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Regional paleohydrologic and paleoclimatic settings of wetland/lacustrine depositional systems in the Morrison Formation (Upper Jurassic), Western Interior, USA

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Abstract

During deposition of the Upper Jurassic Morrison Formation, water that originated as precipitation in uplands to the west of the Western Interior depositional basin infiltrated regional aquifers that underlay the basin. This regional groundwater system delivered water into the otherwise dry continental interior basin where it discharged to form two major wetland/lacustrine successions. A freshwater carbonate wetland/lacustrine succession formed in the distal reaches of the basin, where regional groundwater discharged into the Denver–Julesburg Basin, which was a smaller structural basin within the more extensive Western Interior depositional basin. An alkaline–saline wetland/lacustrine complex (Lake T'oo'dichi') formed farther upstream, where shallower aquifers discharged into the San Juan/Paradox Basin, which was another small structural basin in the Western Interior depositional basin. These were both wetlands in the sense that groundwater was the major source of water. Input from surface and meteoric water was limited. In both basins, lacustrine conditions developed during episodes of increased input of surface water. Inclusion of wetlands in our interpretation of what had previously been considered largely lacustrine systems has important implications for paleohydrology and paleoclimatology.

The distal carbonate wetland/lacustrine deposits are well developed in the Morrison Formation of east-central Colorado, occupying a stratigraphic interval that is equivalent to the "lower" Morrison but extends into the "upper" Morrison Formation. Sedimentologic, paleontologic, and isotopic evidence indicate that regional groundwater discharge maintained shallow, hydrologically open, well oxygenated, perennial carbonate wetlands and lakes despite the semi-arid climate. Wetland deposits include charophyte-rich wackestone and green mudstone. Lacustrine episodes, in which surface water input was significant, were times of carbonate and siliciclastic deposition in scarce deltaic and shoreline deposits. Marginal lacustrine deposits include ooid and skeletal packstone–grainstone, siltstone, and sandstone. Distal lacustrine units are skeletal mudstone–wackestone, microbialites, and laminated (siliciclastic) mudstone. Differentiation between wetlands and distal lacustrine units is not always possible. Palustrine features, Magadi-type chert (MTC), and evaporites record episodes of increased aridity and exposure.

Farther upstream, during deposition of the upper part of the Brushy Basin Member, the ancestral Uncompahgre Uplift imposed a barrier to shallow, eastward-flowing groundwater that discharged into the San Juan/Paradox Basin on the upstream side of the uplift. This created the closed hydrologic setting necessary for development of an alkaline–saline wetland/lacustrine complex ("Lake" T'oo'dichi'). Silicic volcanic ash, delivered by prevailing winds from calderas west and southwest of the basin, contributed to the pore-water evolution in the sediments. A distinctive lateral hydrogeochemical gradient, reflecting increasing salinity and alkalinity in the pore waters, altered the ash to a variety of authigenic minerals that

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define concentric zones within the basin. The basinward progression of diagenetic mineral zones is smectite → clinoptilolite → analcime ± potassium feldspar → albite. The groundwater-fed wetlands were shallow and frequently evaporated to dryness. Scarce laminated gray mudstone beds record distinct episodes of freshwater lacustrine deposition that resulted from intermittent streams that carried detritus well out into the basin.

Keywords: Wetlands; Lakes; Hydrology; Climate; Late Jurassic; Morrison Formation

1. Introduction

Two depositional successions within the Morrison depositional basin—carbonate successions that developed in the downstream reaches of the basin, and alkaline–saline deposits of Lake T'oo'dichi' that developed in the upstream parts of the basin—have been interpreted as dominantly lacustrine in origin (Bell, 1986; Johnson, 1991; Merkel, 1996; Dunagan, 1998, 2000b; Turner and Fishman, 1991, 1998). A reexamination of these "lacustrine" successions suggests that both contain significant intervals dominated by wetland deposition.

Reinterpretation of the major lacustrine successions in the Morrison Formation is driven by a reevaluation of the environments based largely on paleohydrologic considerations. Recent reinterpretation of other deposits as largely wetlands that were previously thought to be lacustrine (Quade et al., 1995, 2003; Wright and Platt, 1995) has shed new light on ancient wetlands and the importance of groundwater in continental systems (Ford and Pedley, 1996; Evans, 1999; Tandon and Andrews, 2001; Pedley et al., 2003). For these reasons, we will use the term "lacustrine" or "lake" in reference to Morrison and other deposits that might be partly or largely reinterpreted as wetland deposits. Modern wetlands are recognized on the basis of ecological, sedimentological, and hydrological parameters (Cowardin et al., 1979); however, defining parameters vary considerably (e.g. see Cowardin et al., 1979; Zoltai, 1979; Navid, 1989; Finlayson and Moser, 1991). The hydrology of lakes and wetlands is centered on the relative contributions of groundwater and surface water (Cowardin et al., 1979). For the purpose of our reinterpretation, wetlands occur when groundwater predominates and lakes develop when surface water is sufficient to be the major input of water into the lowlands (Currey, 1990). Wetlands occur where groundwater table intersects the landscape and they receive surface water largely in the form of overland or sheet flow. Lakes receive their surface water largely through rivers and streams that enter the basin although in many cases they are partly fed by groundwater. These hydrologic distinctions are often difficult to resolve when examining ancient lacustrine and wetland deposits, especially when both systems occur in lowlands that often are sites of both regional discharge and local base-level for surface flow. However, the distinctions have important implications for interpretation of the Morrison paleoecosystem.

In the Morrison paleoecosystem, a re-evaluation of the paleohydrology for both of the major "lacustrine" systems is based largely on sedimentologic and geochemical evidence. First, the paucity of shoreline and deltaic deposits indicates that surface water was not a major component in either the upstream alkaline–saline or downstream carbonate "lacustrine" systems. This paucity of surface water is consistent with a Late Jurassic semi-arid climate, based on numeric models (Moore et al., 1992; Valdes, 1992, 1993), sedimentologic, paleontologic, and geochemical evidence (Peterson and Turner-Peterson, 1987; Turner and Fishman, 1991, 1998; Parrish, 1993a,b; Peterson, 1994a,b; Ekart and Cerling, 1996; T. Demko, written communication, 1998; Dunagan, 1998; Litwin et al., 1998; Schudack et al., 1998; Dunagan, 2000a,b; also see papers in this volume). Secondly, standard interpretation of stable isotope results from the Morrison "lacustrine" carbonate succession would lead to a hydrologically open interpretation despite the lack of evidence for significant surface water input. The apparent contradictions are resolved when the carbonate succession is reinterpreted to include a significant amount of wetland deposits as this then accommodates both the isotopic and sedimentologic data.

This paper documents the evidence and arguments that prompted the authors to consider groundwater, instead of surface water, as a major hydrologic component for both the carbonate successions in the downstream reaches of the Morrison depositional basin and the more proximal alkaline–saline deposits of what has been named “Lake” T’oo’dichi’. As a result, both of these deposits may be interpreted more appropriately as predominantly wetlands, a freshwater wetland in the case of the downstream carbonate successions and an alkaline–saline wetland in the case of the deposits of “Lake” T’oo’di-

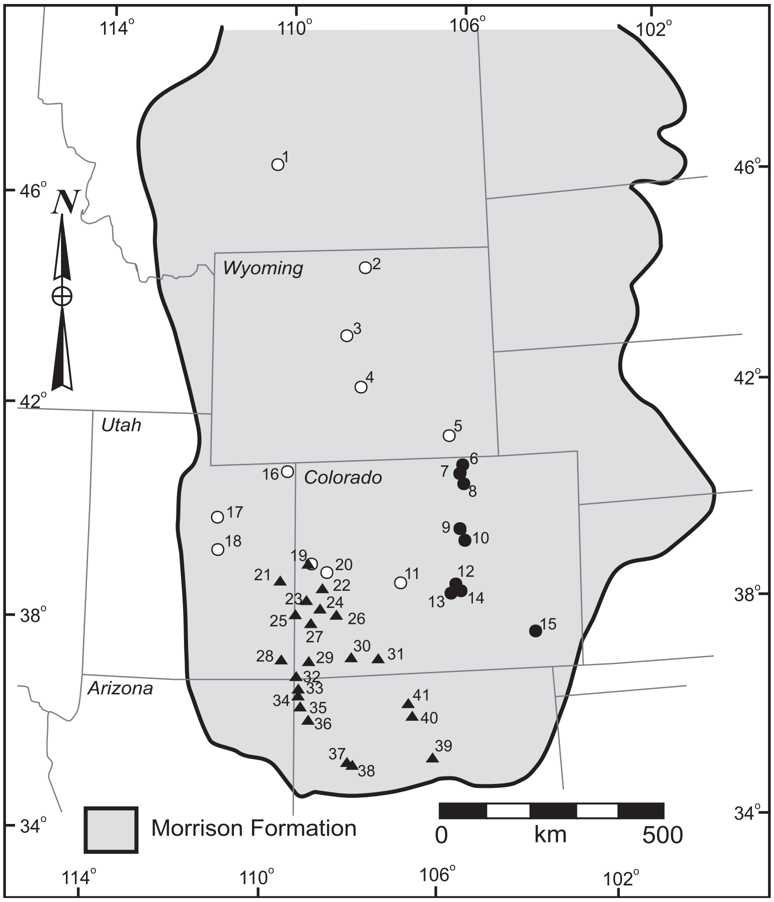

Fig. 1. Map showing the geographic distribution of the Morrison Formation across the Western Interior of the conterminous United States based on subsurface data and outcrop exposures (base map from Peterson, 1972). Open circles—reconnaissance localities for carbonate deposits; dark circles—detailed carbonate wetland/lacustrine sections; dark triangles—detailed Brushy Basin section. 1 (Belt, MT), 2 (Big Horn National Recreation Area, WY), 3 (Thermopolis, WY), 4 (Arminto, WY), 5 (Como Bluff, WY), 6 (Park Creek Reservoir, CO), 7 (Highway 287 roadcut, north of Ft. Collins, CO), 8 (Horsetooth Reservoir, CO), 9 (I-70 roadcut, Denver, CO), 10 (West Alameda Parkway, Morrison, CO), 11 (Gunnison, CO), 12 (Cope’s Nipple, Cañon City, CO), 13 (Skyline Drive, Cañon City, CO), 14 (Marsh–Felch Quarry, Cañon City, CO), 15 (Bravo Canyon, near Purgatoire River, CO), 16 (Dinosaur National Monument, Vernal, UT), 17 (Cleveland–Lloyd Quarry, near Price, UT), 18 (Moore Cutoff, near Moore, UT, in the San Raphael Swell), 19 (Colorado National Monument, CO), 20 (Fruita, CO), 21 (Dewey Bridge, UT), 22 (Escalante Canyon, CO), 23 (Blue Mesa, CO), 24 (Vancorum, CO), 25 (Lisbon Valley, CO), 26 (Norwood Hill, CO), 27 (Big Gypsum Valley, CO), 28 (Montezuma Creek, UT), 29 (McElmo Canyon, CO), 30 (Durango, CO), 31 (Piedra River, CO), 32 (Four Corners, CO), 33 (Beclabito, NM), 34 (Oak Springs, NM), 35 (Sanostee Wash, NM), 36 (Toadlena, NM), 37 (Goat Mountain, NM), 38 (Blue Peak, NM), 39 (Galisteo Dam, NM), 40 (Capulin Peak, NM), 41 (Deadmans Peak, NM). See Turner-Peterson (1987), Turner and Fishman (1991), and Dunagan (1998) for detailed locality information.

chi'. In both cases, however, true lacustrine intervals do exist.

2. Stratigraphic and geographic distribution of wetland/lacustrine deposits

Late Jurassic epicontinental sedimentation in the North American Cordillera lowland plain is recorded in the Morrison Formation (Fig. 1). The Morrison Formation is Late Jurassic (Kimmeridgian–Tithonian) in age based on isotopic (Kowallis et al., 1998) and biostratigraphic constraints (Litwin et al., 1998; Schudack et al., 1998). The Morrison paleoecosystem included a wide spectrum of terrestrial and minor marine environments represented in the sedimentary record by alluvial plain, eolian, fluvial, lacustrine, and nearshore marine deposits (Peterson, 1994a,b; Turner and Peterson, this volume). The regional stratigraphic relationships are discussed in Turner and Peterson (this volume). For our purposes, the Morrison Formation may be informally subdivided into the "lower" and "upper" portions based on the clay change that is marked by the vertical change from predominantly illitic mixed-layer clays to predominantly smectitic mixed-layer clays (Fig. 2; Keller, 1953, 1962; Owen et al., 1989). Illitic mixed-layer clays dominate in the undifferentiated "lower" Morrison and Colorado Plateau equivalents (Windy Hill, Tidwell, Salt Wash, Junction Creek, and lower Brushy Basin members), whereas the "upper" Morrison and its stratigraphic equivalent (upper Brushy Basin member) are dominated by smectitic mixed-layer clays.

