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JURASSIC STRATIGRAPHY IN THE HAGAN BASIN, NORTH-CENTRAL NEW MEXICO

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Abstract—Jurassic strata exposed in the Hagan basin are assigned to four formations (ascending): Entrada, Todilto, Summerville and Morrison. The Entrada Sandstone disconformably overlies the Petrified Forest Formation of the Upper Triassic Chinle Group and consists of two members also recognized in west-central New Mexico: (1) the medial silty member, as much as 20 m of mostly reddish brown sandstone and siltstone overlain by the (2) upper sandy member, as much as 29 m of mostly yellowish gray trough-crossbedded sandstone. The Todilto Formation disconformably overlies the Entrada Sandstone and consists of two members named here: (1) the Luciano Mesa Member (limestone member of previous usage), as much as 6 m of mostly gray kerogenic limestone, overlain by (2) the Tonque Arroyo Member (gypsum member of previous usage), as much as 61 m of mostly white gypsum/anhydrite. The Summerville Formation conformably(?) overlies the Tonque Arroyo Member of the Todilto Formation and is as much as 57 m of cyclically bedded red and gray sandstone, mudstone and siltstone. The Salt Wash Member of the Morrison Formation disconformably overlies the Summerville Formation and is as much as 75 m of mostly grayish yellow sheets of fluvial sandstone and conglomerate with some interbeds of olive and brown mudstone. The Salt Wash Member grades upward into the Brushy Basin Member of the Morrison Formation, as much as 128 m of mostly variegated olive, gray and brown bentonitic mudstone/siltstone. The Jackpile Member of the Morrison Formation overlies the Brushy Basin Member and is as much as 62 m of mostly light gray and pale orange, trough-crossbedded sandstone. Cretaceous strata of the Dakota Formation disconformably overlie the Jackpile Member of the Morrison Formation in the Hagan basin. The Hagan basin Jurassic section aids confident lithostratigraphic correlation of Jurassic rocks on the southern Colorado Plateau to the west (San Ysidro) with Jurassic rocks on the western edge of the southern High Plains to the east (Romeroville). This correlation indicates almost total continuity of the Jurassic section from the Colorado Plateau to the southern High Plains with little change in thicknesses or facies. This continuity casts doubt on some recent interpretations of Jurassic depositional systems on the Colorado Plateau because these interpretations fail to consider the entire depositional basin.

INTRODUCTION

The Hagan basin is an eastward-tilted half graben that forms an embayment on the northeastern side of the Albuquerque basin (Fig. 1). Sedimentary rocks exposed in the Hagan basin range from Mississippian to Pleistocene in age. A thick and regionally complete section of Jurassic rocks is exposed in the Hagan basin, but has been little described in the published literature other than by Kelley and Northrop (1975). Here, we describe this section and correlate it to Jurassic strata on the Colorado Plateau to the west and the southern High Plains to the east.

PREVIOUS STUDIES

Previous studies of Jurassic strata exposed in the Hagan basin (Fig. 2) are those of Harrison (1949), Stearns (1953), Reynolds (1954), Swift (1956), Smith (1962), Kelley and Northrop (1975), Picha (1982), and Pigman and Lucas (1989).

Harrison (1949) assigned the Jurassic section in the Hagan basin to the Entrada Sandstone, Todilto Formation and Morrison Formation. He mapped the Entrada "as one massive sandstone, with a thickness of 120 feet" (Harrison, 1949, p. 82). Harrison (1949) recognized a two-part Todilto Formation consisting of a lower unit of limestone overlain by a gypsum unit (total thickness = 252 ft). Harrison (1949) did not subdivide the Morrison Formation, describing it as "742 feet of shale, thin limestone and sandstone."

Reynolds (1954, p. 25–28) recognized the same Jurassic stratigraphic units in the Hagan basin as Harrison (1949) but reported different thicknesses: Entrada = 145 ft, Todilto = 136 ft and Morrison = 450 ft. However, Stearns (1953, p. 465, fig. 2) assigned the section to the Entrada, Wanakah and Morrison formations. In so doing, Stearns included strata identified by Harrison (1949) and Reynolds (1954) as Todilto Formation in the Wanakah as a Todilto limestone member.

Swift (1956) studied Jurassic strata in north-central New Mexico and first subdivided the Morrison Formation in the Hagan basin into members. In a section measured at Tonque Arroyo, Swift (1956, p. 52–55) identified 832+ ft of Morrison Formation divided into three members (ascending): (1) 251 ft of Cachana Member (a new stratigraphic name that was never published), alternating beds of mudstone and sandstone above the Todilto Formation; (2) 222 ft of "Warm Springs Member" (a new stratigraphic name never published), cliff-forming sandstones; and (3) 359 ft of Brushy Basin Member, mostly bentonitic mudstone. Swift's (1956) description of these units make it clear how they relate to currently recognized subdivisions of the Morrison Formation in the Hagan basin (Fig. 2).

Smith (1961) provided a brief review of Jurassic strata near Albuquerque, including those exposed in the Hagan basin. He identified the Jurassic section here, based primarily on Harrison (1949) and Reynolds (1954), as Entrada Sandstone overlain by Morrison Formation divided into a "lower member" and a Brushy Basin Member (Fig. 2).

Kelley and Northrop (1975, p. 53–57) recognized the same Jurassic stratigraphic units in the Hagan basin as had Harrison (1949) and Reynolds (1954). Picha (1982, p. 48–58) also followed earlier workers in identifying the lower two Jurassic units in the Hagan basin as Entrada Sandstone and Todilto Formation. He first pointed out that the Todilto consists of two members, a lower limestone member and an upper gypsum member. Picha (1982) assigned Jurassic strata above the Todilto to the Morrison Formation, dividing it into four members (ascending): Recapture Shale, Westwater Canyon Sandstone, Brushy Basin Shale and Jackpile Sandstone members. Pigman and Lucas (1989) essentially used the same stratigraphic nomenclature but identified a thin Wanakah Formation between the Todilto and Morrison formations (Fig. 2). They also divided the Entrada Sandstone into two distinct members.

This review of previous studies of Jurassic strata indicates that most uncertainty has focused on strata between the Todilto and Morrison formations. Our nomenclature of these rocks follows Anderson and Lucas (1992) in assigning cyclically-bedded fine sandstones and siltstones between the Todilto and Morrison formations to the Summerville Formation. Morrison Formation subdivisions used here are those of Anderson and Lucas (1995). These subdivisions and correlations are discussed in the final section of this article.

