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JURASSIC STRATIGRAPHY OF THE SOUTHEASTERN COLORADO PLATEAU, WEST-CENTRAL NEW MEXICO: 2020 SYNTHESIS

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Abstract—Jurassic strata exposed on the southeastern Colorado Plateau in west-central New Mexico encompass part of the southern edge of the Jurassic outcrop belt in the Western Interior. The water-deposited Jurassic stratigraphic units pinch out or are truncated southward in west-central New Mexico, so that in the southernmost reaches of the Jurassic outcrop belt the entire Jurassic section is merged eolian sandstones. These merged eolian sandstones are assigned to the Zuni Sandstone, and to the north and northeast the Jurassic section is assigned to (in ascending order) the Entrada Sandstone (Dewey Bridge and Slick Rock members), the Todilto Formation (Luciano Mesa and Tonque Arroyo members), the Summerville Formation, the Bluff Formation (main body and Recapture Member), the Acoma Tongue of the Zuni Sandstone (all in the San Rafael Group) and the Morrison Formation (Salt Wash, Brushy Basin and Jackpile members). The ages of Jurassic lithostratigraphic units in west-central New Mexico range from Callovian to Tithonian based on regional stratigraphic relationships and on radioisotopic ages and biostratigraphic data, mostly from Utah and Colorado. The lithostratigraphy advocated for Jurassic strata in west-central New Mexico provides the basis for a Jurassic sequence stratigraphy in west-central New Mexico that recognizes four regional unconformities: J-2 (base of the Entrada and Zuni sandstones), J-3 (base of the Todilto Formation), J-5 (base of the Salt Wash Member of the Morrison Formation) and K-0 (base of the Cretaceous Dakota Formation).

INTRODUCTION

Jurassic strata are well exposed on the southeastern Colorado Plateau in west-central New Mexico (Fig. 1). These strata have yielded uranium, groundwater and building stone that have long made them a major focus of geologic studies, especially in the latter half of the 20th century (e.g., Condon and Peterson, 1986; Lucas and Heckert, 2003). Extensive stratigraphic analyses and mapping were an integral part of these studies and have led to a stratigraphic nomenclature that has both evolved through time and been a major source of debate (Fig. 2). Here, I present a brief review of the Jurassic stratigraphy of west-central New Mexico that employs a Jurassic stratigraphic nomenclature that embodies sound application of stratigraphic principles, reflects regional lithostratigraphic architecture and has a firm basis in defensible correlations. This review is an update of Lucas and Heckert (2003) and incorporates much information, including some of the illustrations, published in that earlier review.

SOME HISTORY

Several articles have reviewed previous studies of the Jurassic stratigraphy of west-central New Mexico (e.g., Baker et al., 1936; Condon and Peterson, 1986; Lucas and Anderson, 1998; Lucas and Heckert, 2003; Cather et al., 2013), obviating the need for a detailed review here. Instead, I briefly trace the development of Jurassic stratigraphic concepts and nomenclature, emphasizing the key works of Dutton (1885), Darton (1928a, b), Baker et al. (1936, 1947), Dane and Bachman (1965), Condon and Peterson (1986) and Lucas and Anderson (1998; Fig. 2).

Marcou (1858) "guessed" a Jurassic age for some of the strata exposed in west-central New Mexico (because they overlie red beds he considered Triassic), and Dutton (1885) followed suit, lacking any compelling evidence to assign any of the strata to the Jurassic (Lucas, 2001, 2003). Dutton (1885) coined the names Wingate Sandstones (considered by him to be

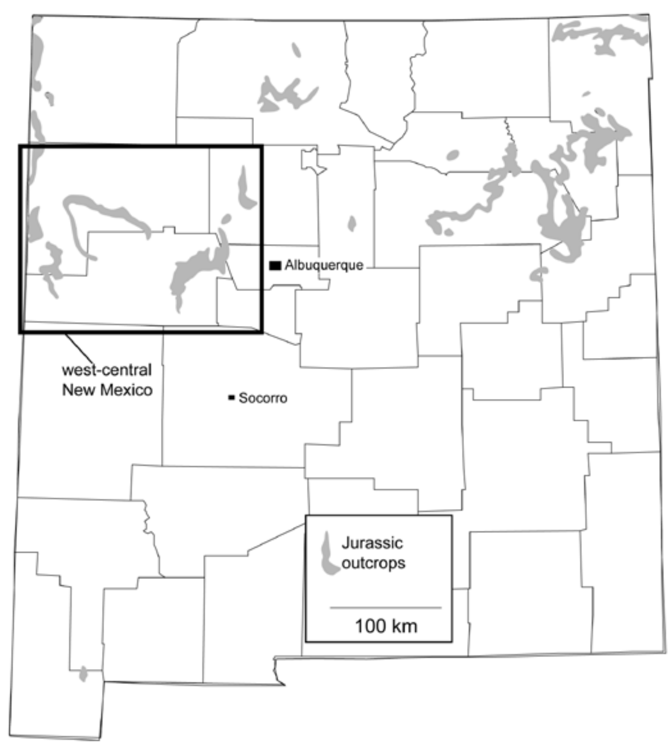

FIGURE 1. Location of outcrops of Jurassic strata in New Mexico with the area of west-central New Mexico indicated (after Dane and Bachman, 1965, and Lucas and Heckert, 2003).