Within the Morrison depositional basin, "lacustrine" carbonates are best developed in the distal parts of the depositional basin (Denver–Julesburg Basin, Fig. 3), downstream from the main alluvial plain that developed during deposition of the Salt Wash and Westwater Canyon Members (Fig. 2). The carbonates are thus most abundant east of westernmost Colorado. The most well developed successions are in east-central Colorado where they first appear directly

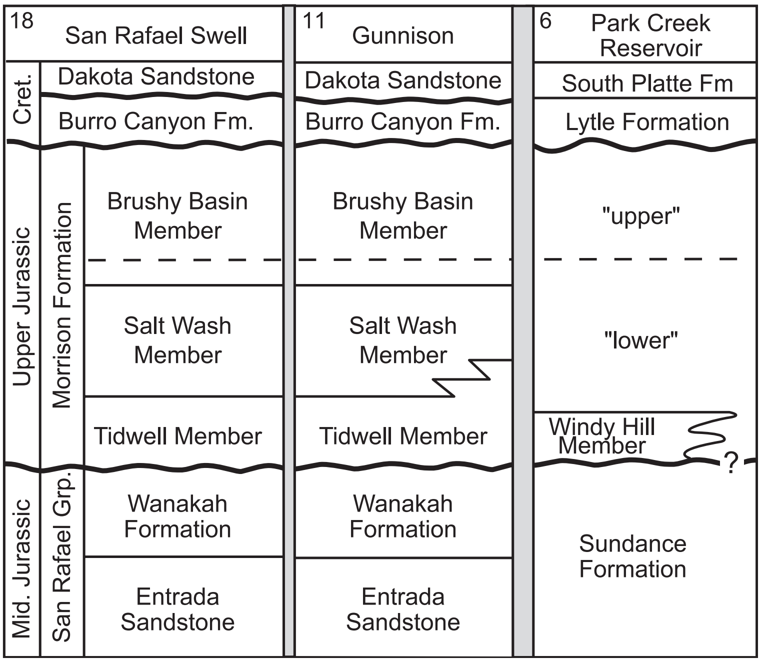

Fig. 2. Schematic chart illustrating Morrison Formation nomenclature and associated stratigraphic units (O'Sullivan, 1992; Peterson, 1994a,b; Dunagan, 1998). The J-5 unconformity (basal) and K-1 unconformity (upper) separate the Morrison Formation from associated stratigraphic units above and below the Morrison Formation across the southern part of the Western Interior. The dashed line represents the clay change. Locations of sections are shown in Fig. 1.

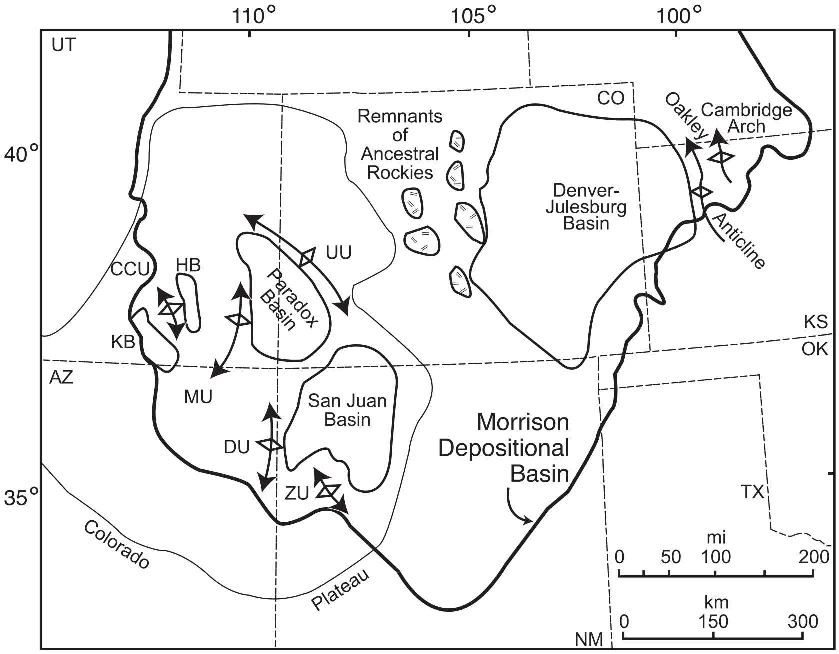

Fig. 3. Map showing the structural elements that were active during the Late Jurassic. CCU, Circle Cliffs Uplift; DU, Defiance Uplift; HB, Henry Basin; KB, Kaiparowits Basin; MU, Monument Upwarp; UU, Uncompahgre Uplift; ZU, Zuni Uplift. After Merriam (1955), Peterson (1957, 1986, 1994a,b), and Turner and Fishman (1991).

above the Windy Hill Member and equivalents, chiefly in the "lower" Morrison and to a lesser extent in the "upper" Morrison Formation. The uppermost Morrison in east-central Colorado is dominated by fluvial and associated overbank mudstone deposits (see Demko et al., this volume). "Lacustrine" carbonate deposits are scarce elsewhere in the Morrison Formation.

Alkaline–saline "lacustrine" deposits associated with the Lake T'oo'dichi' complex were deposited in the San Juan/Paradox Basin (Fig. 3). These deposits occur in the upper Brushy Basin Member in the east-central part of the Colorado Plateau (Fig. 4). Stratigraphically, this extensive "lacustrine" complex is equivalent to "lacustrine" carbonate deposits that occur above the clay change in east-central Colorado (Fig. 2).

Freshwater pond deposits, represented chiefly by laminated and massive gray–green mudstone units, occur locally in the Tidwell, Salt Wash, Westwater Canyon, and Brushy Basin Members of the Colorado Plateau and in the undifferentiated Morrison Formation of eastern Colorado. These freshwater pond deposits usually occur in association with fluvial sandstone units.

3. Methods

Field, stratigraphic, and petrographic observations of the wetland and lacustrine successions were accomplished by detailed measured sections, X-ray diffraction analyses, and thin section analyses. Cathodoluminescence (CL) and stable isotopic analyses were conducted on the carbonate units; scanning electron microscopy was used to supplement analyses of tuffs. Details of the 41 outcrop locations and descriptions were given in Turner and Fishman (1991) and Dunagan (1998).

X-ray diffraction techniques used to distinguish authigenic minerals associated with tuff deposits are described in Turner and Fishman (1991). Petrographic analyses of carbonates were supplemented by examination of polished hand samples and the staining of selected thin-section with a mixed stain of Alizarin Red S and potassium ferricyanide. Based on the

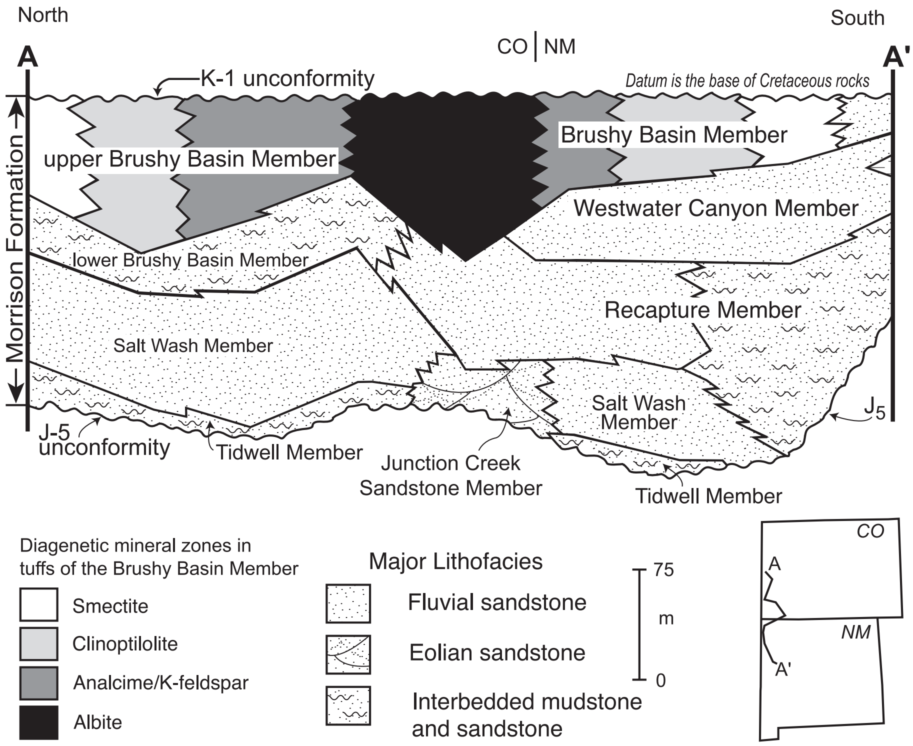

Fig. 4. Stratigraphic relationships of the Morrison Formation on the Colorado Plateau along a north–south transect (see inset map). J-5 and K-1 are regional unconformities bounding the Morrison Formation on the Colorado Plateau. Modified from Turner and Fishman (1991, Fig. 2).

sedimentary, paleontologic, and textural features, the general siliciclastic lithofacies and carbonate microfacies were determined.

Stained thin sections were used to identify predominantly monomineralic phases in the selection of carbonate samples for isotopic analysis. Selected thin sections also were examined using a Citl Cold Cathode Luminescence 8200 mk3 microscope under the following operating conditions: 10–12 kV and 150–180 μA. Detailed petrographic and CL microscopy were used to determine the degree of alteration in primary depositional and pedogenic phases. Micrite sampling focused on billet areas where contamination by diagenetic components such as heterogeneous and mottled micritic fabrics, clusters of dolomicrite crystals, micrite associated with root traces, and calcite and dolomite cement in voids would be minimized.

Samples for stable oxygen and carbon isotope analyses were collected by drilling 0.3–8.0 mg of individual carbonate depositional and selected diagenetic components from polished thin-section billets using a microscope-mounted microdrill assembly. Organic matter was removed by roasting the powdered carbonate samples at 380 °C for 1 h. Samples were reacted using two methods: (1) off-line reaction with 100% H_3PO_4 at 25 °C for 24 h; and (2) in a Carbo-Flo helium-sparged common acid bath at 120 °C in 100% H_3PO_4.

To evaluate the isotopic contribution of dolomite-derived CO_2 in micritic samples that contain both calcite and up to 15% dolomite, a timed-extraction procedure was used (Epstein et al., 1963; Walters et al., 1972). The CO_2 produced after reacting for 1 h was generated primarily from calcite dissolution. A mixture of calcite- and dolomite-derived CO_2 evolves over the next 3 h, but the gas produced after 4 h of reaction is considered representative of dolomite-derived CO_2. Samples identified through petrographic staining techniques that contain up to 15% dolomite in micrite yielded <0.12 μmol of dolomite-derived CO_2/mg of sample. Given the low yields of dolomite-derived CO_2, the isotopic composition of the micritic samples was assumed to be primarily calcite-derived. The isotopic ratios were measured on a Finnigan MAT Delta plus mass spectrometer at the University of Tennessee and the isotopic results are reported in standard delta-per mil (‰) relative to PDB (Craig, 1957). The five primary laboratory standards indicate an external precision ($\pm 1\sigma$) of ± 0.08 for δ^{13}C and ± 0.04 for δ^{18}O. Isotopic results obtained from the common acid bath were corrected to 25 °C.

4. Carbonate-dominated wetlands and lakes

Terrestrial carbonate deposits, from Grand Junction to east-central Colorado, represent a variety of depositional settings including wetland, marginal lacustrine, distal lacustrine, and undifferentiated wetland/lacustrine environments. In both lakes and wetlands, sedimentation was primarily associated with carbonate production derived from biogenic and bio-induced sources. The most well developed carbonate successions are present in the "lower" and "upper" Morrison Formation in east-central Colorado (Dunagan, 1998, 2000b). These intervals are dominated by limestone and mudstone intervals with lesser amounts of calcareous sandstone and siltstone. Siliciclastic sedimentation was restricted to areas near local uplifts (i.e. the Ancestral Rocky Mountains), fluvial units, or marginal lake settings.