ENTRADA SANDSTONE

The oldest Jurassic strata exposed in the Hagan basin are assigned to the Entrada Sandstone (Figs, 3, 4, 5A). Here, the Entrada disconformably overlies conglomerate/conglomeratic sandstone of the Correo Member of the Petrified Forest Formation of the Upper Triassic Chinle Group or mudstone of the Petrified Forest Member above the Correo Member (Lucas et al., 1988; Lucas, 1991). The upper two members of the Entrada

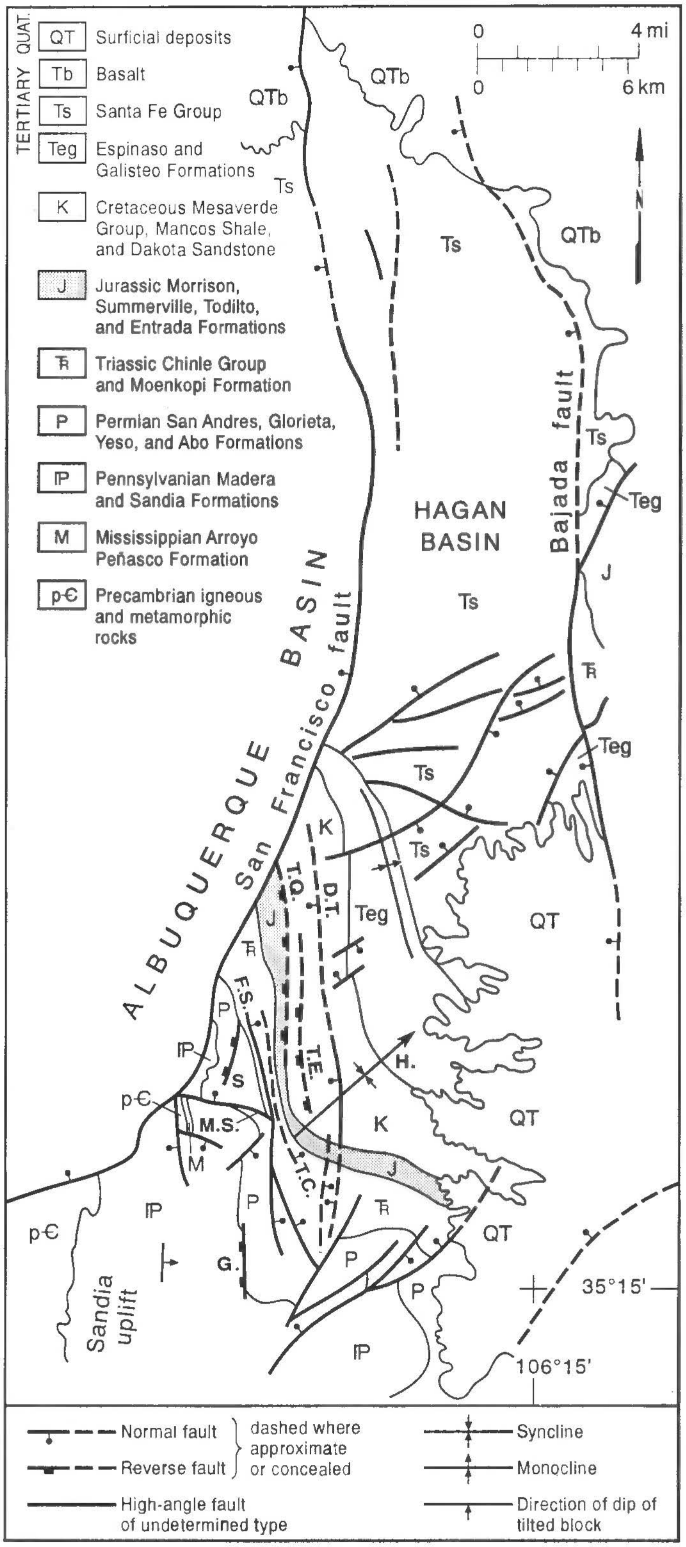

FIGURE 1. Generalized geologic map of Hagan basin (after Woodward and Picha, 1989).

recognized in west-central New Mexico are present in the Hagan basin—medial silty member and upper sandy member (Fig. 5A). The Iyanbito Member is absent.

The medial silty member is 17.4 to 20.2 m thick and is mostly reddish brown (10R 5/4), very fine-grained, moderately well-sorted subarkose. Silty sandstone beds are common, and coarse-grained, poorly-sorted sandstone beds are present locally. Strata are generally massive to thickly bedded, poorly preserved laminations are present and beds are friable. A major color change from pale reddish brown to yellowish gray occurs near the top of the medial silty member. This color change cuts across sedimentary structures and in some places occurs in the lower part of the overlying upper sandy member. Above the color change, when it occurs within the medial silty member, the rock is pale olive.

The upper sandy member of the Entrada is 18.3 to 28.9 m thick. It is mostly yellowish gray (5Y 8/1), fine- to medium-grained, moderately sorted subarkose. Sublitharenites are common and have black, lithic grains. Iron-rich concretions and liesegang banding also are common. The upper sandy member is thickly bedded with abundant, large-scale crossbeds. These crossbed sets have a generally southward dip direction which is consistent with what has been observed on the Colorado Plateau. In the eastern Hagan basin, the member is thickest, and a massive, horizontally-laminated sandstone is present at the top. The basal contact of the upper sandy member is erosional and scours through laminations at the top of the medial silty member. Along this contact, pale olive mudstone and clay galls are present.

TODILTO FORMATION

Luciano Mesa Member

The lower member of the Todilto Formation—long referred to informally as the limestone member—is here named the Luciano Mesa Member. The name is for Luciano Mesa, a prominent northwestern extremity of the Llano Estacado in western Quay/eastern Guadalupe County (T9N, R26–27E) near the type section. The type section of the Luciano Mesa Member is in the SW¼ SW¼sec. 28, T9N, R26E along the southern margin of Bull Canyon and has already been described and illustrated by Lucas et al. (1985b, fig. 1.11c), Lucas et al. (1985a, fig. 9.9, middle section) and Lucas and Kietzke (1986, fig. 3). At the type section, the Luciano Mesa Member is approximately 1 m thick. The base of the member is a 20-cm-thick interval of clastics. This interval consists of a basal, strongly crossbedded gray and green sandstone that lies with erosional unconformity on the Entrada. The contact is often marked by a thin, black-stained sandstone. Above this basal sandstone is another sandstone distinguished by its planar bedding and smaller grain size. A 30-cm-thick interval of microlaminated calcareous shale overlies this sandstone, which contains numerous thin sandstone lenses outlined by diagenetic gypsum near its top. The overlying 20-cm-thick, microlaminated limestone is kerogenic and grades upward into calcareous laminated shale. The top of the Luciano Mesa Member at its type section is about 15 cm of ledge-forming, poorly laminated carbonate containing numerous vugs filled with secondary calcite. The vugs are selectively located in rounded, oval "algal"-like structures, and some contain thin needles of secondary gypsum. The structures, however, lack the finely laminated structure typical of most algal stromatolites. At the type section, the Exeter Sandstone (Lucas et al., 1985b, 1987) overlies the Luciano Mesa Member with apparent unconformity.

The Luciano Mesa Member of the Todilto Formation crops out over an area of 88,000 km^2 in northern New Mexico and southwestern Colorado. Maximum thickness is 13.3 m, and the unit is often separated into a lower, thinly laminated and an upper massive limestone. This lower unit has been refered to as the "platey limestone" (e.g., Lookingbill, 1953; Hutson, 1958). In some areas, the fine laminations are contorted and microfolded and are referred to as "crinkly limestone." Varve counting suggests that the Luciano Mesa Member represents 14,000 years (Anderson and Kirkland, 1960). In the central part of its outcrop belt, the Luciano Mesa Member is overlain by the Tonque Arroyo Member of the Todilto Formation. Elsewhere, younger Jurassic strata overlie the Luciano Mesa Member.

