Stratigraphy and depositional environments of middle and upper Jurassic rocks, southeastern San Juan Basin, New Mexico

Orin J. Anderson and Spencer G. Lucas, 1996, pp. 205-210

in:

Jemez Mountains Region, Goff, F.; Kues, B. S.; Rogers, M. A.; McFadden, L. S.; Gardner, J. N.; [eds.], New Mexico Geological Society 47th Annual Fall Field Conference Guidebook, 484 p.

This page is intentionally left blank to maintain order of facing pages.

STRATIGRAPHY AND DEPOSITIONAL ENVIRONMENTS OF MIDDLE AND UPPER JURASSIC ROCKS, SOUTHEASTERN SAN JUAN BASIN, NEW MEXICO

ORIN J. ANDERSON[1] and SPENCER G. LUCAS[2]

[1]New Mexico Bureau of Mines and Mineral Resources, Socorro, NM 87801; [2]New Mexico Museum of Natural History and Science, 1801 Mountain Road NW, Albuquerque, NM 87104

Abstract—Middle Jurassic rocks of the southeastern San Juan Basin pertain to the San Rafael Group (in ascending order): Entrada Sandstone, Todilto Formation, consisting of the basal Luciano Mesa Member and the Tonque Arroyo Member (previously gypsum member), Summerville Formation, and Bluff Sandstone. The latter is not everywhere mappable. These units record deposition under an arid climate, on a broad coastal plain and/or in a paralic salina associated with the southern margin of the Curtis-Sundance seaway during Callovian–Oxfordian(?) time. Disconformably overlying Upper Jurassic rocks are assigned to the Morrison Formation, consisting of the basal, sandstone-dominated Salt Wash Member, the claystone-dominated, slope-forming Brushy Basin Member, and the sandstone-dominated Jackpile Member. Basal Morrison sediments record a significant climatic change with the onset of Late Jurassic time. More humid climates are strongly suggested by the relatively thick fluvial sequences containing rip-up clasts, local woody trash impressions, numerous scour-and-fill sequences and coarse-grained to pebbly sandstones. In addition, land-vertebrate fossils are much more abundant in the Morrison Formation than in underlying Jurassic rocks, suggesting a greater carrying capacity and biomass production. The climatic change is in turn related to the continued northward drift of Laurasia, which, by Late Jurassic time, brought this area of North America into the zone of prevailing westerly winds.

INTRODUCTION

The southeastern San Juan Basin (SESJB) lies within the Colorado Plateau physiographic province and is characterized by generally northward-dipping Mesozoic sedimentary rocks. Tectonic elements bounding the San Juan Basin are the Nacimiento Mountains to the east, and immediately to the south, the Rio Grande rift, which is part of the Basin and Range physiographic province (Fig. 1). In this area, near the southern end of the Nacimiento Mountains, a complete section of the San Rafael Group (Middle Jurassic) and the Morrison Formation (Upper Jurassic) is exposed. These rocks are described here and correlated to Jurassic strata elsewhere in the San Juan Basin, in the Chama embayment and in the Hagan basin on the eastern side of the Rio Grande rift.

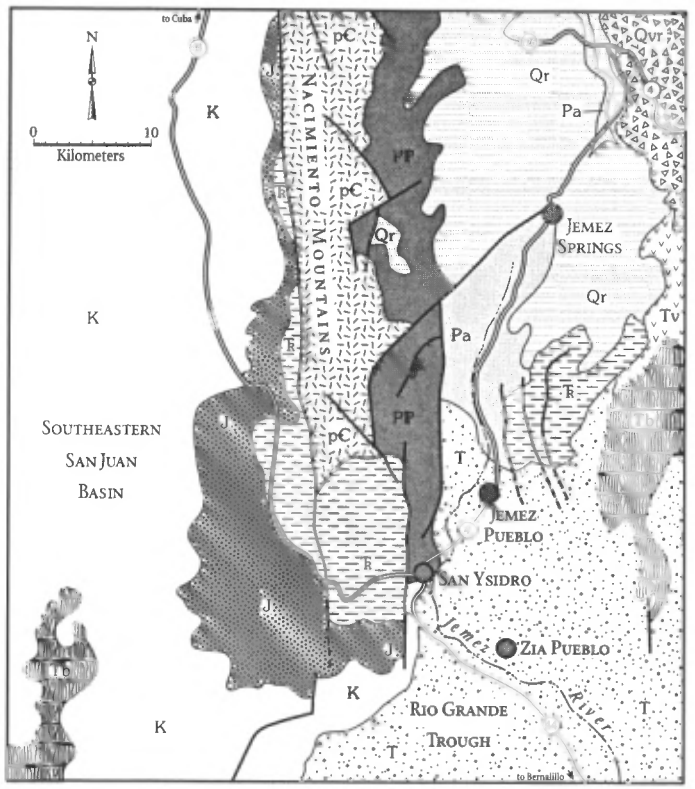

FIGURE 1. Index map of southeastern San Juan Basin, showing major structural features, outcrops of Jurassic rocks, highways, and towns. Qvr = Valles rhyolite; Qr = rhyolites and tuff; T = Neogene basin fill deposits; Tb = Neogene basalts; Tv = Neogene volcanic rocks, undivided; K = Cretaceous sedimentary rocks; J = San Rafael Group and Morrison Formation; TR = Chinle Group; P = Permian rocks; P ℙ= Permian and Pennsylvanian rocks; p-C = Precambrian schist, gneiss, and granite.