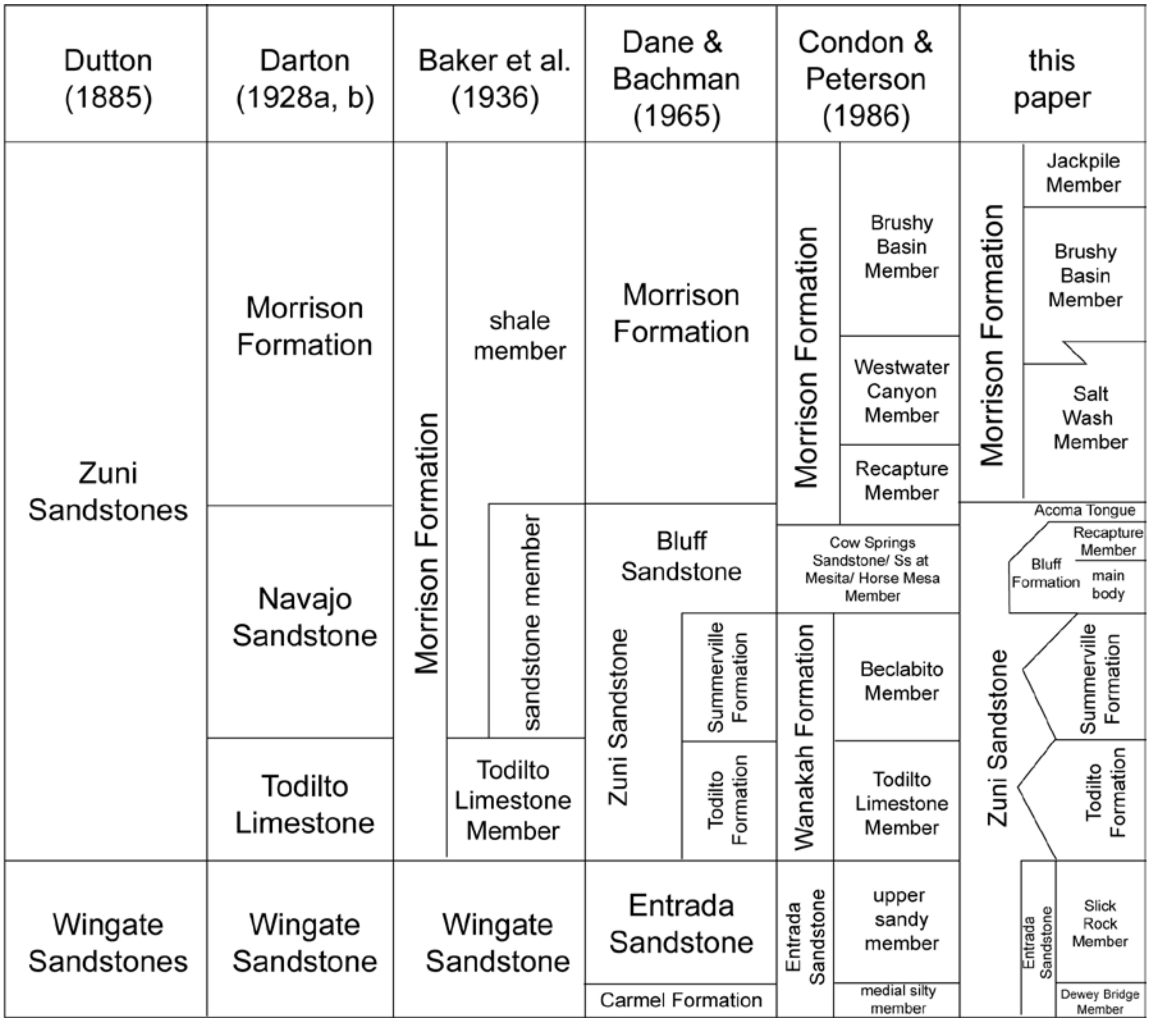

FIGURE 2. Development of Jurassic stratigraphic nomenclature in west-central New Mexico (modified from Lucas and Heckert, 2003).

Triassic) and Zuni Sandstones for Jurassic strata in west-central New Mexico (Lucas, 2003; Fig. 2).

Darton's (1928a, b) view of the Jurassic stratigraphy of west-central New Mexico (Fig. 2) was based primarily on the work of Gregory (1917), including the erroneous placement of the Todilto Formation beneath the Navajo Sandstone. Darton (1928a) recognized the Wingate Sandstone *sensu* Dutton but did not use the term Zuni Sandstone. Instead, he assigned most of the Jurassic section to the Todilto, Navajo and Morrison formations, the latter considered by Darton to be most likely of Cretaceous age (Fig. 2).

The classic monograph by Baker et al. (1936) represented the first explicit attempt to assemble a synthetic Jurassic stratigraphy of much of the Colorado Plateau. It corrected some earlier mistakes; for example, the Navajo Sandstone was correlated correctly so that the Todilto Formation was placed much higher in the section (Fig. 2). The Morrison base was moved down to include the Todilto Formation and all overlying Jurassic strata (Fig. 2).

Baker et al. (1936) also made a significant error in concluding that the San Rafael Group of Utah (Carmel, Entrada and Summerville formations of Gilluly and Reeside, 1928) pinched out between the Morrison and Wingate in the Four Corners, north of Red Rock, Arizona (Baker et al., 1936, pl. 2 and fig. 7). Therefore, they indicated that Dutton's Wingate Sandstone in west-central New Mexico is much older than (stratigraphically lower than) the San Rafael Group of Utah.

This and other errors were corrected by Baker et al. (1947) in a five-page published note that repudiated the principal conclusions of their 1936 monograph. Thus, they removed the Todilto and Summerville from the Morrison, and, at least in Colorado and New Mexico, considered them members of Burbank's (1930) Wanakah Formation. They also concluded that the Red Rock cliffs at Fort Wingate, type section of Dutton's Wingate Sandstone, were correlative to Gilluly and Reeside's Entrada Sandstone. The simplest solution would have obeyed priority and replaced the name Entrada with Wingate and given a new name to the lower eolianite of the Glen Canyon Group that had erroneously been called Wingate. Instead, Baker et al. (1947, p. 1667) argued that "through use in numerous publications, they [Wingate and Entrada *sensu* Baker et al., 1936] are firmly entrenched in geologic literature and are well known to many geologists….the abandonment of this nomenclature through the application of the principles of priority would be unfortunate and confusing." Therefore, Baker et al. (1947) continued usage of Wingate Sandstone for the lower eolianite of the Glen Canyon Group, abandoned Dutton's type Wingate locality, and called the type Wingate strata Entrada. Nevertheless, this actually did much violence to usage, at least in New Mexico, where Wingate Sandstone *sensu* Dutton (1885) was well entrenched in the geologic literature (e.g., Darton, 1928a; Heaton, 1939; Dobrovolny et al., 1946) and had even been embodied in Darton's (1928b) geologic map of New Mexico.