A reference section of both the Luciano Mesa and Tonque Arroyo members of the Todilto are here established for the northwestern New Mexico area. The reference section is located west of San Ysidro, just southwest of NM-44 in the SE¼ SW¼ sec 30, T16N, R1E on the Ojito Spring 7½ min quadrangle. This easily accessible section lies 1800 ft (545 m) east of New Mexico Principal Meridian and 1000 ft (303 m) south of NM-44 (UTM coordinates 1329837E, 3939127N). Here, the Luciano Mesa Member is approximately 2.8 m thick. The basal 0.4 to

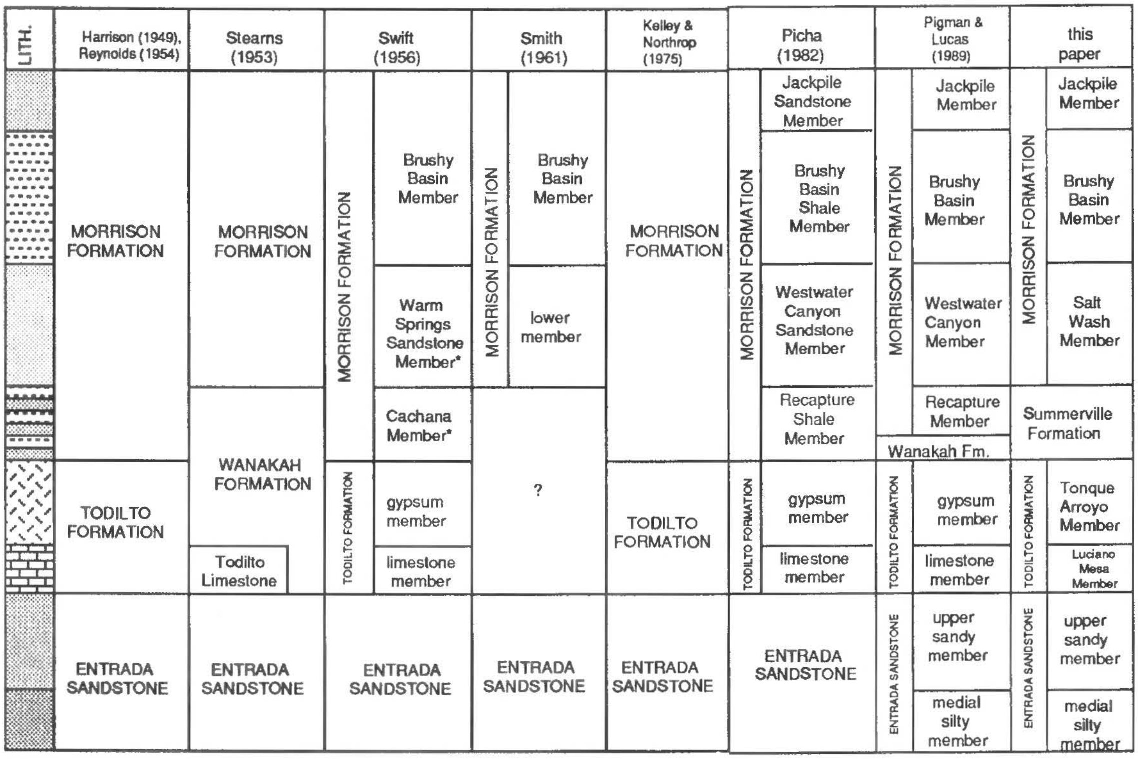

FIGURE 2. Previous geologic nomenclature of Jurassic strata in the Hagan basin compared with that advocated in this article. Names marked with asterisks (*) are informal nomenclature that was never published.

0.5 m consists of ripple laminated calcarenite with 0.5-cm-thick gypsum in interbeds and organic-rich shale lenses 1-3 mm thick. This is overlain by up to 1.3 m of laminar limestone and calcarenite which forms a transition into the overlying thinly bedded kerogenic limestone facies (Fig. 6). The overlying Tonque Arroyo Member locally is as much as 18 m thick and forms barren, hummocky topography.

Tonque Arroyo Member

Strata formerly termed the "gypsum member" of the Todilto Formation are here named the Tonque Arroyo Member. The name is for Tonque Arroyo, near the type section of the member, which is in the NW¼ NW¼ sec. 12, T13N, R5E (Fig. 4; Appendix 1). At its type section, the Tonque Arroyo Member is 61.0 m thick and consists of massive and brecciated white gypsum, which, in its lower part, contains some 1–2-mm-thick carbonate layers. Here, the Tonque Arroyo Member of the Todilto Formation is disconformably(?) overlain by the Summerville Formation.

The thickness of the Tonque Arroyo Member varies greatly over short distances due to erosion (Lookingbill, 1953; Hutson, 1958), to the dune topography of the underlying Entrada (Tanner, 1965; Vincellette and Chittum, 1981), to a combination of dune and subaqueous bar formation modified by "non-karst solution" (Tanner, 1972) or to karst solution (Stapor, 1972). The Tonque Arroyo Member crops out over a broad area of north-central and west-central New Mexico. Throughout its area of occurrence it is conformable on the Luciano Mesa Member and is disconformably overlain by the Summerville or Morrison formations.

Todilto in Hagan basin

As in west-central New Mexico and along the Nacimiento uplift, the Todilto Formation in the Hagan basin can be divided into Luciano Mesa and Tonque Arroyo members (Figs. 4, 5A–B). The Luciano Mesa Member is 3.7 to 5.7 m thick. It grades over an interval of 0.2 to 0.6 m, from the underlying upper sandy member of the Entrada Sandstone to sandstone with paper thin carbonate laminae with sandy partings to the main bed of kerogenic, medium gray (N6) laminated limestone (Fig. 5B). The upper portion of this limestone generally has crinkly laminae, and locally the entire bed is contorted. The top of the limestone is generally a massive, brecciated limestone that varies considerably in thickness. Locally, highly disrupted laminae are present. In the eastern Hagan basin, this unit is sandy, vuggy and coarsely crystalline.

The overlying Tonque Arroyo Member is as much as 61.1 thick and is mostly white (N9), massive, brecciated gypsum/anhydrite with some thin clay laminae. In the eastern Hagan basin, the Tonque Arroyo Member pinches out locally where the underlying Entrada Sandstone and overlying Summerville Formation commonly thicken.

SUMMERVILLE FORMATION

In the western Hagan basin, the Summerville Formation is 41.8 to 57.2 m thick. The basal interval of the Summerville Formation includes a limestone that contains small flecks of chalcedony that resemble the beds of moderate red (5R 4/5) micro- to cryptocrystalline chalcedony ("agate bed") that locally mark the top of the gypsum. The overlying Summerville is mostly pale red (5R 6/2) to yellowish gray (5Y 7/2), fine- to medium-grained sublitharenite and siltstone that is massive to parallel laminated. Sandstones are grayish red (5R 4/2) to yellowish-gray (5Y 7/2), and fine- to medium-grained. They are interbedded with variegated grayish red (5R 4/2) and greenish gray (5GY 6/1) mudstone and siltstone (Figs. 4, 5C). Beds are medium to thickly bedded with horizontal parallel laminations and low angle trough crossbeds. The mudstones contain some gray carbonate nodules. Bone fragments, a tooth and vertebrae of the sauropod dinosaur *Camarasaurus* were collected from the upper part of the Summerville Formation (Hunt and Lucas, 1993).

MORRISON FORMATION

As to the west, three members of the Morrison Formation can be recognized in the Hagan basin (in ascending order): Salt Wash, Brushy Basin and Jackpile (Figs. 3, 4, 5D–F). The Salt Wash Member forms prominent cliffs and low ridges. Mudstone-dominated intervals of the Brushy Basin Member form slopes, whereas sandstone-dominated intervals form prominent hogbacks. The Jackpile Member and overlying Dakota Formation form prominent cliffs and a hogback at the top of the Morrison Formation.