PREVIOUS STUDIES

Kelley and Wood (1946) investigated the area immediately to the southeast of the San Juan Basin for petroleum potential. In their stratigraphy, the Morrison Formation was extended downward to include the Todilto Formation. This redefinition of the Morrison was not perpetuated by Chenoweth (1953) in his work in the southeastern San Juan Basin, nor by Freeman and Hilpert (1956). Freeman and Hilpert recognized two upper San Rafael Group units—the Summerville Formation and Bluff Sandstone—in the southeastern part of the San Juan Basin. However, they chose to include the fine-grained, reddish to ocher, horizontally-bedded strata overlying the Bluff Sandstone in the Morrison Formation. In essence, these upper strata represent a reappearance of the Summerville lithotype and demonstrate that the San Rafael Group did not everywhere end with deposition of eolianites (Bluff Sandstone), as is commonly thought. Nonetheless, this fine-grained facies was referred to as the Recapture Member of the Morrison Formation, one of the member names that Gregory (1938) introduced in southeastern Utah. These strata were so assigned, even though Freeman and Hilpert (1956) acknowledged that the unit "interfingers" with the Bluff Sandstone, and that it is finer grained than typical basal Morrison sandstones. This perception of the stratigraphy influenced subsequent work in the SESJB.

Woodward and Schumacher (1973) studied the San Ysidro area, 35 km north of the areas that Chenoweth and Freeman and Hilpert studied. Woodward and Schumacher did not recognize Bluff Sandstone in their area, and thus lacking a good lithostratigraphic basis for differentiating a "Recapture Member" and Summerville Formation, they used the informal term "lower part of the Morrison Formation" for the entire interval. They correctly recognized these strata as all belonging to one formation. We contend that this formation, encompassing both the "Recapture Member" and Summerville Formation of Freeman and Hilpert (1956), should be recognized as part of the San Rafael Group rather than as Morrison strata (Anderson and Lucas, 1995).

In his discussion of Upper Jurassic rocks in the Ojito Spring area (just west of San Ysidro), Flesch (1974) recognized Summerville strata underlying a three-part Morrison Formation. His basal Morrison unit, the "Recapture Member," however, is merely a more sandy facies of the upper San Rafael Group or Summerville Formation, perhaps a Bluff Sandstone equivalent. His upper two Morrison units were designated as the Westwater Canyon and Brushy Basin Members.

Manley et al. (1987), in compiling the geology of the Aztec 1:100,000 sheet, extended the Morrison Formation down to the top of the Todilto

Formation. In their concept of Middle Jurassic rocks of north-central New Mexico, the upper San Rafael Group is locally missing.

STRATIGRAPHY AND SEDIMENTATION

Entrada Sandstone

The Entrada Sandstone is the basal unit of the San Rafael Group in the SESJB. Figure 2 illustrates the correlation of the San Rafael Group across the southern San Juan Basin based upon our measured section and those of Flesch (1974). The Entrada is for the most part an eolianite, and perhaps the most widespread of the Jurassic eolianites on the Colorado Plateau. In this area, the Entrada is approximately 22 m thick. Although member subdivision is generally not practical here, the upper 6 to 12 m are bleached and contrast in color with the typically red underlying strata.

The Entrada is a fine- to medium-grained, well-sorted, well-rounded quartzose sandstone. It ranges from well cemented to somewhat friable, but in either case, the cementing agent is carbonate. Trough or festoon crossbedding is common, but horizontal bedding is present locally at various levels. The horizontally bedded facies probably relates to a type of non-dunal deposition such as a succession of sand sheets. Sand sheet deposition likely took place in areas marginal to the erg or main dune fields.

The crossbedded facies generally exhibits crossbed dip directions to the south or southwest, but in many outcrops crossbedding is indistinct. The observed crossbed dip direction is consistent with the hypothesis that this part of the continent lay much nearer the equator during mid-Jurassic time and, as such, was in the zone of northeast trade winds (Kocurek, 1981), or modified trade winds (Kocurek and Dott, 1983). Kocurek and Dott also noted an increase eastward across northern New Mexico of facies associated with sand sheet deposition at the expense of the highly crossbedded dunal deposits.

Todilto Formation

Throughout much of northern New Mexico, the Entrada Sandstone is overlain by the Todilto Formation. The Todilto consists of a basal limestone, which in most areas is less than 3 m thick. Conformably overlying the limestone, but discontinuous laterally, is an evaporite-anhydrite-se-