4.1. Sedimentary characteristics

The carbonate units (15–200 cm thick) include limestone and rare dolostone beds in which six microfacies have been recognized: ooid skeletal packstone–grainstone, carbonaceous packstone, intraclastic packstone, peloidal skeletal packstone–grainstone, peloidal skeletal mudstone–wackestone, and micritic mudstone (Fig. 5A–C; Dunagan, 1998). Morrison limestones are commonly fossiliferous and include microbialites (Fig. 5A), oncoids, charophyte gyrogonites and encrusted stems, thin-shelled unionid bivalves, ostracodes, gastropods (prosobranch and pulmonate), comminuted plant debris, and bone fragments with lesser amounts of sponge spicules and conchostracans (Dunagan, 2000b).

Various sedimentary features characterize Morrison carbonate units at the local scale. Oolitic units are composed of normal, superficial, and compound ooids with lesser amounts of bioclasts, peloids and carbonate intraclasts, lithoclasts, and detrital quartz sand (Lockley et al., 1986; Dunagan, 1998). Magadi-type chert layers (Dunagan, 2000a), detrital quartz silt and sand, green mudstone rip-up clasts, reworked lithoclasts (volcanic, siltstone, and Magadi-type cherts), altered volcanic shards, peloids, fenestral pores with illuviated clays, and framboidal pyrite are present. Minor bioturbation in micrite-rich microfacies is also present. Vertebrate trackways are locally present (Lockley et al., 1986; Dunagan, 1998). Faint, poorly preserved lamina are present in association with microbialite deposits, micritic mudstones, and peloidal skeletal mudstones–wackestones. Cross-lamina in ooid packstone–grainstone and peloidal skeletal packstone beds are up to 30 cm thick. Starved quartz silt and peloid ripples were locally observed.

The limestone units exhibit abundant palustrine characteristics that include pseudomicrokarst, pedogenic, and evaporative features (Dunagan, 1998, 2000a). Pseudomicrokarst includes complex voids filled with vadose and internal sediment, micritic clasts, and calcite cement produced by brecciation and grainification (Fig. 5C; Dunagan, 2000a). Pedogenic features include root traces (mm to decimeter-scale), columnar and stacked rhizoconcretions. Evaporative palustrine features include circumgranular, desiccation, horizontal, and septarian cracks (Fig. 5C; Dunagan, 2000a). The intensity and abundance of these palustrine features increase stratigraphically upward. Subaerial exposure surfaces are locally present. Microkarstic features were also observed, such as dissolution of metastable skeletal allochems and dissolution voids. Calcite pseudomorphs after gypsum (Fig. 5D), halite, and trona; gypsum nodules replaced by calcite (< 1 cm); and anhydrite and halite pore-fillings are also present locally (Dunagan, 2000a). Laterally, carbonate units become nodular, brecciated, and pedogenically modified as they grade into or interbed with green mudstone, sandstone or siltstone intervals, and fluvial overbank or paleosol deposits (Fig. 6A,B).

Two siliciclastic mudstone lithofacies are associated with Morrison carbonate deposits—green mudstones and dark brown to gray, smectitic mudstones (Dunagan, 1998). Green mudstones are the most abundant of these two types of siliciclastic mudstone,

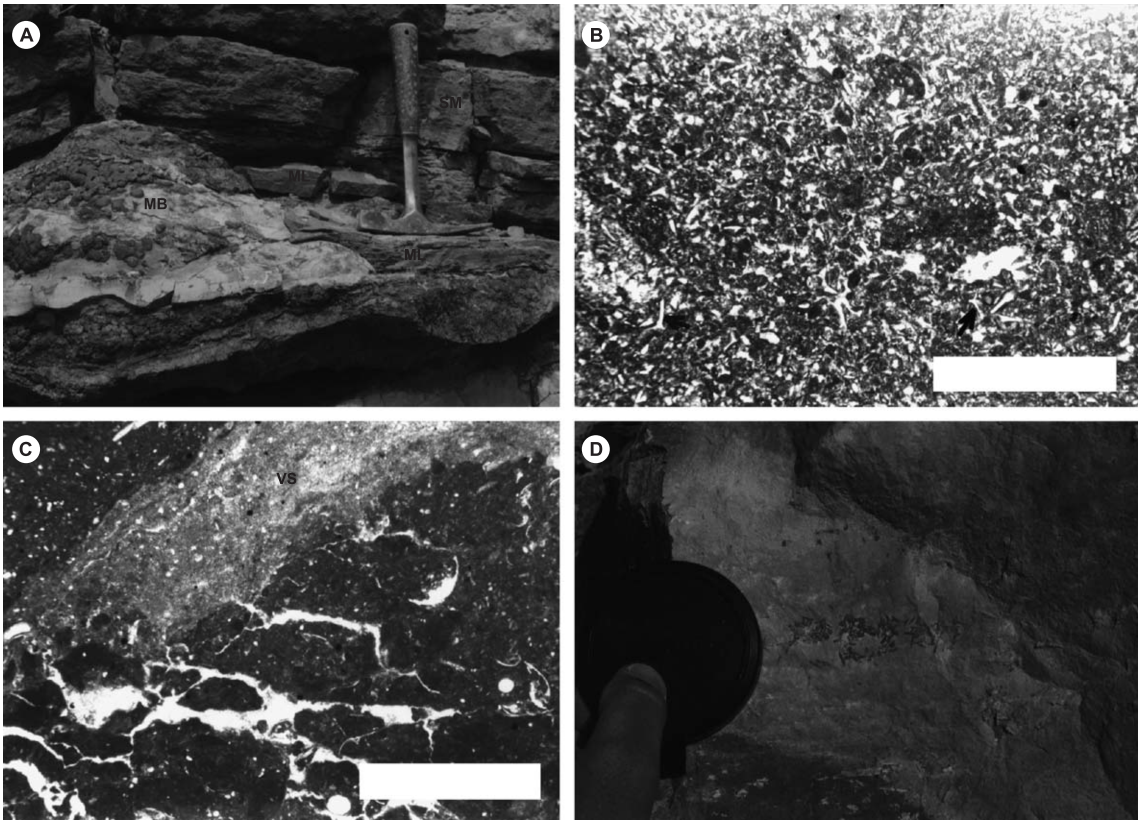

Fig. 5. Examples of wetland and lacustrine carbonate features and microfacies. (A) Partially silicified microbial bioherm (MB) with onlapping microbial laminates (ML) and overlying skeletal mudstone (SM) deposits (Park Creek Reservoir, Colorado, #6). Hammer for scale is approximately 28.5 cm long. (B) Photomicrograph of intraclastic peloidal grainstone with volcanic shards (arrows; Highway 287, Colorado, #7). Scale bar equals 2 mm. (C) Photomicrograph of micritic skeletal mudstone with abundant pseudomicrokarst features (Cope's Nipple, Colorado, #12) and numerous ostracode fragments. Pseudomicrokarst includes brecciation and grainification, circumgranular cracks, and vadose silt (VS) infilling pseudomicrokarstic voids. Scale bar equals 2 mm. (D) Photograph of calcite pseudomorphs after lenticular gypsum rosettes (Highway 287, Colorado, #7). Lens cap diameter is approximately 5 cm.

comprising up to 47% of the limestone–mudstone "lacustrine" intervals in east-central Colorado. The predominately illitic green mudstone units range from 2 to 400 cm thick, lack apparent bedding, and laterally grade and pinch out into paleosols, overbank deposits, and limestone units (Fig. 6A). Minor detrital quartz silt- and sand-grains as well as carbonate nodules (< 4 cm) that characterized by septarian and circumgranular cracks are present. Charophyte gyrogonites, gastropods, unionid bivalves, bone fragments, and ostracodes are locally observed both in the green mudstone and in carbonate nodules. Red to purple mottles are common. Dark brown, smectitic mudstones were only locally observed at two localities (# 8, 14). These dark brown mudstones were approximately 25 cm thick, slightly calcareous, and laminated with minor soft-sediment deformation, detrital quartz silt grains, and rare ostracode fragments. Exposure features were not observed in the dark brown mudstones.

Sandstone and siltstone lithofacies (2 to 150 cm) are fine-grained and calcareous. These units have lens-like geometries and are typically laterally discontinuous, grading into green mudstones, limestones, and overbank deposits (Dunagan, 1998). The sandstones are typically structureless as a result of bioturbation, although few distinct burrows were observed. Plant and bone fragments are also present.

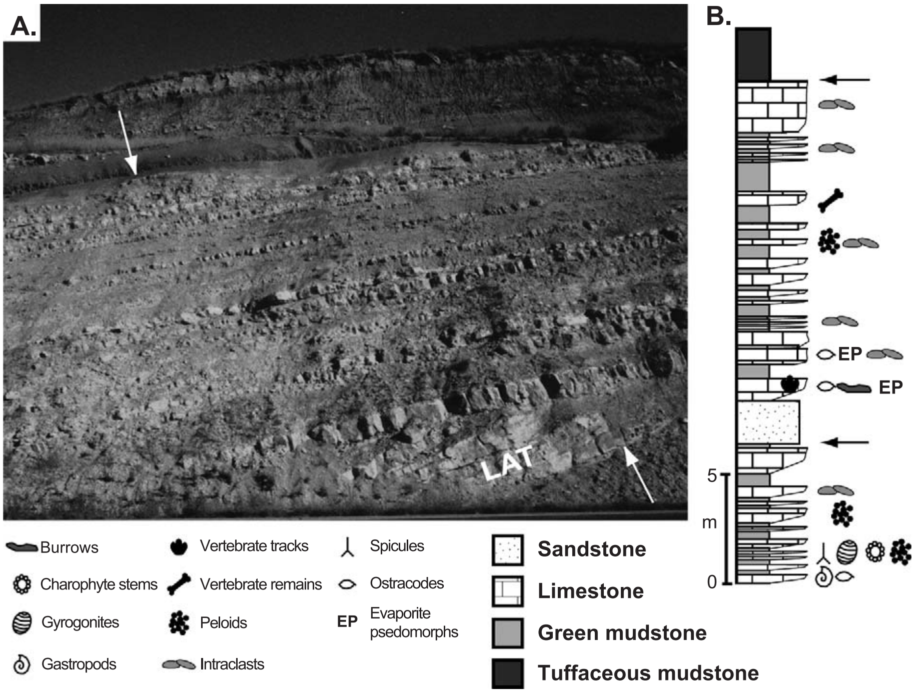

Fig. 6. (A) A typical sequence of carbonate deposits (weathering with positive relief) interbedded with green mudstone (Highway 287, Colorado, #7). Approximately 20 m is shown between the arrows. Basal part of photograph shows a fluvial sandstone bed with lateral accretion sets (LAT). White arrows show areas that correspond to areas of partial stratigraphic log in (B). (B) Partial stratigraphic log of locality #7.

Locally, the sandstones have symmetrical ripple marks as well as rare thin gypsum interbeds (< 4 cm thick) and teepee structures. The siltstones commonly are laminated and contain carbonized plant, conchostracan, ostracode, and bone fragments.

4.2. Interpretation

Sedimentologic and paleontologic features suggest the terrestrial carbonates (limestone and dolostone), green mudstone, dark brown mudstone, sandstone, and siltstone represented a mosaic of marginal and distal lacustrine, and undifferentiated wetland/lacustrine environments that dominated significant portions of the distal Morrison alluvial plain. Lacustrine settings are characterized by the presence of laminations and scarce deltaic or shoreline deposits. Because distal lacustrine units cannot always be traced laterally to shoreline deposits, a lack of definitive fluvial influence is not necessarily an indication of wetland deposition. Thus, sedimentologic evidence permits delineation of three environments: marginal lacustrine (shoreline and deltaic), distal lacustrine (laminated), and undifferentiated wetland/lacustrine.

4.2.1. Marginal lacustrine deposits

Shoreline and minor deltaic features characterize the marginal lacustrine carbonates of the Morrison and are represented by laterally extensive siltstone, sandstone, intraclastic packstone and ooid grainstone lithofacies. The meandering nature of the fluvial systems differs from the large, braided fluvial complexes typical of the Morrison Formation farther west (Tyler and Ethridge, 1983; Turner-Peterson, 1985, 1986; Peterson, 1994a,b). These low-energy streams were distal from the primary siliciclastic source areas to the west and southwest (i.e. Elko and Mogollon Highlands) and were probably dominated by a fine-grained suspended load and a Ca^{2+} and HCO_3^--rich dissolved load.

The low-gradient ramp-like lake margins were subjected to frequent emergence and pedogenic modification based on the abundance of subaerial exposure features, pseudo-microkarst and microkarst, root traces, and mottling (i.e. palustrine features). Intraclastic lithofacies point toward exposure, desiccation, and reworking along the shallow lake margins. Conchostracans and burrows suggest ephemeral inundation in smaller secondary carbonate ponds and around the margins of Morrison lakes. Locally, vertebrate trackways were present along wave-influenced shorelines characterized by cross-lamina and ooid grainstones. The presence of relatively clean ooid grainstone deposits suggests that moderate to high energy-regimes were locally present along lacustrine margins (Lockley et al., 1986).

