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PALEOCLIMATIC SETTING OF THE UPPER JURASSIC MORRISON FORMATION

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The Upper Jurassic Morrison Formation was deposited near the western margin of Laurasia, inboard of the western cordilleran range. Global atmospheric circulation patterns during the Late Jurassic are thought to have been more zonal than the previous Early and Middle Jurassic meridional patterns characteristic of the Pangaean megamonsoon. The paleoclimate of the Morrison basin is interpreted to have been semi-arid with some seasonal rainfall. Climate models suggest the area was in a region under the influence of subtropical westerly winds. This is supported by paleowind directions from eolian sandstones. An interpretation of low annual rainfall, due to rain-shadow effects from the mountains to the west, is supported by the presence of eolian sandstones, evaporite deposits, saline, alkaline lake facies, and calcareous paleosols preserved in the Morrison. However, other evidence, including plant and invertebrate fossils, indicates that some areas had bodies of perennial water.

Keywords: Morrison Formation; Atmospheric circulation; Semi-arid; Seasonality

INTRODUCTION

The Upper Jurassic Morrison Formation was deposited during a time of major change in global paleoclimate (Vakhrameyev, 1982; Parrish, 1992). The supercontinent Pangaea, assembled during the Late Paleozoic and Early Mesozoic, had broken up into Gondwana and Laurasia. Megamonsoonal or meridional atmospheric circulation patterns, characteristic of Pangaean time (Parrish and others, 1986; Kutzbach and Gallimore, 1989; Crowley and others, 1989; Dubiel and others, 1991; Parrish, 1993a), gave way to

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more zonal patterns as the continents dispersed (Parrish and Curtis, 1982; Parrish and Doyle, 1984).

The Morrison depositional basin, which was located along the western margin of Laurasia in the low mid-latitudes (Fig. 1), was in a unique position to record evidence of these paleoclimatic changes within its sedimentary fill. The basin was inboard of a tectonically active region, which produced both accommodation space and sediment to fill it (Currie, this volume) over a relatively short period of time (Kowallis *et al.*, this volume), and was proximal to some marine influence, at least during deposition of the stratigraphically lowest units (Peterson and Turner-Peterson, 1987).

In the first part of this chapter, we provide an overview of the results of conceptual and numerical paleoclimate models based on Late Jurassic paleogeography and how they relate to the Morrison basin. In the second part, we review sedimentary paleoclimatic indicators reported from the Morrison Formation. Finally, in the last section, proxy data are compared with model results.

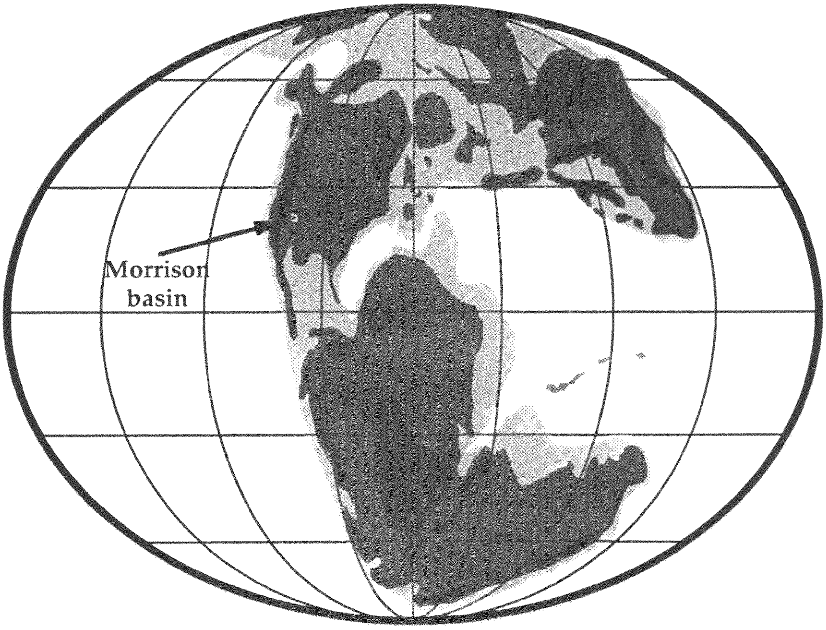

FIGURE 1 Late Jurassic paleogeographic reconstruction showing position of the Morrison depositional basin. Light gray, shallow shelf. Medium gray, exposed land. Black, highlands. Modified from Ross (1992).

