Base of the Morrison Formation, Jurassic of northwestern New Mexico and adjacent areas

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Base of the Morrison Formation, Jurassic, of northwestern New Mexico and adjacent areas

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Abstract

The Morrison Formation-San Rafael Group contact is herein resolved and placed at a regionally traceable scour surface and sequence boundary at the base of the Salt Wash Member of the Morrison Formation. In addition, the internal stratigraphy of the Morrison is simplified with only two members, the Salt Wash and the Brushy Basin, recognized for regional correlation purposes. Thus, the confusing, duplicative, and overlapping members, which included Bluff Sandstone, Recapture Shale, and Westwater Canyon Sandstone, are not recognized, and the names are either abandoned or are reassigned to the San Rafael Group. This newly established Morrison concept and internal stratigraphy recognizes and follows useful mapping units that aid in regional correlations. The sequence boundary at the base of the Morrison has climatic implications related to the northward drift of the North American continent through Jurassic time.

Introduction

Considerable uncertainty and difference of opinion exist with regard to the base of the Morrison Formation (Upper Jurassic) in the San Juan Basin of northwestern New Mexico and adjacent areas (Fig. 1). Much of this confusion reflects the fact that in this area the base of the Morrison was not determined by correlation with the lithologies at the formation type section near Morrison, Colorado (Waldschmidt and LeRoy, 1944), but rather by correlation to a western Morrison or the Morrison of Utah. We have found that the longstanding subdivision of this western Morrison into four or more members lacks lithostratigraphic significance, contains overlapping units, employs duplicative nomenclature, and ignores a regionally traceable scour surface that is of great stratigraphic significance and mapping applicability. Extending this four-member subdivision into the San Juan Basin in the 1950s during the height of uranium exploration activities resulted in uncertain correlations and a Morrison basal contact that was not based on lithologic contrast. This trivialization of the formation concept further resulted in the inclusion of San Rafael Group strata in the overlying Morrison. We critically review the pertinent literature and present our own observations based primarily on fieldwork and restudy of many of the stratigraphic sections reported in the older literature. Laboratory studies, primarily grain size and cementing agents in the sandstones, provided further information for our interpretations and conclusions.

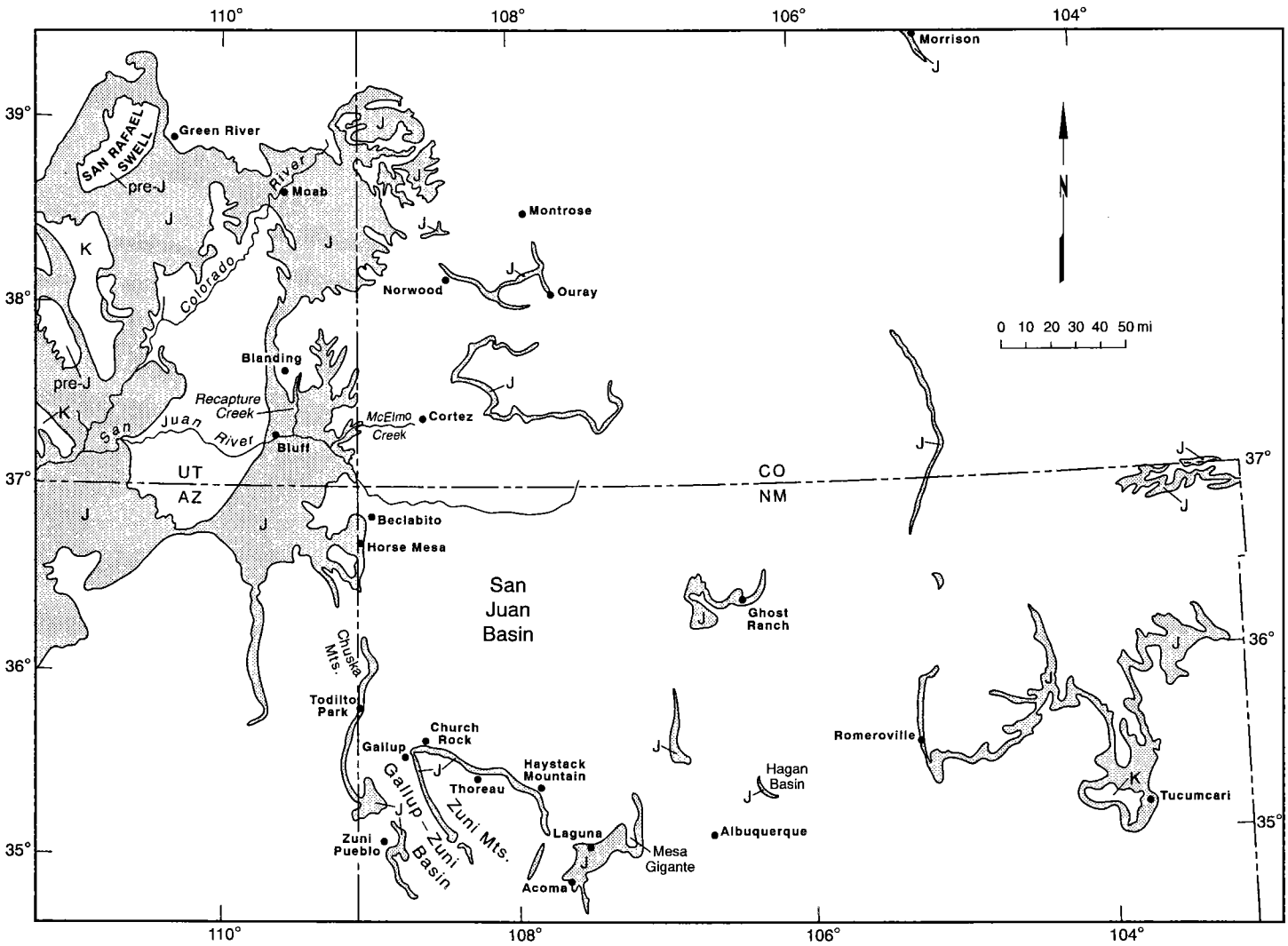

FIGURE 1—Index map of northwestern New Mexico and adjacent areas. J, outcrops of Jurassic rocks.