4.2.2. Distal lacustrine deposits

Dark brown laminated mudstone and poorly laminated carbonate lithofacies (micritic mudstone, microbialites, and peloidal skeletal mudstone and wackestone) dominated the low-energy distal lacustrine settings (Dunagan, 1998). The geographic restriction of these deposits; the presence of pseudomicrokarst, karst-like features resulting from pedogenesis and plant rooting activity; and desiccation cracks suggest relatively shallow water deposition with episodic subaerial exposure (palustrine conditions), even in the distal reaches of Morrison lakes. The laminated deposits suggest that the bottom waters of Morrison lakes may have experienced temporary stratification at the local scale; however, the limited areal extent as well as the poor preservation of laminations in the carbonate deposits, the lack of gyttja or sapropel deposits (Merkel, 1996), and the absence of definitive fish remains (Freytet and Plaziat, 1982) indicate that the water columns of Morrison lakes were primarily oxygenated and holomictic.

4.2.3. Undifferentiated wetland/lacustrine deposits

Certain lithofacies—peloidal skeletal mudstone–packstone, carbonaceous packstone, and micritic mudstone that lack laminations, as well as the massive calcareous green mudstone—have characteristics that do not allow for differentiation into either lacustrine or wetland settings. The presence of filter- and suspension-feeding invertebrates, such as freshwater unionid bivalves, sponges, and ostracodes, associated with these lithofacies confirm that siliciclastic deposition in the lakes and wetlands in the downstream portions of the Morrison basin was minor. The siliciclastic material was deposited along lake margins where fluvial systems entered the lakes or where overland flow enter the carbonate wetlands. The siliciclastic material that moved into carbonate lakes and wetland areas was filtered out by a fringing vegetated zone that acted as a sediment filter, which reduced the potential influx of siliciclastics farther into the water body. This fringing vegetated zone was formed by colonization of shallow-water marsh and land plants around lake margins and wetlands and these deposits contained significant amounts of detrital quartz sand or silt. The fine-grained nature of the siliciclastics in these deposits suggests that much of the detrital material was derived from overland flow rather than fluvial processes.

The ubiquitous nature of charophyte stems and gyrogonites in the carbonate units also attests to the limited input of fluvial siliciclastics into the carbonate lakes and wetlands. The widespread distribution of charophytes suggests a photic zone relatively free of sediment, which is consistent with water bodies that did not have significant input from streams.

The undifferentiated wetland/lacustrine lithofacies are characterized by the same palustrine features associated with marginal-lacustrine settings. Palustrine features (pseudomicrokarst and pedogenic cracks) in the carbonate nodules associated with green mudstones and the structureless nature of the green mudstones suggest that the mud originated as suspended load in sheet floods deposited along lake margins or in wetland areas. The paucity of skeletal grains in the green mudstones reflects intense bioturbation, meteoric dissolution, and pedogenic leaching along marginal lacustrine or wetland areas. Gleying of the mudstones would have resulted from groundwater saturation in later carbonate-producing wetlands or lakes.

Where present, unionid bivalves, prosobranch gastropods, and sponges suggest perennial, well-oxygenated conditions. Adjacent to lake margins or in the wetlands, local reducing and anoxic conditions allowed for the accumulation of limited macroplant debris preserved as carbonaceous impressions (see Parrish et al., this volume). A prolific bacterial population is suggested by the presence of framboidal pyrite scattered throughout the carbonate units. The processes of carbonate sedimentation in the carbonate wetlands and lake margins were similar to those in distal lacustrine settings. Whereas Morrison carbonates lack abundant molds of macroplants typically associated with tufas (Ford and Pedley, 1996; Pedley et al., 2003), the commonly preserved encrusted stems of charophytes observed at the petrographic scale suggest a groundwater influence on carbonate sedimentation. The calcification of charophyte stems served as an important contributor to the biogenically induced inorganic calcite (micrite). Degradation of the calcified charophyte stems and other skeletal fragments was the major source of carbonate mud in the Morrison carbonates.

4.3. Stable isotopes

The degree of alteration in primary depositional and pedogenic phases may be determined by detailed petrographic and catholuminescence microscopy. Valero Garcés and Gisbert Aguilar (1993) noted that carbonate phases have undergone diagenetic alteration very early in units that exhibit non-luminescent cements and an abundance of vadose and subaerial exposure features. In the Morrison Formation, nonferroan micrite and microspar are the dominant phases and display a range of dull to moderate luminescence. In the Morrison carbonates, the abundance of depositional components that exhibit dull luminescence, and the abundance of vadose and subaerial exposure features suggest very early diagenetic stabilization for much of the carbonate succession. In addition, the preservation of cyanobacterial tubules, charophyte stems, and clotted "aggregates" of micrite within Morrison carbonates are indicators of minimal post-depositional alteration (Wright et al., 1997). Low-magnesium calcite, a stable phase of calcite, is the most common carbonate precipitate in freshwater lakes (Kelts and Hsü, 1978). The abundance of low-magnesium calcite in the micritic matrix of Morrison carbonates suggests preservation of the original geochemical composition and that the primary depositional phase is non-ferroan calcitic micrite. Samples from this phase were microdrilled for isotopic analysis.

4.3.1. Results

Carbonate from modern and ancient lacustrine and wetland deposits display a wide range of isotopic compositions (Keith and Weber, 1964; Tandon and Andrews, 2001); however, these carbonates typically have depleted isotopic ratios of ^{18}O and of ^{13}C when compared to coeval marine carbonates (Keith and Weber, 1964). The isotopic composition of Morrison carbonates are similarly depleted (Fig. 7, Table 1).

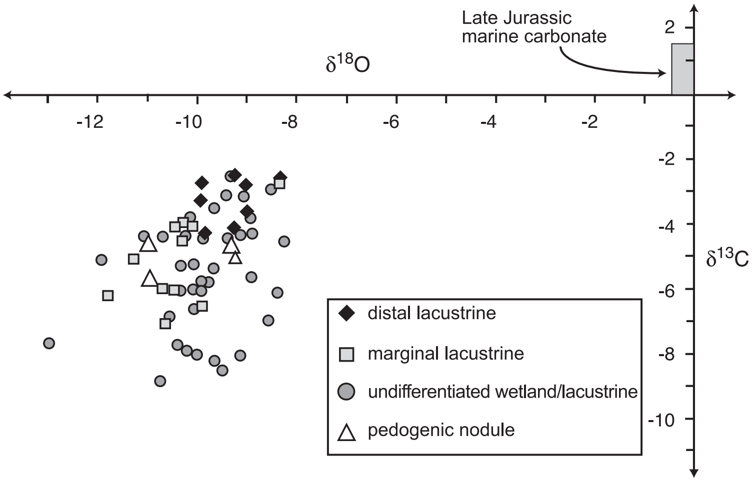

Fig. 7. Stable isotopic compositions (PDB) of the primary depositional and pedogenic components from the Morrison Formation. The Late Jurassic marine carbonate field is based on data from Lindh (1984). Isotope results are reported in standard delta-per mil (‰) relative to PDB (Craig, 1957).

Table 1
Detailed stable oxygen and carbon isotope compositions of the calcite micritic matrix for the marginal lacustrine, distal lacustrine, undifferentiated wetland/lacustrine, and pedogenic carbonate phases in the Morrison Formation (east-central Colorado); mudstone (mdst), wackestone (wkst), packstone (pkst), grainstone (grst)

Sample	Description	$\delta^{18}O$	$\delta^{13}C$
Marginal lacustrine			
H-23.5-A	brecciated clast in silty intraclast wkst	−10.72	−5.96
H-38.7-A	mdst with detrital quartz silt	−10.49	−6.01
H-41.0b-B	clast encircled by circumgranular crack in skeletal intraclast wkst–pkst	−10.66	−7.03
HR-11.25-A	skeletal mdst with abundant detrital quartz	−10.46	−4.09
HR-65.2-A	intraclast; intraclast–skeletal pkst, pseudomicrokarst	−11.82	−6.19
MFQ-18.2-A	mdst; abundant detrital quartz and evaporite pseudomorphs	−8.37	−2.77
MFQ-23.9-B	skeletal mdst above clastic (quartz and feldspar) fining upward bed (2–3 cm)	−10.32	−4.53
MFQ-23.9-E	mdst laminae between coarse clastic beds	−10.30	−3.98
MFQ-24.1-A	mdst; 5 mm from evaporite pseudomorphs (2 cm)	−10.11	−4.08
WAP-6.6-A	bioturbated mdst with volcanic rock fragments (VRF)	−9.92	−6.44
WAP-18.8-A	mdst with abundant VRF and detrital quartz sand	−11.30	−5.08
	Average (*n*=11)	−10.41	−5.11
Distal lacustrine			
SD-18.15-B	bioturbated, faintly laminated skeletal wkst; minor dolomicrite	−9.01	−2.90
SD-18.5-A	bioturbated, faintly laminated skeletal wkst	−8.34	−2.65
SDS-1.45-C	skeletal wkst; numerous ostracode fragments	−9.96	−3.33
HR-7.5-7.65B-A	skeletal mdst; Magadi-type cherts (MTC) common	−9.03	−3.66
HR-7.85-A	skeletal mdst between two MTC lens	−9.26	−4.16
HR-10.0-A	skeletal mdst below MTC lens	−9.85	−4.33
PCS-12.5a-1-A	mdst laminae in skeletal pkst layers above microbial buildups	−9.93	−2.78
PCS-12.5a-2-B	mdst laminae in skeletal pkst layers above microbial buildups	−9.27	−2.57
	Average (*n*=8)	−9.33	−3.30
Undifferentiated wetland/lacustrine			
CQ-29.6A-B	skeletal wkst–pkst; minor dolomicrite (<10%)	−10.71	−4.42
CQ-29.6B-A	skeletal peloidal wkst–pkst; minor dolomicrite (<10%)	−8.52	−2.99
H-23.9-A	skeletal mdst with minor dolomicrite	−9.92	−5.75
H-24.25-A	silty skeletal mdst	−10.09	−6.02
I70-27.6-A	clayey mdst; minor dolomicrite	−9.68	−5.36
I70-40.4-A	mdst; fenestral porosity, pseudomicrokarst, burrows;	−10.35	−5.28
I70-42.7-A	mdst with abundant pseudomicrokarst	−8.92	−4.33
I70-51.7-A	clayey mdst	−10.08	−6.62
I70-51.7-B	clayey mdst	−8.92	−5.61
I70-51.7-C	clayey mdst	−9.78	−5.79
I70-55.3-A	marly mdst	−10.77	−8.80
I70-55.3-B	marly mdst	−9.15	−8.01
I70-55.3-C	marly mdst	−9.67	−8.17
I70-55.3-D	marly mdst	−9.51	−8.47
I70-64.2-A	laminated skeletal wkst; near intergranular porosity	−9.93	−6.05
MFQ-23.9-A	skeletal mdst	−10.56	−6.82
MFQ-23.9-C	light-colored mdst laminae	−9.41	−4.47
MFQ-23.9-D	mdst	−9.14	−4.36
P2-1.25-A	clay-rich mdst; pseudomorphs after evaporites present	−10.03	−7.98
P2-1.25-B	clay-rich mdst; pseudomorphs after evaporites present	−10.21	−7.86
P2-1.25-C	clay-rich mdst; pseudomorphs after evaporites present	−10.42	−7.67
P2-10.0-A	skeletal-peloid-intraclast pkst; pseudomorphs after gypsum present	−11.08	−4.40
P2-9.05-A	laminated clay-rich and silty mdst; rhizoturbated	−9.43	−3.16
PT-[-0.1]-A	microbially laminated skeletal mdst; MTC clasts	−9.89	−4.49
PT3-0.5-A	skeletal mdst below oncoid skeletal pkst	−9.07	−3.20

Table 1 (*continued*)