IMPLICATIONS OF LATE JURASSIC PALEOGEOGRAPHY

Paleogeography is the fundamental boundary condition for the distribution of paleoclimatic patterns (e.g., Ziegler and others, 1977; Parrish, 1982). The area of exposed land, latitudinal distribution of the continents, and paleotopography are the most important parameters in determining paleoclimatic conditions. Thus, both qualitative, conceptual climate models and quantitative, numerical climate models (General Circulation Models) are intrinsically based on paleogeographic reconstructions, and their results would intuitively seem to be more meaningful with increasing accuracy of these reconstructions. However, even with accurate paleogeographic reconstructions, the results of any paleoclimate model must be thought of as a hypothesis to be tested, rather than as evidence to be used in interpretation (Glancy and others, 1993). It is within this context that the following model results are summarized.

Conceptual Circulation Model

A conceptual circulation model is a theoretical, qualitative reconstruction of large-scale atmospheric circulation patterns based on: (1) paleogeography; and (2) general principles of atmospheric circulation established from modern analogues (Parrish, 1982). Patterns of rainfall, the distribution of climatically sensitive deposits, and ocean circulation can then be inferred from these types of reconstructions. Parrish and Curtis (1982) and Parrish and others (1982) presented conceptual circulation models for seven stages in the Mesozoic and Cenozoic, including the latest Jurassic (Volgian). Parrish (1992) then refined the models for the Jurassic using an updated paleogeographic reconstruction.

The modeled atmospheric circulation patterns for the Late Jurassic are illustrated in Fig. 2. The large-scale atmospheric features that would have had important effects on the Morrison depositional basin are the subtropical high-pressure cell in the eastern paleo-Pacific during Northern Hemisphere winter (Fig. 2(A)), and the low-pressure cell over North America during the Northern Hemisphere summer (Fig. 2(B)). The Morrison basin was situated between 30°N and 40°N latitude, within a belt of year-round westerly winds. During the winter these winds would have emanated from the Pacific subtropical high-pressure cell, and during the summer would have flowed into the low-pressure cell over central North America. Paleowind directions from eolian sandstones in the Morrison (see Fig. 2), support