Dane and Bachman (1965), in their state geologic map of New Mexico, well reflected the 1960s consensus on Jurassic stratigraphy in west-central New Mexico (Fig. 2). This was the official U.S. Geological Survey (USGS) stratigraphy, and it was that of Gilluly and Reeside (1928) and the corrected regional correlations of Baker et al. (1947), with some of the gaps in their coverage filled by Harshbarger et al. (1957). Dane and Bachman (1965) thus recognized a Jurassic section of Carmel, Entrada, Todilto, Summerville, Bluff and Morrison formations laterally equivalent in part to eolian sandstones they called Zuni Sandstone (Fig. 2).

In the 1980s, a new USGS lithostratigraphy of the southern Colorado Plateau (Fig. 2) was agreed on, well summarized by Condon and Peterson (1986). The Jurassic stratigraphy in west-central New Mexico advocated here (Fig. 2) is that of Anderson and Lucas, published in a series of articles: Anderson and Lucas (1992, 1994, 1995, 1996, 1997, 1998), and Lucas and Anderson (1996, 1997, 1998), and elaborated by Lucas and Woodward (2001), Lucas et al. (1995, 1999, 2001, 2005, 2014) and Lucas (2004, 2014, 2018). This is also the Jurassic stratigraphy used on the current geological map of New Mexico (NMBGMR, 2003). Indeed, the present article is largely a summary of the Anderson-Lucas Jurassic stratigraphy in west-central New Mexico, and more extensive discussion and justification of it can be found in the articles just cited.

Some Lithostratigraphic Conventions

The lithostratigraphic nomenclature advocated here recognizes most of the units of the USGS stratigraphers (e.g., Condon and Peterson, 1986) but applies different names to some of them. The differences in names largely reflect disagreements over regional correlations. Thus, because almost all of the names used for Jurassic lithostratigraphic units in west-central New Mexico are based on type sections in Utah and Colorado, the correlation of those names from their type sections is critical to the nomenclature used. The Anderson-Lucas Jurassic stratigraphy developed in the 1990s was based in large part on restudy of all the type sections of Jurassic units recognized on the Colorado Plateau and their regional correlation based on fieldwork.

Lithostratigraphy is a taxonomy of lithostratigraphic units based on their lithology and stratigraphic architecture. Like any good taxonomy, a good lithostratigraphy contains the maximum amount of information by conveying an accurate stratigraphic architecture and correlations. Sound lithostratigraphy is also parsimonious. It uses a minimum of names — only those necessary to denominate mappable lithologic units (formations) and their unambiguous subdivisions (members and beds). Formations are mappable at a scale of 1:24,000. Only a single name is needed for each lithosome. Formation (and group) boundaries are at surfaces of lithologic contrast, and chronostratigraphic (time) boundaries are not confused with lithostratigraphic boundaries. Physical stratigraphic evidence (e.g., lithologic changes, stratal geometry, and/or presence or absence of subjacent strata) is used to identify unconformities, and they are assigned a time value based on chronostratigraphy.

The lithostratigraphy of Jurassic strata in west-central New Mexico advocated here is just such a parsimonious lithostratigraphy. However, the stratigraphy employed by the USGS (see Condon and Peterson, 1986) did not follow these practices, nor do the relatively recent recommendations of Cather et al. (2013), which do little more than recommend we continue to use the USGS lithostratigraphic nomenclature of Jurassic units in west-central New Mexico.

LITHOSTRATIGRAPHY

Jurassic strata in west-central New Mexico (Fig. 1) crop out in four distinct outcrop belts: (1) in the southeastern San Juan Basin along the western flank of the Nacimiento uplift and in the northern portion of the Rio Puerco fault zone near San Ysidro in Sandoval County; (2) on the northern part of the Lucero uplift north of the point where the Cretaceous Dakota Formation rests on Upper Triassic strata of the Chinle Group; (3) on the northern dipslope of the Zuni Mountains and along its monoclinally-controlled western edge; and (4) along the New Mexico-Arizona state line, which is in part along the eastern edge of the Defiance uplift. The lithostratigraphy, of course, varies somewhat across these outcrop belts, but a fairly uniform lithostratigraphic nomenclature can be applied to most of the Jurassic strata across west-central New Mexico (Fig. 3).

West-central New Mexico encompasses part of the southern edge of the Jurassic outcrop belt in the Western Interior (e.g., Silver, 1948; McKee et al., 1956). Thus, some of the Jurassic stratigraphic units pinch out or are truncated southward in west-central New Mexico, so that in the southernmost reaches of the Jurassic outcrop belt the entire Jurassic section is merged eolian sandstones (a succession of the eolian sandstone units, missing the intercalated non-eolian strata, as is best seen at Zuni Pueblo: Figs. 4-5). Lucas and Heckert (2003) referred to these as the water-deposited and the eolian lithofacies belts (Fig. 4). Therefore, a dual lithostratigraphic nomenclature needs to be used for some of the Jurassic section in west-central New Mexico, one that reflects this merger of lithostratigraphic units (Fig. 2).

In west-central New Mexico, the water-deposited lithofacies belt begins at about I–40 and extends northward into the San Juan Basin. This lithofacies belt includes several water-deposited Jurassic units, the Todilto, Summerville and Morrison formations, not found to the south in the eolian lithofacies belt. These water-deposited units are intercalated with eolian units, so that the water-deposited lithofacies belt consists of a section of Middle and Upper Jurassic eolian and water-deposited strata (Fig. 4).