Review and discussion of previous work

The first formal use of the name Morrison as a stratigraphic unit in Utah was that of Gilluly and Reeside (1928), who designated the strata overlying their San Rafael Group as Morrison Formation. The basic lithologic distinction was that variegated shale, medium- to coarse-grained sandstones, and mudstones of the Morrison tended to be slope formers above the brightly colored, thick, cliff-forming sandstones and gypsiferous beds of the San Rafael Group. Gilluly and Reeside recognized two members in their Morrison strata. The lower was a light-gray to tan, coarse-grained, pebbly sandstone that exerted significant influence on topography near the San Rafael Swell and Green River and northwest of Moab (Fig. 1). This lower unit was called the Salt Wash Sandstone Member, a name that Lupton (1912) had introduced for these beds in Salt Wash, 15 mi (24 km) southwest of Green River. (Lupton described this unit as a member of the McElmo Formation, a name subsequently abandoned as essentially a synonym of the Morrison Formation.) In retrospect, Gilluly and Reeside's basal contact of the Morrison was a well-justified stratigraphic decision. It provided a Morrison base that is an easily recognized lithologic break. The pebbly, trough-crossbedded Salt Wash Member contains rip-up clasts, clay galls, and other sedimentary features that readily identify it as a fluvially deposited sandstone very different from underlying fine-grained San Rafael Group strata. The channel scour at their Morrison base is a regionally traceable surface, which again is a major aid to geologic mapping. In modern terminology, the base of the Morrison, as picked by Gilluly and Reeside, is a sequence boundary, one that reflects climatic and base-level changes and that records the onset of widespread braidplain deposition of Morrison strata during Late Jurassic time.

The upper part of the Morrison Formation in southeastern Utah consists largely of claystone and was not given a member name by Gilluly and Reeside (1928). This upper unit is the only part of the formation that can be correlated lithologically with confidence to the type Morrison Formation near Morrison, Colorado (Fig. 1).

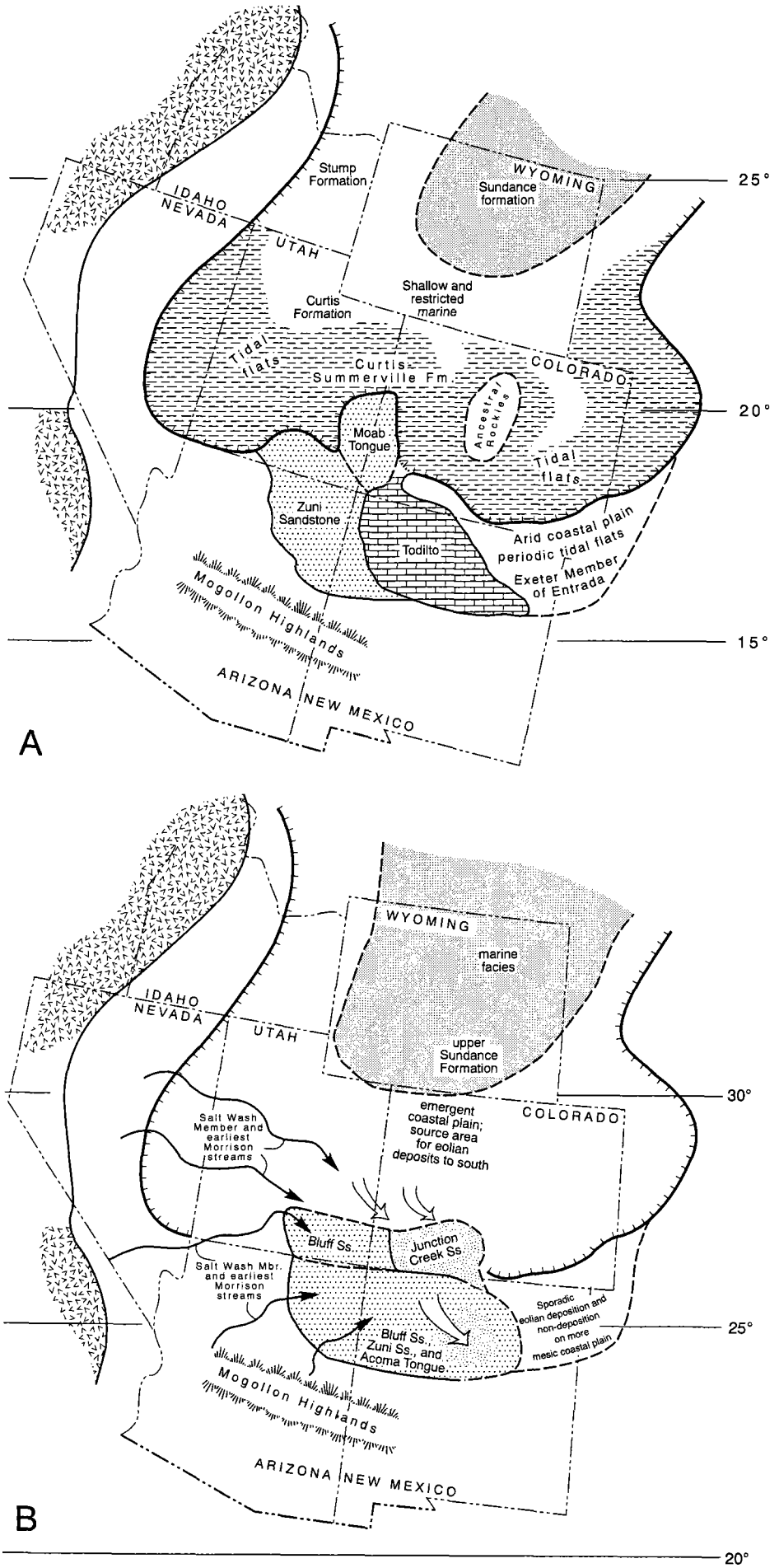

FIGURE 2—**A**, Middle Jurassic paleogeography of southern margin of Sundance Seaway and associated tidal flats, arid coastal plain, sabkha depositional systems (horizontal dashes). Erg development represented by Moab Tongue (of Entrada Sandstone) and the Zuni Sandstone. Evaporites represented by the Todilto. Modified from Anderson and Lucas, 1994. **B**, Late Jurassic paleogeography of area south of Sundance Seaway, illustrating onset of fluvial deposition across San Rafael Group strata by earliest "Morrison" streams. Modified from Anderson and Lucas, 1994.