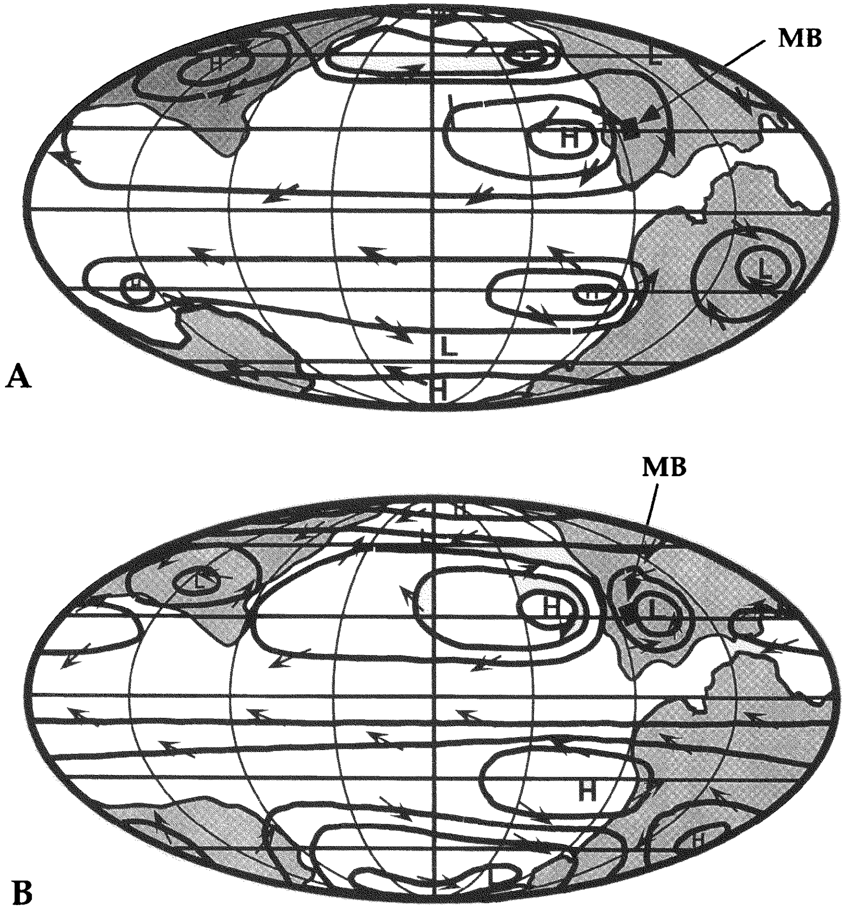

FIGURE 2 Conceptual climate model based on Late Jurassic paleogeography. MB, Morrison depositional basin. H, Relative high pressure. L, Relative low pressure. Arrows, resultant winds. (A) Northern Hemisphere winter. (B) Northern Hemisphere summer. Modified from Parrish (1992).

an interpretation of a westerly dominated wind regime (Parrish and Peterson, 1988; Peterson, 1988).

Patterns of relative precipitation and ocean currents for the Late Jurassic are illustrated in Fig. 3. The Morrison basin is shown to be in an area of relative aridity. Parrish and others (1982) made this interpretation based on: (1) the latitudinal position of the area within the subtropical dry belt; and (2) the assumption that the western cordillera was high enough to act as a barrier to maritime air masses from the Pacific, placing the western interior

