The Whitmore Point Member of the Moenave Formation: Early Jurassic Dryland Lakes on the Colorado Plateau, Southwestern USA

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ABSTRACT: The Lower Jurassic Whitmore Point Member of the Moenave Formation in Arizona-Utah, USA, comprises fish- and coprolite-bearing shales, siltstones, sandstones, and minor limestones. These facies were deposited in ephemeral and perennial lakes subject to episodic desiccation and incursions of coarse clastics during floods. Meromictic conditions developed during perennial episodes, probably due to salinity stratification, which enhanced preservation of organic matter in gray to black shales. These lakes formed on the floodout of a north-northwest oriented (relative to modern geography) system of mainly ephemeral streams on a broad and open floodplain. The Whitmore Point Member both overlies and interfingers laterally with alluvial red-bed facies of the Dinosaur Canyon Member of the Moenave Formation. The vertical transition from alluvial to lacustrine sedimentation recorded by the Dinosaur Canyon and Whitmore Point members of the Moenave Formation most probably resulted from a eustatically-controlled rise in base level during the Early Jurassic (Hettangian). The Dinosaur Canyon Member also interfingers laterally with eolian dune deposits of the Wingate Sandstone, which was deposited by winds that reworked coastal plain sediments to the north of the study area. Thus, on this part of the Colorado Plateau, fluvial, lacustrine and eolian sedimentary facies were deposited contemporaneously in laterally adjacent paleoenvironments.

INTRODUCTION

In the American Southwest, the Late Triassic and Early Jurassic are well recognized for the aridification of the Colorado Plateau. The paleogeography of the region at this time presents a mosaic of eolian, alluvial and lacustrine depositional environments that existed contemporaneously in an arid or dryland environment. The spectacularly exposed Triassic-Jurassic Wingate Sandstone, which marks the onset of Mesozoic erg sedimentation, is a predominantly eolian unit that was deposited across a broad area of northern Arizona, northwestern New Mexico, southwestern Colorado and southeastern Utah. Exposures in northern Arizona demonstrate that the western edge of this erg interfingered with alluvial and lacustrine sediments of the Dinosaur Canyon and Whitmore Point members, respectively, of the Moenave Formation (Clemmensen *et al.* 1989; Tanner and Lucas 2007). This paper explores the paleogeographic and paleoclimatologic context of the lacustrine deposits of the Whitmore Point Member, which occurs in the upper part of the Moenave Formation in northernmost Arizona and southern Utah.

REGIONAL SETTING

During the early Mesozoic, a retro-arc basin formed on the western edge of the North American craton as a result of the initial growth of the Cordilleran magmatic arc (Dickinson 1981). The continental portion of this basin extended from southwestern Texas to northern Wyoming and was the site of terrestrial sedimentation from the Late Triassic through the Early Jurassic (Lucas *et al.* 1997). At this time, the Colorado Plateau was situated within the basin at near-equatorial latitudes (5° to 15°N, Scotese 1994; Molina-Garza *et al.* 1995; Kent and Olsen 1997). Sedimentation during the Late Triassic to Early Jurassic was controlled primarily by streams flowing north to northwest across a broad, low gradient alluvial plain. The source area for these sediments was mainly the Mogollon highlands, located approximately 500 km to the south and southwest, and to a lesser extent the Uncompahgre highlands located 200 to 300 km to the east and northeast (Blakey and Gubitosa 1983; Marzolf 1994).

Mainly alluvial strata of the Chinle Group strata were deposited unconformably during the Late Triassic (Carnian to Rhaetian) on Middle Triassic or older strata following an interval of lowered base-level and incision. Following another interval of lowered base-level and incision that may have coincided with tectonic reorganization of the basin and fore-bulge migration (Tanner 2003), basal Moenave strata were deposited unconformably on strata of the Chinle Group. The basal Moenave-Chinle (Owl Rock Formation) unconformity has been termed the J-0 unconformity and was long considered to coincide with the Triassic-Jurassic boundary (*e.g.*, Pipiringos and O'Sullivan 1978); Tanner and Lucas (2007) recently have demonstrated that this unconformity is correlative with the Tr-5 unconformity that underlies the Rock Point Formation of the Chinle Group (Lucas *et al.* 1997). Uppermost Moenave strata, of the Dinosaur Canyon Member and the Whitmore Point Member where present, or the laterally equivalent Wingate Sandstone, are overlain disconformably by the Kayenta Formation of the Glen Canyon Group. In the northern part of the Moenave outcrop belt, including all of the outcrop area of the Whitmore Point Member, the basal Kayenta Formation consists of the coarse, conglomeratic sandstones of the Springdale Sandstone Member.