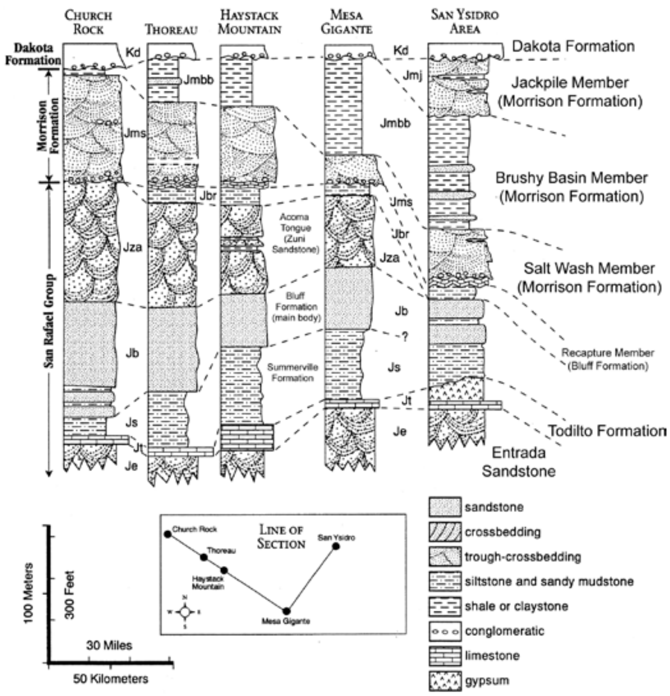

FIGURE 3. Regional correlation of Jurassic strata in west-central New Mexico (after Anderson and Lucas, 1996). Kd = Dakota Formation. Morrison Formation members are: Jmj = Jackpile, Jmbb = Brushy Basin, Jms = Salt Wash. San Rafael Group formations are: Jza = Zuni Sandstone (Acoma Tongue), Jb = Bluff Formation (Jbr = Recapture Member), Js = Summerville Formation, Jt = Todilto Formation, and Je = Entrada Sandstone.

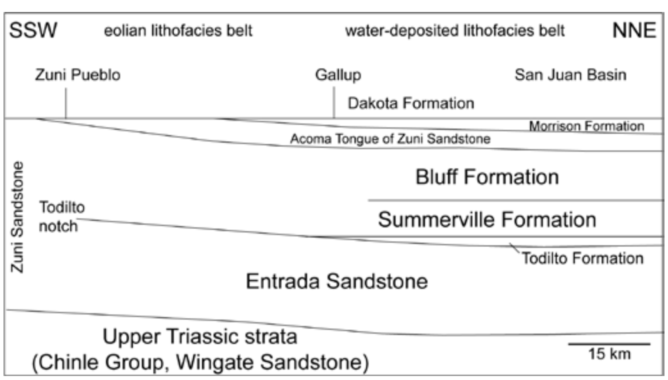

FIGURE 4. Jurassic stratigraphic relationships between the water-deposited and eolian lithofacies belts in west-central New Mexico (after Anderson and Lucas, 1994).

Zuni Sandstone

South of I–40, and best displayed at Zuni Pueblo, the Todilto, Summerville and Morrison formations thin and disappear (either pinchout or are truncated, or a combination of both), and the Jurassic section becomes a succession of eolianites about 150 m thick (Figs. 4-5). I refer to this succession as the Zuni Sandstone, following Anderson (1993), Anderson and Lucas (1994), Lucas and Anderson (1997), and Lucas and Heckert (2003).

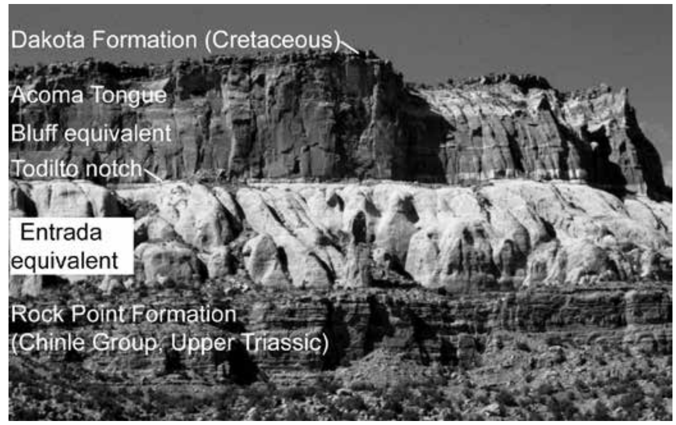

FIGURE 5. Type section of the Zuni Sandstone at Dowa Yalaane near Zuni Pueblo (SE 1/4 T10N, R19W, McKinley County), showing the correlation of units advocated here (see Fig. 4).

At Dowa Yalaane (Taaiyalone), the sacred mesa of the Zuni People near Zuni Pueblo, which is the type section of the Zuni Sandstone (Dutton, 1885; Anderson, 1983, 1993; Lucas and Heckert, 2003), the formation can be divided into three units (Fig. 5). The lower ~80 m is eolian sandstone that, based on stratigraphic position and lithology, I correlate to the Entrada Sandstone to the north. A prominent notch (break) in the sandstone above that interval is the unconformity surface that marks the pinchout/truncation of the Todilto Formation and the Summerville Formation. The eolian sandstone above the notch, about 60 m thick, is here equated to the main body of the Bluff Formation based on its stratigraphic position and lithology. The surface above the Bluff interval represents the pinchout/truncation of the Recapture Member of the Bluff Formation (Note that this guidebook's roadlogs follow Gregory (1938) and Condon and Peterson (1986), among others, in placing the Recapture Member in the Morrison Formation; see discussion of the Bluff and Morrison formations below). The eolian sandstone above that is the Acoma Tongue of the Zuni Sandstone of Anderson (1993). The surface above the Acoma Tongue is the pinchout/truncation of the Morrison Formation and is overlain by the Cretaceous Dakota Formation. However, I stress that these purely lithostratigraphic correlations of the Zuni Sandstone to units to the north and northeast merit further study and verification from other data.

Entrada Sandstone

The dominantly eolian Entrada Sandstone is at the base of the Jurassic section across much of west-central New Mexico. Still, the stratigraphic relationships and nomenclature at the base of the Jurassic section in west-central New Mexico have long been a contentious problem. As noted above, Dutton (1885) applied the name Wingate Sandstones to the oldest "Jurassic" strata near Fort Wingate in McKinley County, New Mexico. More than 40 years later, in Utah, Gilluly and Reeside (1928) named the same lithostratigraphic unit the Entrada Sandstone. As noted above, Baker et al. (1936) miscorrelated

Dutton's type Wingate and Gilluly and Reeside's type Entrada to such an extent that Wingate came to be applied to a much older eolian sandstone interval (in the Glen Canyon Group) on the southern Colorado Plateau, and Dutton's type Wingate came to be called Entrada.