Perhaps the most significant attribute of this early-recognized Morrison–San Rafael Group contact is the lithogenetic contrast it represents. The uppermost San Rafael Group strata were assigned by Gilluly and Reeside to the Summerville Formation. The Summerville consists of thinly bedded, parallel-bedded, very fine grained gypsiferous sandstone or siltstone, with lesser mudstone and bedded gypsum or carbonate near the top. Summerville strata and related San Rafael Group eolianites form a sequence deposited in a marginal marine, tidal flat, arid coastal plain, or sabkha setting with persistent erg development (Entrada and Zuni Sandstones) around the southern margins of the Sundance seaway (Fig. 2A). This paleogeography was also recognized by Imlay (1954), Kocurek and Dott (1983), Harshbarger et al. (1957), Brenner (1983), Anderson and Lucas (1992, 1994), and Ridgley (1989), among others. With this paleogeographic and paleodepositional basin concept, the post-San Rafael Group sequence takes on added significance. The pebbly, coarse-grained, trough-crossbedded sandstones of the Salt Wash Member of the Morrison Formation represent fluvial (braidplain) deposition and higher energy systems, which in turn indicate higher gradients and an increase in coarse siliciclastic supply during Late Jurassic time (Fig. 2B). Paleoflow direction was generally eastward (Craig et al., 1955; Harshbarger et al., 1957; Saucier, 1967; Turner–Peterson, 1986). This delineates a source area to the west in an area of known Middle to Late Jurassic back-arc volcanism (Fig. 2B). Uplift preceding and associated with the volcanism provided the source area for the basal Morrison pebbly sandstone beds, which backfilled a very moderately incised topography. Continued volcanism, dominated by latite and rhyolitic ash (Kowallis et al., 1991), provided much of the source rock for the claystone-dominated (largely smectite) upper part of the Morrison Formation. The distinctive, smectitic, claystone may also be found in partings in the lower Morrison, thus providing further lithologic contrast with the underlying San Rafael Group. A climate change accompanied the transition from San Rafael Group to Morrison deposition. The arid conditions, so obviously recorded in Middle Jurassic San Rafael Group strata, were moderated considerably by Late Jurassic time as the North American continent drifted northward into more temperate zones and into the zone of prevailing westerlies (Kocurek and Dott, 1983; Dickinson, 1989; Fig. 3). The uppermost strata of the San Rafael Group near Bluff, Utah as well as southeastward in the San Juan Basin consist of eolianites with well-expressed, thick sets of eastward-dipping foresets. These foresets signal the arrival of the Four Corners area in the zone of prevailing westerlies during latest Callovian–early Oxfordian time (Dickinson, 1989). Basal Morrison beds rest disconformably on these foresets near Gallup, at Church Rock, near Laguna, and at Mesa Gigante (Fig. 1); however, at the later locality, horizontally bedded red siltstone and fine-grained sandstone intervene to form the top of the San Rafael Group.

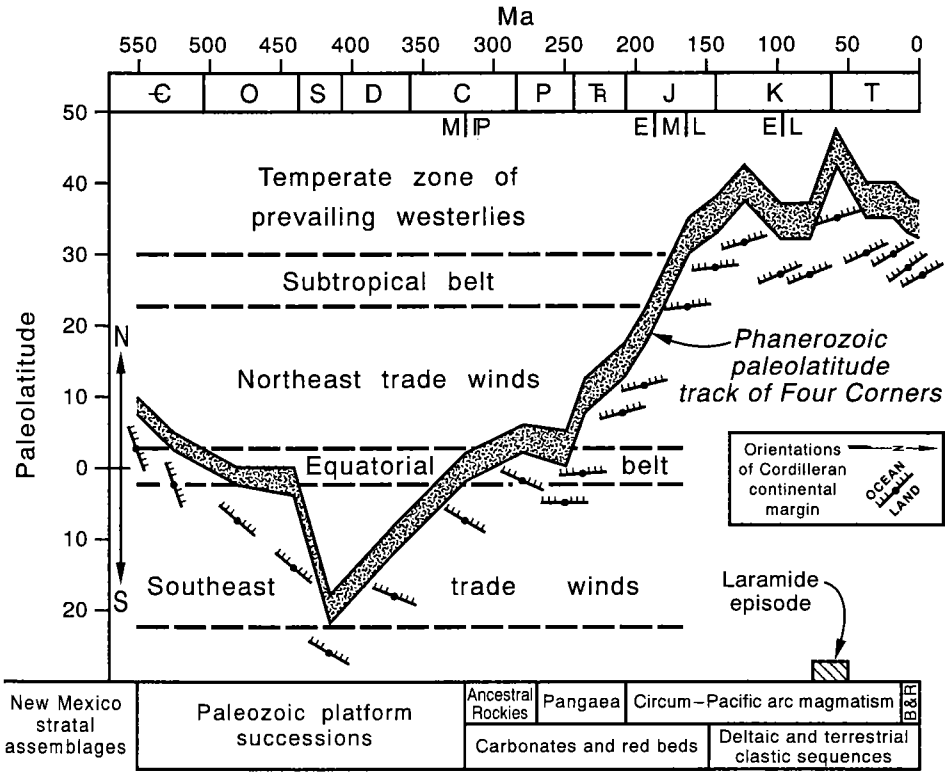

FIGURE 3—Phanerozoic paleolatitude track (stippled area) of the Four Corners area, illustrating the northward drift of that area into the zone of prevailing westerlies in Middle to Late Jurassic time. Modified from Dickinson, 1989.

Comparison of the above described "western Morrison" with the type Morrison of the Front Range may raise the legitimate question of why the lower sandstone-dominated interval (Salt Wash Member) was included with the Morrison by Gilluly and Reeside (1928). The type section consists almost entirely of claystone or shale (Waldschmidt and LeRoy, 1944). However, some sandstones are present in the lower part of the type Morrison and throughout the Front Range from Ralston Creek Reservoir, Colorado, southward to Romeroville, New Mexico (Fig. 1). These sandstones, commonly in the lower 50 ft (15 m), have not been emphasized because the slope-forming, upper claystone part dominates the formation. The lesser sandstone present in this eastern Morrison outcrop belt is consistent with position in the facies tract, the more distal portion of the Morrison depositional basin. Coarse-grained deposition began earlier and proceeded at a higher rate to the west (proximally). Thus, provenance and basin configuration account for differences in lithologies and thicknesses between the type area and the "western Morrison." Moreover, the Salt Wash Member intertongues with the upper claystone facies, providing further reason to regard the Salt Wash as part of the Morrison. The sharp lithologic contrast at the base of the Salt Wash has already been discussed. Herein lie the reasons for the differences between the type Morrison Formation and that of Utah or the "western Morrison"; the western Morrison represents a more proximal facies.