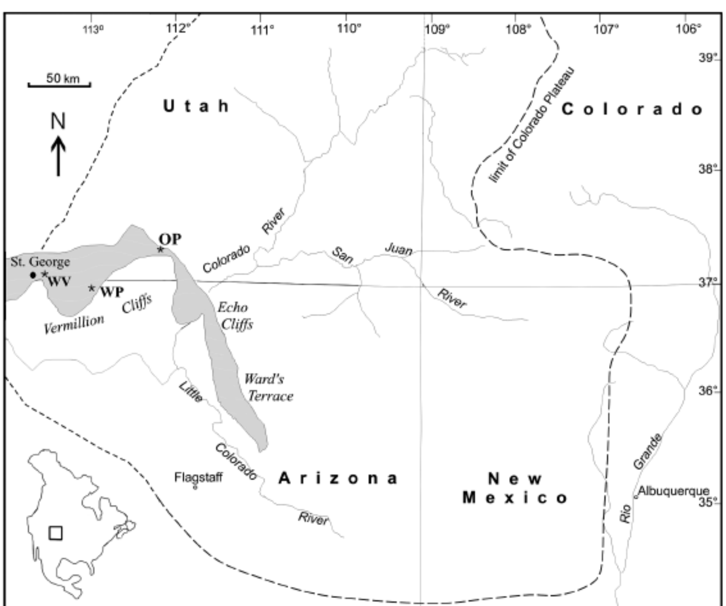

Fig. 1. Location map outlining the position of the Colorado Plateau and area of outcrop of the Moenave Formation (shaded gray), including the Dinosaur Canyon and Whitmore Point members. Old Paria (=OP), Whitmore Point (=WP) and Warner Valley (=WV) are locations referred to in text at which sections in Fig. 3 were measured.

LITHOSTRATIGRAPHY

In Arizona and Utah, the Moenave Formation comprises a succession of terrestrial red beds (sandstone, siltstone, and mudstone) deposited by fluvial, lacustrine, and eolian processes. These strata are exposed in cliffs, on buttes, over mesas, and in canyons from Ward's Terrace in Arizona, northward along the Echo Cliffs and Vermillion Cliffs of northernmost Arizona, in southern Utah from the vicinity of St. George as far north as Cedar City, and extending westward into easternmost Nevada (Fig. 1; Harshbarger *et al.* 1957; Irby 1996a; Lucas and Heckert 2001; Tanner and Lucas 2007). The Moenave Formation is the lowermost part of the Glen Canyon Group and is, subdivided into, in ascending order, the Dinosaur Canyon and Whitmore Point members (Fig. 2). Over most of its outcrop belt, the Dinosaur Canyon Member overlies the calcrete-bearing mudstones of the Owl Rock Formation of the Chinle Group (Lucas 1993; Lucas *et al.* 1997) with pronounced unconformity. Moenave Formation strata are overlain unconformably, in turn, by fluvial sandstones of the basal Kayenta Formation.

The type area of the Dinosaur Canyon Member is located east of Cameron, Arizona, where it comprises reddish-orange to light brown siltstones and sandstones of inferred fluvial and eolian origin, in proportions that vary across the outcrop belt (Harshbarger *et al*. 1957); in general, eolian facies increase in proportion to the south and east (Tanner and Lucas 2007). The Wingate Sandstone, which is exposed to the east of the Moenave Formation outcrop belt, comprises predominantly eolian dune sandstones and interdune sandstones and mudstones (Clemmensen *et al*. 1989). The Wingate Sandstone is considered a partial correlative of the Moenave Formation as it intertongues discernibly with the Dinosaur Canyon Member (Harshbarger *et al*. 1957; Clemmensen *et al*. 1989; Marzolf 1993; Tanner and Lucas 2007).

Wilson (1967) described the Whitmore Point Member to distinguish the purple and gray laminated mudstones and shales that are present stratigraphically high in the Moenave Formation in the northwestern part of the outcrop belt from the orange to red sandstones and mudstones of the underlying Dinosaur Canyon Member. He established the type location at Whitmore Point, a south-facing promontory on the Vermillion Cliffs, 30 km WSW of the town of Fredonia, in Mohave County, Arizona (sec. 15, T 40N, R 5W; Figs 1; 3; 4: A). In many locations, the fine-grained Whitmore Point strata are truncated by thick-bedded cliff-forming sandstones of the Springdale Sandstone Member of the Kayenta Formation with meter-scale erosional relief. However, as we note below, sandstone ledges with a "Dinosaur Canyon" aspect occur between the distinctive Whitmore Point strata and the overlying Springdale Sandstone in some locations, suggesting that the Whitmore Point and Dinosaur Canyon members interfinger somewhat. The thickness of the Whitmore Point varies regionally; it is 22 m thick at the type location in northern Arizona, and consistently 17 m to 23 m in southwesternmost Utah and adjacent Nevada. The facies that characterize this member thin to the east of the type area in the eastern Vermillion Cliffs, and pinch out in the Echo Cliffs as they are replaced by laterally equivalent facies of the upper Dinosaur Canyon Member (Fig. 3).