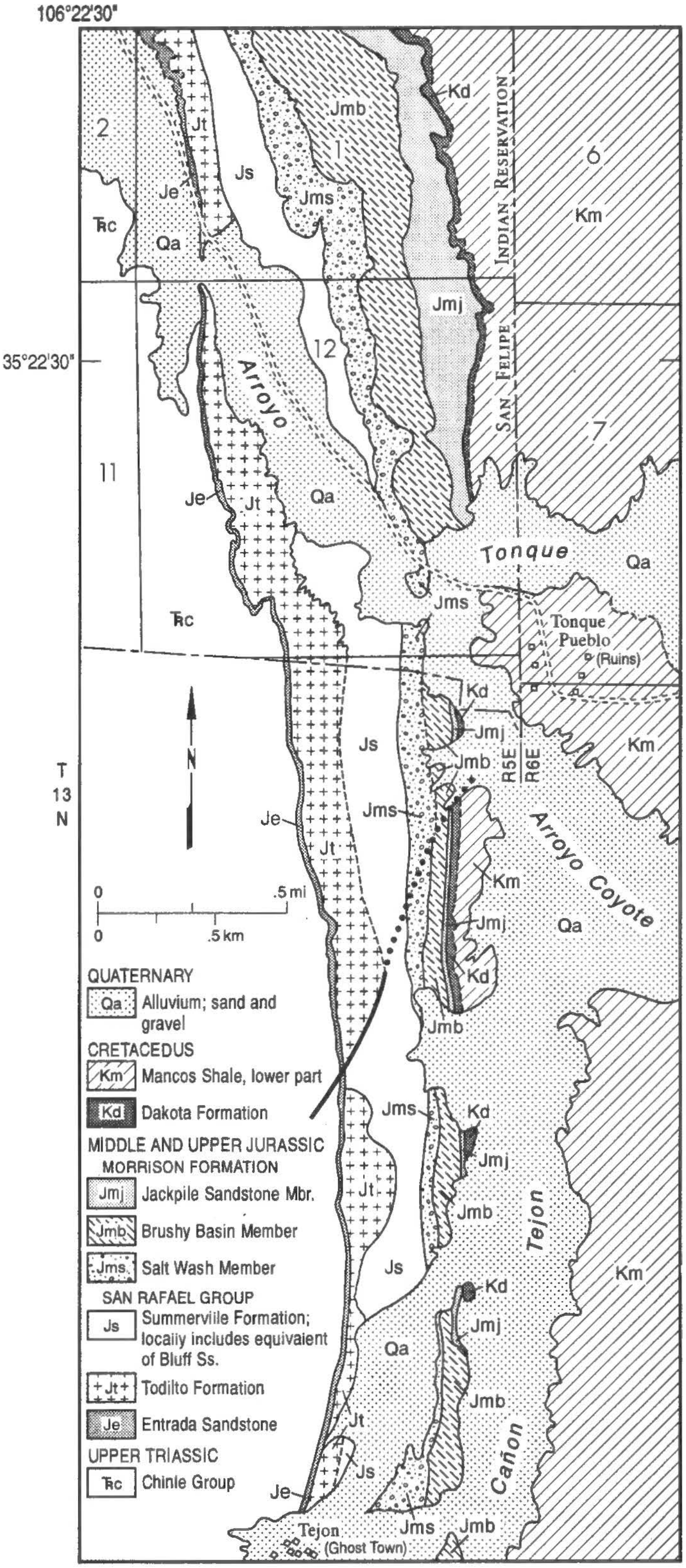

FIGURE 3. Geologic map of Jurassic strata in the Hagan basin.

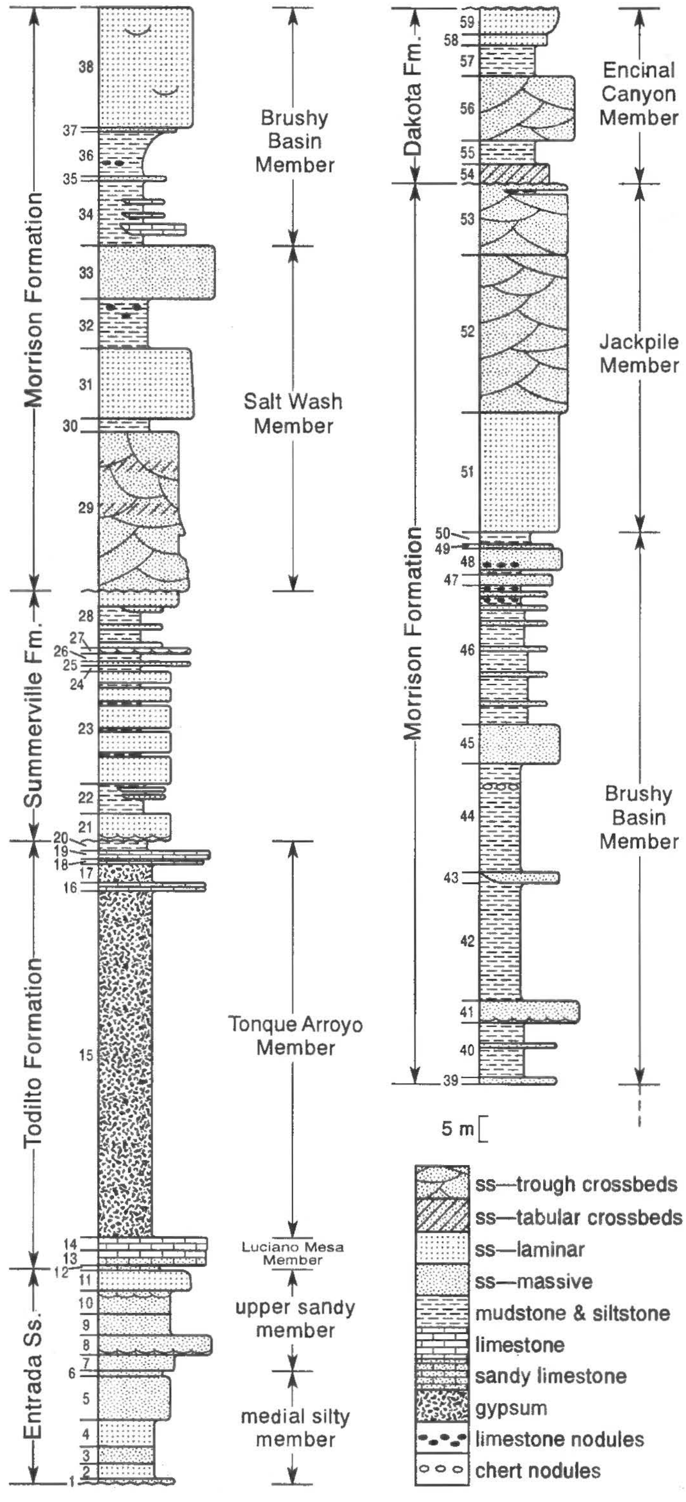

FIGURE 4. Measured stratigraphic section of Jurassic strata in the Hagan basin. See Appendix for description of lithologic units.

Picha (1982) previously advocated extending the Morrison Member terminology of the southeastern Colorado Plateau into the Hagan basin (Fig. 2). We follow him in doing so, except we refer strata he termed Recapture Member to the Summerville Formation (see Anderson and Lucas, 1992) and replace the name Westwater Canyon with Salt Wash (see Anderson and Lucas, 1995). With regard to the latter, it is possible that the basal Morrison sandstones in the Hagan basin are part of a sandbody(ies) correlative to but not continuous with Salt Wash (=Westwater Canyon) sandstones of the southeastern Colorado Plateau. If so, the basal Morrison sandstones in the Hagan basin could be assigned a new member name, a practice we avoid until their stratigraphic separateness is demonstrated, if indeed it can be demonstrated at all.