These regional aspects of Morrison stratigraphy and the basal contact with the San Rafael Group as established by Gilluly and Reeside (1928) provide a clear overview of Morrison stratigraphy. We now review later work that complicated this stratigraphy and inadvertantly introduced an element of confusion, which has persisted for more than 50 years.

Gregory's work

The most significant work on the Morrison Formation of southeastern Utah was that of Gregory (1938). In his detailed report on the "San Juan Country," Gregory subdivided the Morrison into four members. In ascending order these were the (1) Bluff Sandstone Member, (2) the Recapture Shale Member, (3) the Westwater Canyon Sandstone Member, and (4) the Brushy Basin Shale Member. It is instructive to compare Gregory's subdivision with the Morrison Formation of Gilluly and Reeside, as we have done in Fig. 4.

The Bluff Sandstone is for the most part an eolianite particularly well developed

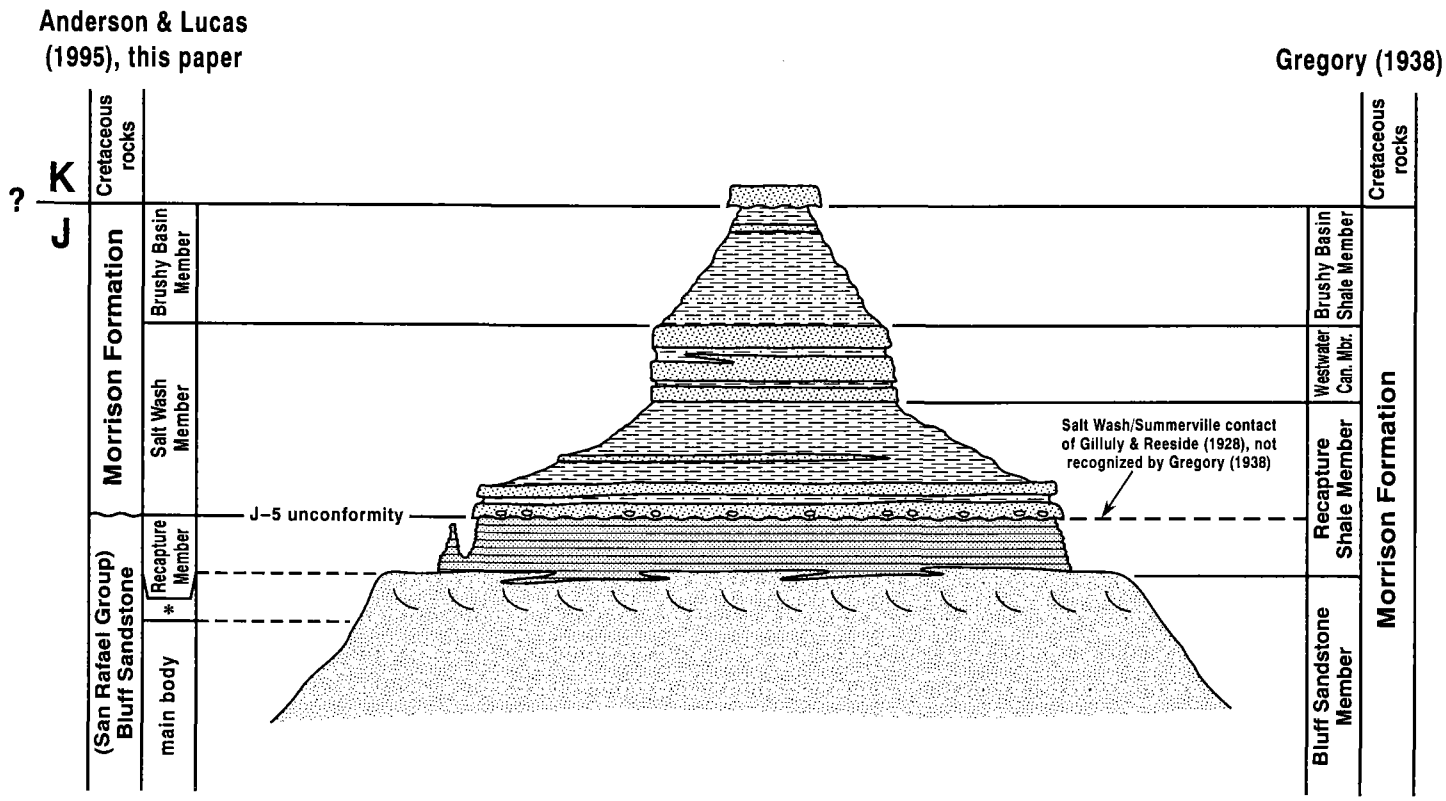

FIGURE 4—Diagram of stratigraphic sequence exposed at mouth of Recapture Creek, 8 km east of Bluff, Utah, contrasting the stratigraphic concepts of Gregory (1938) on right with concepts and nomenclature advocated in this paper on left. *Crossbedded unit correlates with Acoma Tongue of Zuni.

and exposed near Bluff, Utah (Fig. 1). At the type locality 5 mi (8 km) west of Bluff along Butler Wash, the unit is as thick as 126 ft (38 m) and consists of very fine to lower medium-grained, mostly crossbedded sandstone. It does not constitute a facies or lithology that was previously considered to be present northward or eastward in the Morrison Formation; nor does it occupy the same stratigraphic position as the basal Salt Wash Member of Gilluly and Reeside's stratigraphy. Moreover, Gregory did not offer an explanation for the inclusion of this sandstone unit in the Morrison. Goldman and Spencer (1941) recognized the Bluff as a pre-Morrison lithology (well-sorted, frosted, fine- to medium-grained, quartzose sandstones of eolian origin) and correlated it with the Junction Creek Sandstone in southwestern Colorado. On a lithologic basis, Craig et al. (1955) removed the Bluff from the Morrison Formation and included it in the uppermost San Rafael Group. We concur with Craig et al. (1955) and regard the Bluff Sandstone and the closely associated Acoma Tongue of the Zuni Sandstone of west-central New Mexico (Anderson, 1993) as part of the upper San Rafael Group throughout the Four Corners area and southeastward into the San Juan Basin.