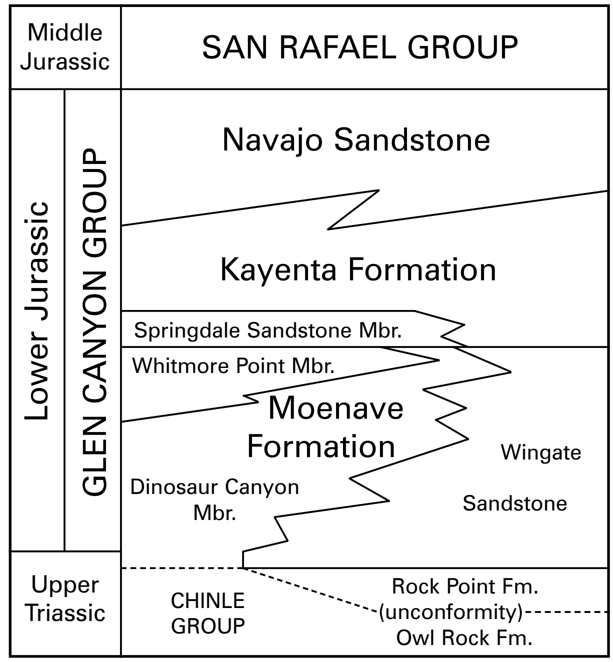

Fig. 2. Stratigraphy of Upper Triassic and Lower Jurassic in the study area.

AGE

The age of the Moenave/Wingate strata is established by a combination of vertebrate fossils, ichnofossils, palynomorphs, and paleomagnetic evidence. The lower Dinosaur Canyon Member hosts *Grallator*-dominated trackways that lack *Eubrontes*, suggesting, although not proving, a latest Triassic (Rhaetian) age for the base of the Moenave Formation (Morales 1996; Lucas *et al*. 1997, 2005). Magnetostratigraphic correlation of the lower Moenave strata to the Newark basin section also suggests a latest Triassic age for the lower portion of the Dinosaur Canyon Member (Molina-Garza *et al*. 2003). Furthermore, the laterally equivalent relationship with the Wingate Sandstone, which contains a demonstrably Upper Triassic tetrapod fauna (the phytosaur *Redondasaurus*) and ichnofauna (the crurotarsan track *Brachychirotherium*: Lucas *et al*. 1997; Lockley *et al*. 2004), indicates a Late Triassic age for at least the lower part of both formations. Fossils of the crocodylomorph *Protosuchus* and tracks of the dinosaur ichnotaxa *Eubrontes* and *Otozoum* (Irby 1996b) from the upper Wingate Sandstone and the middle to upper Dinosaur Canyon Member indicate that the upper parts of both formations are likely of Hettangian age (Lucas and Heckert 2001; Lucas *et al*. 2005). The Whitmore Point strata have produced fossils of semionotid fish and a palynoflora that is dominated by *Corollina* spp., also indicating an Early Jurassic, probably Hettangian age (Peterson and Pipiringos 1979; Litwin 1986) for the uppermost

