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JURASSIC STRATIGRAPHY IN WEST-CENTRAL NEW MEXICO

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ABSTRACT.—Jurassic strata in west-central New Mexico encompass part of the southern edge of the Jurassic outcrop belt in the Western Interior. Some of the Jurassic 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. Therefore, a dual lithostratigraphic nomenclature needs to be used for Jurassic strata in west-central New Mexico, one that reflects the two different lithofacies belts. For convenience, we refer to these as the water-deposited and the eolian lithofacies belts. The Jurassic section in the water-deposited lithofacies belt is (in ascending order) the Entrada Sandstone (Dewey Bridge and Slick Rock members), Todilto Formation (Luciano Mesa and Tonque Arroyo members), Summerville Formation, Bluff Sandstone (main body and Recapture Member), Acoma Tongue of the Zuni Sandstone and Morrison Formation (Salt Wash, Brushy Basin and Jackpile members). In the eolian lithofacies belt, the entire Jurassic section is assigned to the Zuni Sandstone. The "Iyanbito Member" of the Entrada Sandstone is Triassic strata of the Wingate Sandstone and thus is removed from the Entrada, and the name Iyanbito Member is abandoned. The lithostratigraphy we advocate for Jurassic strata in west-central New Mexico is parsimonious; it reflects regional lithostratigraphic geometry, embodies sound application of stratigraphic principles and is both practical and useful to geologists. It provides a sound basis for a Jurassic sequence stratigraphy in west-central New Mexico that recognizes four regional unconformities: J-2 (base of Entrada and Zuni sandstones), J-3 (base of Todilto Formation), J-5 (base of Salt Wash Member of Morrison Formation) and K-0 (base of Cretaceous Dakota Sandstone).

INTRODUCTION

Jurassic strata are well exposed in west-central New Mexico, principally along the northern flank of the Zuni uplift and the eastern edge of the Colorado Plateau (Fig. 1). First assigned a Jurassic age by Marcou (1858), and a focal point of Dutton's (1885) classic study of the geology of the Zuni plateau, the Jurassic strata of west-central New Mexico have yielded uranium, groundwater and building stone that made them a major focus of geologic study, especially in the latter half of the twentieth century. Extensive stratigraphic analysis and mapping were an integral part of this study, and have lead to a complex stratigraphic nomenclature that has both evolved through time and been a major source of debate (Fig. 2). Here, we review the Jurassic stratigraphy of west-central New Mexico to advocate a Jurassic stratigraphic nomenclature that reflects regional lithostratigraphic geometry, embodies sound application of stratigraphic principles and is both practical and useful to geologists.

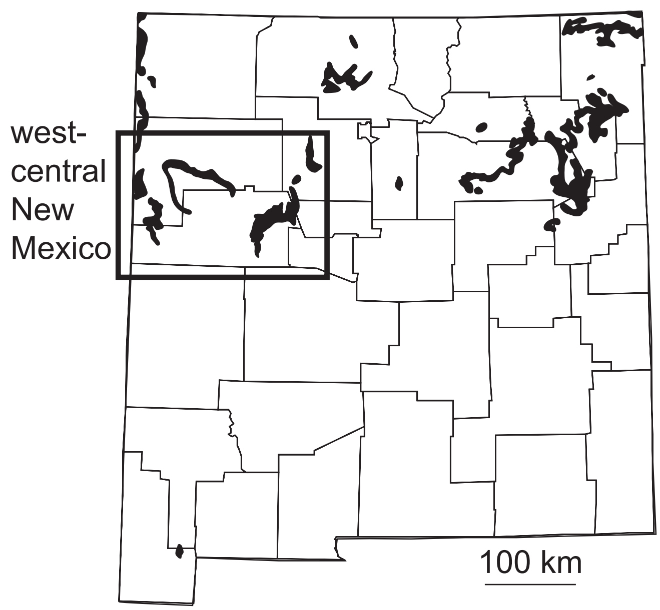

FIGURE 1. Outcrops of Jurassic strata in New Mexico (after Dane and Bachman, 1965) with the area of west-central New Mexico indicated.

PREVIOUS STUDIES

Various articles review 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, 2003), obviating the need for an extensive review here. Instead, we briefly trace the development of Jurassic stratigraphic concepts and nomenclature between 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) essentially "guessed" a Jurassic age for some of the strata exposed in west-central New Mexico, 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 Triassic) and Zuni Sandstones for strata in west-central New Mexico now deemed Jurassic (Lucas, 2003; Fig. 2).

Darton's (1928a) summary of the geology of New Mexico represented nearly half a century of work after Dutton, and his view of the Jurassic stratigraphy of west-central New Mexico was based primarily on the work of Gregory (1917). Thus, Gregory's (1917) mistake of believing that the Todilto Formation underlies the Navajo Sandstone was repeated by Darton (Fig. 2). The mistake was based on miscorrelation of the eolian sandstone interval above the Todilto Formation in west-central New Mexico (Bluff Sandstone of this paper) with the Navajo Sandstone of eastern Arizona, a much older and stratigraphically lower eolian sandstone. Otherwise, Darton (1928a) recognized the Wingate Sandstone *sensu* Dutton but did not use the term Zuni Sandstone. Instead, he assigned this part of the section to the Todilto, Navajo

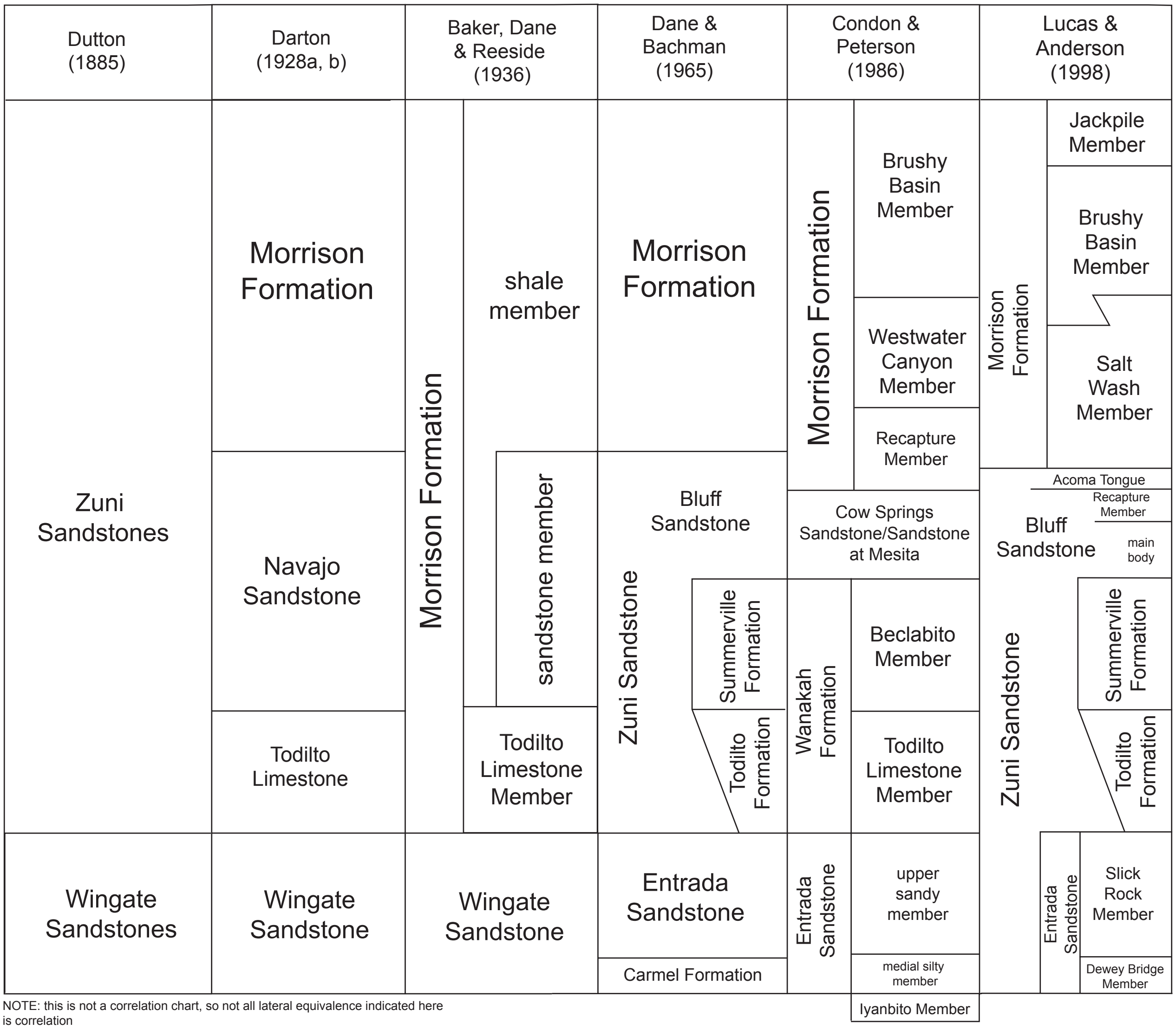

FIGURE 2. Development of Jurassic stratigraphic nomenclature in west-central New Mexico. The stratigraphy advocated here is that of Lucas and Anderson (1998).