Gregory defined his overlying "Recapture Shale Member" from exposures near the mouth of Recapture Creek 5 mi (8 km) east of Bluff. He described it as a unit that encompassed a wide variety of lithologies as well as a very significant, regionally traceable scour surface (Fig. 4). The total reported thickness was 290 ft (88 m) and consisted of a basal 40–55 ft (12–17 m) of red sandstone overlain by coarse-grained, pebbly sandstone followed by a "shaly" section. The significance of Gregory's *Recapture member* is twofold. First, the lower 40–55 ft (12–17 m) of red sandstone are very fine grained, silty, parallel bedded and slightly gypsiferous. These strata are very similar in lithology and sedimentary features to the Summerville Formation. The Summerville (which underlies the Bluff Sandstone) was deposited in arid coastal plain and sabkha environments. Thus, it would appear that the basal "Recapture Shale Member" of Gregory was associated with the brief return of sabkha conditions locally following deposition of the eolian Bluff. Gregory's basal "Recapture Shale" also intertongues with the Bluff Sandstone (Fig. 4), demonstrating its genetic and temporal association with that unit. This intertonguing, though not so stated, undoubtedly was the reason for inclusion of the Bluff in the Morrison Formation.

In contrast, the sandstones above the basal 40–55 ft (12–17 m) of Gregory's "Recapture Shale" are medium to coarse grained and conglomeratic with clay galls and rip-up clasts and are fluvial in origin; the basal red sandstone and interfingering Bluff Sandstone exhibit little evidence of fluvial influence. We contend that the abrupt change in lithology and sedimentary features at the top of the "red sandstone" unit reflects a change from sabkha conditions to fluvial braidplain deposition in the overlying unit. The contact is also marked by a regionally traceable scour surface that represents a diastem or unconformity, albeit with a poorly constrained time value, and as noted above, a sequence boundary. We further contend this unconformity is the San Rafael Group–Morrison Formation contact; as picked, this contact is consistent with the earlier lithologic descriptions of the San Rafael Group basal Morrison contact offered by Gilluly and Reeside (1928), and most importantly, the contact is readily mappable. Thus, the basal 40–55 ft (12–17 m) of Gregory's "Recapture Shale" is reassigned to the San Rafael Group as the Recapture Member of the Bluff Sandstone (Fig. 4, left side). Lithologically (fine-grained, thinly bedded, gypsiferous sandstone and silty sandstone) and lithogenetically (sabkha, arid coastal plain) these strata belong in the San Rafael Group.

The second significant aspect of Gregory's "Recapture Shale" is that the base of the medium- to coarse-grained pebbly sandstone 40–55 ft (12–17 m) above the base at the type locality correlates with the unit that Lupton (1912) and Gilluly and Reeside (1928) recognized as the Salt Wash ☞

Member (Fig. 4). Gregory's description of these strata at the type locality is very similar to the description that Lupton as well as Gilluly and Reeside gave for their basal Salt Wash Member. The two units occupy the same stratigraphic position although the Bluff Sandstone is not present to the north in the vicinity of Lupton's type Salt Wash, which is just southeast of Green River (Fig. 1). Distance between the two areas (southeast of Green River to Bluff) is approximately 100 mi (160 km); however, the stratigraphic sequence is similar. Not recognizing the significant lithologic break above the base of his "Recapture Shale Member" constituted a stratigraphic oversight by Gregory. Aside from the important correlation with the Salt Wash that was missed, he did not recognize a major change in lithology and depositional environments at this break and thus included parts of the San Rafael Group and the basal Morrison Formation in one member—his "Recapture Shale".

Gregory also noted the pebbly sandstone beds near Blanding, Utah, 20 mi (32 km) to the north in the same part of the section as the "Salt Wash sandstones," but he hesitated to assert the correlation. It is of interest to note that Stokes (1944) did recognize a Salt Wash unit low in Gregory's "Recapture Shale," but this observation has been ignored for 50 years.

Gregory (1938) introduced another member name for these pebbly sandstone beds near Blanding. From the excellent outcrop near the confluence of Cottonwood Wash and Westwater Canyon, just south of Blanding, Gregory named a 175-ft-(53-m-)thick, sandstone section the "Westwater Canyon sandstone member." Significantly he did assign the name only "tentatively" because "its exact equivalency to the typical Salt Wash sandstone has not been satisfactorily established." We recognize that the "Westwater Canyon sandstone member" is a synonym of Salt Wash Member and that the latter name has priority. The type sections of the two units occupy the same stratigraphic position, are of essentially identical lithology, and are of similar thickness (Fig. 5). Correlation problems resulted not only from this duplicative nomenclature, but also because the type "Westwater Canyon Sandstone" was miscorrelated southward within a 20-mi (32-km) distance such that at the type locality of the "Recapture Shale" the newly named "Westwater Canyon sandstone member" was included. The "Westwater" was erroneously correlated with a locally prominent, fine-grained sandstone that was present 180 to 250 ft (54 to 76 m) above the base of the pebbly sandstone at Recapture Creek.

Further correlation problems resulting from this duplicative nomenclature manifested themselves on many maps (Hintze and Stokes, 1964; Hackman and Olson, 1977; O'Sullivan and Beikman, 1963; Moench, 1963, Thaden et al., 1967), and