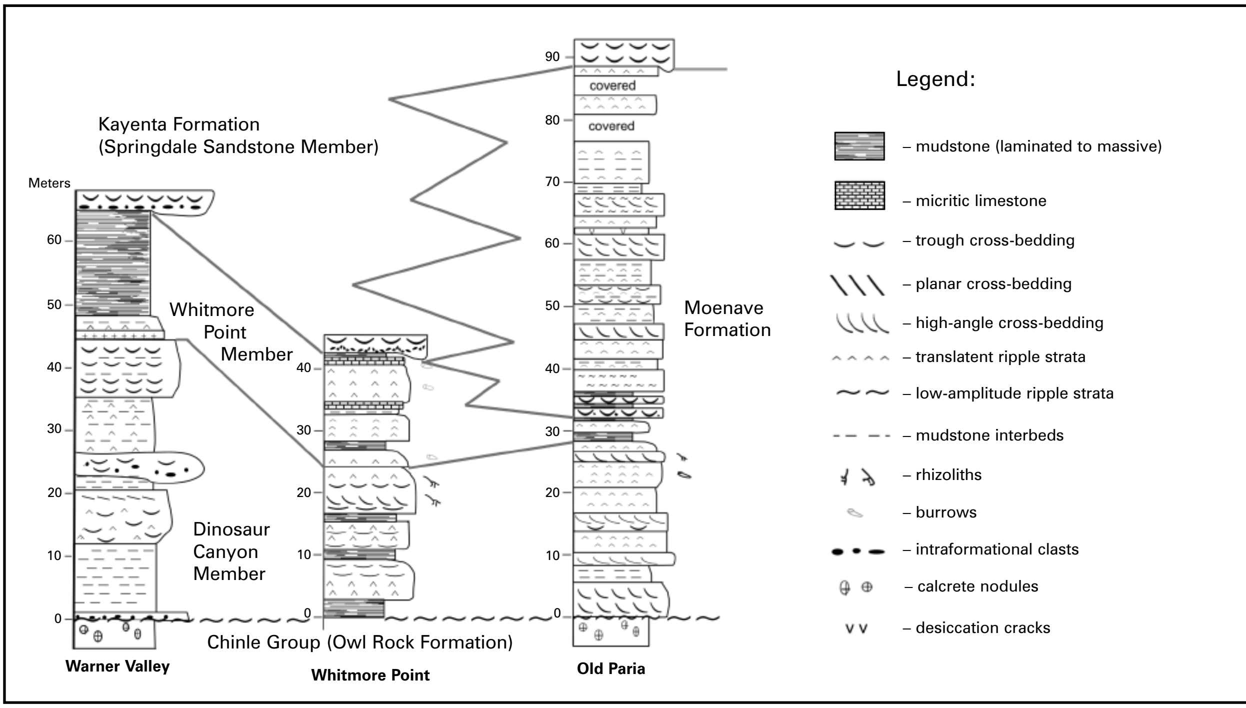

Fig. 3. Cross-sections illustrating lateral relationships of lithofacies for the Moenave Formation. West-east cross-section across northern part of study area from Warner Valley (near St. George) to Old Paria. No horizontal scale is implied (see Fig. 1 for section locations).

Moenave Formation. Whitmore Point strata exposed at St. George, Utah, contain an exceptionally well preserved, but low diversity tetrapod Lower Jurassic ichnofauna consisting entirely of *Eubrontes* and *Grallator*.

LITHOLOGY

At the type location, the Whitmore Point Member overlies the strata of the Dinosaur Canyon Member, which comprise 22 m of slope-forming red mudstone, blocky-weathering siltstone with rhizoliths in beds up to 0.9 m thick, ledge-forming ripple-laminated sandstone beds up to 1.7 m thick, and 2.2 m of sandstone with meter-scale trough cross-beds. The base of the Whitmore Point Member is a grayish-purple, ripple-laminated sandstone bed that overlies orange-red sandstone and mudstone of the Dinosaur Canyon Member. The Whitmore Point Member here consists of 22 m of gray, purple, red, green, and ochre-hued shale, siltstone, sandstone and minor limestone. Individual shale and siltstone beds within the units typically are laterally continuous for distances of up to hundreds of meters. The sandstones, however, are particularly variable in thickness, with individual beds varying from 20 cm or less to 1.8 m across the visible outcrop face. Sandstone beds are typically very fine-grained and display ripple translatent lamination, and in some instances, climbing ripples. Sandstone-filled desiccation cracks commonly penetrate the top 10 cm of underlying shale and mudstone beds. The contact between the sandstones and finer-grained beds is typically sharp. Shale and siltstone beds contain fish scales, fish and tetrapod bones and conchostracans, particularly near the top of the member. Limestone beds are thin and ripple-laminated. Similar lithologies occur in other exposures of the Whitmore Point Member to the east and west.

At the type location, the Whitmore Point Member consists of six units that are distinguishable on the basis of their color. We are able to trace these units to an adjacent promontory, 2 km to the west of the type location, although the thickness of these units varies slightly (Figs 4: B, C). The six units are as follows: (1) the lower 2.5 m of the member comprises mainly gray to grayish-purple, ripple translatent laminated sandstone interbedded with thin shales; (2) the overlying 0.7-m-unit is a distinctive ochre-hued bed of ripple-laminated sandstone with interbedded mudstone that is easily traceable 2 km to the west; (3) the succeeding 4.2 m comprises mainly gray to green siltstone and shale with interbedded calcareous ripple laminated