Salt Wash Member

The Salt Wash Member is 71.9 to 75.1 m thick and is mostly thick, massive to very thickly bedded, grayish yellow (5Y 8/4) sheets of

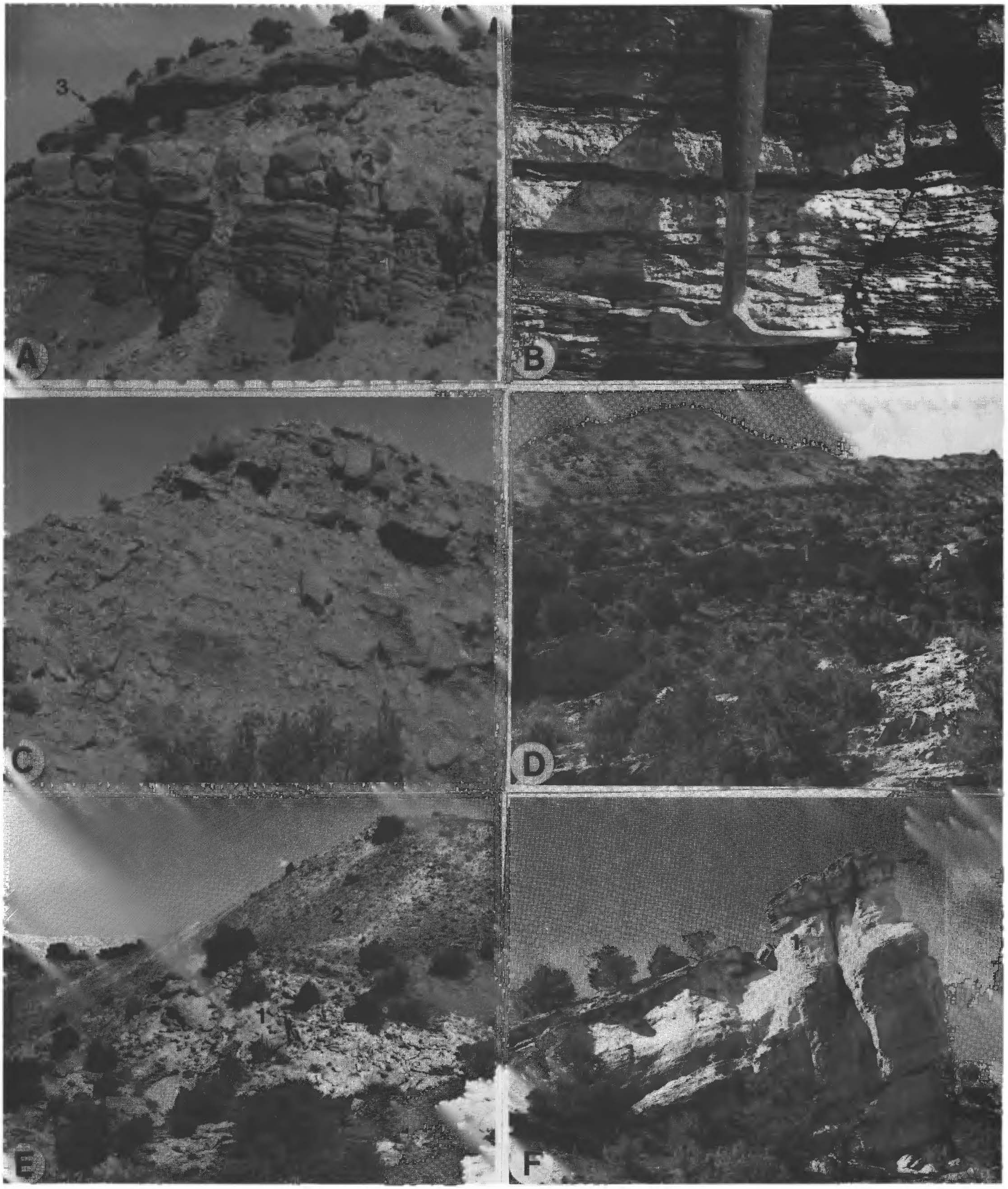

FIGURE 5. Photographs of selected Jurassic outcrops in the Hagan basin. A, Lower part of Jurassic section exposed on bluff NE of Puertecito SE¼SW¼SW¼ sec. 10, T12N, R6E, shows medial silty (1) and upper sandy (2) members of Entrada Sandstone overlain by Luciano Mesa Member of Todilto Formation (3) capped by Tertiary Ortiz Gravel (4). B, Close-up of characteristic thinly laminated kerogenic limestone of Luciano Mesa Member of Todilto Formation (unit 13 of measured section, Fig. 4). C, Lower part of Summerville Formation (units 20–23 of measured section, Fig. 4). D, Salt Wash Member (1) and Brushy Basin (2) members of Morrison Formation in the measured section (Fig. 4), SE¼ sec. 1, T13N, R5E. E, Characteristic contact of Salt Wash (1) and Brushy Basin members of Morrison Formation (units 38–41 of the measured section, Fig. 4). F, Jackpile Member of Morrison Formation (1) overlain by Dakota Formation (2), NW¼SE¼ sec. 5, T12N, R6E.

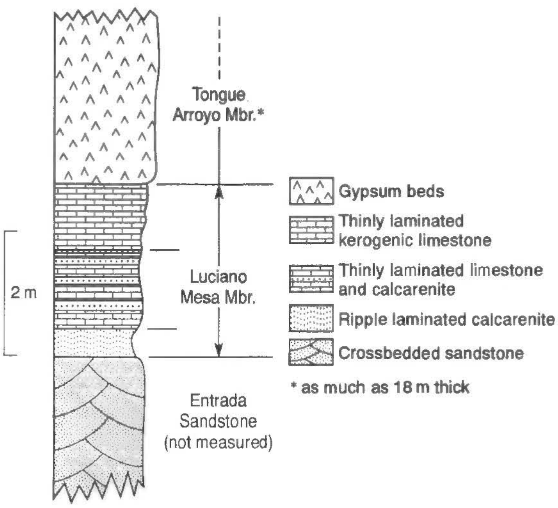

FIGURE 6. Reference section of the Luciano Mesa Member of the Todilto Formation near San Ysidro.

subarkose and arkose separated by thick beds of pale olive (10Y 6/2) and pale brown (5YR 5/2) mudstone and siltstone (Figs. 4, 5D–E). The sandstones are fine to medium grained and moderately well sorted. White spots are common on weathered surfaces and appear to be clay and calcite cement replacing altered feldspar grains. Sandstones are generally trough crossbedded or subhorizontally laminated; minor tabular crossbedding is present. The bases of thick sandstone beds are often erosional as indicated by scours into underlying mudstones. These scours are generally filled by small scale, trough-crossbedded sandstones containing a coarse-grained to pebbly lag of clay galls and limestone. The upper part of the Salt Wash Member consists of alternating beds of sandstone of Salt Wash lithology and mudstone of Brushy Basin Member lithology. The Salt Wash–Brushy Basin contact thus is gradational and intertonguing.

Brushy Basin Member

The Brushy Basin Member is 79.4 to 128.1 m thick and consists mostly of laterally persistent intervals of mudstone and siltstone that are variegated pale olive (10Y 6/2), greenish gray (5GY 6/1) and grayish brown (5YR 6/2), interbedded with yellowish gray (5Y 8/1) to grayish yellow green (5GY 7/2) fine-grained subarkose (Figs. 4, 5E). These subarkose beds are typically lenticular with subhorizontal laminations, trough crossbeds and minor ripple lamination. The sandstone beds thicken and stack locally to form resistant hogbacks. The mudstone and siltstone intervals form slopes and strike valleys. The mudstone beds generally contain carbonate nodules.