Sample	Description	$\delta^{18}O$	$\delta^{13}C$
Undifferentiated wetland/lacustrine			
PCR-12.0B-A	skeletal mdst–wkst; abundant fenestral and interskeletal porosity and pseudomicrokarst	−12.99	−7.64
PCR-5.0-A	bioturbated skeletal mdst; minor detrital quartz sand	−9.68	−3.56
PCS-18-A	clayey mdst near red mottling	−9.34	−2.58
PCS-18-B	clayey mdst	−10.16	−3.82
SD-12.75B-A	skeletal mdst–wkst; minor detrital quartz sand and pseudomicrokarst	−8.94	−3.87
SD-7.25-.35-1-A	carbonate nodule (skeletal mdst) in green mdst	−8.26	−4.56
SD-7.25-.35-2-A	carbonate nodule (skeletal mdst) in green mdst	−10.26	−4.39
WAP-0.8-0.87-A	silty mdst	−10.10	−5.26
WAP-5.0-A	Mdst	−8.58	−6.94
WAP-7.05-A	mdst with abundant green mdst rip-up clasts	−8.39	−6.12
WAP-10.3-A	skeletal mdst	−11.94	−5.12
WAP-10.4-A	skeletal mdst	−10.34	−6.04
	Average (n)	−9.84	−5.57
Pedogenic carbonate			
H-13.2-1-A	pedogenic nodule	−9.24	−5.08
H-8.6-A	pedogenic nodule; <15% dolomicrite	−11.00	−4.69
HR-15-A	pedogenic nodule with minor cracks	−10.97	−5.77
HR-24.9-1-A	pedogenic nodule with minor cracks; <15% dolomicrite	−9.33	−4.75
	Average (*n*=4)	−10.14	−5.07

For the Morrison Formation, distal lacustrine carbonates have $\delta^{13}C$ values from −2.6‰ to −4.3‰, and $\delta^{18}O$ values from −8.3‰ to −9.9‰; marginal lacustrine carbonates show an increase in isotopic heterogeneity as compared to the distal lacustrine carbonates, with $\delta^{13}C$ values ranging from −2.7‰ to −7.03‰, and $\delta^{18}O$ from −8.3‰ to −11.8‰ (Fig. 7). Undifferentiated wetland/lacustrine values have $\delta^{13}C$ values from −2.5‰ to −8.8‰, and $\delta^{18}O$ values from −8.2‰ to −12.9‰. The distal lacustrine facies are typically enriched in ^{18}O and ^{13}C as compared to the marginal lacustrine and undifferentiated wetland/lacustrine values; in general, the carbonate isotopic compositions of undifferentiated wetland/lacustrine, marginal lacustrine, and distal lacustrine units are enriched in ^{18}O and ^{13}C when compared to diagenetic pore-filling carbonate phases (Dunagan, 1998).

Linear regression analysis by use of the "least squares" method (Koch and Link, 1971) of the $\delta^{18}O$ and $\delta^{13}C$ values revealed a lack of strong covariant trends through closely spaced samples from selected stratigraphic intervals ($r=0.1$ to 0.50) and throughout the wetland/lacustrine carbonate succession for all the isotope results ($r=0.36$). According to Talbot (1990), a high correlation between $\delta^{18}O$ and $\delta^{13}C$ requires r values greater than or equal to 0.7.

4.3.2. Interpretation of isotopic data

Oxygen isotope ($\delta^{18}O$) values of lacustrine carbonates reflect the mineral precipitation temperature and the isotopic composition of the lake water (Talbot and Kelts, 1990). The lake water values are a function of the isotopic values of the meteoric and groundwater inputs, potential evaporation, and interplay between different water sources in the basin (Talbot and Kelts, 1990; Alonso-Zarza, 2003). Biogenic factors (i.e. organic productivity) are the primary controls on the carbon isotopic ($\delta^{13}C$) values for lakes (McKenzie, 1985).

The covariance between $\delta^{18}O$ and $\delta^{13}C$ is a commonly used standard in distinguishing lacustrine carbonates that precipitated in hydrologically open or closed lakes (Talbot, 1990; Talbot and Kelts, 1990). In a hydrologically open lake, water has a short residence time. As a result, the oxygen isotopic composition of the carbonates is relatively invariant ($r<0.7$) and should be closely related to the bulk isotopic compositions of inflow waters (Talbot, 1990; Talbot and Kelts, 1990). Hydrologically closed lake waters display a characteristic, highly correlated covariance ($r \geq 0.7$; Talbot, 1990; Talbot and Kelts, 1990), which reflects evaporative concentration of heavier isotopes in the evolving isotopic composition of lake waters (Platt, 1992).

The distal lacustrine, marginal lacustrine, and undifferentiated wetland/lacustrine carbonates of the Morrison Formation lack covariant trends between $\delta^{18}O$ and $\delta^{13}C$ values ($r = 0.1-0.50$) and display relatively invariant oxygen isotopic compositions ($\delta^{18}O = -9.93$ ‰; $\pm 1\sigma = 0.93$). The standard interpretation, following Talbot (1990) and Talbot and Kelts (1990), would suggest that carbonate deposits represented hydrologically open "lacustrine" systems in the Morrison paleoecosystem. However, the "lacustrine" interpretation implies major surface water input delivered by streams, which is inconsistent with the sedimentologic, paleontologic, and paleoclimate data including: (1) the paucity of evidence for fluvial–lacustrine deposits as suggested by only limited shoreline and deltaic features; (2) the intermittent nature of stream deposits that are present (Turner and Peterson, this volume), which is consistent with the Late Jurassic semi-arid to arid climate; and 3) the widespread distribution of charophytes in addition to filter- and suspension-feeding biota, all of which suggest limited siliciclastic input.

The isotopic data thus support our reinterpretation that many of the "lacustrine" carbonates were groundwater-fed and therefore better interpreted as paleowetlands. Groundwater discharge allowed carbonate wetlands and lakes to exist, and the replenishment by groundwater prevented evaporative enrichment in the semi-arid Late Jurassic climate. As a result, the narrow range of $\delta^{18}O$ and $\delta^{13}C$ values for the distal lacustrine deposits reflects the isotopic composition of the groundwater in the downstream reaches of the Morrison basin in east-central Colorado. Small variations in $\delta^{18}O$ and $\delta^{13}C$ values from distal lacustrine carbonates reflect minor oscillations in temperature, inflow-evaporation balance, and limited interaction with soil zone CO_2 (Talbot, 1990; Tandon and Andrews, 2001).

The greater range in $\delta^{18}O$ displayed by the marginal lacustrine and the undifferentiated wetland/lacustrine carbonates is a result of interaction with isotopically light meteoric waters. Petrographic evidence of the most depleted $\delta^{18}O$ and $\delta^{13}C$ values is consistent with meteoric diagenesis. The most depleted samples ($\delta^{18}O$ values < -12 ‰) have either abundant pseudomicrokarst or microsparitic textures. Pedogenic modification of lacustrine or wetland carbonates typically results in lower $\delta^{18}O$ and $\delta^{13}C$ values due to calcite stabilization in the presence of isotopically light meteoric fluids and fluids charged with soil-derived CO_2 (Allan and Matthews, 1982; Platt, 1992; Tandon and Andrews, 2001).

Isotopically light $\delta^{18}O$ water composition recorded in Morrison carbonates reflects deposition in a dry continental interior, consistent with isotopic depletion associated with progressive rainout eastward across the Western Interior (D. Ekart and T. Cerling, written communication, 1998; Turner and Peterson, this volume). The depleted meteoric water fell in the highland regions to the west and entered regional aquifers that discharged in the downstream portions of the basin. Discharge of these regional aquifers was the primary source of water for the distal carbonate wetlands and also contributed to the distal lakes. The least altered $\delta^{18}O$ values of the distal lacustrine units in the Morrison thus reflect the depleted isotopic composition of regional groundwater.

The marginal lacustrine and undifferentiated wetland/lacustrine carbonates were isotopically heterogeneous with respect to carbon ($\delta^{13}C = -2.5$ ‰ to -8.8 ‰). Typically in lacustrine settings, mechanisms proposed to explain variations in $\delta^{13}C$ values include: (1) variations in biological productivity (McKenzie, 1985; Talbot, 1990, 1994); (2) input of detrital marine carbonate (Oberhänsli and Allen, 1987; Platt, 1992); (3) diagenetic production of isotopically heavy ^{13}C due to bacterial methanogenesis in anoxic subenvironments (Irwin et al., 1977; Talbot and Kelts, 1990) or isotopically light ^{12}C from bacterial sulphate reduction (Irwin et al., 1977); and (4) input from isotopically light soil-derived CO_2 (Allan and Matthews, 1982; Cerling, 1984).

Sedimentologic features and paleoecologic relationships (Dunagan, 1998, 2000a) indicate that Morrison carbonate lakes and wetlands were characterized by shallow-water, and primarily, holomictic conditions. While Morrison carbonate wetlands and lakes may have experienced variations in biologic productivity, ^{13}C-enrichment of the surface waters, which is common in many modern eutrophic lakes, such as Lake Greifen and Lake Zürich (McKenzie, 1985), did not occur due to the lack of sustained stratification in the water columns. The negative $\delta^{13}C$ values of Morrison lacustrine and wetland carbonates are also atypical of ^{13}C-enriched 'methanic' carbonates (Talbot and Kelts, 1990). In addition, no detrital marine carbonate clasts have been observed in the Morrison Formation in east-central Colorado. However, dissolved inorganic carbon (DIC) may have been derived from Pennsylvanian and Permian marine carbonate rocks in the highland source areas. The depleted $\delta^{13}C$ lacustrine and wetland values could have been influenced by marine DIC (with depleted $\delta^{13}C$ values) transported as part of the dissolved load in Morrison groundwater and streams. Calcium (Ca^{2+}) and bicarbonate (HCO_3^-) required for carbonate deposition may have had similar sources.

The heterogeneity associated with the $\delta^{13}C$ values of marginal lacustrine and wetland carbonates is best explained by contact with isotopically light soil-derived CO_2, the isotopic composition of which varies in ^{13}C depending on the extent of vegetative cover in a dominantly siliciclastic soil (Allan and Matthews, 1982; Platt, 1992; Tandon and Andrews, 2001). The abundance of palustrine features displayed by these deposits indicates that pedogenic processes played a critical role in shifting the isotopic composition to more depleted $\delta^{13}C$ values as well as the sedimentary fabric of these carbonates. The input of isotopically light, soil-derived CO_2 varied as a function of the intensity and length of pedogenesis of Morrison marginal lacustrine and wetland carbonates, and the amount of oxidized C_3 organic matter within the lake. Microbial respiration associated with bacterial sulfate reduction near the sediment–water interface, as suggested by the presence of framboidal pyrite, probably contributed isotopically light carbon as well.

Pedogenic carbonate nodules from paleosols within the carbonate succession in east-central Colorado generally have a relatively homogeneous isotopic composition, with $\delta^{13}C$ from -4.6‰ to -5.7‰ PDB and $\delta^{18}O$ from -9.2‰ to -11.0‰ PDB (Fig. 7). These data are similar to Morrison paleosol carbonate data from the Colorado Plateau, where $\delta^{18}O$ values range from approximately -6.5‰ to -12‰ PDB (D. Ekart and T. Cerling, written communication, 1998); these paleosol carbonate values were used to estimate the oxygen isotopic composition of paleoprecipitation in the Morrison paleoecosystem ($\delta^{18}O = -9$‰ to -17‰, SMOW). Their estimates were based on the correlation between the isotopic composition of modern soil carbonate and associated meteoric waters from a variety of environments that have a range in mean annual temperature of 30 °C (Cerling and Quade, 1993). In east-central Colorado, pedogenic carbonate in the Morrison displays a narrower range of oxygen isotopic composition ($\delta^{18}O = -9.24$‰ to -11.00‰, PDB; Fig. 7) than for pedogenic carbonates elsewhere in the Morrison. This isotopic composition would correspond to calculated $\delta^{18}O$ meteoric water values of -7.3‰ to -9.0‰ SMOW at 25 °C using Friedman and O'Neil's (1977) calcite–water fractionation factor. The $\delta^{18}O$ isotopic composition of pedogenic carbonate tends to be 2–4‰ heavier than local meteoric waters due to evaporative enrichment of soil water (Quade et al., 1989). It is possible that the calculated "meteoric" isotopic composition from Morrison pedogenic carbonates reflects an evaporated soil–water composition. Alternatively, the isotopic composition could reflect the influence of groundwater on pedogenic carbonate.

4.4. Other climatic and hydrologic indicators

Platt and Wright (1992) noted that the evolution of palustrine facies is strongly affected by climatic setting. Their study of Carboniferous to Quaternary palustrine carbonate deposits in Europe and the United States indicates that three characteristic types of palustrine sequences are recognizable, each deposited under different climatic regimes: semi-arid, intermediate, and sub-humid (Platt and Wright, 1992).