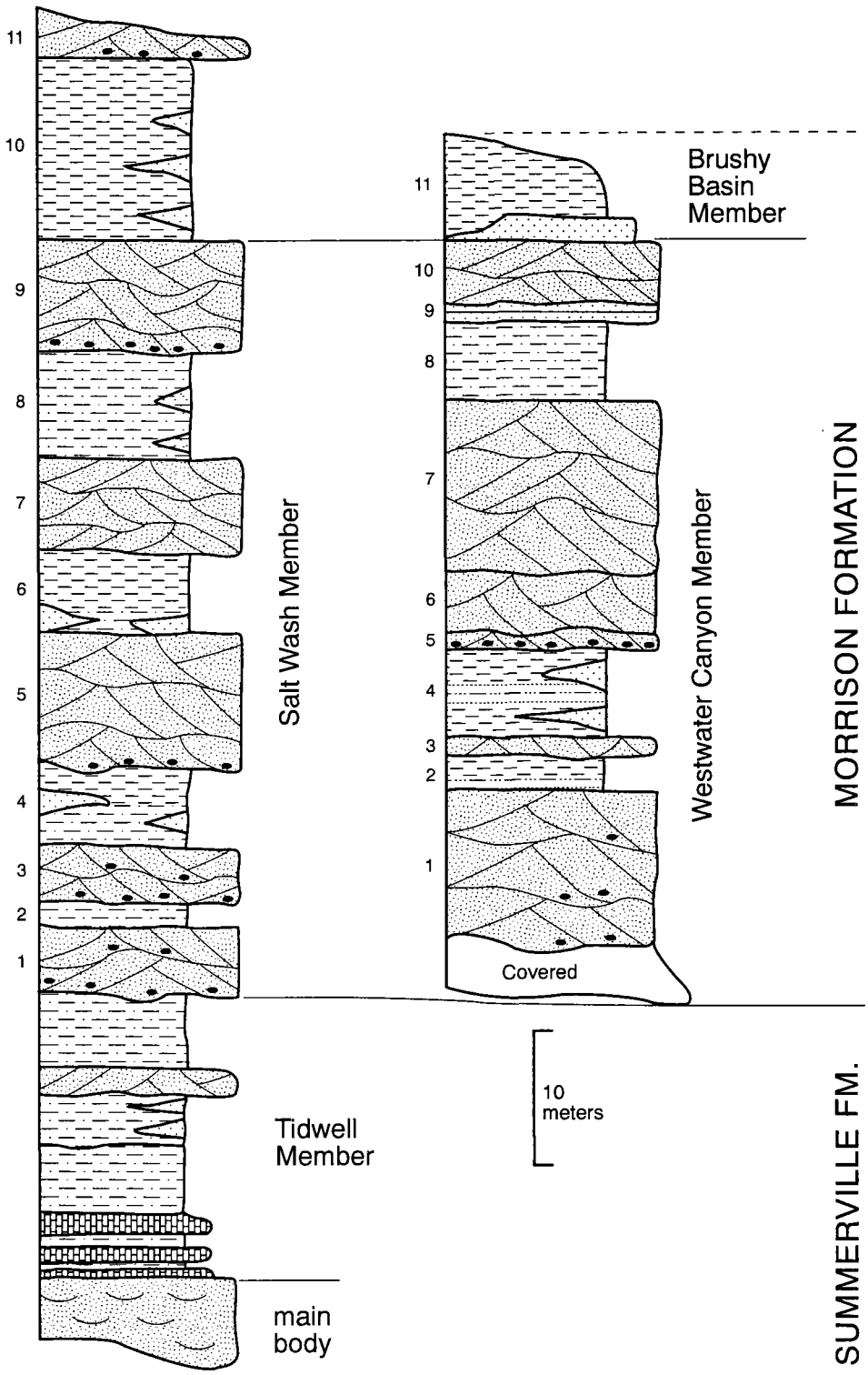

FIGURE 5—Type sections of Salt Wash and Westwater Canyon Members of the Morrison Formation. Measured sections are in Table 1.

stratigraphic diagrams (Condon and Huffman, 1984; Peterson and Turner–Peterson, 1987; Peterson, 1988) that attempted to show the relationship among Gregory's various units, namely the "Westwater Canyon sandstone," the "Recapture shale," and the earlier recognized Salt Wash Member. A clear example of these efforts is included here as Fig. 6A. These attempts did not acknowledge that Gregory named the "Westwater Canyon sandstone" only tentatively and that Stokes had earlier recognized a partial Salt Wash–"Recapture Shale" correlation. Gregory invited further investigation with several of his statements. Of great significance was his recognition of an unconformity at the base of his type "Westwater Canyon Sandstone Member" and that this "sandstone may prove to mark the beginning of a cycle of

TABLE 1—Type section of Salt Wash Member of Morrison Formation measured in the NW¼sec. 19 T23S R18E, Grand County, Utah. Section starts at UTM 12590639E, 4295274N and ends at UTM 12587750E, 4295482N. Strata are flat-lying. Stratigraphic column is in Fig. 5.

Unit	Lithology	Thickness (m)
Brushy Basin Member:		
11.	Sandstone and conglomeratic sandstone; sandstone is very pale orange (10YR8/2) with dark-gray (N3) spots, weathers pale yellowish brown (10YR6/2); conglomeratic sandstone is very light gray (N8), weathers pale brown (5YR5/2); fine- to medium-grained; subarkosic; subangular; moderately sorted; conglomerate clasts are mudstone pebbles to 1 cm in diameter; trough-crossbedded; forms a ledge.	Not measured
10.	Mudstone; greenish-gray (5GY6/1); not calcareous; upper 5 m very bentonitic; has ledgy lenses of sandstone that are pinkish gray (5YR8/1), very fine grained, subarkosic, subrounded, moderately sorted, and calcareous; forms a slope.	13.6
Salt Wash Member:		
9.	Sandstone; very light gray (N8); fine- to medium-grained; quartzose; subrounded; well-sorted; calcareous; conglomeratic base of unit is matrix-supported pebbles to 1 cm in diameter of light greenish-gray (5GY8/1) mudstone and chert and jasper pebbles to 0.5 cm in diameter; trough-crossbedded; forms a cliff; unit is multistoried channel bodies.	8.2
8.	Sandy siltstone; pale-red (5R6/2) with mottles of greenish gray (5GY6/1) and pinkish gray (5YR8/1); bentonitic; calcareous; contains lenses of sandstone that are moderate brown (5YR8/1), well sorted, and calcareous; forms a slope.	8.3
7.	Sandstone; very pale orange (10YR8/2); very fine to fine-grained; quartzose; subrounded; well-sorted; calcareous; trough-crossbedded; forms a ledge; unit is multistoried channel bodies with prominent scoured base.	7.3
6.	Silty mudstone; same colors and lithology as unit 8; lower 1–2 m has ripple-laminated sandstones; forms a slope.	6.5
5.	Sandstone; pinkish-gray (5YR8/1); very fine grained; quartzose with a few feldspars; subrounded; well-sorted; calcareous; basal conglomerates of channel bodies are pale-olive (10Y6/2) mudstone pebbles to 15 mm in diameter in pale yellowish-brown (10YR6/2) matrix; trough-crossbedded; unit is multistoried channel bodies; forms a ledge.	9.3
4.	Silty mudstone; grayish-red (10R4/2) and light greenish-gray (5GY8/1); calcareous; has some ledgy beds of sandstone that are very pale orange (10YR8/2), very fine grained, subarkosic, subrounded, well sorted and ripple laminated with much horizontal bioturbation on bedding planes; forms a slope.	5.1
3.	Sandstone; white (N9); very fine grained; quartzose; subrounded; well-sorted; calcareous; some conglomerate as in unit 5 at channel bases; trough-crossbedded; forms a ledge; multistoried channel bodies.	4.0
2.	Silty mudstone; same colors and lithology as unit 4; forms a slope.	1.5
1.	Sandstone; very light gray (N8); very fine to medium-grained; subarkosic; subangular; moderately sorted; calcareous; some very coarse to coarse-grained parts have red and black chert pebbles; trough-crossbedded; scour base with flute casts and tool marks; multistoried channel bodies that fine upward to bioturbated tops.	5.3

sedimentation that continued until interrupted by pre-Dakota erosion." We concur with this statement when the correct name Salt Wash is substituted for "Westwater Canyon Member." He also stated that ultimately it may be found that the Morrison is composed of several formations. We have read thoroughly the work of Gregory and remeasured most of his Morrison sections and have come to the conclusion that

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Type section of Westwater Canyon Member of the Morrison Formation measured in the NW1/4 sec. 31 T37S R22E, San Juan County, Utah, near the mouth of Westwater Canyon where it meets Cottonwood Canyon; section begins at UTM 12628460E, 4154718N and ends at UTM 12628433E, 4154722N. Strata are flat-lying. Stratigraphic column is in Fig. 5.