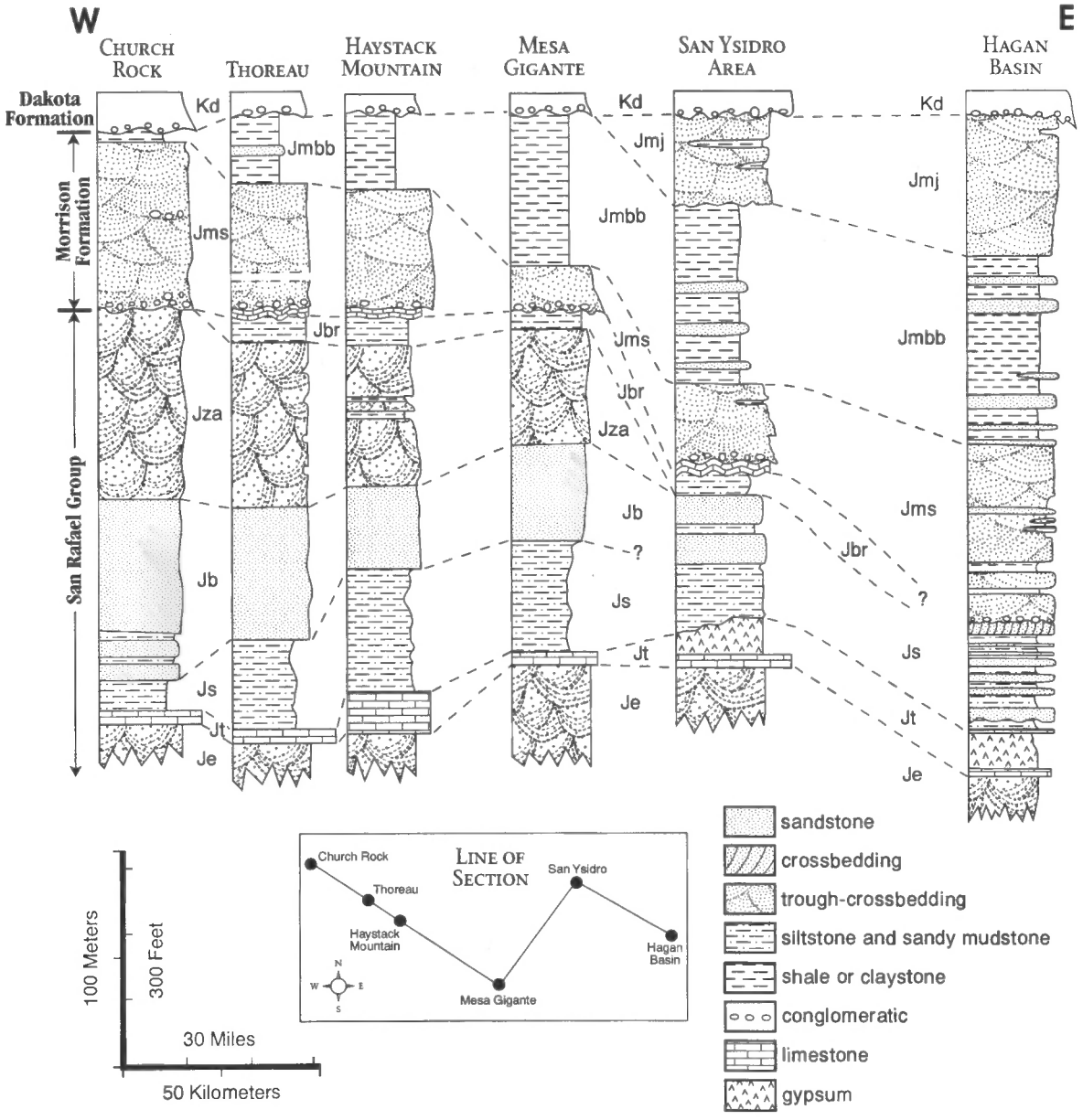

FIGURE 2. Regional correlation of Jurassic rocks, southern San Juan Basin to Hagan basin. Morrison Formation members are, Jmj = Jackpile, Jmbb = Brushy Basin, Jms = Salt Wash; San Rafael Group Formations are, Jza = Zuni Sandstone (Acoma Tongue), Jb = Bluff Sandstone (Jbr = Recapture Member), Js = Summerville Formation, Jt = Todilto Formation, Je = Estrada Sandstone.

quence (Fig. 2). Composed of these two lithologies, the Todilto is thus the most distinct lithostratigraphic unit in the Mesozoic of northern New Mexico.

Lucas et al. (1995) introduced formal names for the two lithologic units of the Todilto. The basal limestone unit was named the Luciano Mesa Member, for exposures on Luciano Mesa, a prominent feature in western Quay/eastern Guadalupe counties (T9N, R26–27E). The overlying evaporite section, formerly known as the "gypsum member," was named the Tonque Arroyo Member for exposures along Tonque Arroyo in the Hagan basin (T13N, R5E).

A reference section of both the Luciano Mesa and Tonque Arroyo Members of the Todilto Formation was established by Lucas et al. (1995). This section is located west of San Ysidro, just southwest of NM-44 in sec. 30, T16N, R1E, on the Ojito Spring 7½-min quadrangle (see map in Day 1 road log, this volume). Here, the Luciano Mesa Member is 2.8 m thick. The basal 0.5 m consists of ripple laminated calcarenite with 0.5-cm-thick gypsum interbeds and paper-thin organic-rich shale laminae. This is overlain by as much as 1.3 m of laminar limestone and calcarenite, which grade upward into the thinly bedded kerogenic limestone facies (Fig. 3). The Tonque Arroyo Member, in contrast, consists of gypsum (anhydrite in the subsurface) as much as 18–20 m thick locally, and forms a barren, hummocky topography. The great thickness variations across the basin and local absence of the Tonque Arroyo Member suggest that the unit precipitated in brine pools that dotted the surface as a sabkha environment replaced a shallow water, carbonate-rich system during the transition from Todilto to Summerville deposition. Lateral relationships between the Tonque Arroyo Member and the partly contemporaneous Summerville are not easily observed because of poor outcrop, exacerbated by the fact that subsurface anhydrite changes to gypsum upon exposure. This change is accompanied by an increase in volume of approximately 48% (Heard and Rubey, 1966). This volume increase distorts and obscures the relationship with the laterally adjacent and overlying basal beds of the clastic Summerville.

Regional stratigraphic relationships with the San Rafael Group in the type area of eastern Utah indicate that the Todilto is temporally and stratigraphically equivalent to the marine Curtis Formation (Anderson and Lucas, 1992; Kirkland et al., 1995). Inasmuch as the Curtis in part grades laterally southeastward into Summerville strata, the above discussion of Tonque Arroyo–Summerville relationships is consistent with a Curtis–Todilto correlation. Absolute age control of these units is lacking; however, by the process of regional correlation with the better constrained Sundance Formation, Imlay (1980) determined that the Curtis is of late middle Callovian age. Gilluly and Reeside (1928) reported the presence of bivalves (*Ostrea strigilecula* and *Camptonectes stygius*) plus *Pentacrinus asteriscus* and echinoid fragments in the Curtis Formation. Though not conclusive, the occurrence of these forms is consistent with a Callovian age.