Abundant pseudo-microkarst, pedogenic, and subaerial exposure features, collectively referred to as 'palustrine' (Freytet and Plaziat, 1982), are present in the lacustrine and wetland carbonates of the Morrison Formation. Morrison palustrine carbonate features suggest that Morrison lake margins and wetlands were repeatedly subjected to fluctuations in water-level. Based on the abundance of pseudo-microkarst features and the relative paucity of organic matter, evaporites, and calcrete horizons, Morrison palustrine features collectively imply deposition under Platt and Wright's (1992) 'intermediate'-type climatic conditions between semi-arid and sub-humid.

More recently, Alonso-Zarza (2003) noted that terrestrial carbonate units deposited in semi-arid climates typically exhibit development of widespread pseudo-microkarst and a lack of preserved organic matter. What might be considered evidence under Platt and Wright's (1992) palustrine classification for "wetter" conditions in Morrison palustrine carbonates (marginal lacustrine and undifferentiated wetland/lacustrine) instead reflects groundwater discharge in the downstream portion of the depositional system where these carbonates were deposited, giving the appearance of increased humidity in an otherwise semi-arid climate.

The interpretation of palustrine carbonate deposits as wetlands or marshes is not new. Wright and Platt (1995) argued that the term 'palustrine' is based on the word paludal, meaning swampy or marshy, and that palustrine carbonates should also be reappraised as "seasonal wetlands" and not simply marginal lacustrine settings. These seasonal wetlands have variable hydroperiods, from permanently flooded to intermittently exposed to intermittently flooded (Cowardin et al., 1979), due to the seasonal nature of groundwater discharge (Wright and Platt, 1995). The influence of groundwater in ancient palustrine carbonate deposits (Tandon and Andrews, 2001; Pedley et al., 2003; Quade et al., 2003), particularly in semi-arid climates (Sanz et al., 1995; Gierlowski-Kordesch, 1998; Alonso-Zarza, 2003) has gained increased attention.

Other climatically and hydrologically sensitive sedimentologic features associated with Morrison carbonate lake and wetland deposits, such as pedogenic carbonate nodules, evaporites, and Magadi-type chert, also point toward deposition in a semi-arid climate (Dunagan, 2000a). Petrographically, the pedogenic carbonate is composed of nodules and micro-nodules that display circumgranular cracks, craze planes, and evidence for multiple cycles of nodule breaking, healing and re-cracking similar to features observed in marginal lacustrine carbonates (Dunagan, 2000a).

Evaporite nodules, pore-fillings, and pseudomorphs are locally present in the undifferentiated wetland/lacustrine carbonates. The evaporites and evaporite nodules represent periods characterized by high evaporation rates relative to groundwater and surface water input into Morrison wetland and lakes. In addition, the local presence of evaporites (as pseudomorphs), rare teepee structures, and small scale brecciation and grainification associated with the marginal lacustrine carbonates points toward short-term climatic shifts on an annual to decadal scale to dominantly arid conditions. Prior to carbonate deposition, bedded gypsum–mudstone deposits represent deposition within evaporitic marine embayments laterally equivalent to the Windy Hill Member of the Morrison Formation (O'Sullivan, 1992; Peterson, 1994a,b) or, less likely, deposition in evaporitic playas that were apparently restricted to the lowermost Morrison Formation. In either case, gypsum deposition occurred in hydrologically closed basins that developed prior to carbonate deposition but also developed under semi-arid to arid conditions in eastern and western Colorado and southeastern Utah.

Magadi-type cherts (MTC) represent important indicators of continental hydrochemistry in lacustrine successions and have been reported from a variety of ancient and modern lacustrine settings (see references in Hay, 1968; Surdam et al., 1972; Sheppard and Gude, 1986; Schubel and Simonson, 1990; Krainer and Spötl, 1998). Magadi-type cherts (MTC) are associated with the microbialite-rich and poorly laminated charophyte-rich lacustrine deposits primarily in lower Morrison carbonate sequences immediately above the Windy Hill Member and its equivalents in east-central Colorado (Dunagan, 2000a). Although the dynamics of this chert forming process are not completely understood, the restriction of modern MTC to semi-arid environments and primarily limnological settings characterized by high alkalinity ($pH>9.0$–9.5; Eugster and Jones, 1968; Hay, 1968; Sheppard and Gude, 1986) suggests that the Morrison MTC were similarly restricted to lacustrine intervals characterized by high alkalinity.

4.5. Summary of carbonate wetlands and lakes

Carbonate-forming wetlands, and to a lesser degree carbonate lakes, were an important depositional environment of the Morrison paleoecosystem in east-central Colorado. The reinterpretation of these carbonate deposits as primarily wetlands has important implications for the interpretation of ancient lacustrine–palustrine carbonates, particularly those units deposited under semi-arid settings.

In general, deposits associated with the carbonate lakes and wetlands of the Morrison Formation are similar to those described from the preliminary studies of deposits associated with the “Las Tablas de Daimiel” of Spain, one of the few modern examples of an extensive, shallow-water carbonate-producing wetland (Alonso-Zarza, 2003). Morrison deposits are similar to the Quaternary wetland deposits of the U.S. southern Great Basin (Quade et al., 1995, 2003). The Morrison deposits, although largely interpreted as wetlands rather than lacustrine in origin, have sedimentologic and paleontologic features in common with deposits in the Lower Cretaceous Rupelo Formation of Spain (Platt, 1989), the Upper Cretaceous–Lower Tertiary of southern France (Freytet and Plaziat, 1982) and Bolivia (Camoin et al., 1997), the Paleocene–Eocene Flagstaff Formation of Utah (Wells, 1983), the Middle Eocene of Spain (Alonso-Zarza et al., 1992), and the Oligocene Lower Freshwater Molasse of Switzerland (Platt, 1992).

An interesting question that arises in the reconstruction of the paleolandscape during Morrison deposition is whether or not the ancestral Rocky Mountains were positive. From the composition of detrital clasts in the Front Range area of Colorado, it appears that the ancestral Rocky Mountains contributed at least some detrital material to the Denver–Julesburg Basin (Fig. 3), but preservation of the Morrison Formation across most of the region suggests that the Rocky Mountains were not a significant positive area and probably did not contribute significant amounts of sediment. The degree of connectivity between the proximal and distal parts of the basin can be discerned partly from the presence of wetland carbonate units, at least in the lower part of the Morrison, as far west as Grand Junction, Colorado, which is west of the ancestral Rocky Mountains. Also, evidence for fluvio-lacustrine interconnectivity is suggested by minor mixed siliciclastic and carbonate lacustrine deltaic deposits in eastern and central Colorado (localities #10, 12, 14; Jackson, 1979; Dunagan, 1998) and Wyoming (Medicine Bow anticline, Bone Cabin Quarry; F. Peterson, written communication, 2000) and by fluvial channels and crevasse splays closely associated with the carbonate lakes. The fine-grained nature of these deltaic deposits in east-central Colorado may be partially explained by the dominance of suspended or dissolved loads in distal Morrison fluvial systems. Paleobiogeography associated with two taxa of freshwater gastropods (*Amplovalvata cyclostoma*, *Mesauriculstra* spp.) suggests a west-to-east drainage across the Ancestral Rockies (Evanoff et al., 1998).

5. Alkaline–saline wetland/lacustrine deposits of Lake T’oo’dichi’

An extensive alkaline–saline wetland/lake complex developed during deposition of the upper part of the Brushy Basin Member of the Morrison Formation in the San Juan/Paradox Basin that developed upstream of the ancestral Uncompahgre Uplift, an area that covered present-day northeastern Arizona, northwestern New Mexico, southeastern Utah, and southwestern Colorado (Fig. 3; Turner-Peterson, 1987; Turner and Fishman, 1991). The wetland/lake complex persisted approximately 2 million years, based on ^{40}Ar/^{39}Ar dates from altered ash beds within the lacustrine deposits (Kowallis et al., 1998). This ancient wetland/lacustrine complex is the largest and oldest alkaline–saline wetland/lake delineated in the geologic record and has been named Lake T’oo’dichi’ (Turner-Peterson, 1985, 1987; Turner and Fishman, 1991), which is Navajo for “bitter water”. Although originally interpreted as largely lacustrine in origin (Bell, 1986; Turner-Peterson, 1987; Turner and Fishman, 1991, 1998), we are revisiting the interpretation of “Lake” T’oo’dichi’ on the basis of the relative roles of groundwater and surface water in the formation of the deposits. Detailed lithofacies descriptions have been presented elsewhere (Turner and Fishman, 1991), and the lithofacies information presented below represents an overview for the purposes of reevaluating the paleohydrology.

5.1. Depositional characteristics

Tuffs, consisting of altered silicic volcanic ash (2–50 cm thick), comprise the dominant and most distinctive lithofacies of the alkaline–saline wetland/lacustrine complex of Lake T’oo’dichi’ (Fig. 8A, B). These tuffs contain a variety of authigenic minerals including mixed-layer illite/smectite, clinoptilolite, analcime, potassium feldspar, albite, quartz, chalcedony, chlorite, kaolinite, barite, calcite, and dolomite

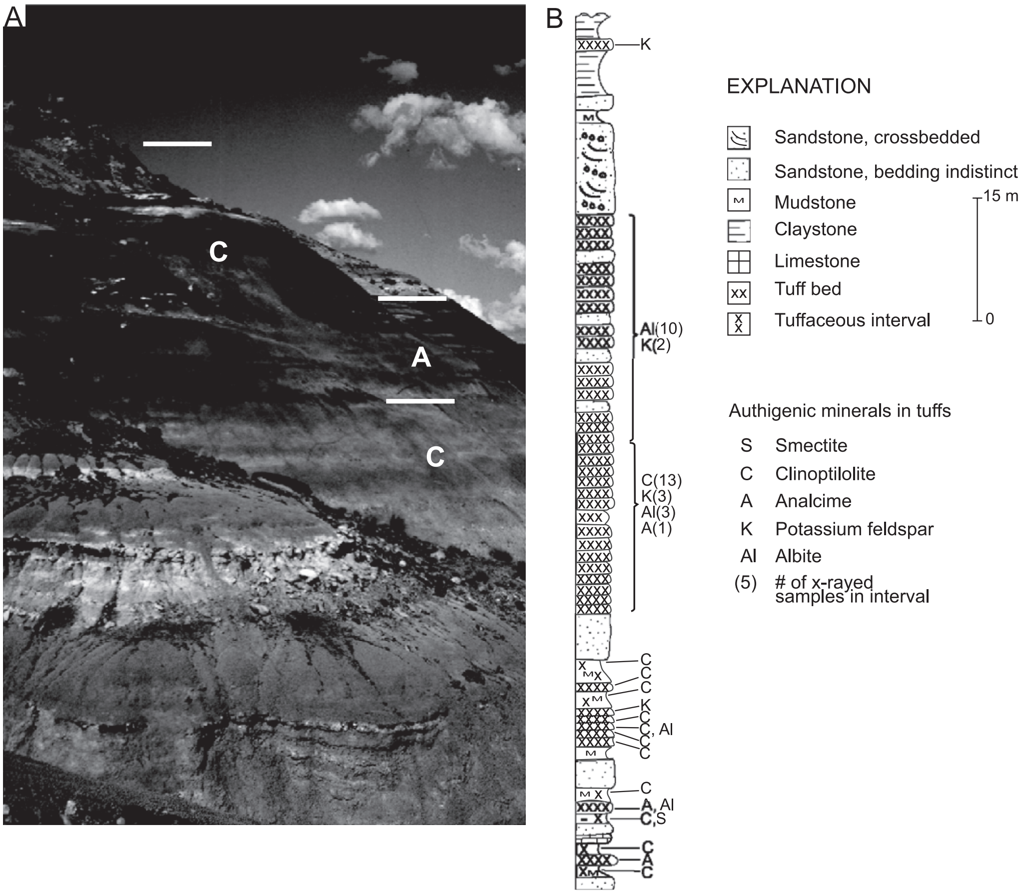

Fig. 8. (A) Outcrop of the Brushy Basin Member at Montezuma Creek, Utah (#28), within the clinoptilolite diagenetic mineral zone. Note the rounded slopes that result from "popcorn" weathering of smectitic clays. C, intervals of clinoptilolite-bearing tuffs; A, intervals in which tuffs contain authigenic albite and potassium feldspar. Interval is 108 m thick. (B) Partial stratigraphic log of locality (#28).