Condon and Peterson (1986) well summarized the current thinking of the USGS on Entrada stratigraphy (Fig. 2). They followed Green (1974) and recognized a tripartite Entrada Sandstone in west-central New Mexico — 1) his lower "Iyanbito Member," 2) a medial silty member, and 3) an upper sandy member — that has been mapped by several workers, including Cooley et al. (1969). Robertson and O'Sullivan (2001) named the "medial silty member" the Rehoboth Member of the Entrada Sandstone and indicated correlation of the upper sandy member with the Slick Rock Member (Wright et al., 1962) of the Four Corners (also see O'Sullivan, 2003).

In contrast, Lucas and Heckert (2003; also see Heckert and Lucas, 1998; Lucas and Anderson, 1998; Lucas et al., 2001) excluded the "Iyanbito Member" from the Entrada. As Harshbarger et al. (1957) and Cooley et al. (1969) well demonstrated, it is the equivalent of the "Lukachukai Member" of the Wingate Sandstone (sensu Harshbarger et al., 1957) and therefore a unit of likely Late Triassic age beneath the J-2 unconformity. The "medial silty member" of the Entrada in west-central New Mexico is equivalent to the Dewey Bridge Member of Wright et al. (1962), and the upper sandy member is equivalent to their Slick Rock Member. Therefore, the Rehoboth Member of Robertson and O'Sullivan (2001) is an unnecessary junior synonym of the Dewey Bridge Member (Lucas et al., 2001). To support these conclusions, which are consistent with the stratigraphy and the mapping of Harshbarger et al. (1957) and Cooley et al. (1969), Lucas and Heckert (2003, fig. 3) correlated numerous stratigraphic sections of the Entrada and Wingate sandstones with the type sections of the Dewey Bridge (southeastern Utah) and Slick Rock (southwestern Colorado) members through the Four Corners southward along the Chuska Mountains and across west-central New Mexico.

The Entrada Sandstone in west-central New Mexico thus consists of two members, Dewey Bridge and Slick Rock, though the Wingate Sandstone is usually too thin in cliff exposures to be mapped separately from the Entrada (Fig. 6). The Dewey Bridge Member is up to 18 m thick and consists of moderate reddish brown to moderate reddish orange, laminar and ripple laminar silty sandstone and siltstone. Some small scale cross-beds are present locally. The overlying Slick Rock Member forms bold cliffs in west-central New Mexico up to 122 m thick. It is pinkish-gray, yellowish-gray and moderate reddish-orange sandstone that is very fine to medium grained and mostly cross-bedded, though some tabular bedding is present.

Todilto Formation

The Todilto Formation is one of the most distinctive lithostratigraphic units in the Jurassic section of west-central New Mexico—a striking interval of limestone and/or gypsum in a section dominated by sandstone, siltstone and mudstone (Fig. 7). The unit is found across much of west-central New Mexico as a relatively thin interval of dark gray, kerogenic limestone, the Luciano Mesa Member of Anderson and Lucas (1996). However, in the eastern part of west-central New Mexico, north and east of Grants, near Mesita and Mesa Gigante, the upper, gypsum member of the Todilto Formation (Tonque Arroyo Member of Anderson and Lucas, 1996) is also present above the Luciano Mesa Member and beneath the Summerville Formation (Fig. 7). This gypsum member represents a smaller, evaporitic basin that developed after the larger salina basin in which the limestone member was deposited (Lucas et al., 1985; Armstrong, 1995; Kirkland et al., 1995; Fig. 8).

The Luciano Mesa Member is up to 9 m thick and is light- to medium-gray, mostly microlaminated, kerogenic micrite. Anderson and Kirkland (1960) suggested that the microlaminae form varved couplets, and they counted these couplets to estimate a deposition duration of about 14,000 years for the Luciano Mesa Member. Folding in the limestones of the Luciano Mesa Member ranges in scale from millimeters to meters, and many of the large folds are the loci of uranium

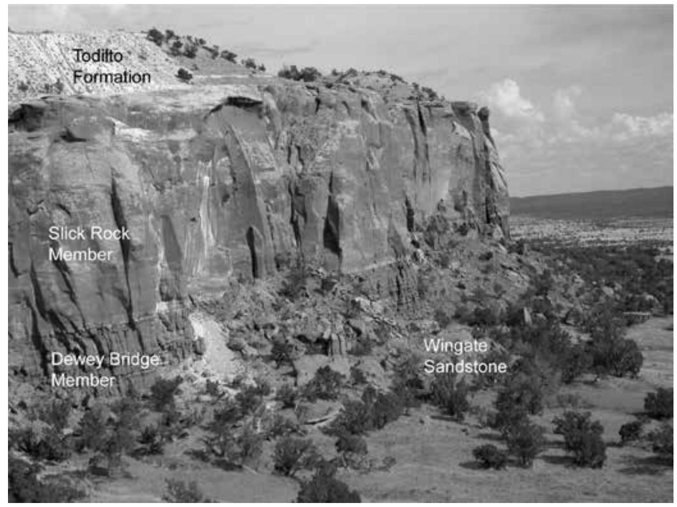

FIGURE 6. Outcrop of Entrada Sandstone just north of Thoreau (NW 1/4 T14N, R12W). Note thin and massive Wingate Sandstone at base of cliff, overlain by thick-bedded Dewy Bridge Member of Entrada Sandstone.

FIGURE 7. Outcrop of Todilto Formation at the mesa just north of Mesita (NW 1/4 T9N, R11W, Cibola County).