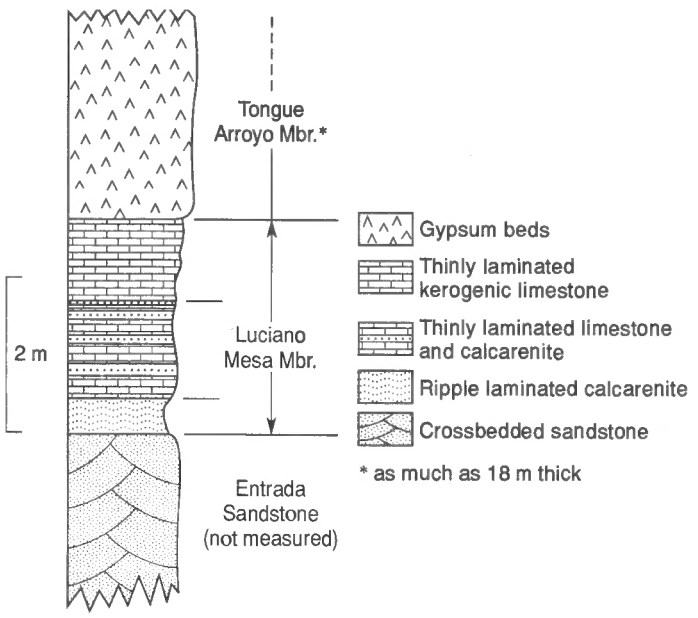

FIGURE 3. Stratigraphic description of Luciano Mesa Member of Todilto Formation at reference section for northwest New Mexico near San Ysidro.

Fossil fish collected locally, as well as in the eastern part of the Todilto depositional basin, from the Luciano Mesa Member (Kirkland et al., 1995) are the same species as those collected and described from the Hulett Member of the Sundance Formation in Wyoming. These are *Hulettia americana* and *Todiltia schoewei*, and while not age diagnostic, other evidence (regional correlations) indicates an early to middle Callovian age for this part of the Sundance Formation. Thus, by correlation, the Todilto is of middle Callovian age. The association of the Todilto depositional basin with the Sundance sea is provided by the presence of the fish, but the periods of direct connection were of short duration. The carbonate-evaporite deposition took place in a paralic salina (Lucas et al., 1985).

Depositional environments and origin of the Todilto limestone and gypsum facies have been the subject of discussion and controversy. Although the basal portion is commonly a laminar calcarenite and thus largely clastic, the Todilto is basically an evaporitic sequence. It accumulated in a depositional basin near the southern margin of the Curtis–Sundance inland sea (Kocurek and Dott, 1983; Anderson and Lucas, 1994; Kirkland et al., 1995). The subject of controversy has centered on whether or not a persistent connection or passageway to the main seaway existed; in essence, was the Todilto marine or nonmarine?

Marine influence is indicated by the presence of marine fossil fish in the lower (limestone) part of the Todilto (Koerner, 1930; Bradbury and Kirkland, 1966; Lucas et al., 1985; Kirkland et al., 1995). However, the low abundance and diversity of fauna are strong evidence against the argument for a persistent, open access to the seaway. Rather, it suggests rapid isolation of the Todilto depositional basin and the development of hypersaline, low oxygen conditions, in the bottom waters at least. How the basin was replenished to permit extensive evaporite deposition during the later stages is not completely clear. In an excellent paper, Kirkland et al. (1995) suggested that a combination of periodic marine flooding plus surface runoff probably provided the $CaSO_4$ to the evaporite basin. In addition, the possibility of eolian transport of $CaSO_4$ into the basin from the margins of the Curtis seaway was raised by Anderson and Lucas (1992).

Summerville Formation

In the San Ysidro area, the Summerville Formation is as much as 80 m thick (Fig. 2). The basal interval is a maroon or grayish red siltstone or silty mudstone that typifies the base of the unit throughout the San Juan Basin. It is generally a slope former, but locally, where well indurated, it forms a steep slope or cliff where the horizontal bedding that characterizes the unit can be observed. The overlying strata contain much crossbedded, fine-grained sandstone in beds as thick as 15 m. These sandstones may be equivalents of the Bluff, but they are interbedded with the maroon and grayish red strata that comprise the basal part of the formation, are somewhat lenticular, and thus difficult to map. For these reasons they are included here as part of the Summerville. The sandstone beds lack fluvial characteristics and appear to be eolian. Above the sandstone-dominated interval, which is as much as 30 m thick, the Summerville lithotype (maroon siltstone) is repeated. This pattern of a return to typically sabkha-deposited, horizontal, parallel-bedded strata at the top of the San Rafael Group has been noted at many localities throughout the Colorado Plateau (Anderson and Lucas, 1995).

All these strata down to or including the Todilto previously were included in the Morrison Formation (Kelley and Wood, 1946; Woodward and Schumacher, 1973; Woodward and Ruetschilling, 1976; Manley et al., 1987). Flesch (1974) correctly recognized a thin Summerville facies (reddish brown siltstone or mudstone with thinly interbedded gypsum) overlying the Todilto. However, he selected a horizon, based on the last appearance of gypsum, and first appearance of thick eolian sandstone beds, to define the Summerville–Morrison transition. We believe the fine-grained eolian sandstones and interbedded siltstones included in the Morrison by Flesch (1974) properly belong in the San Rafael Group.

At the top of the Summerville in the San Ysidro area is a 0.1-to-0.2 m thick, grayish pink carbonate bed (Fig. 2). The bed commonly has vague vertical striations or patterns that may represent solution-redeposition features, or they may be biogenic structures. The upper and lower bounding surfaces are slightly irregular, and the bed itself is interpreted as a pedogenic carbonate. Although thin, its presence is significant as it marks a diastem or unconformity at the top of the San Rafael Group sequence, which is characterized by arid depositional systems. In the Thoreau area the carbonate bed in this position is somewhat thicker (Figure 2). The overlying fluvial sediments of the Morrison Formation represent not only a sharp contrast in depositional environments but also more mesic climatic conditions. This evidence for a diastem, in addition to the sharp lithologic contrast provided by the overlying sediments, has not received much attention in previous investigations.