(Bell, 1983; Turner and Fishman, 1991). The tuffs exhibit few sedimentologic features, consistent with the destruction of primary sedimentary structures during alteration of the volcanic ash following deposition. Most of the ash was airfall in origin based on ubiquitous shard textures (Fig. 9) and locally, accretionary lapilli and altered pumice fragments (Turner and Fishman, 1991), with minor reworking suggested by local thickening and thinning of the tuffs. Preservation of delicate shard textures (Fig. 9) and accretionary lapilli indicate that any reworking of the airfall ash was slight. Similarly, biotic associations are limited, the probable result of the inhospitable nature of the lake waters. Locally abundant burrows of one type indicate that only one kind of burrowing organism found the alkaline–saline waters habitable (S. Hasi-

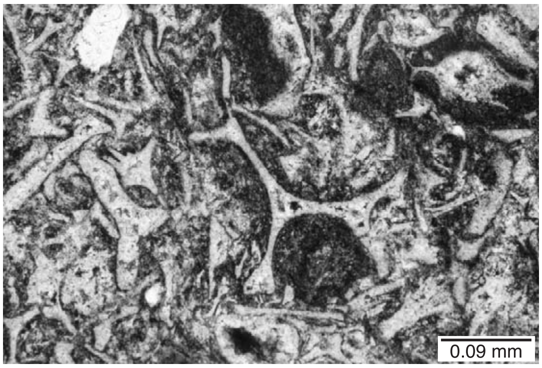

Fig. 9. Photomicrograph of bubble-wall shards replaced mostly with chalcedony (light areas) from a clintoptilolite-bearing tuff in the Brushy Basin Member from Dewey Bridge, Utah (#21). Groundmass contains clinoptilolite (dark areas) and chalcedony.

otis, oral communication, 1997). The low diversity of trace fossils is consistent with deposition in a harsh environment. Shallow rooting structures occur in some of the tuffs, indicating that vegetation grew locally, either as aquatic plants in the shallow waters or as terrestrial plants, in association with incipient soil formation during times of exposure associated with low water levels that the wetland/lake complex evaporated to dryness.

Distinct concentric authigenic mineral zones within the ancient wetland/lake system are defined on the basis of a few diagnostic authigenic minerals or mineral assemblages within the tuffs (Fig. 10). Progressing basinward, these zones are defined by smectite, clinoptilolite, analcime + potassium feldspar, and albite. Recognition of this basinward progression of concentric authigenic mineral zones in the tuffs, which is a lateral zonation characteristic of alkaline–saline lakes (Sheppard and Gude, 1968), led to the delineation of Lake T'oo'dichi' (Turner-Peterson, 1987). Younger analogues for the alkaline–saline wetland/lacustrine deposits of the Lake T'oo'dichi' basin include Pleistocene Lake Tecopa in California (Sheppard and Gude, 1968), where the characteristic concentric zonation of authigenic minerals was first noted.

Fluvial sandstones in the Brushy Basin Member within or near the wetland/lake complex of Lake T'oo'dichi' are primarily fine to medium grained, and locally conglomeratic. They form laterally dis-

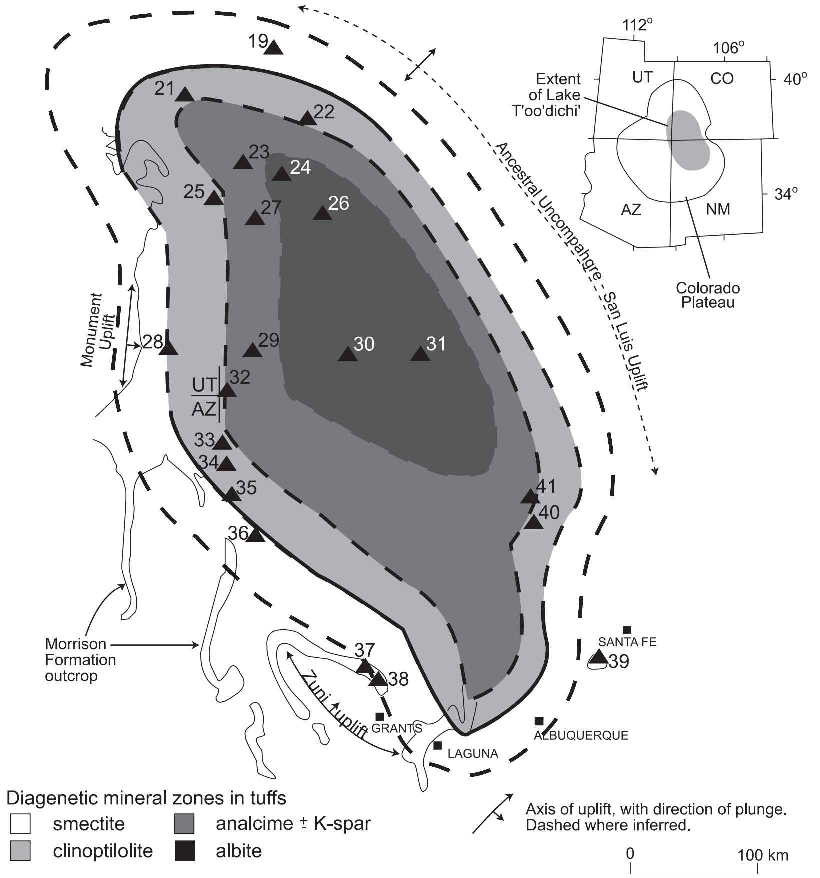

Fig. 10. Map showing the basinward progression of concentric diagenetic mineral zones in the tuff lithofacies, Brushy Basin Member, Morrison Formation (from Turner and Fishman, 1991). See Fig. 1 for locality numbers. The mineral zones are used to outline the ancient wetland/lake complex of Lake T'oo'dichi', which occupied the combined area of the San Juan and Paradox Basins. Note the major structural elements that were active during deposition and that controlled wetland/lake geometry.

continuous to sheet-like lenses (25 cm to 13 m thick) that may be locally stacked. Scour surfaces are common and locally marked by abundant rip-up clasts. Trough and planar cross-stratification, and low-angle to flat laminations are also common. There are no distinct vertical trends in grain size or sedimentary structures, and paleocurrent directions indicate that transport was generally to the east–northeast, consistent with regional paleoflow directions. These stacked, cross-bedded, sheet-like fluvial sandstones were deposited in streams that were marginal to, and occasionally flowed across, the ancestral wetland/lake basin (Turner and Fishman, 1991). Along the southern edge of the San Juan Basin in New Mexico, these fluvial sandstones are similar to the sheet-like sandstones of the fluvial complexes of the underlying Westwater Canyon Member. Away from the margin and toward the center of the wetland/lake basin, fluvial sandstones of the Brushy Basin Member are more isolated and are interbedded with the tuffs. The streams were mostly intermittent in nature and flowed across the San Juan/Paradox Basin during dry periods, based largely on the lack of evidence for deltaic deposits or reworking of sand in nearshore zones of the basin. Instead, fluvial sandstones interbed with wetland/lacustrine deposits and commonly extend well across the basin, presumably deposited during infrequent storms that carried sediment across the low-gradient basin during times that it had dried up entirely. The presence of rip-up clasts of tuff along the basal scour surface of the fluvial sandstones is further evidence that streams episodically flowed when the basin was dry (Turner and Fishman, 1991).

Streams that entered the wetland/lake basin also carried finer-grained material that was deposited as overbank mudstones. Tuffs are therefore interbedded with fluvial sandstones and their associated overbank mudstone and sandstone units. The overbank mudstone beds are illitic and typically red in color, in contrast to the typically green smectitic mudstones deposited in "Lake" T'oo'dichi'. Some of the green smectitic mudstones may also have been deposited marginal to the wetland/lake, in areas characterized by a high water table. Thus, a typical vertical section through the upper part of the Brushy Basin Member in the vicinity of Lake T'oo'dichi' deposits contain tuffs, fluvial sandstone, and reddish overbank mudstones (illitic) interbedded with green overbank and wetland/lacustrine mudstones (smectitic). Alteration of volcanic ash in the green smectitic mudstones obliterated almost all of their primary sedimentary structures. Carbonate nodules associated with these green mudstones locally preserve shard textures, evidence of the original ash that altered to smectite. Limestones are rare in the alkaline–saline wetland/lacustrine complex. The scarce limestone beds are generally unfossiliferous but locally contain charophytes (Peck, 1957).

5.2. Interpretation

In the semi-arid to arid climate that characterized deposition of the Morrison Formation, surface water was limited to predominantly intermittent streams and a few perennial streams (Turner and Peterson, this volume). Meteoric water in the dry continental interior would also have been limited and probably seasonal in nature (Parrish and others, this volume). The lack of evidence for fluvial–lacustrine interaction in Lake T'oo'dichi', as evidenced by the lack of deltaic or shoreline deposits, indicates that the streams that entered the San Juan/Paradox Basin were intermittent and thus not a significant source of water. It appears likely, therefore, that groundwater, rather than surface water, was the dominant source of water in Lake T'oo'dichi'. The dominant role of groundwater in the system and the lesser role of surface water indicate that the deposits of "Lake" T'oo'dichi' originated largely in a wetland environment.

The Uncompahgre Uplift played a crucial role in the development of the Lake T'oo'dichi' complex by acting as a barrier to shallow groundwater flow, which created the circumstances for development of an extensive alkaline–saline wetland on the upstream side of the uplift. Additional factors that contributed to the development of Lake T'oo'dichi' were the delivery of silicic volcanic ash from calderas that lay to the west and southwest, and the high evaporation rate in the dry climate (Turner and Fishman, 1991). Alteration of the ash contributed to the alkalinity of the pore waters through hydration and solution of the silicic volcanic glass, which was highly reactive (Hay, 1966; Jones et al., 1969; Sheppard and Gude, 1987). The high evaporation rate further concentrated the pore waters. Development of the alkaline–saline wetlands was itself evidence of aridity, as high evaporation rates are required to concentrate the pore waters sufficiently to generate an alkaline–saline brine. The wetland/lacustrine deposits in the Lake T'oo'dichi' basin, like all alkaline–saline wetlands and lakes, required a hydrologically closed basin, with no surface outlets, in which evaporation exceeded precipitation and runoff (Jones, 1966; Garrels and MacKenzie, 1967; Hardie and Eugster, 1970; Surdam and Sheppard, 1978).

Development of the hydrogeochemical gradient that resulted in the distinctive concentric zonation of diagenetic mineral zones in the tuffs of Lake T'oo'dichi' reflects variations in pore-water chemistry that developed in the shallow groundwater in the volcanic ash-rich sediments. The basinward progression of diagenetic mineral zones (Fig. 10) probably reflects the summation of water level changes in the basin with time and, thus, pore water composition in the wetland/lacustrine sediments. During water table highstands, when relatively fresh, dilute pore waters existed in sediments across the basin, volcanic ash altered to smectite or zeolites. During dryer periods when water levels in the basin were low, pore waters were more concentrated, and ash-rich sediments in the center of the San Juan/Paradox Basin were bathed in highly alkaline and saline brines; here, the lower activity of water drove reactions toward more anhydrous phases, causing replacement of hydrous phases (zeolites) by anhydrous phases (feldspars). Return to higher levels did not reverse the reactions that occurred in the central zones during low stands because the kinetics of the reactions favored preservation of the more anhydrous minerals (feldspars, chlorite, and illitic clays). In contrast, marginal wetland/lake sediments were never exposed to the highly alkaline–saline pore waters and thus the more hydrous minerals (smectite and clinoptilolite) remained the dominant phases (Turner and Fishman, 1998). Thus, the concentric zonation of diagenetic mineral zones observed in the wetland deposits of Lake T'oo'dichi' reflects basinward trends in average pore-water composition that developed in response to changes in the hydrology of the basin through time.

The shape of the wetland/lacustrine complex that defines the Lake T'oo'dichi' complex, a somewhat kidney bean shape, is a reflection of the influence of basin geometry and paleostructural trends (Fig. 10). Because the zonation of diagenetic minerals is a reflection of lateral hydrogeochemical gradients that developed in the pore waters, the distribution of diagenetic minerals, and indeed the formation of the wetland/lake complex itself, were sensitive to patterns in groundwater flow. The groundwater flow, in turn, responded to the paleotopography. Thus, in the area near Moab, Utah, in the northwestern parts of Arches National Park, the contours of ancient Lake T'oo'dichi' apparently nose up northward into the area of the present-day Salt Valley anticline, suggesting that a topographic depression existed in the same area during Morrison deposition.