On the western side of the Hagan basin, a mudstone-dominated interval is highly silicified and contains a bed of moderate red (5R 4/6) chalcedony (Fig. 4, unit 44). A similar silicified bed in the Brushy Basin Member was described by Flesch (1974) near San Ysidro, and these beds closely resemble the "altered vitric ash" described by Bell (1986). On the eastern side of the Hagan basin, a vertebra and tooth of the

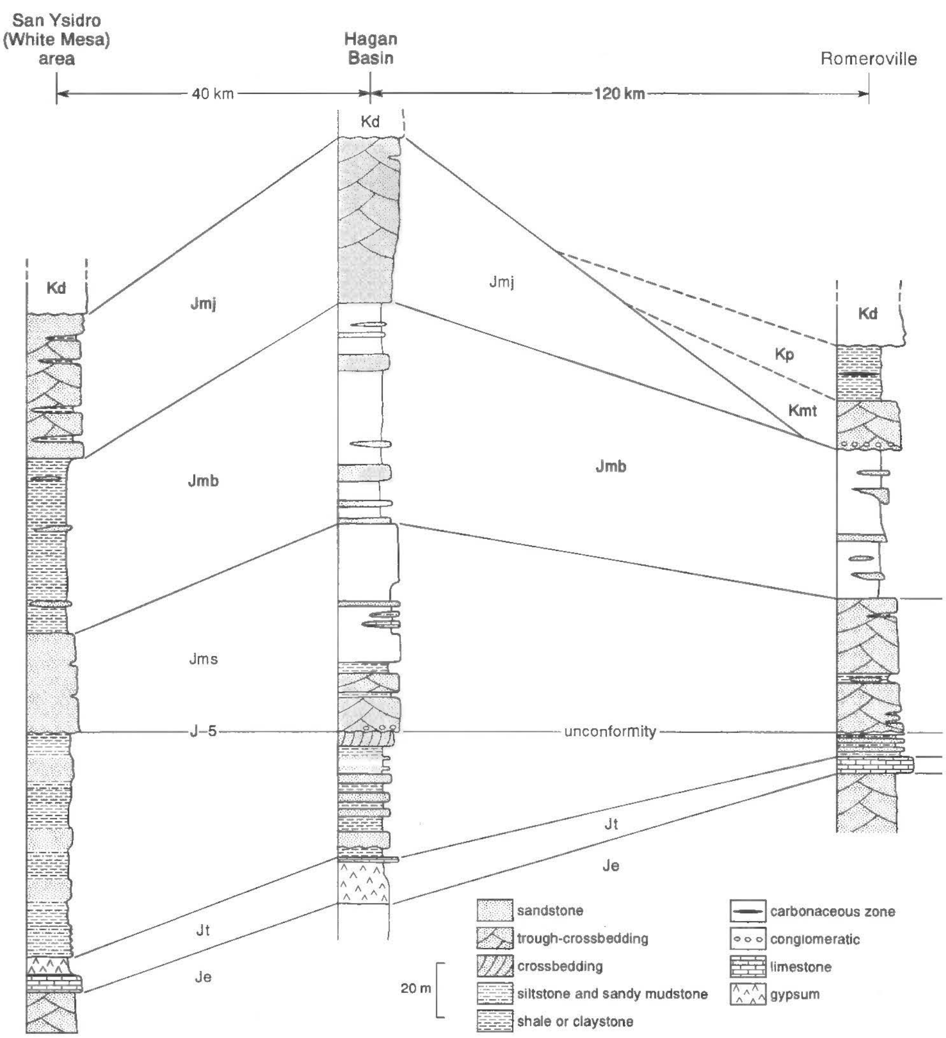

FIGURE 7. Correlation of Jurassic section from the southern Colorado Plateau (San Ysidro) through the Hagan basin to the southwestern edge of the southern High Plains (Romeroville).

sauropod dinosaur *Camarasaurus* were collected from the Brushy Basin Member (Hunt and Lucas, 1993).

Jackpile Member

The Jackpile Member is 33.3 to 62.5 m thick and is mostly very light gray (N8) to very pale orange (10YR 8/2), fine- to medium-grained, moderate to poorly sorted subarkose with an argillaceous matrix (Figs. 4, 5F). Lenses of pale olive (10Y 6/2) mudstone are common. The sandstone is generally crossbedded, and white mottles of clay and/or calcite cement are present on weathered surfaces. Iron-rich concretions and iron staining are common. In the eastern Hagan basin, a resistant, laterally persistent yellowish gray (5Y 8/1), coarse-grained to pebbly bed with an erosional base marks the base of the Jackpile Member.

The basal part of the Dakota Formation (Encinal Canyon Member) disconformably overlies the Jackpile in the Hagan basin. The contact is marked by an erosional, scoured surface that separates crossbedded Jackpile from horizontally laminated Encinal Canyon Member. Relief at the scour surface is commonly less than 1 m, but it is a laterally persistent, mappable contact that marks a change from lithologies below which contain subarkose and tend to be more thickly bedded, to lithologies above which include quartzarenites and sublitharenites in more thinly bedded units. The Encinal Canyon Member is as much as 37.0 m thick and consists mostly of white to pale orange, moderate to poorly sorted, fine- to medium-grained quartzarenite with a matrix of clay and calcite cement (Fig. 4). Beds of variegated grayish red and grayish yellow green mudstone with gray carbonate nodules are present locally. The Encinal Canyon Member is generally horizontally laminated with some tabular crossbeds. Iron-rich concretions and iron-staining are common.

DISCUSSION

Lithostratigraphic correlation of the Jurassic section exposed in the Hagan basin with that exposed along the Colorado Plateau edge near San Ysidro and along the southwestern edge of the southern High Plains at Romeroville is straightforward (Fig. 7). All Jurassic units are continuous across this transect except the Tonque Arroyo Member of the Todilto Formation, which pinches out between the Hagan basin and Romeroville. Other than this, the correlation demonstrates the continuity of the Jurassic section from the Colorado Plateau onto the High Plains, pointed out by some earlier workers (e.g., Lucas et al., 1985a). Furthermore, sandstones we identify as Salt Wash Member of Morrison Formation at San Ysidro and in the Hagan basin—formerly termed Westwater Canyon Member—clearly correlate to basal Morrison sandstones at Romeroville (Fig. 7). These sandstones at Romeroville are correlated magnetostratigraphically to Salt Wash Member sandstones in western Colorado (Steiner et al., 1994), further supporting the identification of all basal Morrison sandstone intervals as Salt Wash advocated by Anderson and Lucas (1995).

Recent analysis of Jurassic depositional systems in the southern Western Interior treat the southeastern edge of the Colorado Plateau as if it were the southeastern edge of the depositional basin (e.g., Luttrell, 1993; Peterson, 1994). This was obviously not the case. Our correlation (Fig. 6) indicates the Middle and Late Jurassic depositional basin extended far to the east of the Colorado Plateau; it actually went at least as far east as western Oklahoma/western Kansas (Kocurek and Dott, 1983; Lucas et al., 1985a).

Recognition of the Jurassic depositional system east of the Colorado Plateau will cause modification of some published models of Jurassic deposition in the southern Western Interior. This is most obvious in the case of Lake T'oo'dichi', a putative large saline-alkaline lake in which the Brushy Basin Member of the Morrison Formation was deposited (Turner and Fishman, 1991) Lake T'oo'dichi' supposedly dominated the Four Corners area and its eastern edge corresponds to the southeastern border of the Colorado Plateau in New Mexico. Extension of the Brushy Basin Member (with the same lithologies as found on the southeastern Colorado Plateau) into the Hagan basin and out onto the southern High Plains suggests that the playa margin facies along the Plateau edge (Turner and Fishman, 1991) has been misinterpreted. Either Lake T'oo'dichi' was much larger than envisioned or new model of Brushy Basin Member deposition must be advanced.