Morrison Formation

In the San Ysidro area, the Morrison Formation is approximately 150 m thick. It consists of a basal, sandstone-dominated member, as much as 36 m thick, which we regard as the Salt Wash Member (formerly called Westwater Canyon Member) (Anderson and Lucas, 1995). Conformably overlying and commonly intertonguing with the Salt Wash Member is the variegated claystone of the Brushy Basin Member. The Brushy Basin is as much as 80 m thick and is a slope former. A third unit, recognized locally and throughout the SESJB, is the Jackpile Sandstone Member (Owen et al., 1984). It is of variable thickness, but locally is approximately 30 m thick. The Jackpile is not discussed further in this paper.

The Salt Wash Member consists of trough crossbedded, fine- to coarse-grained sandstone, with chert pebble conglomeratic zones—mainly in the basal part—interbedded with thinner units of mudstone and siltstone. The sandstones locally tend to have the pale yellow or pale yellowish orange colors of the Cretaceous rocks in this region. Flesch (1974, p. 186) described them as "yellowish to tan, iron-stained subarkosic to arkosic arenites (70–96%), and minor interbedded and intertongued nonresistent claystones."

The sandstones contain rip-up fragments or clay clasts, woody trash impressions, chert pebble conglomeratic lenses, and locally vertebrate fossil remains. All these sedimentary characteristics indicate deposition in a vast fluvial channel system. Crossbed dip directions locally are to the east and southeast, and consistent with what has been observed in other parts of the San Juan Basin (Saucier, 1967). Paleoflow direction as deciphered from the crossbed pattern is to the east and southeast. Source areas lay to the west in a magmatically active area of what is now Nevada–Utah–Arizona, and to a lesser extent to the south and southwest in the Mogollon highlands (Kocurek and Dott, 1983; Anderson and Lucas, 1994).

Overlying the Salt Wash and intertonguing with it is the Brushy Basin Member. The Brushy Basin is approximately 80 m thick in the San Ysidro area but is locally variable in thickness. It consists of variegated, smectitic claystone and lesser, lenticular fine-grained and medium-grained sandstone. This slope-forming unit with its unique color lends the scenic quality which is associated with the Morrison throughout much of the Colorado Plateau.

The Brushy Basin is the most widespread and widely recognized member of the Morrison. Deposition was dominated at times by extensive volcanic ash falls that spread eastward from eruptive centers to the west in Nevada (Kowallis et al., 1991; Christiansen et al., 1994) and fell on vast floodplains dotted with lakes. Fluvial reworking of this material and diagenetic alteration produced the smectitic claystone and thin sandstone beds that characterize the unit. The high pH, silica-rich environment that prevailed in this depositional system is reflected in the thin, resistant sandstones which are tightly cemented with chalcedony (Flesch and Wilson, 1974). The thin, dense, lacustrine limestone beds so prevalent in many areas throughout the extent of Brushy Basin strata are not in evidence in the SESJB.

Upper Morrison (Brushy Basin Member) deposition was uniform and widespread. It extended from central Utah, southward to the type area in the topographic feature called Brushy Basin 12 km northwest of Monticello, eastward across Colorado and northern New Mexico, onto the High Plains of northeastern New Mexico and western Oklahoma, and northward through Wyoming and Montana. This lithofacies has previously been described and restricted to northwestern New Mexico and adjacent parts of the Colorado Plateau (Turner and Fishman, 1991). Turner and Fishman interpreted deposition in this restricted area to have taken place in an alkaline lacustrine environment, which they named Lake T'oo'dichi'. However, recognition of Brushy Basin lithotypes far beyond the supposed reaches of Lake T'oo'dichi' requires modification of the lacustrine model.

Although a lacustrine origin for much of the Brushy Basin Member is not disputed, it is unlikely that a permanent, continuous body of water existed across the area from Utah to Oklahoma. Moreover, the presence of numerous fine-grained sandstone beds (<0.5 m to 3 m in thickness) throughout the Brushy Basin Member indicate overbank deposition on a broad floodplain within a vast fluvial system. Periodic ash falls in the drainage basin likely overwhelmed this fluvial system and created major stream avulsion events. Lakes of considerable size thus dominated the floodplain environment and provided the depositional setting for much of the Brushy Basin claystones.

The floodplain–lake model thus envisioned incorporates the existence of major lacustrine depositional systems while also better accommodating the observed physical parameters of the Brushy Basin Member. These include the vast areal extent of the Brushy Basin Member—such that the size of the water body in the one-continuous-lake model seems implausible—and the presence of fluvial (overbank) deposits throughout the member. Additionally, chert pans reported in typical Brushy Basin strata in the Cubero, New Mexico area (Maxwell, 1982) suggest small, shallow, alkaline lakes which periodically (seasonally) shrank and swelled.

In addition to age data for the Brushy Basin Member provided by land vertebrates (see following section), recent studies have focused on radiometric dating methods. Kowallis et al. (1991) reported on bentonite beds from the Brushy Basin Member in Montezuma Creek, southeastern Utah. These samples were collected from a stratigraphic horizon approximately 20 m below the top of the member and yielded $^{40}Ar/^{39}Ar$ ages between 153 and 145 Ma. This confirms a Late Jurassic (late Kimmeridgian to Tithonian) age for the Brushy Basin Member. Kowallis et al. (1991), nonetheless, pointed out that the lack of age data from the uppermost part of the Brushy Basin Member leaves open the possibility that Morrison Formation deposition persisted into Early Cretaceous time. The Kimmeridgian–Tithonian age is consistent with determinations based on land vertebrates (sauropods), which have been assigned to the Comobluffian faunachron (Lucas, 1993).

PALEONTOLOGY

Relatively few fossils have been reported from Jurassic strata exposed along the flanks of the Nacimiento and Jemez uplifts or in the Chama basin. Two occurrences from the Summerville Formation and three from the Morrison Formation are of interest.