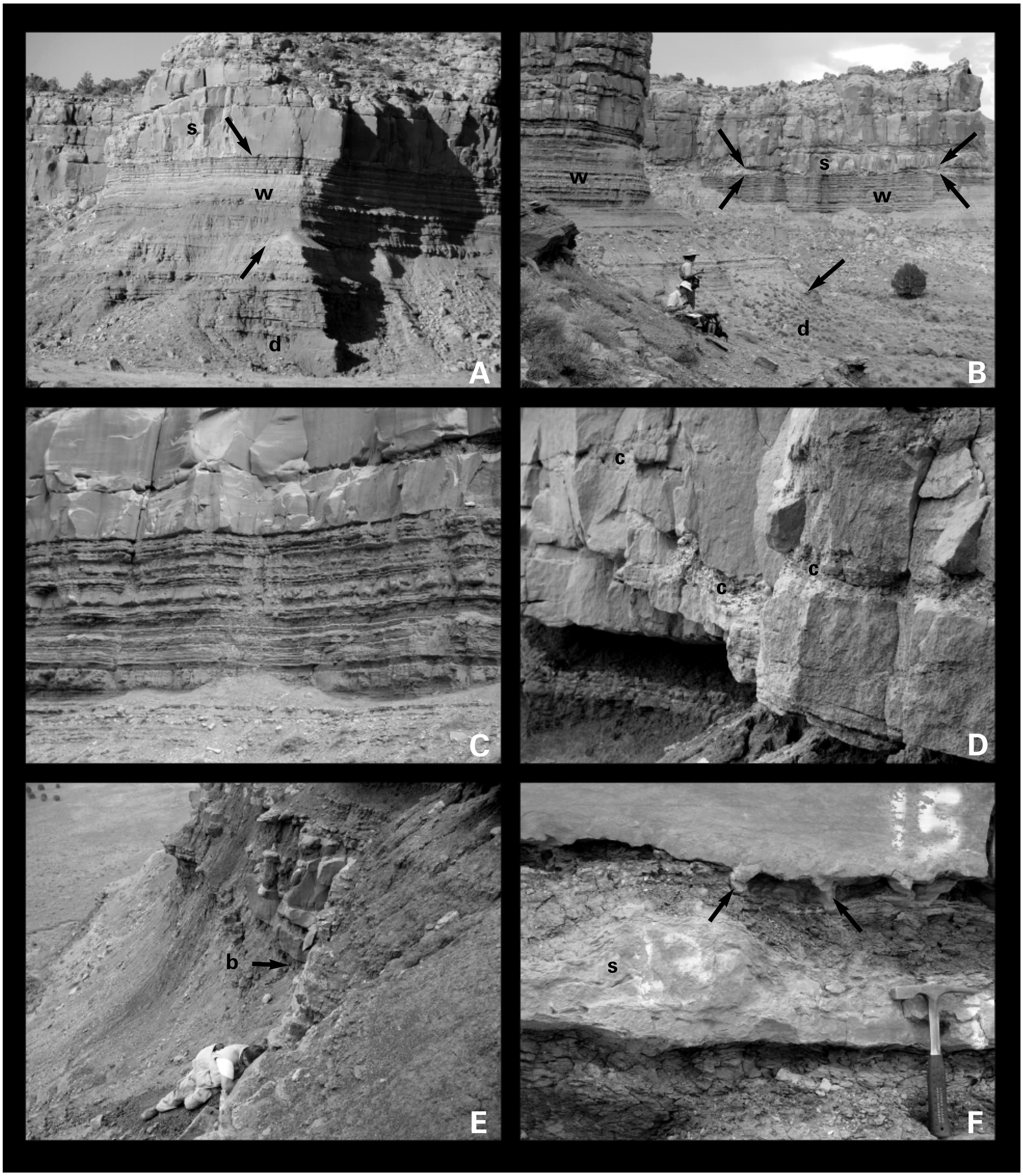

Fig. 4. A – Outcrop at Whitmore Point, the type location for the Whitmore Point Member. Arrows at the contact between Dinosaur Canyon Member (d) and Whitmore Point Member (w) and at upper contact of Whitmore Point strata with the Springdale Sandstone Member of the Kayenta Formation (s). B – Overview of the Whitmore Point Member 2 km to the west of the type locality. Arrows at lower Whitmore Point (w) contact and at contact with overlying "Dinosaur Canyon" type sandstones. Springdale Sandstone (s) above scours down into these sandstones. C – Highlight from location B illustrating lateral continuity of interbedded shales, siltstones and sandstones. D – Contact of fine-grained Whitmore Point strata and coarse-grained Springdale sandstones with conglomeratic lenses (c). E – Slope of Unit 3 (at location B) exposing gray and black shale. A black shale bed (b) underlies the sandstone ledge. F – Limestone bed at base of Whitmore Point section at St. George, Utah (Johnson Farm track site) contains a domal stromatolite (s). The sandstone layer above (labeled 15) hosts a tetrapod trackway on the upper surface. Sandstone-filled desiccation cracks (arrows) extend downward from the base of the sandstone bed.

sandstones; (4) the succeeding 6.0 m consists of red mudstone and calcareous sandstone displaying ripple-translatent stratification; (5) a second distinctive 1.5 m ochre-hued sandstone ledge forms another unit that is easily correlatable; and (6) the uppermost 7.0 m comprises gray to reddish-purple siltstone with abundant fish scales and conchostracans and calcareous, gray, ripple-laminated sandstone and thin burrowed sandy limestone.

These strata are overlain by thick-bedded, coarse- to very coarse-grained sandstone that is trough cross-bedded and contains lenses of mudstone rip-up clasts (Fig. 4: D). We note up to 4 m of erosional relief at the base of this unit. Based on the disconformable nature of this contact, we assign this sandstone to the Springdale Sandstone Member of the Kayenta Formation (Lucas and Tanner 2006). To the west of Whitmore Point, and at other locations, finer-grained Whitmore Point strata are erosionally truncated by fine-grained multi-storeyed sandstones that more closely resemble the Dinosaur Canyon strata below than the Springdale Sandstone Member above (Fig. 4: B). These sandstones are in turn erosionally truncated by the coarser, conglomeratic sandstones that are characteristic of the Springdale Sandstone Member.