and Morrison formations (though note that Darton thought the Morrison to be most likely of Cretaceous age; Fig. 2).

The classic monograph by Baker, Dane and Reeside (1936) was the first explicit attempt to assemble a synthetic Jurassic stratigraphy of much of the Colorado Plateau. This monograph provided an extensive and useful review of earlier work. It corrected some earlier mistakes; for example, the Navajo Sandstone was correlated correctly so that the Todilto was placed much higher in the section, correcting Gregory's errors (Fig. 2). However, miscorrelation of the Wingate Sandstone, as had been done by Gregory (1917), continued. Also, the Morrison base was moved down to include the Todilto and all overlying Jurassic strata (Fig. 2). This bizarre decision lumped together units that are very different lithologically, but it may have been advocated to avoid problems of correlation within this interval.

Baker et al. (1936) also made a significant error (see their plate 2) in believing that the entire 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. Therefore, they believed that the San Rafael Group of southeastern Utah was pinching out to the south (their fig. 7), so that in west-central New Mexico Dutton's Wingate Sandstone was much older than (stratigraphically lower than) the San Rafael Group of Utah.

This and other errors were corrected in 1947, when Baker, Dane and Reeside, in a five-page-long published note, repudiated the principal conclusions of their 66-page-long, 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 agreed with Heaton (1939) on a broader distribution of the Entrada Sandstone, and in particular, 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. Dutton was dead, and

Reeside had been party to two major blunders—unnecessarily naming the Entrada (with Gilluly in 1928) and miscorrelating it regionally (with Baker and Dane in 1936). The simplest solution, which would have obeyed priority, would have 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. 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. It would have been simpler to follow priority.

By the 1950s, a new consensus had emerged on the Jurassic stratigraphy on the southern Colorado Plateau. This was the official U. S. Geological Survey stratigraphy, and it was embraced eagerly by most of those who worked on the economic geology of the Jurassic strata, especially in the uranium fields. This regional stratigraphy 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), in their state geologic map of New Mexico, well reflected the 1960s consensus on Jurassic stratigraphy in west-central New Mexico (Fig. 2). They 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 and lower San Rafael Group strata they referred to the (now forgotten) Thoreau Formation of Smith (1954; Fig. 2).

It is interesting to compare the Jurassic stratigraphy of Dane and Bachman (1965) with that of Lucas and Anderson (1998), which is the stratigraphy advocated here (Fig. 2). At the formation level, the two stratigraphic schemes are nearly identical. So, how can we explain the very different stratigraphy developed by the U. S. Geological Survey during the 1970s and 1980s (Fig. 2) and well summarized by Condon and Peterson (1986)? The explanation, as detailed in articles by Anderson and Lucas (1992, 1994, 1995, 1996, 1997, 1998), Lucas and Anderson (1996, 1997, 1998), Lucas and Woodward (2001) and Lucas et al. (1999, 2001), is that numerous conceptual, methodological and empirical errors in the work of U. S. Geological Survey stratigraphers Pipringos, O'Sullivan, Peterson, Condon and their collaborators set back by nearly three decades the development of a workable Jurassic stratigraphy on the southern Colorado Plateau.

The conceptual errors included confounding lithostratigraphy and chronostratigraphy. Thus, in the scheme of regional Jurassic unconformities proposed by Pipiringos and O'Sullivan (1978), the unconformities were assumed to be time boundaries. The J-5 unconformity was thus equated with the Middle-Late Jurassic boundary. When evidence was presented that part of the upper Summerville Formation is of Late Jurassic age, the J-5 unconformity had to be placed within the Summerville despite a total lack of physical stratigraphic evidence of an unconformity within the formation.

Methodological errors were many. The most obvious included using preoccupied names and renaming the same stratigraphic unit over and over again. A good example is the Survey stratigraphers' insistence on using the preoccupied name Wanakah Formation and their unecessary renaming of the Bluff Sandstone, so that this unit has at least four names (see below). Empirical errors were legion and are best exemplified by the myriad miscorrelations of the Entrada Sandstone by O'Sullivan, discussed by Lucas et al. (2001) and reviewed below. The article in this guidebook by O'Sullivan (2003) continues a tradition of misrepresentation and miscorrelation of Jurassic strata at both the outcrop and the regional scale.

The Jurassic stratigraphy in west-central New Mexico advocated here (Fig. 2) is that of Anderson and Lucas, published in a series of articles between 1992 and 1998 (see bibliography), with some minor modifications based on data gathered since then. Indeed, this 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 their articles.

LITHOSTRATIGRAPHY

West-central New Mexico encompasses part of the southern edge of the Jurassic outcrop belt in the Western Interior (e.g., 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. Therefore, a dual lithostratigraphic nomenclature needs to be used for Jurassic strata in west-central New Mexico, one that reflects the two different lithofacies belts (Fig. 2). For convenience, we refer to these as the water-deposited and the eolian lithofacies belts, and review lithostratigraphy in each.

Water-deposited Lithofacies Belt

In west-central New Mexico, the water-deposited lithofacies belt begins at about Interstate Highway 40 and extends northward into the San Juan Basin. We define this lithofacies belt to include 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. 2).

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 at the base of the Jurassic section in west-central New Mexico remain a contentious problem. As noted above, Dutton (1885) applied the name Wingate Sandstones to the oldest Jurassic strata near Fort Wingate in McKinley County. More than 40 years later, in Utah, Gilluly and Reeside (1928) named the same lithostratigraphic unit the Entrada Sandstone. 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 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 U.S. Geological Survey on Entrada stratigraphy. They followed Green (1974) and recognized a tripartite Entrada Sandstone in west-central New Mexico—"Iyanbito," medial silty and upper sandy members—that has been mapped by several workers, including Cooley et al. (1969). Very recently, 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).

We previously presented, in preliminary form, a very different view of Entrada regional stratigraphy (Heckert and Lucas, 1998; Lucas and Anderson, 1998; Lucas et al., 2001). We thus exclude 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 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).

We have a detailed database upon which to base our stratigraphic conclusions that consists of measured sections from 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 (Fig. 3). These sections indicate the following:

1. The "Iyanbito Member" (= "lower sandy member" of Cooley et al., 1969) rests with profound unconformity (Tr-5 unconformity) on the Upper Triassic Owl Rock Formation of the Chinle Group in west-central New Mexico (also see Green, 1974). To the northwest, along the western flank of the Chuska Mountains, the stratigraphic position of the "Iyanbito Member" is occupied by the Wingate Sandstone or the Wingate Sandstone plus Rock Point Formation. Nowhere outside of west-central New Mexico in the Entrada outcrop belt, including the type Entrada section in Utah, is there a stratigraphic interval of the Entrada equivalent to the "Iyanbito Member."