Ridgley (1989) reported the trace fossils *Rhizocorallium* sp., *Thalassinoides* sp. and *Arenicolites curvatus* and the nonmarine mollusc *Vetulonaia* sp. from strata she termed Wanakah Formation in the Ghost Ranch–Gallina area of Rio Arriba County. These are strata we assign to the Summerville Formation, and the trace fossil assemblage documented by Ridgley (1989) indicates marine influence on Summerville deposition, not lacustrine deposition as she concluded. The unionid bivalve *Vetulonaia*, however, suggests freshwater environments were locally and periodically present during Summerville deposition in the Ghost Ranch area.

Theropod dinosaur footprints (Fig. 4) are present in the Summerville Formation just west of Navajo Peak and the Chama River at UTM 13346460E, 4037151N. The footprints are preserved as concave relief in a yellowish gray to very light gray, fine-grained, subangular, micaceous litharenite that is about 13 m above the top of the Todilto Formation. There are 15 tridactyl footprints preserved here. Some have preserved claw impressions, and all are longer than wide, supporting their identification as theropod (see Meyer and Hauser, 1994). These footprints will be described in detail elsewhere. However, we note here that they are the second record of Jurassic dinosaur footprints from New Mexico. The first published record is of theropod footprints from near Las Vegas in San Miguel County (Lucas et al., 1990), also from the Summerville Formation.

FIGURE 4. Theropod dinosaur footprints in the Summerville Formation west of Navajo Peak, Rio Arriba County, New Mexico. A, overview of two footprints. B, close view of footprint on right in A. Scale in inches.

Isolated and fragmentary dinosaur bones and teeth are common in the Salt Wash and Brushy Basin Members of the Morrison Formation near San Ysidro (Lucas and Hunt, 1985; Hunt and Lucas, 1993). Three localities in the Brushy Basin Member in this area (Fig. 5) have produced identifiable remains of sauropod dinosaurs:

1. NMMNH locality 344 at UTM 13326790E, 3930690N (SW¼ NW¼ NE¼ sec. 26, T15N, R1W) is in a fluvial channel sandstone about 16 m below the Brushy Basin–Jackpile contact (Schwartz and Manley, 1992). This is the type locality of *Seismosaurus hallorum*, claimed to have been the longest (up to 52 m long) of all sauropods (Gillette, 1991), but now known to have been about 30 m long (Paul, 1992).

2. NMMNH locality 369 at UTM 13331175E, 3934000N (NE¼ NW¼ NW¼ sec. 17, T15N, R1E) is about 34 m below the Brushy Basin–Jackpile contact. This site produced a partial skeleton of *Diplodocus carnegiei* (Hunt and Lucas, 1993).

3. NMMNH locality 55 at UTM 13334565E, 3931105N (SW¼ NE¼ SE¼ SW/4 sec. 22, T15N, R1E) is about 65 m below the Brushy Basin–Jackpile contact. This site produced a partial skeleton of *Camarasaurus supremus* (Rigby, 1982; Lucas and Hunt, 1985; Hunt and Lucas, 1993).

These sauropods are representative of the Comobluffian land-vertebrate faunachron of Lucas (1993), of probable Kimmeridgian–Tithonian age.

DISCUSSION AND CONCLUSIONS

Middle Jurassic deposition in the San Juan Basin occurred in shallow epicontinental basins under arid regimes. The Entrada Sandstone accumulated in a vast erg, shaped and sustained by the northeast trade winds. Source areas include broad reaches of arid coastal plain to the north and northeast, enlarged by a relative sea level drop and lowstand (Kocurek and Dott, 1983).

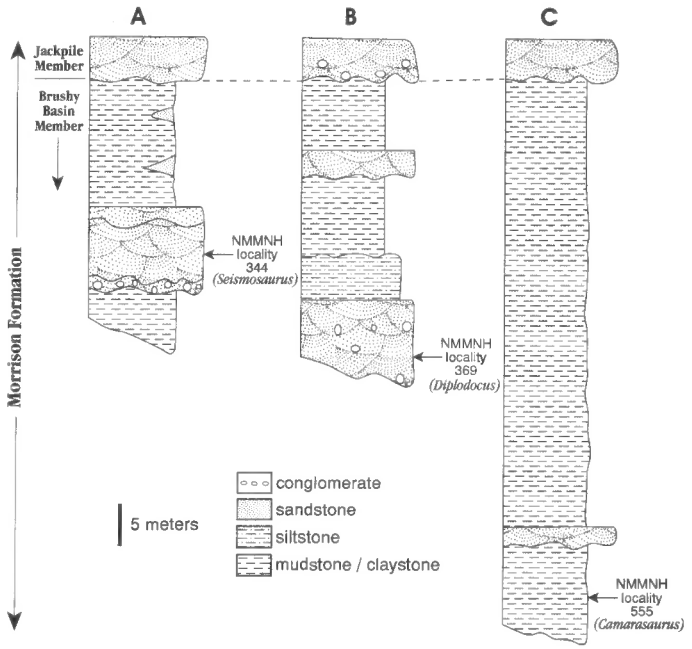

FIGURE 5. Correlation of Morrison Formation sauropod localities near San Ysidro. Locations of sections are: A, NW¼ NE¼ sec. 26, T15N, R1W; B, NW¼ NW¼ sec. 17, T15N, R1E; C, SE¼ SW¼ sec. 22, T15N, R1E.

A subsequent relative rise in sea level initiated a transgression that inundated much of the Entrada erg and resulted in deposition of the Curtis Formation in a large part of Utah. Closely associated with this Curtis seaway and intermittently connected with it was the paralic salina extending across much of northern New Mexico and extreme southwestern Colorado in which the Todilto evaporites were precipitated (Kirkland et al., 1995).

Gradual filling of the basin accompanied by northward retreat of the epicontinental seaway brought about the close of deposition in the shallow Todilto basin. This permitted a sabkha-arid coastal plain and locally eolian sandsheet depositional environment to develop as fine-grained clastics interbedded with minor gypsum prograded across the former evaporite basin (Anderson and Lucas, 1992, 1994). These fine-grained, parallel-bedded sediments comprise the Summerville Formation, which is a widespread unit also readily recognizable to the north-northwest where it overlies the Curtis Formation, and to the east in northeastern New Mexico where it overlies the Entrada Sandstone (Anderson and Lucas, 1994).