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APPENDIX 1 – MEASURED SECTION

Section measured in the NE¼SW¼ and the SE¼ sec. 1 and the NW¼ sec. 12, T13N, R5E, Sandoval County, New Mexico.

Unit	Lithology	Thickness (m)
	Dakota Formation	
	disconformity	
	Morrison Formation (Jackpile Member):	
53.	Sandstone; very pale orange (10YR 8/2); fine- to medium-grained, moderately sorted subarkose with angular to subangular grains; argillaceous matrix with calcite cement; contains discontinuous lenses of light greenish gray siltstone that are common near the middle of the unit; white (N9), poorly sorted, coarse-grained pebbly layers near middle of unit; massive and trough crossbedded with minor subhorizontal parallel laminations; weathers dark yellowish brown to grayish brown.	13.0
52.	Sandstone; very light gray (N8); fine- to coarse-grained, poorly sorted subarkose with angular to subangular grains; argillaceous matrix with calcite cement; yellowish orange hematitic spots; chert pebbles and olive-green clay galls along crossbedding laminations; massive with trough crossbed sets from a few cm to m thick; weathers light gray to pale yellowish orange.	28.0
51.	Sandstone; very pale orange (10YR 8/2); fine-grained, poorly sorted subarkose with angular to subangular grains; highly argillaceous matrix with calcite cement; numerous small white spots; hematitic spots; thickly bedded subhorizontal parallel laminations; base of unit rests on either olive green mudstone or greenish gray sandstone; where it overlies sandstone, the contact is gradational.	21.5
	Morrison Formation (Brushy Basin Member):	
50.	Silty mudstone; pale olive (10Y 6/2); not calcareous.	1.9
49.	Sandstone; grayish yellow green (5GY 7/2); very fine- to fine-grained, moderately sorted subarkose with angular to subangular grains; massive; strongly cemented by calcite, giving it a mottled luster when fractured; weathers grayish brown.	0.7
48.	Sandstone; grayish yellow green (5GY 7/2); fine-grained, poorly sorted, argillaceous subarkose; clayey matrix with calcite cement; bottom 0.6–1.0 m of the unit are pale brown (5YR 5/2) shale with pale yellowish brown limestone nodules.	4.9
47.	Sandstone; grayish yellow green (5GY 7/2); very fine-grained to fine-grained, moderately sorted subarkose with angular to subangular grains; strongly cemented by calcite, giving it a mottled luster when fractured; weathers grayish brown.	1.7
46.	Silty mudstone; greenish gray (5GY 6/1) and moderate brown (5YR 3/4); interbedded light olive gray (5Y 6/1), well sorted, angular- subangular sublitharenite sandstone beds 25–75 cm thick; mudstone beds are 1–4.5 m thick; sandstone beds contain angular pebbles of dusky yellowish green siltstone and mudstone and weather brownish black.	25.1
45.	Sandstone; yellowish gray (5Y 8/1); fine-grained, moderate to well sorted subarkose with angular to subrounded grains; massive with faint parallel laminations; calcite cement; weathers dark yellowish brown.	6.7
44.	Mudstone; greenish gray (5GY 6/1); contains flecks of moderate red (5R 4/6) chalcedony and scattered grains of quartz sand; also contains a band of moderate red (5R 4/6) chalcedony.	19.6
43.	Sandstone; light greenish gray (5GY 8/1); fine grained, moderately to well sorted feldspathic litharenite; angular to subrounded grains; calcite cement; a discontinuous lens; weathers pale brown.	1.9
42.	Mudstone; variegated grayish brown and greenish gray; contains lenses of moderate red chalcedony.	21.3
41.	Sandstone; yellowish gray (5Y 7/2); fine- to medium-grained, poorly sorted subarkose; hematitic mottling; clay matrix and calcite cement; medium bedded, lower half is trough crossbedded; weathers grayish orange.	4.5
40.	Mudstone; variegated greenish gray and grayish brown; a bed of fine-grained, poorly sorted arkose present near the middle of the unit.	9.1
39.	Sandstone; pale greenish yellow (10Y 8/2); fine-grained, poorly sorted subarkose with very angular to subangular grains; hematitic spots; calcite cemented.	1.0
38.	Sandstone; grayish orange (10YR 7/4) to dark yellowish orange (10YR 6/6); medium-grained, very well sorted, very porous, poorly cemented, subrounded quartzarenite; matrix contains 1–5 mm diameter white spots of altered grains and/or carbonate cement; hematite-stained iron concretions throughout the unit and form a pebbly soil armor in places; large scale horizontal to subhorizontal sets of parallel laminations with minor trough crossbeds; weathers pale yellowish brown (10YR 6/2); pinches out abruptly to the north and merges with underlying units to the south.	18.9
37.	Sandstone; yellowish gray (5Y 7/2); fine-grained, moderately sorted, strongly cemented subarkose; grains are subangular to subrounded; large areas of calcite cement in optical continuity give the rock a mottled luster; upper 20–25 cm have subhorizontal parallel laminations; top of unit is conglomeratic, with clasts of gray siltstone; weathers grayish brown.	0.9
36.	Mudstone and sandy siltstone; light olive gray (5Y 6/1) and grayish red (5R 4/2) with medium gray (N9) limestone nodules.	8.4
35.	Sandstone; dark greenish gray (5G 4/1); very fine-grained, strongly cemented subarkose; silica cement; lenticular.	0.5
34.	Silty mudstone and siltstone; pale brown (5YR 5/2) and pale olive (10Y 6/2); contains lenses of dark greenish gray, very fine-grained sandstone; contains lenses of sandstone similar in color and lithology to unit 35; base of unit is pale olive (10Y 6/2), clayey, fine-grained, poorly sorted quartzose sandstone.	11.7
	Morrison Formation (Salt Wash Member):	
33.	Sandstone; dusky yellow (5Y 6/4); coarse-grained, well sorted, very porous, calcite-cemented subarkose to arkose; contains blocky white feldspar grains; matrix contains white spots of altered grains and/or carbonate cement; dark brown hematitic spots and iron-rich concretions averaging about 3 cm diameter; massive except for subhorizontal parallel laminations in lower 2–2.5 m of unit; ledge former.	9.7
32.	Silty mudstone; pale brown (5YR 5/2); contains light gray limestone nodules and minor gypsum; top of unit is pale olive (10Y 6/2) mudstone; base of unit is pale olive (10Y 6/2) silty, fine-grained sandstone with dusky yellow mottling.	8.8
31.	Sandstone; grayish yellow (5Y 8/4); medium-grained, moderately sorted, porous, calcite-cemented arkose; grains are angular to subangular and blocky white feldspars are present; white matrix; hematitic mottling; massive to very thickly bedded with subhorizontal parallel laminations; together with unit 29, forms a prominent cliff.	12.0
30.	Mudstone; pale brown.	2.6
29.	Sandstone; grayish yellow (5Y 8/4); fine-grained, poorly to moderately sorted arkose with angular to subangular grains; matrix contains white spots of clay or carbonate cement; hematite stains; iron-rich concre-tions in lower part of unit; subhorizontal parallel laminations in thick (>3 m) large scale sets; some small-scale sets of steeply dipping tabular crossbeds; conglomeratic base of mudstone and sandstone pellets with scour and fill.	26.4
	disconformity	
	Summerville Formation:	
28.	Siltstone and sandstone; variegated greenish gray (5GY 6/1) and grayish red (5R 4/2); top unit is lens of greenish gray (5GY 6/1), very fine-grained, well sorted, strongly calcite cemented, angular–subangular subarkosic sandstone; weathers dark brown and has numerous fractures filled with crystalline calcite; near middle of unit is 25–30-cm thick, pale red, very fine-grained sandstone; base of unit is greenish gray (5GY 6/1), moderately sorted, very fine-grained, strongly calcite cemented, subangular–subrounded, arkosic sandstone; top of unit is similar, 5-m-thick sandstone.	12.5
27.	Sandstone; pale red (5R 6/2); medium-grained, moderately sorted subarkose with angular-subrounded grains; calcite cement; laterally extensive, 15–25-cm-thick sets of low angle, parallel laminated trough crossbeds.	1.0
26.	Silty mudstone; grayish red (5R 4/2); calcareous.	1.5
25.	Sandstone; grayish red (5R 4/2); medium-grained, moderately sorted subarkose; calcite cement; highly friable along sub-	