2. Stratigraphic position, bedforms and lithotypes of the "Iyanbito Member" and Wingate are essentially identical (Harshbarger et al., 1957). Particularly significant are thin beds of siltstone, sandy mudstone and chert pebbles that are common in the Iyanbito Member and also known in the Wingate. Furthermore, compare lithologic descriptions of the "Iyanbito Member" and Wingate Sandstone provided by Robertson and O'Sullivan (2001, p. 59 and 65, respectively); they indicate lithologic identity.

3. The contact of the "Iyanbito Member" with the overlying "medial silty member" of the Entrada is a sharp surface marked by a substantial change in grain size and bedforms. Indeed, at the type section of the "Iyanbito Member" (Fig. 3, Appendix 1), fissures and dessication features in the top of the "Iyanbito Member" are filled with sediment from the overlying Dewey Bridge Member. This readily traceable and mappable contact is the J-2 unconformity, and there is significant stratigraphic relief on the J-2 surface regionally (Figs. 3-4).

4. Robertson and O'Sullivan (2001) correctly describe Entrada depositional systems as "quiet," "low-energy," "lacustrine," "eolian" and "sabkha." So, without unconformities, how can they account for thickness variations in the Iyanbito from 0 to 45 m over short distances? An unconformity-bounded "Iyanbito" Member best explains these thickness variations.

We conclude that the "Iyanbito" is unconformity bounded and equivalent to the Wingate, which is also unconformity bounded where overlain by the Entrada. Iyanbito is an unnecessary synonym of Wingate and should be abandoned.

Robertson and O'Sullivan (2001) and O'Sullivan (2003) reject our correlation (and assignment) of the medial silty member of the Entrada Sandstone in west-central New Mexico to the Dewey Bridge Member of the Entrada of Wright et al. (1962). Instead, Robertson and O'Sullivan (2001) and O'Sullivan (2003) correlate the "middle sandstone" and overlying "red member" of the Entrada in southeastern Utah to the "Iyanbito" and "medial silty" (= "Rehoboth") members, respectively. Not only do they fail to demonstrate this correlation, but our fieldwork indicates it is incorrect.

At Bluff in southeastern Utah (e.g., secs. 29-30, T40S, R21E, San Juan County), the basal unit of the Entrada is an ~ 14 m thick, bench-forming eolian sandstone that rests directly on the Carmel Formation; this is the "middle sandstone" of the Entrada of O'Sullivan (1980), and it is the base of the Slick Rock Member locally. Beds overlying it are ~ 19 m of trough crossbedded sandstone, locally of reddish color, that are the "upper red" (= "red member") of O'Sullivan (1980). Thus, strata of the "red member" at Bluff are typical Slick Rock Member eolianites, and there is no reason to correlate them to the lithologically different "medial silty member" ("Rehoboth Member") to the south, especially as the "red member" at Bluff is well above the Slick Rock Member base.

In the Dry Wash area of southeastern Utah (e.g., the Black Steer Knoll section of O'Sullivan [1980] in sec. 8, T36S, R21E, San Juan County), the Entrada Sandstone is ~ 26 m thick (this is the "middle sandstone" of O'Sullivan). The overlying "red member" of O'Sullivan is reddish brown sandy mudstone and siltstone at the base of the Summerville Formation, not a part of the Entrada Sandstone (cf. Anderson and Lucas, 1992).

Furthermore, at Church Rock in southeastern Utah (sec. 24, T31S, R23E, San Juan County), the unit O'Sullivan (1996) identified as the "red member" of the Entrada actually is the Carmel Formation, and the unit he labeled "middle sandstone" is the Navajo Sandstone (e.g., Weir and Dodson, 1958). Thus, it is clear that O'Sullivan (1980, 1996) mis-correlated the unit he called the "red member" throughout southeastern Utah. At one section it is an interval of sandstone in the Slick Rock Member of the Entrada (at Bluff), at another it is the basal interval of the Sum-

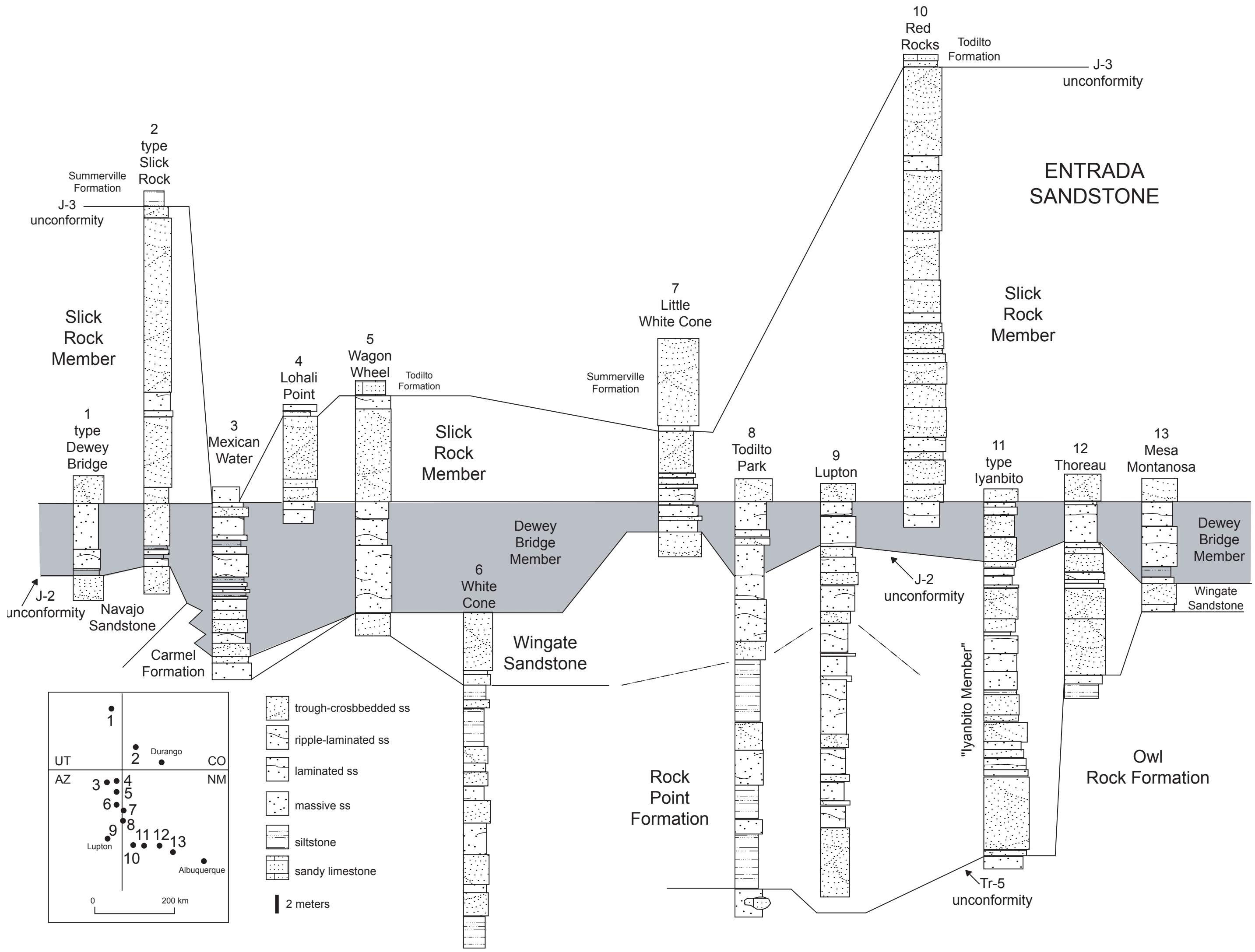

FIGURE 3. Measured stratigraphic sections of the Entrada Sandstone from the Four Corners through west-central New Mexico. See Appendix 2 for map coordinates of the measured sections.

merville Formation (at Dry Wash) and at another it is the Carmel Formation (at Church Rock). Robertson and O'Sullivan (2001) introduce the name Rehoboth Member for the "medial silty member" of the Entrada Sandstone and correlate it to the "red member." Not only do they not document this correlation, but it is readily rejected because the type "Rehoboth" in west-central New Mexico is stratigraphically below the Slick Rock base, and the unit at Bluff in southeastern Utah to which they correlate it is above the Slick Rock base.