Eolian deposition resumed in much of the area as Summerville deposition progressed. In southeastern Utah, near Bluff, and throughout most of the San Juan Basin and southern Colorado, eolianites accumulated to thicknesses of as much as 30 to 60 m. These were designated the Bluff Sandstone (Gregory, 1938) or the Junction Creek Sandstone in southern Colorado. The Bluff represents a mappable lithostratigraphic unit across most of the San Juan Basin, but in the San Ysidro area, the eolianites are thinner, somewhat lenticular, and extensively interbedded with maroon siltstones characteristic of the Summerville (Anderson and Lucas, 1992). This renders them difficult to map and for this reason we have chosen here to include them with the Summerville, pending further mapping efforts.

The inclusion of strata here designated as Summerville Formation in the Morrison Formation by some previous workers is a practice we avoid for several reasons. The primary one is that such a grouping of strata ignores the sharpest lithologic contrast in the entire post-Todilto Jurassic section and obscures it in one formation. This contrast is provided by the base of the coarse-grained, pebbly, trough-crossbedded Salt Wash Member resting disconformably on the finer-grained sediments of the arid-cycle San Rafael Group. The disconformity is further enhanced by a pedogenic carbonate. To ignore this diastem, the associated lithostratigraphic contrast, and the paleoclimatic implications, is to trivialize the concept of the Morrison Formation. Moreover, the inclusion of Summerville strata in the Morrison Formation carries with it the concept that the upper San Rafael Group was not deposited in this small portion of the San Juan Basin. This

creates a very unlikely paleogeography, because it can be demonstrated that upper San Rafael Group deposition was very widespread and uniform and extends eastward out onto the adjacent High Plains of eastern New Mexico and western Oklahoma (Anderson and Lucas, 1992).

At the close of Middle Jurassic time and San Rafael Group deposition, this portion of the North American continent was a part of the supercontinental land mass known as Laurasia. Evidence for northward drift of the land mass throughout the Mesozoic was reviewed by Dickinson (1989), who presented data supporting the arrival of the southern Colorado Plateau area in the zone of prevailing westerly winds at the end of Middle Jurassic time. This event left its mark on eolianites in the San Juan Basin in the form of eastward or northeastward-dipping crossbeds. Basal Morrison sandstones rest on these crossbedded eolianites or, more commonly in the SESJB, on a Summerville lithotype which reappears above the stratigraphically highest eolianite (Anderson and Lucas, 1995).

The base of the Salt Wash Member of the Morrison, aside from the lithologic contrast with underlying sediments, is marked by a regionally traceable scour surface (and/or pedogenic carbonates) and constitutes a mappable horizon across the Colorado Plateau and adjacent High Plains. The onset of Morrison time marks the end of arid-cycle deposition and the initiation of fluvial deposition under much more mesic climates (Anderson and Lucas, 1995). The relative abundance of vertebrate remains and woody trash or petrified wood in the Morrison supports the concept of more humid conditions.

The diastem or unconformity at the base of the Morrison represents the onset of a new litho-tectonic sequence in which a major reorganization of the depositional basin and its provenance occurred during Late Jurassic time. The Morrison source area was a newly emergent magmatic area and tectonically active belt to the west in the Sierra Nevada, which initiated the eastward flowing streams and fluvial deposition in the interior basins to the east.

ACKNOWLEDGMENTS

Lee Woodward and Charles Maxwell reviewed and improved this manuscript. The New Mexico Bureau of Mines and Mineral Resources and the New Mexico Museum of Natural History provided support for field work and drafting of illustrations. Lynne Hemenway and Terry Telles assisted in the preparation of the manuscript. Rebecca Titus prepared most of the illustrations. We are grateful to all of the above.

REFERENCES

Anderson, O. J. and Lucas, S. G., 1992, Middle Jurassic Summerville Formation, northern New Mexico: New Mexico Geology, v. 14, p. 79–92.

Anderson, O. J. and Lucas, S. G., 1994, Middle Jurassic stratigraphy, sedimentation, and paleogeography in the southern Colorado Plateau and southern High Plains: Rocky Mountain Section of Society of Economic Paleontologists and Mineralogists, Mesozoic Systems of the Rocky Mountain Region, U.S.A., p. 299–314.

Anderson, O. J. and Lucas, S. G., 1995, Base of the Morrison Formation, northern New Mexico: New Mexico Geology, v. 17, p. 44–53.

Bradbury, J. P. and Kirkland, D. W., 1966, Upper Jurassic aquatic Hemiptera from the Todilto Formation: Geological Society of America, Special Paper 101, p. 24.

Chenoweth, W. L., 1953, The variegated member of the Morrison Formation in the southeastern part of the San Juan Basin, Valencia County, New Mexico [M.S. thesis]: Albuquerque, University of New Mexico, 86 p.

Christiansen, E. H., Kowallis, B. J. and Barton, M. D., 1994, Temporal and spatial distribution of volcanic ash in Mesozoic rocks of the Western Interior: an alternative record of Mesozoic magmatism: Rocky Mountain Section of Society of Economic Paleontologists and Mineralogists, Mesozoic Systems of the Rocky Mountain Region, USA, p. 73–94.

Dickinson, W. R., 1989, Tectonic setting of Arizona through time: Arizona Geological Society Digest, no. 17, p. 1–16.

Flesch, G., 1974, Stratigraphy and sedimentation of the Morrison Formation (Jurassic), Ojito Spring quadrangle, Sandoval County, New Mexico; a preliminary discussion: New Mexico Geological Society, Guidebook 25, p. 185–195.

Flesch, G. and Wilson, M. D., 1974, Petrography of Morrison Formation (Jurassic) sandstone of the Ojito Spring quadrangle, Sandoval County, New Mexico: New Mexico Geological Society, Guidebook 25, p. 197–210.