Unit	Lithology	Thickness (m)
11.	Brushy Basin Member	Not measured
Westwater Canyon Member:		
10.	Sandstone; yellowish-gray (5Y7/2); fine- to medium-grained; quartzose; subrounded; well-sorted; slightly calcareous; trough-crossbedded; forms a cliff.	4.4
9.	Sandstone; dark greenish-yellow (10Y6/6) and yellowish-gray (5Y7/2); very fine grained; quartzose with some chlorite?; subangular; moderately sorted; not calcareous; laminae; forms a cliff.	1.1
8.	Silty mudstone and muddy siltstone; mudstone is grayish yellow green (5GY7/2); siltstone is reddish orange (10R6/6) to pale reddish brown (10R5/4); not calcareous; contains some nodules of calcareous siltstone that are yellowish gray (5Y7/2); forms a slope.	7.1
7.	Sandstone; yellowish-gray (5Y7/2) and (5Y8/1); very fine to fine-grained; quartzose; subrounded; well-sorted; not calcareous; some medium-grained beds that are calcareous; trough-crossbedded; forms a cliff; unit is multistoried channel bodies.	13.0
6.	Sandstone; yellowish-gray (5Y7/2) and grayish-yellow (5Y8/4); very fine to fine-grained; quartzose with a few feldspars; subrounded; well-sorted; calcareous; trough-crossbedded; forms a cliff; unit is multistoried channel bodies that laterally thins to give way mostly to sandy mudstone like unit 4.	4.7
5.	Sandstone; very pale orange (10YR8/2); fine- to medium-grained; quartzose; subrounded; well-sorted; calcareous; trough-crossbedded; base of unit is matrix-supported conglomerate of chert, jasper, and mudstone pebbles to 12 mm in diameter; unit forms base of big cliff.	0.8
4.	Sandy mudstone; pale-olive (10Y6/2) and light greenish-gray (5G8/1); calcareous; contains 0.3–0.6-m-thick ledges of sandstone that are yellowishgray (5Y8/1); very fine grained, quartzose, subrounded, well-sorted, calcareous, and massive to bioturbated.	6.7
3.	Sandstone; yellowish-gray (5Y7/2); very fine to fine-grained; quartzose; subrounded; well-sorted; trough-crossbedded; forms a ledge.	0.9
2.	Sandy mudstone; same colors and lithology as unit 4.	1.9
1.	Sandstone; grayish-yellow (5Y8/4) and very pale orange (10YR8/2); same lithology as unit 3; trough-crossbedded; some mudstone pebbles; unit is multistoried channel bodies with scour bases and bioturbated topset beds.	11.4