Instead, the correct correlation of the "Rehoboth Member" is that of Rapaport et al. (1952), Allen and Balk (1954), Harshbarger et al. (1957) and Cooley et al. (1969), among many others: it is laterally equivalent to and, in the northwest part of its outcrop area (e.g., at Mexican Water), immediately overlies the lower part of the Carmel Formation (Figs. 3-4). Thus, in west-central New Mexico, the "Rehoboth Member" is the lowest stratigraphic interval of the Entrada Sandstone and is largely equivalent to the Carmel; the name Dewey Bridge Member already exists for this unit (Wright et al., 1962). "Rehoboth Member" is thus an unnecessary name and should be abandoned.

Moreover, compare O'Sullivan's (2003, fig. 2) Entrada section at Mexican Water to our section at the same location (Fig. 3). His section lacks detail and suggests that the Carmel is overlain by a tripartite Entrada section consisting of ~9 m of "lower sandy member," ~10 m of "Rehoboth Member" and ~6 m of "upper sandy member." A more detailed look at this section (Fig. 3) reveals that the Carmel Formation is overlain by a 1.5-m-thick eolian sandstone that was mapped by Cooley et al. (1969, pl. 1, sheet 5) as the "lower sandy member" of the Entrada. We agree with Cooley et al. (1969) and O'Sullivan (2003) that this sandstone is at the base of the Entrada, but O'Sullivan's (2003) thickness of this unit is greatly exaggerated. Above the basal eolian sandstone the entire Entrada section at Mexican Water is ~21 m thick and consists of thin eolian sandstone beds intercalated with gypsiferous, red-bed siltstones and sandstones of characteristic Carmel lithotypes. Cooley et al. (1969) mapped this interval as the "middle silty member" of the Entrada and we interpret it as an intertonguing of upper Carmel and lower Entrada lithotypes at the transition from the Carmel lithosome to the Dewey Bridge Member of the Entrada Sandstone. There is no "upper sandy member" of the Entrada Sandstone at Mexican Water (Cooley et al., 1969), so O'Sullivan's (2003) section fundamentally misrepresents Entrada stratigraphy at that location.

Robertson and O'Sullivan (2001, fig. 3, also p. 63) and O'Sullivan (2003) acknowledge the equivalence of at least part of the Slick Rock Member of the Entrada in southeastern Utah and the "upper sandy member" of the Entrada in west-central New Mexico (Fig. 4). However, they do not apply the term Slick Rock Member to the "upper sandy member" for two reasons: (1) "the Slick Rock Member at its type locality is not overlain by the Todilto Limestone Member, nor by the equivalent Pony Express Limestone Member, of the Wanakah Formation" (p. 63-64); and (2) "the upper part of the Slick Rock Member in Dry Valley and possibly at the type locality is replaced southward by the Wanakah Formation" (p. 64). These are not valid reasons to justify not applying the term Slick Rock Member to the unit in west-central New Mexico that is physically continuous with the Slick Rock Member in southeastern Utah. Furthermore, Robertson and O'Sullivan (2001, p. 64) state that "the upper sandstone member at Gallup may represent, at most, a lower tongue of the type Slick Rock." Yet, the type Slick Rock Member overlies the Dewey Bridge Member, though Robertson and O'Sullivan claim their Rehoboth Member, which is beneath the "upper sandy member" at Gallup, is not correlative to the Dewey Bridge Member, but to a stratigraphically higher unit, well above the base of the Slick Rock Member. Both correlations advocated by Robertson and O'Sullivan (2001) cannot be correct. Instead, the correct correlation indicates that the Entrada Sandstone section at Gallup and throughout west-central New Mexico consists of Dewey Bridge Member overlain by Slick Rock Member (Figs. 3-4).

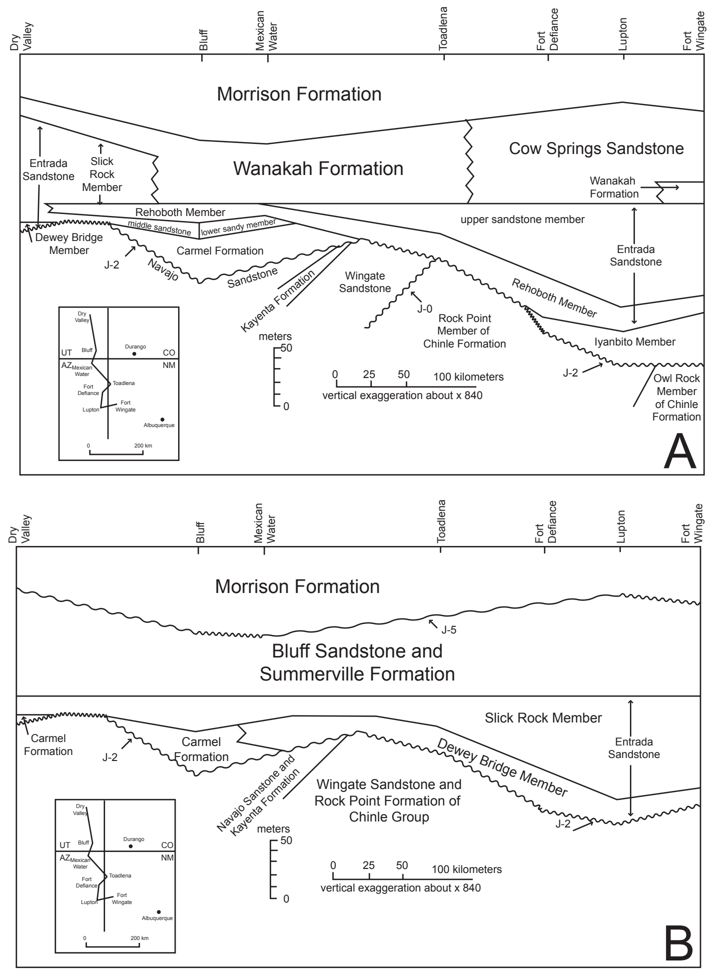

FIGURE 4. Correlation of some Jurassic rocks from southeastern Utah to west-central New Mexico. A, From Robertson and O'Sullivan (2001, fig. 3). B, Correlation advocated in this paper.

Todilto Formation

The type section of the Todilto Formation of Gregory (1917) is at Todilto Park, north of Fort Defiance near the New Mexico-Arizona border (Lucas et al., 2003). 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 Lucas et al. (1995). 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 Lucas et al., 1995) is also present above the Luciano Mesa Member and beneath the Summerville Formation.

Todilto Formation stratigraphy and sedimentation is well understood in west-central New Mexico due to recent work by Lucas et al. (1985, 2000), Armstrong (1995) and Kirkland et al. (1995), among others. In brief, the Luciano Mesa Member is up to 9 m thick and is mostly microlaminated, kerogenic limestone. Anderson and Kirkland (1960) suggested that the microlaminae form varved couplets and counted these couplets to estimate a duration of about 14,000 years for deposition of the Luciano Mesa Member. Fossils (ostracodes, insects, fishes), isotope geochemistry and sedimentologic analysis indicate deposition of the Luciano Mesa Member in a vast, paralic salina (Lucas et al., 1985, 2000; Kirkland et al., 1995). So-called stromatolites in the Todilto Formation of west-central New Mexico are, almost without exception, small-scale intraformational folds (e.g., Green, 1981, 1982). In west-central New Mexico, the upper, gypsum member of the Todilto Formation (Tonque Arroyo Member) is as much as 34 m thick and mostly massive and breciated gypsum. It was deposited in a smaller evaporitic basin that resulted from the shrinking of the salina (Fig. 5).