Unit	Lithology	Thickness (m)
	horizontal parallel laminations.	0.4
24.	Siltstone and mudstone; variegated grayish red (5R 4/2) and greenish gray (5GY 6/1).	1.6
23.	Sandstone; pale red (5R 6/2); medium-grained; moderately to well sorted, porous, subarkose; calcite cemented; angular-subangular grains; sandstone interbedded with 0.5–1.0-m-thick beds of grayish red (5R 4/2) siltstone and mudstone; laterally extensive, low angle trough crossbeds sets are 0.5–1.0 m thick and extend on strike for 10s of m; small-scale sets of high angle trough crossbeds fill scours.	19.6
22.	Siltstone; grayish red (5R 4/2) and greenish gray (5GY 6/1); near top of unit are several lenses of grayish red (5R 4/2), very fine-grained sandstone which is poorly sorted, calcite cemented and angular– subangular.	5.3
21.	Sandstone; grayish pink (5R 8/2); fine grained, moderately to well sorted, porous, calcite-cemented sublitharenite; angular–subangular grains; middle portion of unit is subhorizontally crosslaminated; base has small-scale trough crossbeds that fill scours in unit 20.	4.9
20.	Siltstone; greenish gray (5GY 6/1) and grayish red (5R 4/2); calcareous; most of unit is greenish gray, but upper 0.5 m is grayish red.	1.8
19.	Limestone; medium gray (N5); very finely crystalline (micritic); thinly (7–15 cm) bedded with scattered, small angular flecks of red chert; base of unit friable and locally gypsiferous; fractures filled by milky white calcite; top of unit is very light gray (N8) micrite with angular–subrounded intraclasts of medium light gray (N6) limestone.	1.8
18.	Chalcedony ("agate bed"); moderate red (5R 4/5); microcrystalline to cryptocrystalline; color varies from milky white to dark gray but is mostly pink to red; bed is blocky fragments and nodules separated in places by gypsum; upper surface of unit is flat to slightly undulatory; lower surface is very irregular and vuggy.	0.2
	Todilto Formation (Tonque Arroyo Member, type section)	
17.	Gypsum/anhydrite; pale yellowish brown (10YR 6/2) to moderate orange pink (10R 7/4); contains some thin (<3 cm thick) light gray (5Y 5/2) silty clay layers.	3.7
16.	Gypsum/anhydrite and limestone; gypsum is moderate orange-pink (10R 7/4), limestone is medium light gray (N6); 4 or more limestone lenses range in thickness from 2 to 10 cm and contain flecks of red chalcedony; base of unit is a 5-cm-thick layer of light olive gray (5Y 5/20 silty clay, the top of which is pale yellowish brown (10YR 6/2).	2.2
15.	Gypsum/anhydrite; white (N9); massive and brecciated; in lower part of unit are 1–2-mm-thick layers of carbonate separated by thicker gypsum layers.	61.0
	Todilto Formation (Luciano Mesa Member):	
14.	Limestone; medium light gray (N6) to medium dark gray (N4); massive; contains some 0.1–0.5-mm-thick disrupted crinkly laminations.	2.4
13.	Limestone; medium gray (N5) to medium dark gray (N4); planar laminations; laminae are paper thin to a few mm thick; upper part of unit locally contains crinkled laminations and in places the entire unit appears to be intricately folded.	2.7
12.	Limestone; dusky yellow (5Y 6/4); sandy and laminated; thin, yellowish, fine-grained sandstone laminae separated by thin grayish sandy limestone laminae; unit grades downward by thickening of sandstone laminae into underlying Entrada.	0.6
	Entrada Sandstone (upper sandy member):	
11.	Sandstone; yellowish gray (5Y 7/2); medium- to fine-grained, poorly to moderately sorted subarkose; subrounded-subangular; horizontal parallel laminations in 1–2-m-thick sets; some ripple laminations; liesegang banding and hematitic spots at top of unit.	3.8
10.	Sandstone; yellowish gray (5Y 8/1); fine-grained, moderate to well sorted, subarkose; rounded-subrounded; massive; top 4 m friable with clayey matrix and some pale olive sandy siltstone; a wavy band of color change above base of unit; just above and below color change, sandstone is coarse- to medium-grained, poorly sorted lithic arkose; undulatory (scour) basal contact.	4.4
9.	Sandstone and sandy siltstone; pale reddish brown; fine-grained massive to poorly bedded silty arkose; friable; includes spheroidal concretionary beds and bed of coarse-grained, poorly sorted lithic arkose.	4.0
8.	Sandstone; pinkish gray (5YR 8/1); coarse-grained, well sorted sublith- arenite with subrounded-rounded grains, which appear frosted; basal portion trough crossbedded with coarser grains marking the bedding; sharp basal contact.	3.2
7.	Sandstone; yellowish gray (5Y 8/1); fine-grained, moderately sorted subarkose with subrounded-rounded grains; massive with minor ripple laminations; iron-rich concretions and hematite staining common.	2.9
	Entrada Sandstone (medial silty member):	
6.	Sandstone; pale olive (10Y 6/2); very fine-grained subarkose; massive to fissile; horizons with Fe-rich concretions; base of unit marked by color change and coarser-grained sandstone.	1.2
5.	Sandstone; pale red (10R 6/2); very fine- to fine-grained subarkose; moderately to thickly bedded; beds marked by spheroidal-weathering concretionary layers separated by fissile zones; top of unit marked by a color change that cuts through concretions.	8.0
4.	Sandstone and silty sandstone; moderate brown (5YR 414); very fine- grained; light olive gray mottles; very fissile.	4.7
3.	Sandstone; pale reddish brown (10R 5/4); very fine-grained well-sorted subarkose with angular to subangular grains; moderately bedded with beds marked by ovoid concretions; contains some thin (0.5-cm- thick) beds of dark reddish brown, fissile, micaceous siltstone.	3.3
2.	Sandstone; pale reddish brown (10R 5/4); very fine-grained well sorted subarkose with subangular-subrounded grains; poorly laminated by very friable.	2.6
1.	Sandstone; yellowish gray; medium-grained, well sorted sublitharenite with subangular-subrounded grains; weathers moderate reddish brown (10R 4/6); massive; base of unit scours 10–20 cm into underlying micaceous Chinle mudstone; locally base of unit contains chips of Chinle mudstone.	0.4
	disconformity (J-2 unconformity of Pipiringos and O'Sullivan, 1978)	
	Chinle Group (Upper Triassic)	