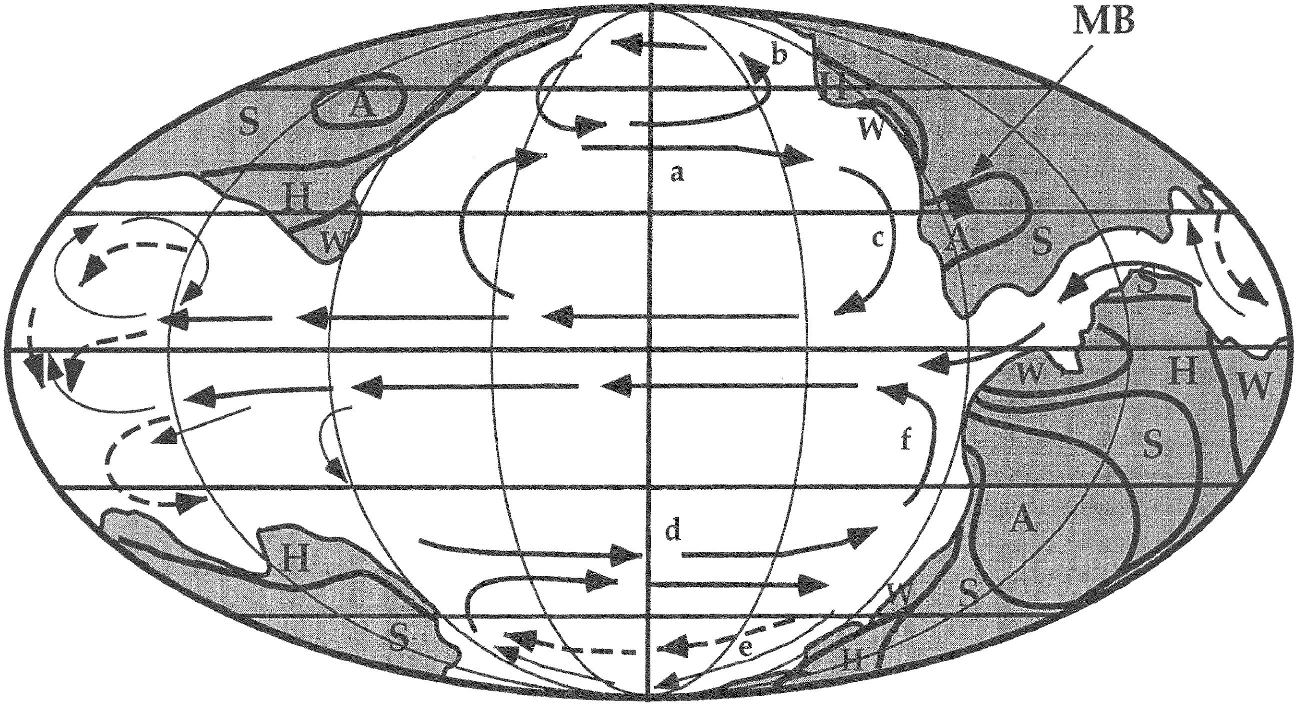

FIGURE 3 Relative precipitation and predicted ocean currents in the Late Jurassic. Thick solid arrows, year-round currents. Thin solid arrows, northern winter currents. Dashed arrows, northern summer currents. a, paleo-North Pacific current. b, paleo-Alaska current. c, paleo-California current. d, South Pacific current. e, Antarctic Peninsula current. f, paleo-Peru current. MB, Morrison basin. A, arid. S, semi-arid. H, subhumid. W, humid. Modified from Parrish (1992).

within a rain shadow. Parrish's (1992) prediction of ocean currents shows a paleo-California current along the western margin of North America (Fig. 3).

General Circulation Models

General Circulation Models (GCMs) are numerical simulations, run on computers, that attempt to reconstruct the large-scale, general motions of the earth's atmosphere. This is accomplished through the solution of a series of basic physical equations, called the atmospheric primitive equations, on a sphere, given realistic boundary conditions (Kiehl, 1992). These boundary conditions, or parameters, can include: (1) sea surface temperatures; (2) surface type (land, water, ice, etc.); (3) surface roughness; (4) land hydrology; (5) surface albedos; (6) ozone mixing ratio; and (7) orography at different scales (Kiehl, 1992). The solutions to the equations, which can be converted to temperature, humidity, and atmospheric pressure, are calculated at discrete grid points (at various scales, depending on the resolution of the model) over a sphere. These values are generally then contoured to present the results. Other climatic parameters, including wind vectors, rainfall, cloud cover, snow depth, and soil moisture may be calculated at the grid points from the basic model results.

Two groups of GCM experiments that have attempted to reconstruct Late Jurassic paleoclimate have recently been reported (Moore and others, 1992a,b; Valdes and Sellwood, 1992). Valdes and Sellwood (1992) used a version of the UK Universities Global Atmospheric Modeling Project program on a paleogeographic reconstruction of Late Jurassic coastlines. A control run of the simulation, which did not include any orographic features, showed distinct continental low pressure cells over Northern and Southern Hemisphere continental areas during their respective summers. Modeled temperatures in western North America ranged from 5°C in the winter to 28°C in the summer in this control run. A sensitivity run with orographic features, including a crude western North American cordilleran range, resulted in higher (> 36°C) summer temperatures (Fig. 4(A)), and a more pronounced summer low pressure cell over western North America (Fig. 4(B)) than that of the control run.

Moore and others (1992a,b) used the Community Climate Model from the National Center for Atmospheric Research run on a Late Jurassic paleogeography including interpreted mountain belts. The model was run with a simulated pCO_2 of 1120 ppm (4X modern), which was interpreted to make the model more closely fit distributions of paleoclimatic indicators.