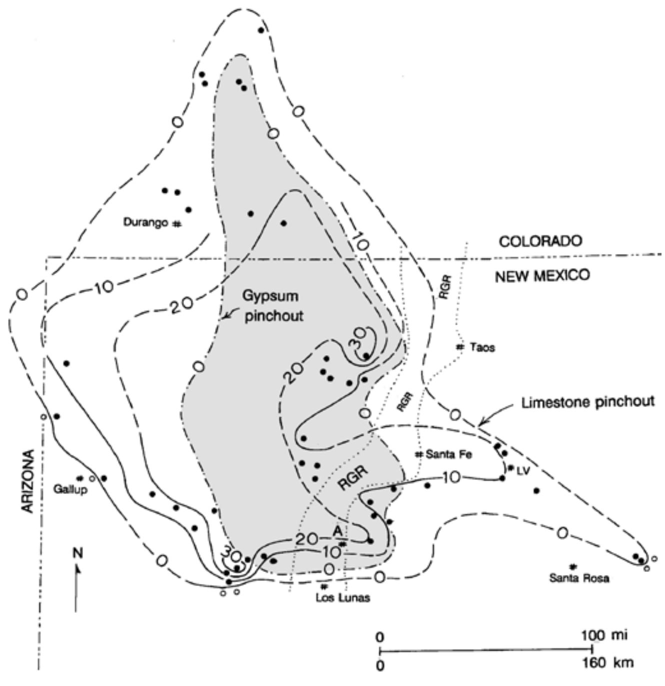

FIGURE 8. Approximate depositional limits of the Jurassic Todilto limestone member (Luciano Mesa Member) and the overlying Todilto gypsum member (Tonque Arroyo Member) (modified from Kirkland et al., 1995). The dotted outline is the Rio Grande rift (RGR). A = Albuquerque, LV = Las Vegas. The isopach contours for the Todilto limestone member are in feet. From Lucas and Woodward (2001).

mineralization. Lucas et al. (2014) examined the Todilto folds to conclude that they have resulted from varied processes that produced dome-like stromatolitic mounds, tepee-like structures, small-scale enterolithic folds and large-scale folds of likely diagenetic origin.

In west-central New Mexico, the upper, gypsum member of the Todilto Formation (Tonque Arroyo Member) is as much as 37 m thick and mostly light-gray to white gypsum (Fig. 7). The gypsum is massive, with chicken-wire texture, or laminated, and grades into anhydrite in the subsurface. Locally, the gypsum beds are contorted due to dissolution and differential expansion and contraction associated with volume changes during conversion of anhydrite to gypsum and vice versa.

Summerville Formation

In west-central New Mexico, the Summerville Formation forms horizontally bedded cliffs or steep slopes between the Todilto Formation and Entrada Sandstone below and the Bluff Formation above (Fig. 7). The Summerville Formation mostly consists of moderate reddish brown, dark reddish brown and grayish red beds of silty sandstone, siltstone and mudstone that are interbedded in a repetitive fashion. Some beds are white or pinkish gray. The sandstone mostly is laminar or ripple laminar, though locally small-scale cross-beds may be present. Some beds are gypsiferous, and some thin beds of gypsum and limestone are present locally. As much as 49 m thick in west-central New Mexico, the Summerville Formation overlies the Todilto Formation and is overlain by the Bluff Formation. The two members of the Summerville – the Beclabito and the Tidwell that are recognized in eastern Utah and adjacent areas (Lucas and Anderson, 1997) – cannot be distinguished in west-central New Mexico. This is because the Tidwell Member is laterally equivalent to the Bluff Sandstone in Utah (Lucas, 2014), so the entire Summerville Formation in west-central New Mexico is the unit named Beclabito Member of the Wanakah Formation by Condon and Huffman (1985).

Summerville strata are present across much of northern New Mexico and southern Colorado and have been assigned various names, including Wanakah, Bell Ranch and Ralston Creek. One name is sufficient for one mappable lithostratigraphic unit of consistent lithotype, so I continue to advocate use of the term Summerville Formation across its entire outcrop belt (also see Anderson and Lucas, 1992, 1994, 1996; Lucas and Anderson, 1997, 1998; Lucas et al., 1999; Lucas and Woodward, 2001; Lucas and Heckert, 2003; Lucas et al., 2005; Lucas, 2014, 2018).

Bluff Formation

In west-central New Mexico, the Bluff Formation gradationally overlies the Summerville Formation and consists of two distinct members. The lower, sandstone-dominated member is the equivalent of the type Bluff Sandstone near Bluff, Utah (Gregory, 1938). In west-central New Mexico, it is as much as 70 m of grayish-yellow, grayish-green, pale-red and moderate-orange, laminated and trough cross-bedded, fine- to medium-grained sandstone (Figs. 9-10). This unit is the main body of the Bluff Formation (Lucas and Anderson, 1997), which is mostly of eolian origin. However, unlike the Slick Rock Member of the Entrada Sandstone, the Bluff in west-central New Mexico generally lacks thick sets of high-angle cross-beds with truncated upper boundaries (reactivation surfaces). Instead, it is dominated by horizontal bedforms (commonly 0.5-5.0 m thick) and indistinctly cross-bedded facies.

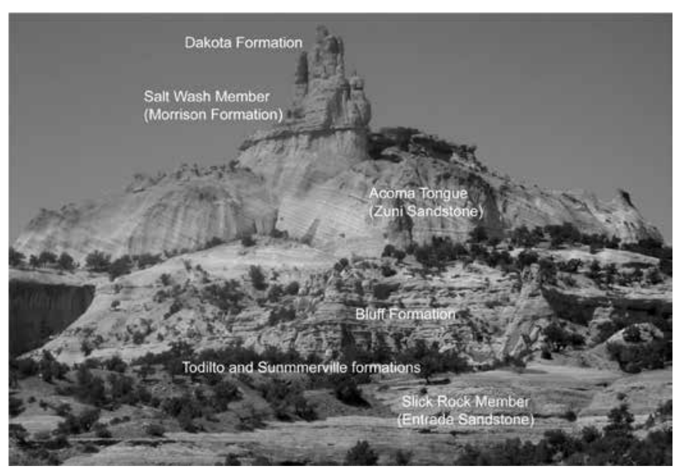

FIGURE 9. The Jurassic section at Church Rock (NE 1/4 T15N, R17W, McKinley County). Note the very thin (less than 5 m thick) interval of the Todilto and Summerville formations near their pinchout.

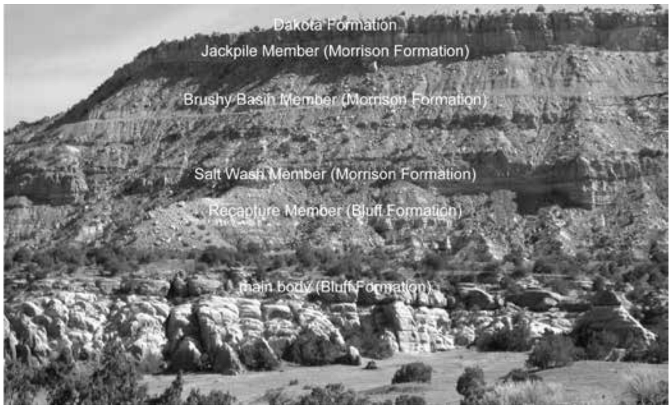

FIGURE 10. Outcrop of the Morrison Formation north of Milan (NE 1/4 T13N, R10W, McKinley County).