Two stratigraphic issues needed to be briefly addressed with regard to the Todilto — its rank in the lithostratigraphic hierarchy and its regional correlation. To anyone familiar with the Todilto, it is one of the most distinctive lithostratigraphic units in the Jurassic section—a striking interval of limestone and/or gypsum in a section dominated by sandstone, siltstone and mudstone. The Todilto Formation is readily mapped as a formation-rank unit, and has been so mapped by many geologists. Despite this, workers of the U. S. Geological Survey have considered the Todilto

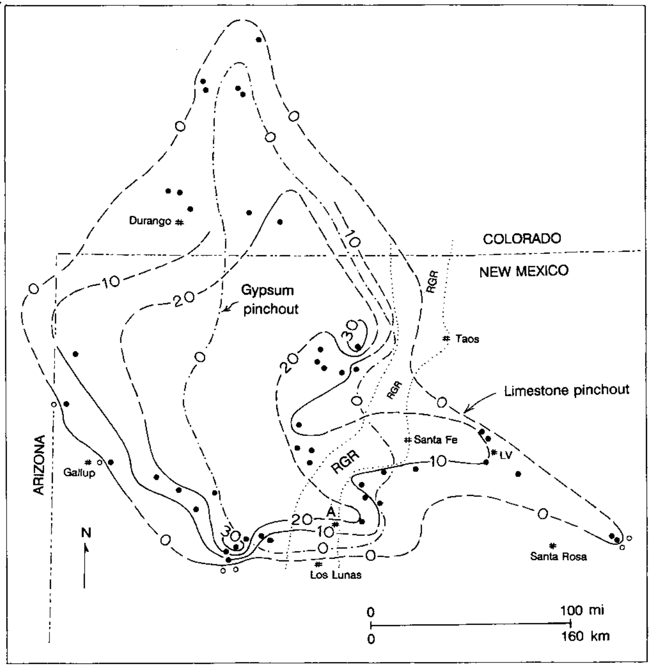

FIGURE 5. Approximate depositional limits of Jurassic Todilto limestone member (Luciano Mesa Member) and overlying Todilto gypsum member (Tonque Arroyo Member) (modified from Kirkland et al., 1995). Dotted outline is Rio Grande rift (RGR). A = Albuquerque, LV = Las Vegas. Structure contours for Todilto limestone member are in feet.

a member of the Morrison Formation (Baker et al., 1936) or a member of the "Wanakah Formation" (e.g., Condon and Peterson, 1986). Neither member designation is warranted, and we continue to recognize the Todilto as a unit of formation rank (Anderson and Lucas, 1992, 1994; Lucas and Anderson, 1997, 1998).

The Todilto Formation in west-central New Mexico occupies the same stratigraphic position as the Curtis Formation in east-central Utah (between the Entrada and Summerville formations). Both units are of Callovian age, but current biostratigraphic data are insufficient to document a precise correlation. Nevertheless, stratigraphic position supports correlation of the Todilto and Curtis formations (e.g., Lucas and Anderson, 1997). Furthermore, the marine transgression recorded by the Curtis Formation represents a regional rise in base level that logically could have produced the Todilto salina, and this supports a Curtis-Todilto "event-stratigraphic" correlation. Thus, there are very good reasons to equate the Todilto base to the J-3 unconformity at the base of the Curtis (Lucas and Anderson, 1996, 1997). Recent arguments for catastrophic flooding at the onset of Todilto deposition (Ahmed Benan and Kocurek, 2000) are also consistent with equating the Todilto base to the J-3 surface.

Despite this, the U.S. Geological Survey has correlated the Todilto Formation with the middle part of the Entrada Sandstone in Utah (e.g., Pipiringos and O'Sullivan, 1978). The basis for this correlation actually has little to do with the Todilto or Curtis, but instead is an outgrowth of a miscorrelation of the Summerville Formation of Utah in which it is considered to be younger than its Colorado-New Mexico equivalent, the "Wanakah" Formation (see later discussion). Anderson and Lucas (1992) presented a detailed refutation of this Summerville-"Wanakah" miscorrelation, discussed below. Therefore, we continue to advocate a Todilto-Curtis correlation.

Summerville Formation

In west-central New Mexico, the Summerville Formation is dominantly fine-grained, horizontally bedded sandstone with some thin interbeds of siltstone/maroon mudstone. Many beds are gypsiferous, and some thin beds of gypsum are present locally. As much as 49 m thick, the Summerville overlies the Todilto and is overlain by the Bluff Sandstone. The two members of the Summerville, Beclabito and Tidwell, recognized in eastern Utah and adjacent areas (Lucas and Anderson, 1997), cannot be distinguished in west-central New Mexico.

The Summerville Formation in west-central New Mexico is *physically continuous* with the Summerville Formation in the type area of southeastern Utah. Numerous surface and subsurface sections (e.g., O'Sullivan, 1980; Anderson and Lucas, 1992) document this continuity, and it was recognized by the 1950s. Thus, the name Summerville Formation was generally and justifiably applied to Jurassic strata in west-central New Mexico (e.g., Dane and Bachman, 1965). Despite this, beginning in the 1980s, workers of the U.S. Geological Survey replaced the name Summerville with "Wanakah," claiming that this unit in New Mexico is stratigraphically below (older than) the Summerville Formation in Utah. Anderson and Lucas (1992) presented a detailed refutation of this miscorrelation and rejected use of the preoccupied name Wanakah Formation in New Mexico or elsewhere. Indeed, 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 we continue to advocate use of the term Summerville Formation across its entire outcrop belt (Anderson and Lucas, 1992, 1994, 1996; Lucas and Anderson, 1997, 1998; Lucas et al., 1999; Lucas and Woodward, 2001).

Bluff Sandstone

In west-central New Mexico, the Bluff Sandstone 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 laminated and trough-crossbedded sandstone. This unit is the main body of the Bluff Sandstone (Lucas and Anderson, 1997). Above it in west-central New Mexico is a thinner (up to 36 m thick) interval of finer-grained sandstones and siltstones assigned to the Recapture Member of the Bluff Sandstone (Lucas and Anderson, 1997, 1998).

The main body of the Bluff is mostly of eolian origin, but unlike the Slick Rock Member of the Entrada Sandstone, the Bluff lacks thick sets of high-angle crossbeds with truncated upper boundaries (reactivation surfaces). Instead, it is dominated by horizontal bedforms (commonly 0.5-5.0 m thick) and indistinctly crossbedded facies. Bedforms and vertical facies stacking suggest eolian sand sheet deposition and fluvial reworking on a broad, arid coastal plain of very low relief.

Previous nomenclature of the Bluff Sandstone interval in west-central New Mexico represents the most confused (and confusing) nomenclature in the entire Jurassic section. Thus, the Bluff has continually been renamed by workers of the U.S. Geological Survey who have been incapable of tracing it across west-central New Mexico and thus recognizing a single, sandstone-dominated lithosome between the Summerville Formation and Morrison Formation. Thus, the Bluff 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 Sandstone. Bluff strata are also included in the "Recapture Member of the Morrison Formation" by many U.S. Geological Survey workers (e.g., Condon and Peterson, 1986). Indeed, unwarranted inclusion in the Morrison Formation of eolian beds of the Bluff or Acoma Tongue of the Zuni Sandstone by various workers of the U.S. Geological Survey (e.g., Condon and Peterson, 1986) has lead to the misconception that eolianites are part of the lower Morrison Formation.

Acoma Tongue of the Zuni Sandstone

Locally, the sandstone interval above the Bluff Sandstone and below the Salt Wash Member of the Morrison Formation, as much as 70 m thick, is a boldly crossbedded eolian sandstone with easterly dipping foresets. 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. The Acoma Tongue is the stratigraphically highest eolianite in the Jurassic section and the top of the San Rafael Group.

Morrison Formation

For many years, the U.S. Geological Survey recognized three principal Morrison Formation members in west-central New Mexico (in ascending order): Recapture, Westwater Canyon and Brushy Basin. A fourth, uppermost Jackpile Member was later recognized after Owen et al. (1984) formalized the name (though, note that Condon and Peterson [1986] ignored the name Jackpile Member [Fig. 2], presumably because it was not formalized by employees of the U.S. Geological Survey).

Detailed work by Anderson and Lucas (1995, 1997, 1998) in southeastern Utah demonstrated that 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 Sandstone (see above), and that 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. 6).