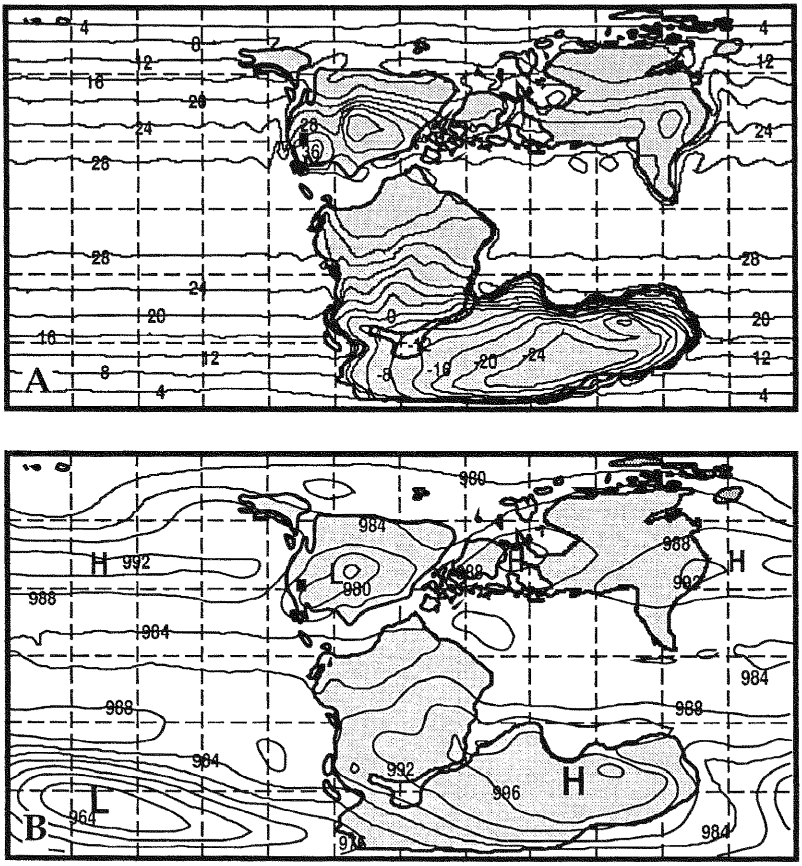

FIGURE 4 General circulation model simulations of Late Jurassic summer temperature and atmospheric pressure with modeled orographic features. Black box over position of Morrison depositional basin. (A) Mean surface temperatures. Units in °C, contour interval 4°C. (B) Mean sea-level pressure. Units in mb, contour interval 4 mb. H, Relative high pressure. L, Relative low pressure. After Valdes and Sellwood (1992).

The model was run on three types of mountain paleotopography: (1) variable (0.5–3 km) based on comparison to modern plate tectonic settings; (2) 1 km highlands, in which all mountains were modeled at that elevation; and (3) 500 m plateaus, in which all continental areas were modeled at that elevation. As one would expect, the model runs with increased paleotopographic contrasts (variable and 1 km highlands) created more complex temperature and pressure patterns than the model run with no contrasts (500 m plateaus). Summer temperature patterns over continental areas were less zonal, and winter temperature patterns more zonal, in the simulations with decreased paleotopographic contrasts. Winter mean sea-level pressure patterns were simpler in the simulations with less relief; however, the summer patterns were controlled dominantly by land-sea distribution. Paleoclimatic conditions in western North America and the Morrison basin were similar in the Moore and others (1992a,b) and Valdes and Sellwood (1992) simulations; that is, the basin was in a warm (summer temperatures ~40°C, winter temperatures ~10°C), arid area and was under the influence of dominantly westerly winds year-round.

SEDIMENTARY PALEOCLIMATIC INDICATORS

Climate is a major, if not dominant control on the formation, transport, and final composition of sediments and sedimentary rocks (Briden and Irving, 1964; Drewry and others, 1974; Parrish and others, 1993). For this reason, certain types of sedimentary rocks have the potential to reflect the climate in which they were formed and deposited. The Morrison Formation contains several types of these sedimentary paleoclimatic indicators (stratigraphic distribution summarized in Fig. 5) which can provide evidence of paleoclimatic conditions in western North America during the Late Jurassic. These proxy indicators are discussed below.

Eolian Sandstones

Eolian sand deposits form dominantly (excepting coastal dunes) in arid and semi-arid climates (McKee, 1979). Eolian sandstones occur in the Tidwell, Salt Wash, Bluff Sandstone, Junction Creek, and Recapture Members in the lower half of the Morrison Formation (Peterson and Turner-Peterson, 1987) (Fig. 5). Most of the eolian deposits in the Morrison interfinger with or are directly correlative to major fluvial complexes, indicating a local source (dry or ephemeral stream channels) for these types of sediments (Peterson and Turner-Peterson, 1987). Paleowind directions determined from these sandstones agree well with the modeled wind regimes discussed previously (Peterson, 1988; Valdes and Sellwood, 1992).