The units described above for the type location occur in the same sequence at a promontory 2 km to the west, although as noted above, the thicknesses of the units differs slightly. The most notable lithologic difference between these two locations occurs in unit 3, which contains a 2.6-m-thick bed of dark gray to black shale in the western outcrop (Fig. 4: E). This occurrence of organic-rich black shale is unique among all the outcrops of the Whitmore Point Member we have studied. Limestone forms only a minor component of the Whitmore Point Member. Wilson (1967) noted the presence of a persistent cherty limestone at the base of the member in the area of Leeds, Utah; we note also at the base of the Whitmore Point Member at St. George, Utah, a 15-cm-thick laminated limestone ledge that contains domal stromatolites up to 20 cm high (Fig. 4: F).

DEPOSITIONAL SETTING

Sedimentologic Model

The laterally continuous shales, siltstones and sandstones of the Whitmore Point Member record deposition in clastic-dominated lakes of varying size and longevity that hosted a low diversity fauna consisting primarily of semionotid fish, conchostracans and various invertebrate burrowers (Fig. 5: A, B). The laminated mudstones were deposited from suspension in bodies of standing water, but evaporation and desiccation of these water bodies is evident from the common occurrence of sand-filled desiccation cracks at the bases of interbedded sandstones. The abrupt contacts between these sandstone beds and the finer-grained lithologies, as well as the presence of climbing-ripple stratification, suggest that sand was deposited rapidly over the fine-grained lake bed, rather than through progradation of the shoreline. The lack of desiccation features at many contacts suggests that, alternatively, bedload (sand-sized) sediment was introduced rapidly into shallow bodies of standing water by episodic sheetfloods on the floodplain. As noted above, several sandstone beds display significant lateral thickness changes and erosional bases. We interpret these as the deposits of stream channels scoured into the lake bed during episodes of exposure. We find no evidence of coarsening-upward facies sequences (*i.e.*, shorelines or deltas) in these strata, suggesting further that the lakes were shallow and probably of insufficient lateral extent for wave-influenced shoreline development. The low-diversity invertebrate fauna, dominated by conchostracans (Fig. 5: A), as well as the low diversity invertebrate ichnofauna (Scoyenia ichnofacies: Fig. 5: B; Lucas *et al*. 2006) similarly suggests shallow and ephemeral lake conditions. The low depth of these lakes most probably was a consequence of the lack of effective impoundment of the floodplain drainage by tectonics (*i.e.*, by local uplift or subsidence; Carroll and Bohacs 1999).

Gray siltstone and shale are common in the Whitmore Point Member, although organic-rich black shale occurs rarely. Nonetheless, this occurrence is consistent with our interpretation that the lakes were ephemeral to shallow perennial. As pointed out by Turcq *et al*. (2002), organic carbon accumulates much faster in smaller lakes than in large oligotrophic lakes. It is generally understood that preservation of organic carbon requires stable stratification of the water column to prevent aerobic decomposition of organic matter in the lake floor sediments. Size and depth are not requirements for this type of stratification, however. Last *et al*. (2002), for example, described salinity stratification in a meromictic modern lake in Saskatchewan with a surface area of 5 km^2 and a mean depth of only 8 m. A semi-arid to arid climate