Above the main body of the Bluff Formation in west-central New Mexico is a thicker (up to 113 m thick) and complex lithosome called the Recapture Member by all workers (Fig. 10). USGS workers recognize the Recapture as the basal member of the Morrison (e.g., Condon and Peterson, 1986), whereas I assign it to the Bluff Formation based primarily on the work of Lucas and Anderson (1997, 1998) and Lucas (2014), which demonstrates the integrity of a Bluff lithesome that includes the Recapture Member. The Recapture is pale reddish-brown, light-brown, dark reddish-brown and greenish-gray beds of fine- to medium-grained sandstone intercalated with some mudstone beds. The sandstones are either massive or tabular or display large scale cross-beds indicative of eolian deposition. Thus, Recapture facies are of both fluvial and eolian origin (e.g., Condon and Peterson, 1986).

The main body of the Bluff Formation has multiple names used by workers of the USGS who do not recognize a single, sandstone-dominated lithosome between the Summerville Formation and Morrison Formation. Thus, the Bluff in west-central New Mexico has been termed “Cow Springs Sandstone,” “Horse Mesa Member of Wanakah Formation” and “Sandstone at Mesita” (e.g., Harshbarger et al., 1957; Condon and Peterson, 1986; Condon, 1989), all unnecessary synonyms of Bluff Formation. Bluff strata are also included in the “Recapture Member of the Morrison Formation” by many USGS workers (e.g., Condon and Peterson, 1986). Indeed, inclusion in the Morrison Formation of eolian beds of the Bluff or Acoma Tongue of the Zuni Sandstone has led to the idea that eolianites are part of the lower Morrison Formation (e.g., Condon and Peterson, 1986). There are no eolianites in the Morrison Formation as that unit is used here.

Acoma Tongue of the Zuni Sandstone

Locally, the sandstone interval above the Bluff Sandstone and below the Salt Wash Member of the Morrison Formation is as much as 70 m thick and is a boldly cross-bedded eolian sandstone with easterly dipping foresets (Fig. 9). This is the Acoma Tongue of the Zuni Sandstone of Anderson (1993), and it is present at various outcrops in west-central New Mexico from near Mesita to Church Rock to Zuni Pueblo (Figs. 3, 4, 5, 9). The striking cross-beds distinguish it from the more flat-bedded Bluff eolian sandstones below (cf. Fig. 9). The Acoma Tongue is the stratigraphically highest eolianite in the Jurassic section and is the top of the San Rafael Group.

Morrison Formation

For many years, the USGS recognized three principal Morrison Formation members in west-central New Mexico (in ascending order): Recapture, Westwater Canyon and Brushy Basin (Fig. 2). A fourth, uppermost Jackpile Member was later recognized after Owen et al. (1984) formalized the name.

Detailed work by Anderson and Lucas (1994, 1995, 1997, 1998) in southeastern Utah demonstrated that, based on lithology and stratigraphic architecture (particularly its relationship to the Bluff main body), the type Recapture Member of the Morrison Formation of Gregory (1938) is best reassigned to the San Rafael Group as the upper member of the Bluff Formation. Furthermore, as demonstrated by Anderson and Lucas (1994), Gregory’s (1938) Westwater Canyon Member of the Morrison Formation is the same unit Lupton (1914) had earlier named Salt Wash Member. In light of these conclusions, the Morrison Formation in west-central New Mexico consists of three members (in ascending order): Salt Wash, Brushy Basin and Jackpile members (Fig. 10).

The Salt Wash Member is the sandstone-dominated lower part of the Morrison Formation, as much as 135 m thick in west-central New Mexico. Its sandstone beds are yellowish gray, reddish gray or red, and fine to coarse grained, locally conglomeratic and are mostly cross-bedded or tabular bedded. Intercalated mudstone and siltstone beds are reddish brown to greenish gray. The Salt Wash Member rests with distinct unconformity on either the Acoma Tongue of the Zuni Sandstone, the Recapture Member or the main body of the Bluff Formation. The absence of the Acoma Tongue and/or the Recapture Member at some sections is *prima facie* evidence of the unconformity, as is the scour-and-fill and substantial change in grain size and lithotypes at the base of the Salt Wash Member (e.g., Anderson and Lucas, 1994, 1997).

The Salt Wash Member grades upward into (and interfingers with) the mudstone-dominated Brushy Basin Member, which is as much as 107 m thick in west-central New Mexico (Fig. 10). Brushy Basin lithologies are mostly mudstone and claystone with intercalated minor beds of sandstone. These mudrock beds are variegated green-reddish brown and grayish purple and are characteristically bentonitic. The sandstone beds are brown and yellowish gray and are fine to medium grained, locally conglomeratic and generally feldspathic. They are either cross-bedded or laminar bedded.

The overlying Jackpile Member (Fig. 10) is as much as 91 m of mostly white, kaolinitic, fine- to medium-grained, cross-bedded sandstone and silica-pebble conglomerate. Minor interbeds of pale green mudstone and siltstone are present. The Cretaceous Dakota Formation rests with evident unconformity on the Jackpile Member across much of west-central New Mexico

CHRONOSTRATIGRAPHY

Most of the data to determine the ages of Jurassic lithostratigraphic units in west-central New Mexico comes from outside of New Mexico, particularly 1) regional stratigraphic correlations of some units to marine units deposited in Idaho and northern Utah, 2) radioisotopic ages from Jurassic strata in Utah and Colorado and 3) available biostratigraphy of these units, also mostly from fossils found in Utah, Colorado and Wyoming (Fig. 11). To summarize briefly:

1. The age of at least the lower part of the Entrada Sandstone is Bathonian-early Callovian based on its stratigraphic relationship to the Carmel Formation, which has yield radioisotopic ages of ~166-167 Ma and contains marine invertebrate fossils (Imlay, 1980).
2. The Todilto Formation is homotaxial with the marine Curtis Formation of Utah. Wilcox (2007) and Wilcox and Currie (2008) recently presented new biostratigraphic data that indicate the lower part of the Curtis Formation is of Oxfordian age. So, this is the age of the Todilto Formation, which had yielded only a temporally long-ranging fish taxon and other endemic taxa that provided no precise biostratigraphic constraints on its age.
3. The Summerville Formation has yielded radioisotopic ages from its upper, Tidwell Member in Utah that indicate it is of Oxfordian age (Trujillo and Kowallis, 2015).
4. The Bluff Formation is bracketed by Late Jurassic units that indicate it is early Late Jurassic in age. However, it has not yielded data by which to determine its age directly.
5. The Salt Wash and Brushy Basin members of the Morrison Formation yield dinosaur and other fossils generally considered to be of Late Jurassic age (e.g., Lucas, 2009). Radioisotopic ages from the Morrison Formation in Utah and Colorado (upper Salt Wash Member, Brushy Basin Member) indicate an age span of about 152-149 Ma and thus indicate a primarily Tithonian age (Trujillo and Kowallis, 2015; Galli et al., 2018; Maidment and Muxworthy, 2019).
6. The possibility that the Jackpile Member of the Morrison Formation is a Lower Cretaceous unit equivalent to the "Burro Canyon" (=Cedar Mountain) Formation to the north merits further investigation (cf. Aubrey, 1986). Indeed, detrital zircon data support that correlation (Dickinson and Gehrels, 2010; Dickinson, 2018) but are not the most robust data for age determinations. Here, the Jackpile Member remains tentatively of Late Jurassic age.

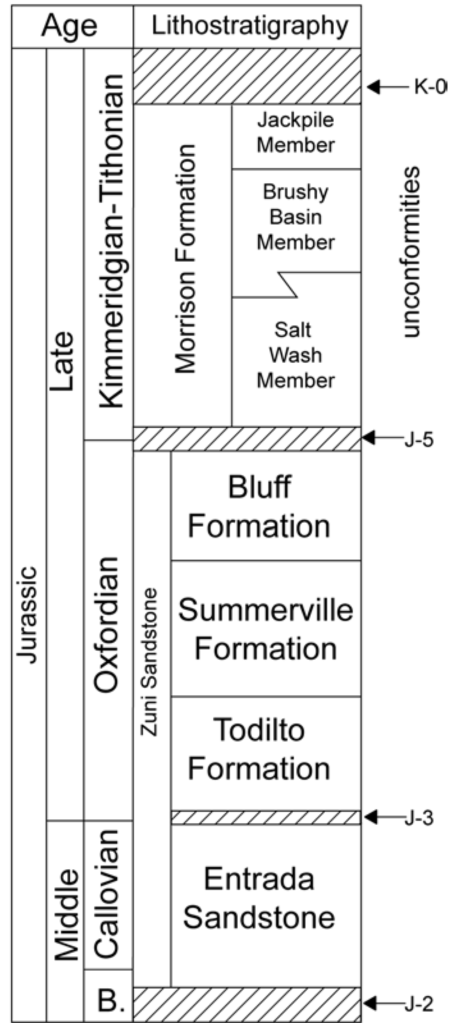

FIGURE 11. Jurassic sequence stratigraphy in west-central New Mexico. B. = Bathonian.

REGIONAL UNCONFORMITIES

Pipiringos and O'Sullivan (1978) proposed a succession of Jurassic unconformities that delimit sequences throughout part or all of the Jurassic Western Interior basin. Four of these regional unconformities can be identified in west-central New Mexico's Jurassic section (Fig. 11).

The J-2 unconformity separates Middle Jurassic strata of the Entrada Sandstone from underlying Upper Triassic strata of the Wingate Sandstone and Chinle Group. This striking unconformity was unambiguously identified across all of the Jurassic outcrop belt in west-central New Mexico by Pipiringos and O'Sullivan (1978). Because the Middle Jurassic Entrada Sandstone rests on Triassic strata, the J-2 unconformity is actually a compound unconformity that includes the J-1 unconformity of Pipiringos and O'Sullivan (1978).

The J-3 unconformity of Pipiringos and O'Sullivan (1978) is the basal transgressive unconformity that separates the Entrada Sandstone from the overlying Curtis Formation (also see Wilcox and Currie, 2008). I correlate the Curtis with the Todilto, which suggests that the Todilto base is the J-3 unconformity. Indeed, local stratigraphic relief, rip-up clasts and floating pebbles, as well as sharp lithologic contrast—kerogenic limestone on eolianite sandstone—suggest the base of the Todilto Formation is an unconformity. Thus, there are good reasons to equate the Todilto base to the J-3 unconformity at the base of the Curtis (Lucas and Anderson, 1996, 1997). Identification of catastrophic flooding at the onset of Todilto deposition (Ahmed Benan and Kocurek, 2000) is consistent with equating the Todilto base to the J-3 surface.

The J-4 unconformity is not evident in west-central New Mexico. The base of the Morrison Formation was identified by Pipiringos and O'Sullivan (1978) as the J-5 unconformity. I recognize this unconformity at the base of the Salt Wash Member of the Morrison Formation across west-central New Mexico, but note that USGS workers have long placed that unconformity stratigraphically lower, in the Bluff or Summerville intervals (e.g., Condon and Peterson, 1986). The J-5 unconformity is a tectonosequence boundary that represents a significant tectonic reorganization of Jurassic depositional systems in the Western Interior. This is the change from the depositional basin of the San Rafael Group, which had a paleoslope down to the northwest, to the depositional basin of the Morrison Formation, which had a paleoslope down to the east (Anderson and Lucas, 1997; Lucas and Anderson, 1997).

The K-0 unconformity of Pipiringos and O'Sullivan (1978) separates Cretaceous strata (Burro Canyon and Dakota formations, possibly the Jackpile Member of the Morrison Formation) from underlying Jurassic strata across west-central New Mexico. In west-central New Mexico, either the Encinal Canyon Member (Albian?) or Oak Canyon Member (Cenomanian) of the Dakota Formation rest with profound unconformity on the Morrison Formation.

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