitation to equatorial New Mexico than it would have received under normal conditions of zonal circulation. It is also possible that the ITZ completely broke down in the western part of the Northern Hemisphere, providing summer dryness throughout a broad latitudinal range of western equatorial and subtropical Pangea. Winter dryness in New Mexico could have resulted from a combination of seasonal southward shifts of the intertropical convergence zone and subtropical high pressure cell (STH), as well as from the influence of a large continental high pressure cell located at mid- to high-latitudes in the northern hemisphere. Winds blowing out of the continental high also could have been responsible for strong northeasterly winds in the Winter.

Another possible contributing factor for the aridity of New Mexico in Early Permian time is an orographic effect of the ancestral Rocky Mountains (Read and Mamay, 1964; Mack et al., 1977). In this model, the northeasterly trade winds were blocked by the mountains, causing increased precipitation on their windward and decreased precipitation on their leeward sides. This may have been important in Wolfcampian time, because the

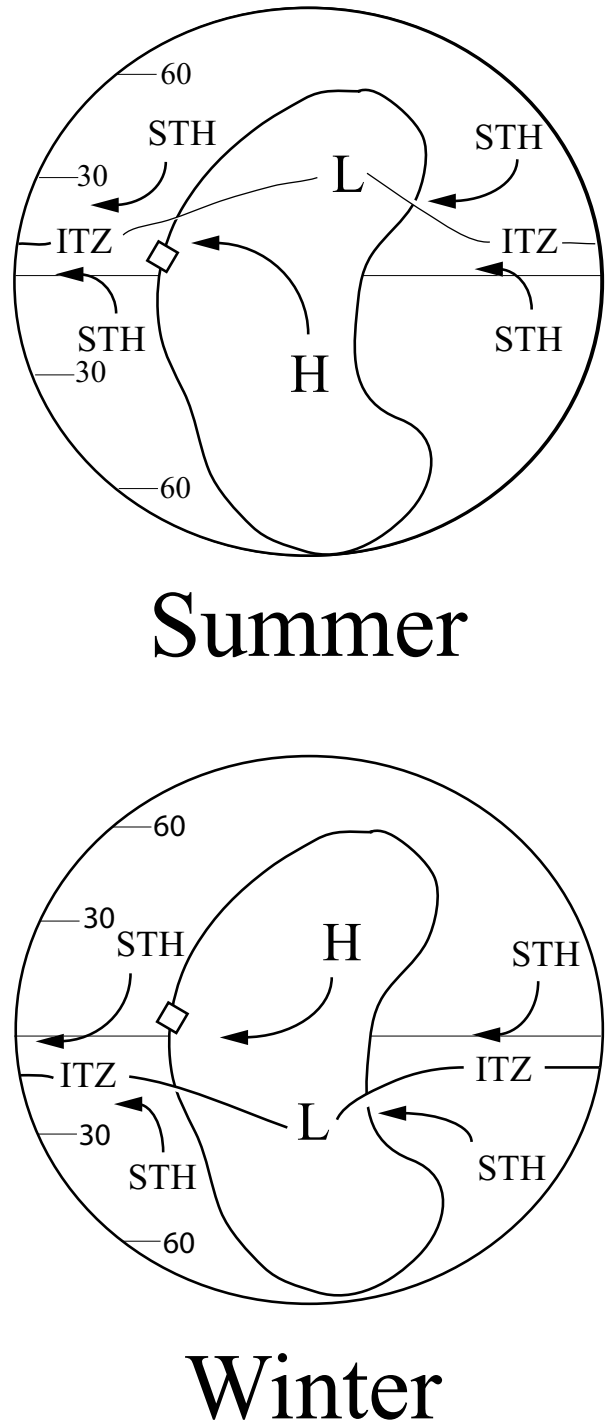

FIGURE 6. Qualitative model of zonal circulation on Pangea during Early Permian time, adapted from Parrish (1993). ITZ=intertropical convergence zone; STH=subtropical high; L=continental low; H=continental high. Arrows denote wind directions. White box is approximate location of New Mexico.

Sierra Grande and Pedernal Mountains were high and Wolfcampian eolian sandstones in Colorado and Wyoming indicate the existence of northeasterly winds (Kottlowski, 1963; Peterson, 1988). An orographic effect in New Mexico is less viable in Leonardian time, however, because the Sierra Grande and Pedernal Mountains had been reduced in relief and onlapped by the Yeso Formation (Kottlowski, 1963, 1985; Roberts et al., 1976).

A third factor that may have contributed to Early Permian aridity in New Mexico is upwelling of cold marine currents along the western coast of equatorial Pangea. Paleowind indicators for both Wolfcampian and Leonardian time show a component of shore-parallel northerly and onshore-directed northwesterly winds in coastal areas of northern Arizona and southeastern Utah (Peterson, 1988). Winds parallel or oblique to the coast commonly create offshore-directed surface ocean currents and the consequent upwelling of deep water along the coast (Parrish, 1998). The upwelling cold, deep water could have generated a local high pressure cell and associated aridity, as occurs today in the Atacama Desert of Peru. Although there is evidence of Late Permian upwelling father north in the form of the Phosphoria Formation, there are no Lower Permian phosphatic marine deposits near New Mexico nor is there any evidence at this time of cold-water marine deposits.

Increasing Aridity Through Time

Lower Permian paleoclimatic indicators in New Mexico suggest an increase in aridity from Wolfcampian to Leonardian time. There is as yet no consensus on the cause(s) of this change. One possibility is northward shift in paleolatitude of New Mexico from Wolfcampian to Leonardian time (Kessler et al., 2001). Several of the numerical models indicate a decrease in precipitation northward from the equator in western Pangea (Kutzbach and Gallimore, 1989; Kutzbach and Ziegler, 1993; Kutzbach, 1994), and the model of Rees et al. (1999) postulates a boundary in western Pangea near ten degrees north that separates tropical summer-wet to the south from desert to the north. If this boundary existed in Early Permian time, then New Mexico may have drifted across it from Wolfcampian to Leonardian time. Although global reconstructions suggest that New Mexico shifted northward during Early Permian time, the amount was only a few degrees of latitude and perhaps not far enough to cross the climatic boundary (Ziegler et al., 1997).

A second possibility for increasing aridity in New Mexico during Early Permian time is the melting of continental glaciers in Gondwana. Continental glaciers were widespread in the southern hemisphere of Pangea from latest Pennsylvanian into early and middle Wolfcampian time (Asselian age), at which time they began to retreat and ultimately to disappear by late Early Permian (Leonardian) or early Late Permian (Caputo and Crowell, 1985; Visser, 1997; Lindsay, 1997; Dickins, 1997; Lopez-Gamundi, 1997). Although the disappearance of continental glaciers undoubtedly affected global temperature gradients, it is not clear how it would have affected equatorial precipitation.

Finally, increasing aridity in New Mexico and elsewhere on Pangea during Early Permian time may have been influenced by rising global temperature due to an increase in concentration of atmospheric carbon dioxide. The theoretical model of Berner (1994) and measurements of $\delta^{13}C$ of paleosol carbonate by Ekart et al. (1999) imply a sharp increase in atmospheric carbon dioxide in Early Permian time, which may have caused greenhouse warming. Once again, the role this process would have had on equatorial precipitation has not been worked out.

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