Freeman, V. L. and Hilpert, L. S., 1956, Stratigraphy of the Morrison Formation in part of northwestern New Mexico: U.S. Geological Survey, Bulletin 1030-J, p. 309–334.

Gillette, D. D., 1991, *Seismosaurus halli*, gen. et sp. nov., a new sauropod dinosaur from the Morrison Formation (Upper Jurassic/Lower Cretaceous) of New Mexico: Journal of Vertebrate Paleontology, v. 11, p. 417–433.

Gilluly, J. and Reeside, J. B. Jr., 1928, Sedimentary rocks of the San Rafael Swell and some adjacent areas in eastern Utah: U.S. Geological Survey, Professional Paper 150, p. 61–84.

Gregory, H. E., 1938, The San Juan Country, a geographic and geologic reconnaissance of southeastern Utah: U.S. Geological Survey, Professional Paper 188, 123 p.

Heard, H. C. and Rubey, W. W., 1966, Tectonic implications of gypsum dehydration: Geological Society of America Bulletin, v. 77, p. 741–760.

Hunt, A. P. and Lucas, S. G., 1993, Jurassic vertebrates of New Mexico: New Mexico Museum of Natural History and Science, Bulletin 2, p. 71–75.

Imlay, R. W., 1980, Jurassic paleobiogeography of the conterminous U.S. in its continental setting: U.S. Geological Survey, Professional Paper 1062, 134 p.

Kelley, V. C. and Wood, G. H., 1946, Lucero uplift, Valencia, Socorro, and Bernalillo counties, New Mexico: U.S. Geological Survey, Oil and Gas Investigations Map 47.

Kirkland, D. W., Denison, R. E. and Evans, R., 1995, Middle Jurassic Todilto Formation of northern New Mexico and southwestern Colorado; marine or nonmarine?: New Mexico Bureau of Mines and Mineral Resources, Bulletin 147, 37 p.

Kocurek, G., 1981, Erg reconstruction, Entrada Sandstone (Jurassic) of northern Utah and Colorado: Paleogeography, Paleoclimatology, and Paleoecology, v. 36, p. 125–153.

Kocurek, G. and Dott, R. H., Jr., 1983, Jurassic paleogeography and paleoclimate of the central and southern Rocky Mountain region: Rocky Mountain Section of Society of Economic Paleontologists and Mineralogists, Mesozoic Paleogeography of the west-central U.S., p. 101–116.

Koerner, H. E., 1930, Jurassic fishes from New Mexico: American Journal of Science, series 5, v. 19, p. 463.

Kowallis, B. J., Christiansen, E. H. and Dieno, A. L., 1991, Age of the Brushy Basin Member of the Morrison Formation, Colorado Plateau, western USA: Cretaceous Research, v. 12, p. 483–493.

Lucas, S. G., 1993, Vertebrate biochronology of the Jurassic–Cretaceous boundary, North American Western Interior: Modern Geology, v. 18, p. 371–390.

Lucas, S. G., Anderson, O. J. and Pigman, C., 1995, Jurassic stratigraphy in the Hagan Basin, north-central New Mexico: New Mexico Geological Society, Guidebook 46, p. 247–255.

Lucas, S. G. and Hunt, A. P., 1985, The Jurassic system in east-central New Mexico: New Mexico Geological Society, Guidebook 36, p. 213–242.

Lucas, S. G., Hunt, A. P. and Huber, P., 1990, Jurassic dinosaur footprints from New Mexico: New Mexico Geological Society, Guidebook 41, p. 319–321.

Manley, K., Scott, G. R. and Wobus, R. A., 1987, Geologic map of the Aztec 1° x 2° quadrangle, northwestern New Mexico and southern Colorado: U.S. Geological Survey, Map I-1730.

Maxwell, C. H., 1982, Mesozoic stratigraphy of the Laguna–Grants region: New Mexico Geological Society, Guidebook 33, p. 261–266.

Meyer, A. C. and Hauser, M., 1994, New sauropod and theropod tracksites from the Upper Jurassic megatracksite of northern Switzerland: Gaia, v. 10, p. 49–55.

Owen, D. E., Watters, L. J. Jr. and Beck, R. G., 1984, The Jackpile Sandstone Member of the Morrison Formation in west-central New Mexico—a formal definition: New Mexico Geology, v. 6, p. 44–52.

Paul, G. S., 1992, The size and bulk of extinct giant land herbivores: Journal of Vertebrate Paleontology, v. 12, supplement, p. 47A.

Ridgley, J. L., 1989, Trace fossils and mollusks from the upper member of the Wanakah Formation, Chama basin, New Mexico: evidence for a lacustrine origin: U.S. Geological Survey, Professional Paper 1808C, p. 1–16.

Rigby, J. K., Jr., 1982, *Camarasaurus supremus* from the Morrison Formation near San Ysidro, New Mexico—the San Ysidro dinosaur: New Mexico Geological Society, Guidebook 33, p. 271–272.

Saucier, E. A., 1967, The Morrison Formation in the Gallup region: New Mexico Geological Society, Guidebook 18, p. 138–144.

Schwartz, H. L. and Manley, K., 1992, Geology and stratigraphy of the *Seismosaurus* locality, Sandoval County, New Mexico: New Mexico Geology, v. 14, p. 25–30.

Turner, C. E. and Fishman, N. S., 1991, Jurassic Lake T'oo'dichi'; a large alkaline, saline lake, Morrison Formation, eastern Colorado Plateau: Geological Society of America Bulletin, v. 103, p. 538–558.

Woodward, L. A. and Ruetschilling, R. L., 1976, Geology of the San Ysidro quadrangle, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Map GM-37, scale 1:24,000.

Woodward, L. A. and Schumacher, O. L., 1973, Morrison Formation of southeastern San Juan Basin, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Circular 129, 7 p.