Within the tuffaceous wetland/lake sediments, high density brines fluxed downward into porous sediments below because the density differences became significant, overcoming the effect of elevation on groundwater head in a basin characterized by a low topographic gradient. Evidence for the downward flux of brines comes from petrographic studies of the sandstones underlying the Lake T'oo'dichi' deposits. Lateral alteration patterns in sandstones of the underlying Westwater Canyon Member coincide with the lateral distribution of the diagenetic mineral zones in the overlying deposits of Lake T'oo'dichi' (Turner and Fishman, 1998). A downward decrease in the intensity of alteration away from the contact with the alkaline, saline wetland/lake beds further implies that pore waters moved downward into the underlying sandstones. This downward movement of dense brines away from wetlands and lakes has been documented in modern settings (Wooding, 1969, 1989; Barnes et al., 1991). The water moves downward both by advection and diffusion of the brine. Thus, the Lake T'oo'dichi' alkaline–saline wetland/lake complex was an area of discharge with respect to the flow of shallow groundwater in the vicinity of the San Juan/Paradox Basin, but locally experienced a downward flux of brine (recharge).

Although largely groundwater-fed, and therefore, dominantly wetland in origin, the Lake T'oo'dichi' basin had distinct episodes of lacustrine deposition. At times, intermittent streams carried sediment and surface water into the basin, creating true lacustrine conditions whenever the amount of surface water entering the basin was greater than the amount of groundwater. During these intervals, freshwater lakes developed. One such interval is marked by a laminated carbonaceous claystone and mudstone unit in the

Four Corners area that is interbedded with zeolitic tuffs of wetland origin. The laminated claystone yielded conchostracans, ferns, cycads, conifers, ginkgophytes, and horsetails (Ash and Tidwell, 1998) and indicates a brief episode of freshwater lacustrine deposition. This freshwater interval grades upward into a clinoptilolite-bearing unit, which signals the return of alkaline–saline wetland deposition.

5.3. Summary of wetland/lacustrine deposition in Lake T'oo'dichi'

During deposition of the upper part of the Brushy Basin Member of the Morrison Formation, several factors contributed to the formation of alkaline–saline wetland/lacustrine deposits of Lake T'oo'dichi in the San Juan/Paradox Basin. Requirements for formation of an alkaline–saline brine are a hydrologically closed basin, high evaporation rates associated with a semiarid to arid climate, and abundant silicic volcanic ash. A hydrologically closed basin developed in the San Juan/Paradox Basin where shallow groundwater discharged upstream of the barrier created by the ancestral Uncompahgre Uplift. Climate played a key role, as the high net evaporation rate was critical to brine evolution within the pore waters of the closed basin (Langbein, 1961). The intermittent nature of both surface and meteoric influences in the wetland permitted concentration of pore waters in the volcanic sediments in the basin. Silicic volcanic sediment that contributed to the geochemical evolution of the pore waters originated in calderas that lay to the west of the Morrison depositional basin. The silicic ash was carried eastward to the basin by prevailing winds. Although wetland deposition predominated in the largely groundwater-fed basin, distinctive lacustrine intervals reflect periods of increased surface water contributions to the basin and episodes of freshwater deposition.

Zeolites similar to those that formed in the tuffaceous beds of Lake T'oo'dichi' are presently forming in modern saline–alkaline wetland and lake environments such as Lake Magadi, Kenya, and Teels Marsh, Nevada (Surdam and Sheppard, 1978). The wetland/lake complex of Lake T'oo'dichi' was large compared to other alkaline–saline wetland/lake complexes (both modern and ancient), which resulted in more significant brine evolution and a greater variety of authigenic minerals (Turner and Fishman, 1991).

6. Freshwater ponds

In addition to the larger wetland/lacustrine systems in the Morrison Formation, small-scale, siliciclastic pond deposits are present locally in the Tidwell, the Salt Wash, and the Brushy Basin Members of the Morrison Formation. These deposits occur as thin (< 1 m, rarely as much as 4 m thick), lenticular, dark gray to gray–green mudstone beds interbedded with fluvial and overbank floodplain siltstone and sandstone deposits (Tyler and Ethridge, 1983; Parrish et al., this volume). The mudstone beds are locally laminated and carbonaceous with comminuted and carbonized plant fragments as well as palynomorphs (Peterson, 1984). These pond deposits also locally contain palynomorphs including the lacustrine alga, *Botryococcus* sp., comminuted carbonized plant fragments, and, rarely, megascopic carbonized plant remains including fern pinnules. Except for the record preserved in coal deposits in the northern part of the Morrison depositional record, most of the palynoflorule and megaflora plant remains in the Morrison deposits occur in the pond deposits.

Local presence of laminae with the paucity of desiccation features suggests deposition in relatively deeper water and/or a stratified water column. However, desiccation and exposure features typically occur in units below and above these pond deposits. These temporary freshwater ponds were a relatively minor lacustrine feature on the Morrison landscape compared to the alkaline–saline and the carbonate wetland/lacustrine successions. The ponds developed where the landscape intersected the local water table or where more regional groundwater discharged through faults and fractures.

7. Implications for Morrison climate and hydrology

The important role of groundwater in the development of the two major wetland/lacustrine systems in the Morrison Formation has important implications for interpretations of Morrison climate and hydrology. The most important implication is that significant bodies of water could be sustained despite the dry continental interior setting of the Morrison depositional basin. Global climate models (GCMs; Moore et al., 1992; Valdes, 1992; Valdes and Sellwood, 1992) indicate a semi-arid to arid climate for the Western Interior during the Late Jurassic, with a high pressure system dominating southwestern North America, which contributed to seasonality with surface temperatures during June/July/August of 30–40 and 0–20 °C during December/January/February. Estimated rainfall amounts and P/E ratios (Moore et al., 1992; Valdes, 1992) suggest direct meteoric contribution to Morrison wetland and lake surfaces would have been minimal. Similarly, the intermittent nature of most streams in the Morrison (Turner and Peterson, this volume), is reflected in the paucity of deltaic and shoreline deposits in the downstream carbonate successions and the lack of them in the alkaline–saline "Lake" T'oo'dichi'.

Other climatically and hydrologically sensitive sedimentologic features associated with Morrison carbonate wetland/lacustrine deposits such as palustrine features, pedogenic carbonate nodules, evaporites, and Magadi-type chert, point toward deposition in a semi-arid climate. Development of alkaline–saline wetland/lakes also requires a semi-arid to arid climate in which evaporation is significantly greater than precipitation and runoff. Thus, climate models and sedimentologic evidence from the Morrison Formation indicate that meteoric and surface water were limited in the dry continental interior basin, and did not contribute significantly to the wetland/lacustrine intervals, except intermittently or seasonally. The evidence indicates that groundwater was the major source of water for both wetland/lacustrine complexes.

Development of the two groundwater-dominated wetland/lacustrine complexes in the Morrison Formation can be attributed to water that originated in highlands to the west of the depositional basin and discharged farther downstream. Regional stream gradients and groundwater flow patterns to the east in the Morrison depositional basin were established during uplift associated with emplacement of a continental-margin magmatic arc west of the basin. Precipitation in these upland source areas provided water to the broad depositional basin that lay to the east, largely by infiltrating regional aquifers that provided conduits for eastward-flowing groundwater and by feeding eastward-flowing streams that entered the greater Morrison depositional basin. Progressive eastward rainout of moisture from the west left the continental interior, the site of Morrison deposition, relatively dry, with surface water delivered by intermittent, and a few perennial, streams. Meteoric water was largely limited to that provided by seasonal storms. The limited surface and meteoric water inputs to the depositional basin were supplemented by groundwater that infiltrated regional aquifers and re-emerged downstream to form the two major wetland/lacustrine successions in the Morrison Formation.

Isotopic and paleontologic evidence from the carbonate successions in the distal parts of the Morrison depositional basin are consistent with the inference that groundwater was the primary contributor to the hydrologically open carbonate wetlands and lakes. Oxygen (δ^{18}O) and carbon (δ^{13}C) isotopic values, and the lack of covariance between the two, are best explained by inferring that the wetlands were replenished by groundwater in the otherwise dry climate. This interpretation best explains the "open hydrologic" signature in spite of the high evaporation rates. The widespread distribution of charophytes and filter- and suspension-feeding biota in the carbonate intervals is also consistent with a significant input of groundwater and a limited input of siliciclastic sediment from streams.

The similarities and differences between the two major wetland/lacustrine depositional systems in the Morrison Formation can be explained by their proximal ("Lake" T'oo'dichi') and distal locations (carbonate successions) within the regional paleohydrologic and paleogeographic setting. The two basins in which the wetland/lacustrine depositional systems developed were the Denver–Julesburg Basin in the distal part of the larger Morrison depositional basin (site of carbonate wetland/lacustrine deposition), and the more proximal San Juan/Paradox Basin (site of the Lake T'oo'dichi' wetland/lacustrine complex) that developed on the upstream side of the ancestral Uncompahgre Uplift (Fig. 3). The Denver–Julesburg Basin was the focus of deep regional groundwater discharge in the distal, downstream parts in the larger Morrison depositional basin. This distal basin, bounded by minor topographically positive structures, with the Ancestral Rocky mountains to the west, and structures in Kansas and Nebraska to the east (Merriam, 1955; Doveton and Chang, 1991), was a natural area for discharge from regional aquifers stratigraphically below the Morrison. Farther upstream, in contrast, the Uncompahgre Uplift retarded eastward flowing groundwater in shallower aquifers. By acting as a downstream barrier to groundwater flow, the Uncompahgre Uplift created the paleotopographic and paleohydrologic conditions that were conducive to the formation of a hydrologically closed basin, required for formation of an alkaline–saline wetland/lake complex in the ancestral San Juan/Paradox Basin.

Both basins experienced high evaporation in the semi-arid climate, but the deep regional discharge of groundwater in the distal reaches maintained predominantly hydrologically open carbonate wetlands and lakes in the Denver–Julesburg basin, in contrast to the hydrologically closed alkaline–saline wetland/lake (Lake T'oo'dichi' complex) that formed farther upstream, in the San Juan/Paradox Basin. Another difference between the wetland/lake systems was the significant input of silicic volcanic ash in the wetland/lake complex of Lake T'oo'dichi', which contributed to the development of alkaline, saline pore-waters. Easterly winds (Poole, 1962; Peterson, 1988) carried significant amounts of airborne ash from calderas to the west at least as far as Lake T'oo'dichi'. Considerably less ash was carried beyond the Uncompahgre Uplift, resulting in predominantly fresher water in the downstream carbonate wetlands and lakes. However, in the downstream carbonate interval minor shard textures and scarce thin smectitic tuffs and clays suggest that at least some volcanic ash reached the distal reaches of the depositional basin and intermittently increased alkalinity and salinity. The presence of Magadi-type chert and evaporites may have been associated with these periods of increased alkalinity and salinity. Interestingly, although the carbonate and alkaline–saline wetlands and lakes were both predominantly fed by the discharge of groundwater, their different positions in the topographic and hydrologic landscape produced two very different wetland/lacustrine depositional systems within the Morrison Formation.

8. Conclusions

Our reexamination of what had previously been considered two largely "lacustrine" systems in the Morrison Formation suggests that both are largely "wetland" systems instead. This implies that groundwater was a major source of water in the Morrison depositional basin. The distinction between wetland and lacustrine deposition is based on the relative importance of groundwater and surface water contributions, with wetlands receiving most of their water from groundwater, and lakes receiving most of their water from surface water. Discussion among geologists and hydrologists concerning this distinction and its application to the interpretation of paleo-lacustrine sequences is in its infancy (R. Forester, written communication, 2003), but the distinction has significant implications for paleohydrologic reconstructions and paleoclimatic interpretations.

Major groundwater systems were responsible for delivering water to the otherwise dry continental interior basin, which resulted in the ability to sustain bodies of water in low lying areas that were the locus of groundwater discharge, in spite of the dry climate and lack of significant input by surface and meteoric water. Water that originated as precipitation in highlands to the west of the depositional basin infiltrated regional aquifers that underlay the basin. In the distal parts of the basin in east-central Colorado (Denver–Julesburg Basin), discharge of groundwater from regional aquifers resulted in predominantly freshwater carbonate wetlands. The carbonate wetland deposits occupy a stratigraphic interval that is chiefly in beds equivalent to the "lower" Morrison but extends into the "upper" Morrison Formation. Farther upstream, the alkaline–saline wetland/lake complex of Lake T'oo'dichi', represented by strata in the upper part of the Brushy Basin Member, formed in a hydrologically closed basin setting that occupied a more upstream position on the alluvial plain, where shallower regional aquifers discharged. Many factors appear to have been conducive to the formation of the alkaline–saline wetland/lake complex, including regional groundwater flow patterns, the paleotopographic setting, addition of volcanic ash to the basin, and climate.

Taken together, the two major wetland/lacustrine systems, whose deposition span a significant part of Morrison deposition, record the importance of groundwater in semi-arid to arid settings and have implications for hydrologic reconstructions, as well as interpretation of sedimentation, in an otherwise dry continental interior setting.

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