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. It rests with distinct unconformity (J-5 unconformity) on either the Acoma Tongue of the Zuni Sandstone or the Recapture Member or the main body of the Bluff Sandstone (Fig. 6). 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. The J-5 unconformity is a tectonosequence boundary that represents a significant tectonic reorganization of Jurassic depositional systems in the Western Interior.

The Salt Wash Member grades upward into the mudstone-dominated Brushy Basin Member, which is as much as 107 m thick in west-central New Mexico. The overlying Jackpile Member is as much as 91 m of mostly kaolinitic, crossbedded sandstone and silica-pebble conglomerate.

Three issues regarding the Morrison Formation merit brief comment:

1. Some workers have informed us that they believe the mineralogy of the basal Morrison Formation sandstone-dominated interval in west-central New Mexico is distinct from that of the type Salt Wash Member in east-central Utah, so that the interval in New Mexico merits a different member name. If this is the case, then Smith's (1954) name Prewitt Member of Morrison Formation has priority for this interval.
2. In west-central New Mexico, the Brushy Basin Member is mudstone dominated but includes significant fluvial channel deposits. It shows no demonstrable facies zonation of clay minerals, *contra* the claims of Turner and Fishman (1991). Therefore, interpretation of Brushy Basin deposition in a large lake ("Lake T'oo'dichi") remains unsupported (Anderson and Lucas, 1997).
3. The regional stratigraphic relationships of the Jackpile Member are uncertain. The possibility that it is a Lower Cretaceous unit equivalent to the "Burro Canyon" (=Cedar Mountain) Formation to the north merits further investigation.

Eolian Lithofacies

South of Interstate Highway 40, and best displayed at Zuni Pueblo, the Todilto, Summerville and Morrison formations thin and disappear (pinch out or are truncated), and the Jurassic section becomes an unbroken succession of eolianites about 150 m thick (Fig. 7). We refer to this succession as the Zuni Sandstone, following Anderson (1993) and Anderson and Lucas (1994).

At Dowa Yalaane (Taaiyalone), near Zuni Pueblo, which is the type section of the Zuni Sandstone (Dutton, 1885; Anderson, 1983, 1993; Lucas, 2003), the Zuni Sandstone can be divided into three units (Figs. 7-8). The lower ~80 m is eolian sandstone equivalent 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 at least part (or all?) of the Summerville Formation. The eolian sandstone above the notch, ~ 60 m thick, is equivalent to the main body of the Bluff Sandstone. The surface above the Bluff interval represents the pinchout/truncation of the Recapture Member of the Bluff Sandstone. 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 Sandstone (Figs. 7-8).

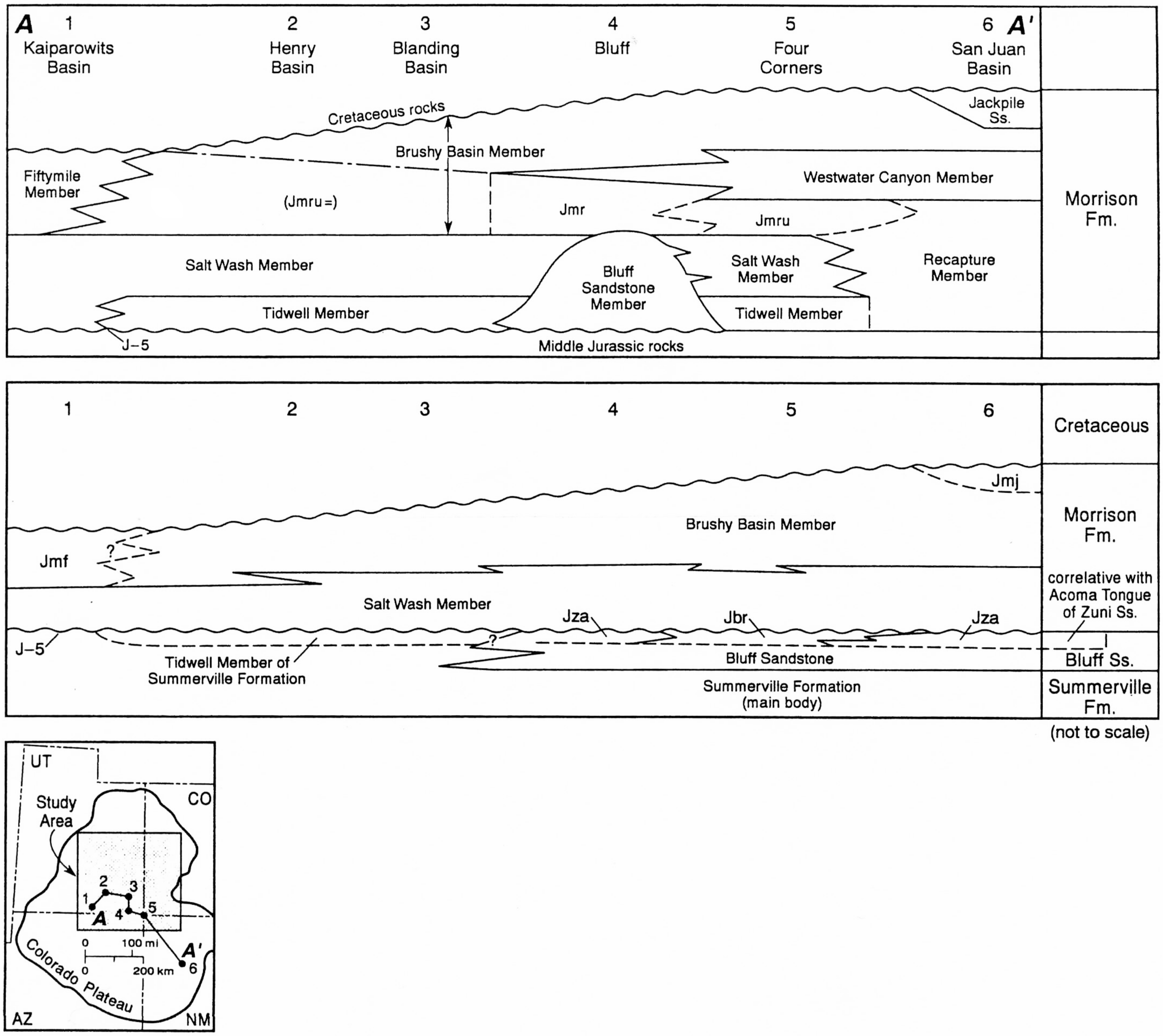

FIGURE 6. Contrast between stratigraphy and correlation of some Middle and Upper Jurassic rocks from Four Corners to west-central New Mexico as envisioned by U.S. Geological Survey (above) and as advocated here (below). After Anderson and Lucas (1997).

The southern edge of the water-deposited lithofacies belt in west-central New Mexico swings northward in eastern Arizona (McKee et al., 1956). Thus, the eolian lithofacies belt accounts for most of the outcrop area of the Middle-Upper Jurassic section in northeastern Arizona. The type section of the Cow Springs Sandstone of Harshbarger et al. (1957) in Arizona is in the eolian lithofacies belt. Strictly speaking, Cow Springs Sandstone, named by Harshbarger et al. (1957) for the unbroken succession of Jurassic eolian sandstones at Cow Springs, Arizona, is a synonym of Zuni Sandstone. However, the name has also been widely misapplied in New Mexico, mostly as a synonym of the Bluff Sandstone (see above).