Paleosols

Some features of soils are climatically sensitive, and these features may be preserved in buried, ancient soils or paleosols (Birkeland, 1984; Retallack, 1990; Mack and James, 1994). These features include: (1) presence, form,

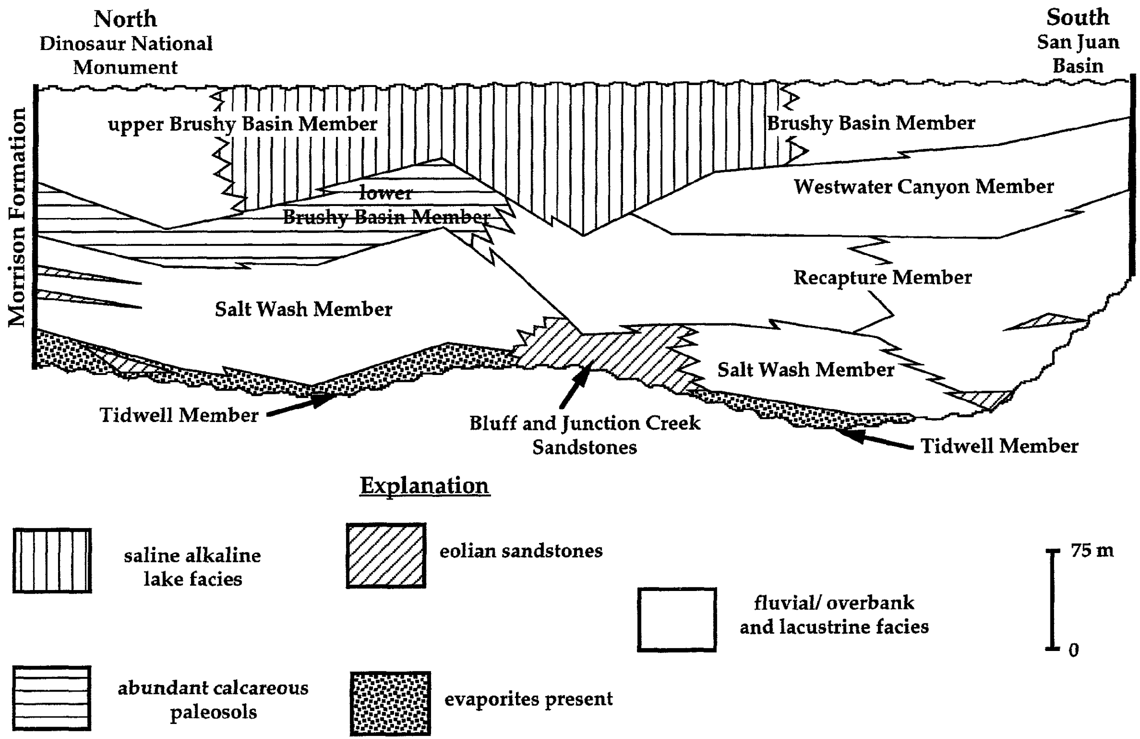

FIGURE 5 Schematic stratigraphic section showing distribution of sedimentary paleoclimatic indicators in the Morrison Formation. Section is roughly north–south from Dinosaur National Monument to San Juan Basin. Modified from Turner and Fishman (1991).

and abundance of pedogenic carbonate minerals; (2) thickness and mineralogy of clay-rich argillic horizons; (3) structures formed by seasonal shrinking and swelling of smectitic clays (mukkara structures); (4) presence and abundance of charcoal in upper soil horizons; and (5) presence and abundance of evaporite minerals in soil horizons (Retallack, 1990; Mack and others, 1993). These features, though not in all paleosols or in all localities, are present in paleosols in the Morrison Formation (personal observation, TMD). Taken as a group, these features indicate that the climate was semi-arid, but with some seasonal rainfall, during the time of pedogenesis.