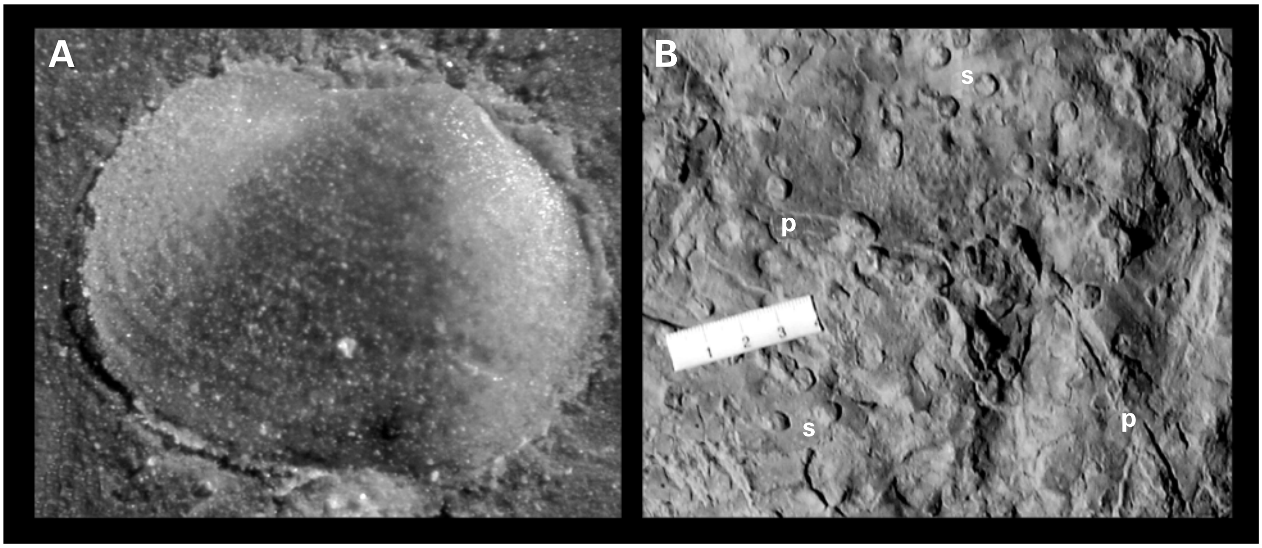

Fig. 5. Selected fossils from the Whitmore Point Member of the Moenave Formation (all from Johnson Farm, St. George, Utah): A – right valve of the conchostracan *Euestheria*; valve is about 3.5 mm wide; B – *Skolithos* (s) and *Palaeophycus* ichnosp. (p) burrows on sandstone surface characteristic of ichnofossil assemblage of the Scoyenia ichnofacies (scale bar in cm).

with pronounced seasonality of precipitation (*i.e.*, monsoonal effect) prevailed on the Colorado Plateau during the early Mesozoic (Kutzbach and Gallimore 1989; Parrish 1993; Tanner 2000; Tanner and Lucas 2007). In this regime, evaporative concentration of water ponded in broad floodplain depressions to a depth of probably no more than 10 m likely resulted in salinity stratification of the water column and meromictic conditions.

Deposition of lacustrine carbonate in this otherwise siliciclastic-dominated depositional system occurred during intervals when the lakes were sediment starved. Stromatolites, as described at St. George, are commonly associated with ephemeral carbonate lakes (Platt and Wright 1991). The Whitmore Point lakes were analogous to those described in the Shuttle Meadow Formation, a lowermost Jurassic formation of the Newark Supergroup in which deposition in an ephemeral system was dominated by sheetflood (Gierlowski-Kordesch 1998).

Regional Context

Much of the underlying and interfingering Dinosaur Canyon strata consist of fining-upward sandstone bodies that were deposited in broad, ephemeral sandy streams as sheet-like deposits of low-relief sandy bedforms (Miall 1996; Reid and Frostick 1997; Tooth 2000a; Tanner and Lucas 2007). Sheetflood processes dominated, resulting in rapid deposition during waning flow, as is typical of many sandy ephemeral rivers on distal braid plains (Miall 1996; Reid and Frostick 1997; Tooth 2000a). These depositional processes are typical of modern drylands, as in the Sinai, for example (Sneh 1983; Miall 1996). In modern dryland stream systems, bank-confined channels evolve downstream to open floodplains, or floodouts, where bedload transport terminates (Tooth 2000b). During the later part of the Moenave depositional interval, rising base level inundated the floodout, resulting in numerous broad but shallow lakes. Thus, the Whitmore Point strata were deposited on the terminal floodplain of the Moenave (Dinosaur Canyon) alluvial system (*cf.* Sneh 1983), during an interval of high base level that allowed the water table to intersect the topographic surface episodically (Fig. 6). As the continuity of Wingate erg deposition provides no evidence of long term climate change, we suggest that the base level may have had a eustatic control. Rising sea level during the Hettangian, following a pronounced Rhaetian regression, has been suggested by the sedimentologic evidence from numerous stratigraphic sections (Haq *et al.* 1987; Hallam and Wignall 2000; Guex *et al.* 2004). Episodes of lowered lake level and desiccation may have been triggered by climatic fluctuations that caused changes in the water table.

The nearby Wingate erg covered as much as 110,000 km^2 (Clemmensen *et al.* 1989), and the Wingate and Moenave formations intertongue along the southwestern margin of this erg (Fig. 6). Clemmensen *et al.* (1989) suggested that the sediment that supplied the Wingate erg was supplied by the north-northwest flowing Dinosaur Canyon stream system, but the deposition of lacustrine sediments across a broad area of the terminal Moenave floodplain was also contemporaneous with erg sedimentation. The Moenave streams ultimately drained into a back-arc sea, the coastal plain of which extended across eastern Nevada (Marzolf 1994; Riggs *et al*. 1996). The marginal marine facies of this seaway likely provided some of the upwind sediment load (Peterson 1988), as evidenced by zircon isotope geochronology. The Laurentian shield to the north provided sediment to the shoreline of the seaway that was transported by coastal currents southward, where it was reworked and incorporated into the Wingate erg (Dickinson and Gehrels 2002).