SEQUENCE STRATIGRAPHY

Sound lithostratigraphy is parsimonious. It uses a minimum of names--only those necessary to denominate mappable lithologic units (formations) and their unambiguous subdivisions (members). 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, presence/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

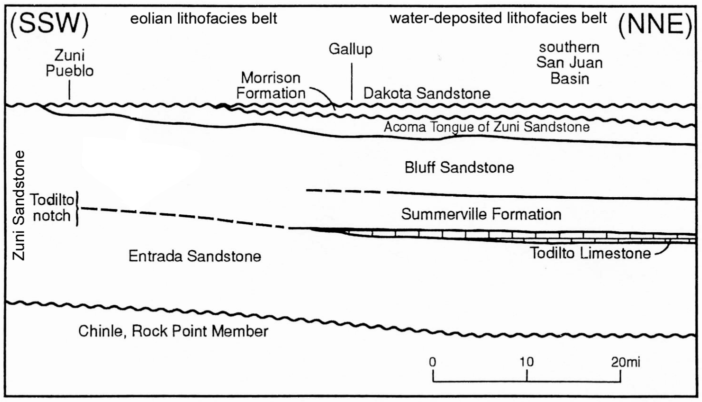

FIGURE 7. Jurassic stratigraphic relationships between the water-deposited and eolian lithofacies belts in west-central New Mexico (after Anderson and Lucas, 1994).

advocated here is just such a parsimonious lithostratigraphy and was so developed by Anderson and Lucas (1992, 1994, 1995, 1996, 1997, 1998) and Lucas and Anderson (1997, 1998).

This lithostratigraphy forms a sound basis for understanding regional Jurassic sequence stratigraphy in west-central New Mexico (Fig. 9). 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.

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 is unambiguously identified across all of the Jurassic outcrop belt in west-central New Mexico.

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. We 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 the J-3 unconformity.

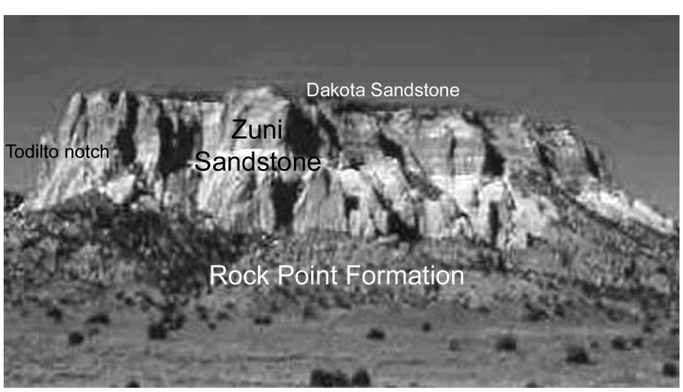

FIGURE 8. Type section of the Zuni Sandstone at Dowa Yalaane near Zuni Pueblo.

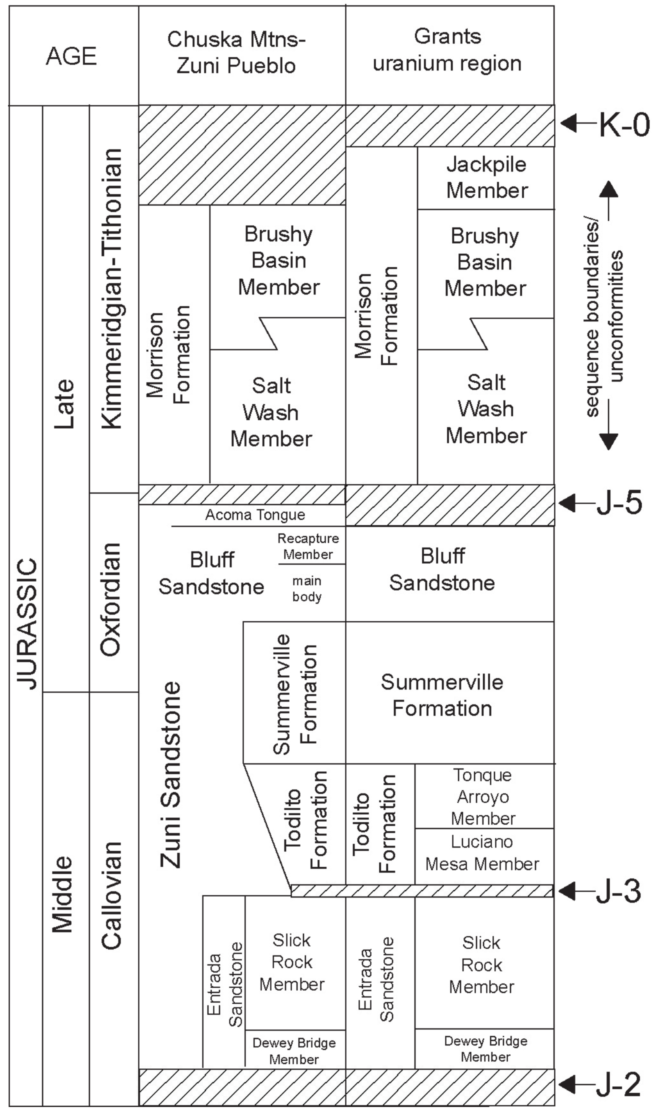

FIGURE 9. Jurassic sequence stratigraphy in west-central New Mexico.

The base of the Morrison Formation was identified by Pipiringos and O'Sullivan (1978) as the J-5 unconformity. We recognize this unconformity at the base of the Salt Wash Member across west-central New Mexico. The K-0 unconformity of Pipiringos and O'Sullivan (1978) separates Cretaceous strata (Dakota Sandstone) from underlying Jurassic strata across west-central New Mexico.

ACKNOWLEDGMENTS

We dedicate this paper to Orin Anderson, whose mapping and field studies greatly furthered understanding of Jurassic stratigraphy in the southern Western Interior and made this paper possible. We are also grateful to the late Charles Maxwell, who was a much understated but remarkably perceptive student of Jurassic stratigraphy. Adrian Hunt and Kate Zeigler reviewed the manuscript.

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APPENDIX 1: MEASURED SECTION OF TYPE "IYANBITO MEMBER"

Section measured in the NW1/4 sec. 15, T15N, R16W, McKinley County, New Mexico, at the same location as Green's (1974) type section.

unit lithology thickness (m)

Entrada Sandstone:

Slick Rock Member:

29 Sandstone; pale red (10R6/2) and pale reddish brown (10R5/4), locally bleached pinkish gray (5YR8/1) to bluish white (5B9/1); very fine-grained, subangular quartzarenite (eolianite); trough crossbedded; weakly calcareous. not measured

Dewey Bridge Member:

28 Sandstone; moderate reddish orange (10R6/6) to pale reddish brown (10R5/4); some spots of grayish orange pink (10R8/2); fine-grained, subangular to subrounded, silty quartzarenite (eolianite); trough crossbedded with some sets of ripple laminations; not calcareous. 0.7

27 Sandstone; moderate reddish orange (10R6/6) to pale reddish brown (10R5/4); some spots of grayish orange pink (10R8/2); fine-grained, subangular to subrounded, silty quartzarenite (eolianite); slightly more indurated than overlying unit; ripple laminated to flaser bedded; not calcareous. 0.9

26 Sandstone; pale red (10R6/2) to pale reddish brown (10R5/6) very fine-grained, subangular to subrounded, slightly silty quartzarenite; faint trough crossbeds and more ripple lamination than underlying unit; weakly calcareous. 3.3

25 Sandstone; moderate reddish orange (10R6/6) to pale reddish brown (10R5/4); very fine- to fine-grained, subrounded, moderately well-sorted quartzarenite; slightly silty; faint trough crossbeds; uncommon ripple laminations; slightly calcareous. 3.4

unconformity (J-2 unconformity of Pipiringos and O'Sullivan, 1978):

Glen Canyon Group:

Wingate Sandstone (type "Iyanbito member" of Green, 1974):

(The base of unit 25 seeps down into cracks and fissure fills as much as 0.3 m into unit 24, as shown below.)

25/24 Mottled, probably originally pale reddish brown (10R5/40 fading into yellowish gray (5Y8/1) and bluish gray (5B9/1); fine- to medium grained, locally coarser, subrounded, moderately sorted quartzarenite; calcareous.