Saline, Alkaline Lacustrine/Playa/Sabkha Facies

Sedimentary facies which contain evaporite minerals must have formed in climates in which evaporation exceeded precipitation, runoff, and groundwater input (Kendall, 1992). The same is true for lacustrine facies that contain early diagenetic minerals such zeolites (analcime, clinoptiolite) and feldspars (Surdam and Sheppard, 1978). Both of these types of facies would have formed under arid or semi-arid conditions. Bedded and nodular gypsum are common in the sabkha facies in the Tidwell Member of the Morrison (Fig. 5), and although it could be of terrestrial and/or marginal marine origin (Peterson and Turner-Peterson, 1987), high evaporative conditions during deposition are still indicated. The Brushy Basin Member contains the deposits of a large saline, alkaline lake (Fig. 5) (Lake T'oo'dichi'), that have abundant early diagenetic zeolites and feldspars as accessory minerals (Turner and Fishman, 1991). The Lake T'oo'dichi' deposits also show signs of repeated wetting and drying (Bell, 1986), and must have been deposited under both playa (little or no standing water) and lacustrine conditions. Bell (1986) and Turner and Fishman (1991) both interpreted the saline, alkaline lake deposits in the Brushy Basin Member to have deposited under arid to semi-arid conditions with episodic, possibly catastrophic, rainfall events.

DISCUSSION AND CONCLUSIONS

The Morrison Formation was deposited in a largely terrestrial basin, inboard of a topographically positive area, in the western interior of Laurasia during the Late Jurassic. At this time in earth history, megamonsoonal atmospheric circulation patterns, characteristic of the earlier Mesozoic, had waned due to the break-up of Pangaea and the opening of the Tethys seaway, and were supplanted by more zonal patterns. The Morrison depositional basin was positioned between 30°N and 40°N latitude. The results of conceptual and numerical climate models both show this area to have been within a belt of sub-tropical westerly winds. A tectonically- and magmatically-active cordilleran belt to the west of the basin acted as a barrier to moist Pacific air masses. This created a rain shadow effect and made the climate semi-arid to arid. Recent geochemical models of the evolution of the concentration of carbon dioxide in the atmosphere (Berner, 1994; Worsley and others, 1994), and proxy estimates of atmospheric pCO_2 from pedogenic carbonate (Cerling, 1991; 1992) indicate that the global average temperature during the Late Jurassic could have been 4–5°C warmer than today; temperatures in the Morrison basin probably were at least this much greater. Sedimentary paleoclimatic indicators in the Morrison, including eolian sandstones, calcareous paleosols, evaporite deposits, and playa/saline, alkaline lake deposits support an interpretation of a dry climatic regime with some periodic, and possibly seasonal, precipitation. The paleoclimatic conditions in the Morrison basin were certainly wetter than those indicated by the underlying Summerville/Wanakah Formation sabkhas and San Rafael Group erg sandstones (Peterson and Turner-Peterson, 1987).

Dodson and others (1980) interpreted the taphonomy, taxonomic composition, and distribution of dinosaur assemblages in the Morrison to reflect a strongly seasonal climate, with some annual water stress. However, other paleontological evidence, including the sporadic occurrence of unionid bivalves and lacustrine gastropods indicates that there were perennial streams and lakes present in the Morrison basin at some times during deposition (Steven Good and Emmett Evanoff, personal communications). The presence of plant fossils in some facies, including horsetails, ferns, seed ferns, cycads, and various gymnosperms, would also suggest that some areas were not under severe water stress year-round (Ash, 1994; Tidwell, 1991; Tidwell and Medlyn, 1992; Tidwell and Ash, 1990). In fact, Ash (1994) and Tidwell (1990) interpret the Morrison flora to be indicative of a humid, tropical climate (see also Ash and Tidwell, this volume). At first glance, these interpretations would seem to be incompatible with those based on sedimentary paleoclimatic indicators. However, biofacies, especially those preserving fossil plants, must be interpreted within the context of paleoecological and taphonomic biases. Plant fossil assemblages typically are not time-averaged (they represent only very short time spans), and they are preferentially preserved in wet, reducing environments (Spicer, 1989).

Therefore, although the plant fossil assemblages from the Morrison do present evidence of humid/wet conditions, they represent only a small spatial, temporal and stratigraphic portion of the sequence. The Morrison landscape and ecosystem must be thought of as a mosaic of physical conditions and paleocommunities which were not static over the time of deposition in the basin.

Sedimentary paleoclimatic indicators in the Morrison Formation would seem to validate some of the results of both conceptual and numerical climate models at the coarsest spatial and temporal scales. However, the climatically significant facies in the Morrison that were discussed in this paper are heterogenously distributed both stratigraphically through the section and spatially across the depositional basin. Further field work and study of these facies and other proxy indicators will lead to further refinement of the climatic picture the Morrison presents.

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