CONCLUSIONS

Deposition of Moenave Formation sediments took place during the latest Triassic to earliest Jurassic in a mosaic of terrestrial subenvironments including fluvial, lacustrine, and eolian during an interval of semi-arid to arid, but seasonal climate. Deposition of Whitmore Point shales, mudstones, sandstones and minor limestones took place on the terminal floodplain, or floodout, of the Dinosaur Canyon stream system in ephemeral and shallow perennial lakes that hosted a low diversity biota.

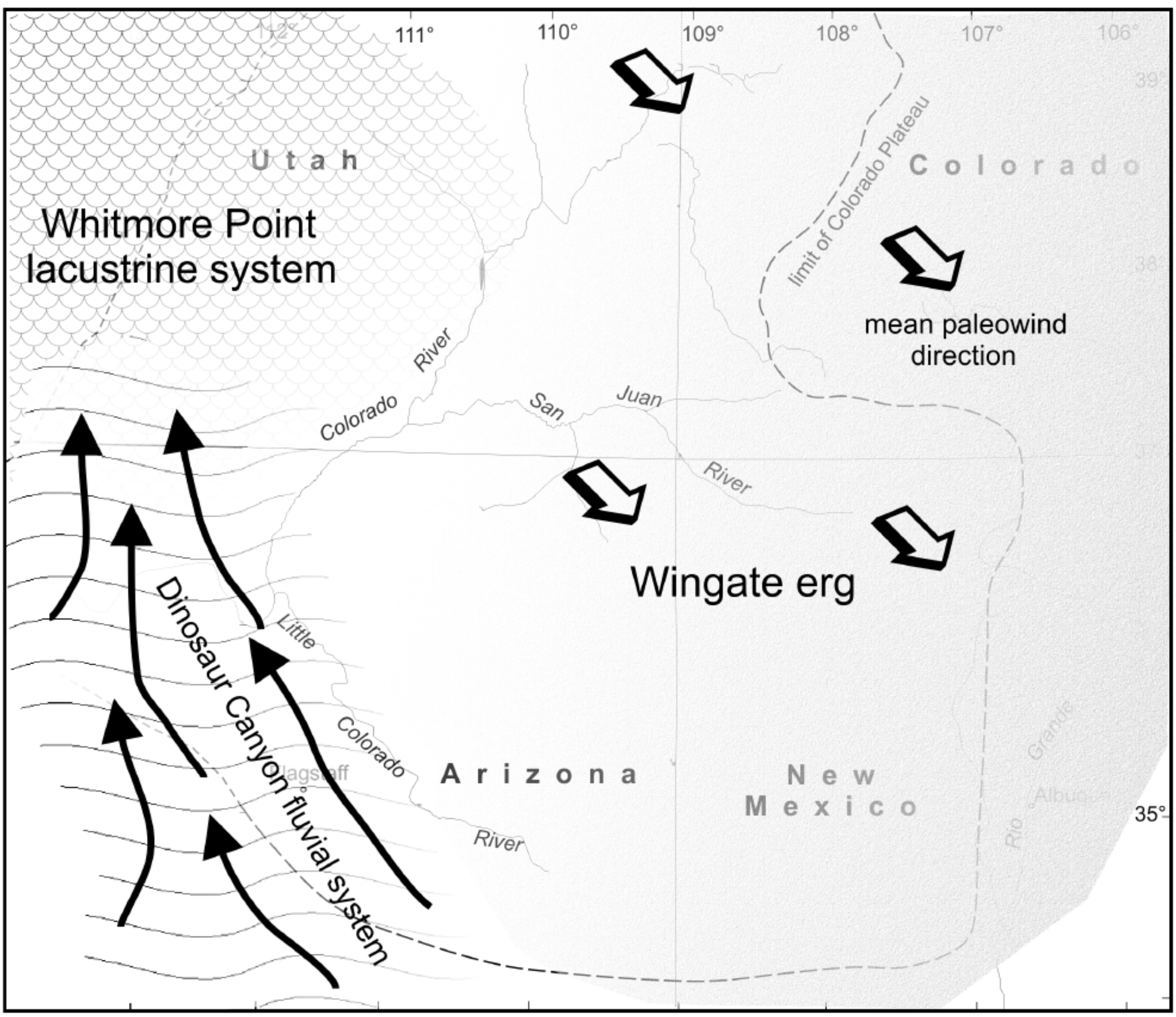

Fig. 6. Paleoenvironmental reconstruction for the Colorado Plateau area during Early Jurassic deposition of the Moenave Formation and Wingate Sandstone.

The lakes were subject to episodic desiccation. The transition from ephemeral stream sedimentation, which characterized Dinosaur Canyon deposition, to Whitmore Point lacustrine sedimentation, resulted from a prolonged rise in base level, probably controlled by eustasy.

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