24 Sandstone; bluish white (5B9/1) with moderate reddish orange (10R6/6) mottles; fine-grained, subrounded-subangular, moderately sorted quartzarenite (eolianite); trough crossbedded; calcareous. 0.8

23 Sandstone; moderate reddish orange (!0R6/6); very fine-grained, subrounded, moderately well-sorted quartzarenite; some faint crossbeds—more prominent than underlying unit; calcareous. 1.6

22 Sandstone; pale reddish brown (10R5/4); very fine- to fine-grained, subrounded moderately well-sorted quartzarenite; locally medium-grained; hackly; slightly silty; weakly calcareous. 1.2

21 Sandstone; light greenish gray (5GY8/1) fresh; weathers moderate orange pink (10R7/4); very fine- to medium-grained, subrounded to rounded, moderately sorted quartzarenite; silty; trough crossbedded; calcareous. 0.2

20 Sandstone; moderate reddish orange (10R6/6) to pale reddish brown (10R5/4); very fine- to fine-grained, subangular to subrounded, moderately well-sorted quartzarenite; locally coarser-grained; trough crossbedded; not calcareous. 4.3

19 Shale parting; same colors and lithologies as unit 17. 0.01

18 Sandstone; moderate reddish orange (10R6/6) to pale reddish brown (10R5/4); fine- to medium-grained, subrounded, poorly sorted quartzarenite; some black and white very coarse-grained-pebbly clasts of clay and chert; trough crossbedded; weakly indurated; calcareous. 1.8

17 Shale parting; grayish brown (5YR3/2); slightly silty; not calcareous. 0.01

16 Sandstone; pale red (10R6/2) to moderate reddish orange (10R6/6); very fine-grained, subrounded, moderately well-sorted quartzarenite; laminar; not calcareous. 2.2

15 Sandstone; same colors and lithologies as unit 13; ripply. 2.3

14 Sandstone; same colors and lithologies as unit 3; laminar in 0.5-m-thick tabular sets with partings like 13. 2.3

13 Sandstone; moderate reddish orange (10R6/6) with grayish orange pink (10R8/2) spots; very fine- to fine-grained, subangular to subrounded, moderately sorted quartzarenite; silty to medium-grained locally; ripply; bioturbated; calcareous. 0.7

12 Sandstone; same colors and lithologies as unit 10. 3.0

11 Sandstone; same colors and lithologies as unit 7; white trough crossbeds. 0.6

10 Sandstone; moderate orange pink (10R7/4) to moderate reddish orange (10R6/6); very fine- to coarse-grained, angular to rounded, very poorly sorted quartzarenite; some white (N9) sand-sized clay rip-ups; trough crossbedded; coarse grains on foresets; calcareous. 3.0

9 Sandstone; moderate reddish orange (10R6/6); very fine- to fine-grained, subangular-subrounded, moderately well-sorted quartzarenite; bioturbated; silty; some mottling to light greenish gray (5GY8/1); calcareous. 1.0

8 Sandstone; moderate reddish orange (10R6/6) trending toward pale reddish brown (10R5/5); very fine- to fine-grained, subrounded, moderately sorted quartzarenite (eolianite); trough-crossbedded; calcareous. 1.1

7 Sandstone; very pale blue (5B8/2) fresh, weathers to light brownish gray (5YR6/1) very coarse- to coarse-grained, well rounded, moderately well-sorted sublitharenite; most lithics are clay and chert; very calcareous. 0.3

6 Sandstone; same colors and lithologies as unit 2. 1.7

5 Sandstone; pale reddish brown (10R5/4) fresh; weathers to moderate reddish brown (10R4/6); subrounded, fine-grained, well-sorted quartzarenite; laminar; not calcareous. 0.6

4	Shale parting; dark reddish brown (10R3/4); silty; = unit 3 of Green (1974); not calcareous.	0.02
3	Sandstone; moderate reddish orange (10R6/6) to grayish red (10R4/2); very fine- to fine-grained, subangular, moderately well-sorted quartzarenite; slightly silty; trough crossbeds; white (N9) coarse grains to pebbles of chert and claystones on foresets; not calcareous.	10.8
2	Sandstone; white (N9), mottled as dark as pale reddish brown (10R5/4); stringers of very coarse-grained to pebbly rounded chert; otherwise fine-grained, subrounded, moderately well-sorted quartzarenite; fills dikes, cracks, and fissures in underlying Owl Rock Formation, as Green (1974) describes; not calcareous.	0.2-0.3

unconformity (Tr-5 unconformity of Lucas, 1993)
Chinle Group:
Owl Rock Formation:

1	Sandstone; mottled grayish red purple (5RP4/2); white (N9) and light greenish gray (5G8/1); fine- to medium-grained, subangular, moderately poorly sorted muddy litharenite; well-indurated; bioturbated; disrupted bedding; not calcareous.	not measured

APPENDIX 2: SECTION LOCATIONS

Map coordinates of the measured sections in Figure 3 are listed here.

Type Dewey Bridge: UTM zone 12, 646109E, 4297255N (sec. 8, T23S, R24E, UT).

Type Slick Rock: UTM zone 12, 683084E, 4211885N (sec. 36, T4N, R19W, CO).

Mexican Water: base at UTM zone 12, 625266E, 4095280N, top at UTM zone 12, 625495E, 4095921N (near Mexican Water, AZ).

Lohali Point: at UTM zone 12, 607891E, 3997107N (sec. 6, T31N, R24E, Apache County, AZ).

Wagon Wheel: at UTM zone 12, 663754E, 4035290N (sec. 12, T35N, R29E, Apache County, AZ).

White Cone: at UTM zone 12, 676363E, 4012496N (San Juan County, NM).

Little White Cone: at UTM zone 12, 678853E, 3997612N (sec. 31, T22N, R21W, San Juan County, NM).

Todilto Park: at UTM zone 12, 684992E, 3982776N (San Juan County, NM).

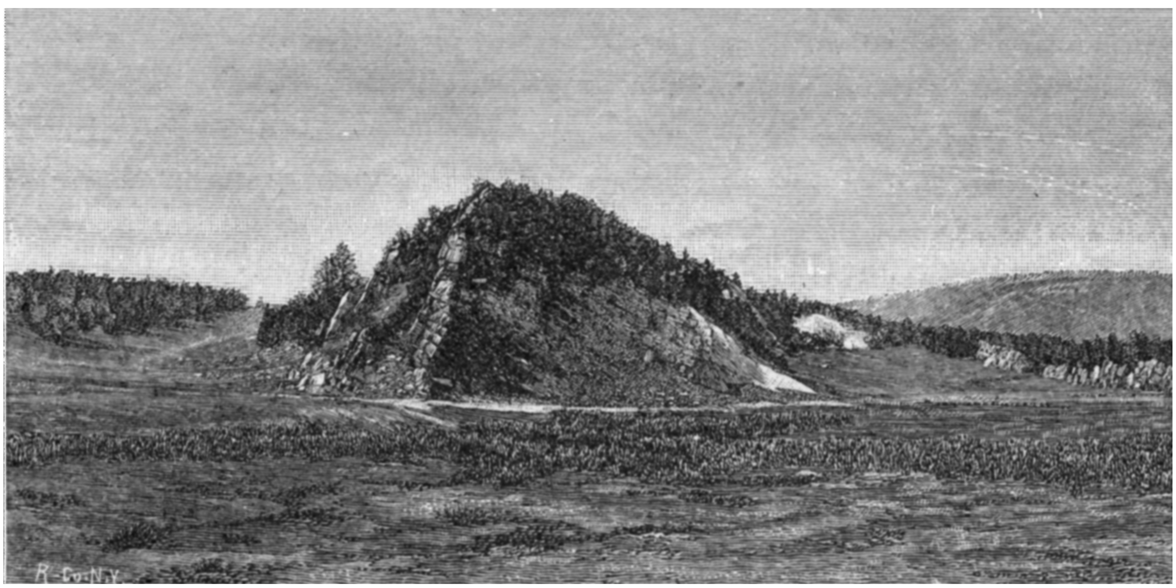
Lupton: at UTM zone 12, 676609E, 3911625N (near Lupton, Arizona)

Red Rocks: SE ¼ sec. 11, T15N, R17W, McKinley County, NM.

Type Iyanbito: NW ¼ sec. 15, T15N, R16W, McKinley County, NM.

Thoreau: at UTM zone 12, 759120E, 3924300N (Cibola County, NM).

Mesa Montañosa: at UTM zone 13, 240940E, 3911731N (Cibola County, NM).



Dutton’s (1885, fig. 6) woodcut photograph of the Nutria monocline.