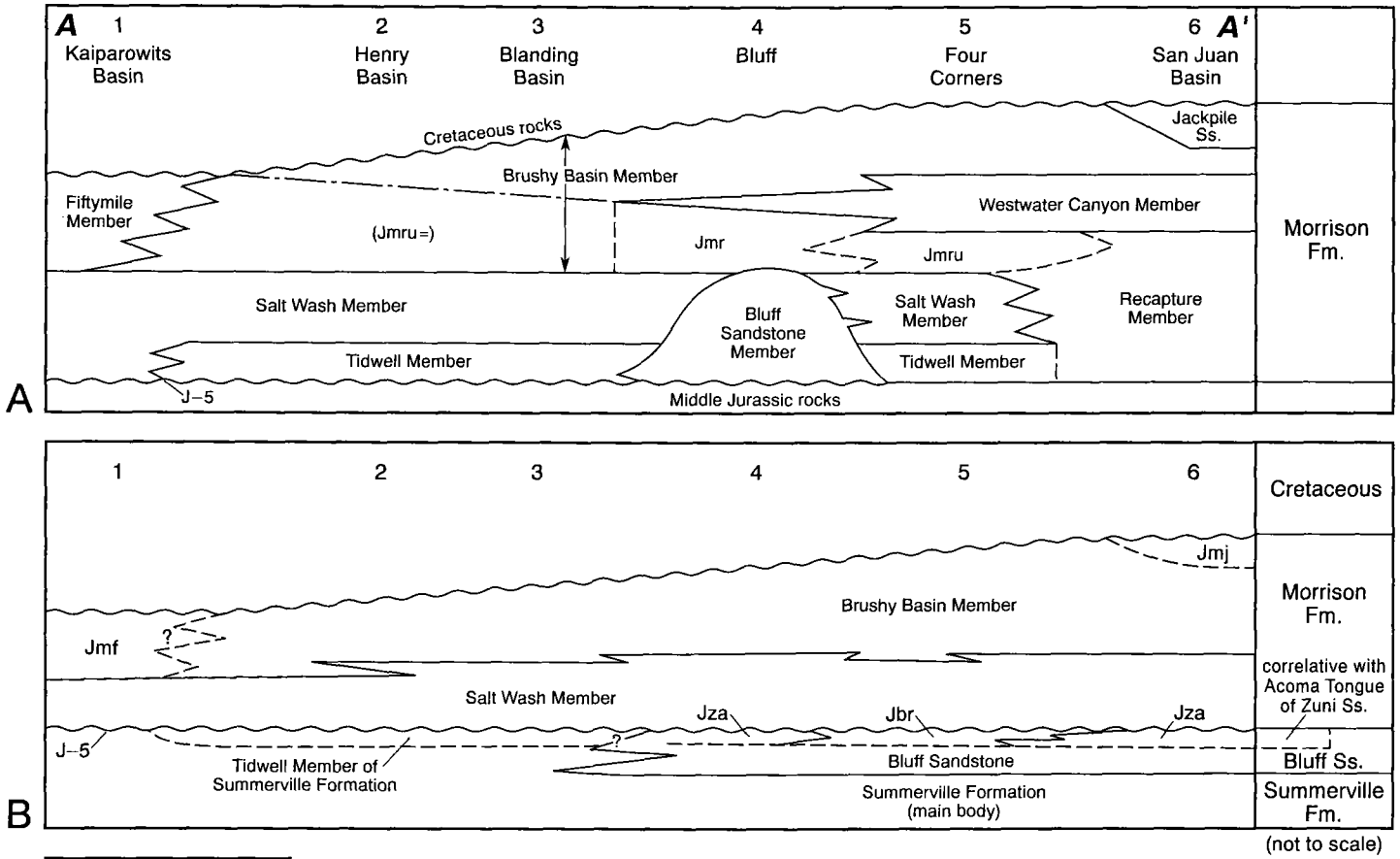

FIGURE 6—**A**, Stratigraphy and correlation of Middle and Upper Jurassic rocks in Four Corners region as envisioned by Peterson and Turner-Peterson (1987). **Jmru**, upper part of Recapture Member of Morrison Formation; **Jmru=**, upper Recapture equivalent. Line of section shown in inset at left. **B**, Stratigraphy and correlation of Middle and Upper Jurassic rocks, same area as **A** above, as proposed in this paper. Major contrasts between this and **A** lie in the recognition of regionally traceable scour surface at base of Salt Wash Member as shown in **B**, and in the fact that **A** cannot be applied by the field mapper. **Jmj**, Jackpile Member of Morrison recognized in southeastern San Juan Basin; **Jmf**, Fiftymile Member of Morrison, a unit recognized by Peterson and Turner-Peterson (1987); **Jza**, Acoma Tongue of Zuni Sandstone; and **Jbr**, Recapture Member of Bluff Sandstone. Both **A** and **B** are diagrammatic.

his intuition was good and his statement was prophetic—his lower "Recapture shale" most surely is part of the San Rafael Group. Our correlations (Fig. 6B) are based on original definitions and lithostratigraphy, plus recognition of sequence boundaries, and contrast sharply with those of Peterson and Turner-Peterson (1987; Fig. 6A), which we contend are unapplicable in the field.

Brushy Basin Member

To complete the discussion of Gregory's four-part Morrison Formation we must consider the upper, most widely recognized, and most extensive unit. It is a claystone-dominated (largely smectitic), slope-forming unit with lesser amounts of sandstone and nodular limestone. The typical grayish-green cast, but common color banding, and the abundant free-swelling clays are the characteristics that stratigraphers most associate with Morrison Formation strata. This unit may be recognized from Montana and South Dakota southward to Arizona and New Mexico, as well as eastward into Oklahoma (Fig. 1). Gregory, however, named it for exposures approximately 9 mi (14 km) northwest of Blanding, Utah, in a topographic feature called Brushy Basin. At this locality the Brushy Basin Member is approximately 450 ft (136 m) thick with only 42 ft (13 m) described as sandstone. Our reconnaissance, however, indicates that the base of this member is not well exposed at the type locality. Elsewhere it is well exposed, and commonly we see an interfingering relationship with the underlying Salt Wash Member. Thus, the upper member—the Brushy Basin—of the Morrison is generally a noncontroversial unit and the only one of the four proposed by Gregory (1938) that has any stratigraphic utility with respect to the Morrison Formation (Bluff and Recapture are retained but properly belong with San Rafael Group strata).

Morrison Formation, northwestern New Mexico

Early attempts (1950s) to correlate and recognize a four-member Morrison Formation in northwestern New Mexico were related to uranium exploration efforts. Some of this work was classified information, other efforts were completed as in-house reports and hence are not generally available to the scientific community (e.g., Rappaport et al., 1952), and some of the work was in the form of graduate student theses (e.g., Chenoweth, 1953). All, however, left some of the aspects of the correlations unclear; for example, no diagrams satisfactorily explained the Salt Wash–Recapture relationship (reportedly interfingered) in the Four Corners area and southward, nor how the Westwater Canyon Sandstone could be extended southward from Recapture Creek into the southern San Juan Basin (C. T. Smith, oral comm.; Smith, 1954). Most of what was called "Recapture Shale" in New Mexico

was pre-Morrison interdunal or minor fluvial facies that interfingered with the upper part of the "Cow Springs Sandstone"; Cow Springs was a name that Harshbarger et al. (1951) suggested as a junior synonym for the Zuni Sandstone, a distinctive crossbedded eolianite in the southwestern San Juan Basin and associated Gallup–Zuni Basin (Anderson, 1993). Thus was born the erroneous concept that Morrison strata, specifically "Recapture Shale," intertongued with or graded southward into the eolian Zuni Sandstone (or to complete the confusion—into "Cow Springs Sandstone").

Formal adoption of Gregory's four-member Morrison Formation in New Mexico came with the work of Craig et al. (1955). As noted above, Craig did not recognize the Bluff Sandstone as part of his Morrison Formation, advocating instead that the Bluff be included with the San Rafael Group. He did not note, however, that the reddish, fine-grained facies at the top of the Bluff was, depending upon location, either interdunal or sabkha-related, and preferred to accept the erroneous interpretation that this fine-grained facies was part of the Salt Wash Member. Thus, Craig made the observation or conclusion, largely from the literature, that in the Four Corners area the Salt Wash and Bluff intertongue, detracting from the value of reassigning the Bluff to the San Rafael Group.

In the San Juan Basin the interbedded reddish facies at the top of, or overlying, the Bluff Sandstone is locally thicker than its counterpart in Utah (herein named Recapture Member of the Bluff) and also exhibits much more fluvial influence. At some localities such as at Thoreau, New Mexico, this fluvial influence is present at intervals throughout 120 ft (36 m) of section above the Bluff Sandstone, and thus the eolian Acoma Tongue of the Zuni is locally displaced by these unnamed waterlaid and interdunal deposits. All of the fluvial facies described here lie below the regional scour surface that marks the base of the overlying Morrison Formation. Thus, the initial correlation of these fluvially influenced strata with Gregory's "Recapture Shale" (Craig et al., 1955 and subsequent USGS workers) was in error because most of the type "Recapture Shale" lies above the regional scour or sequence boundary. In contrast all the strata called "Recapture" in the San Juan Basin by the USGS (Harshbarger et al., 1957; Condon and Huffman, 1984; Condon and Huffman, 1988) demonstrably underlie the regional scour-sequence boundary (Fig. 6) that marks the basal Morrison.

New perspective on the correlation of rocks associated with the San Rafael Group-Morrison contact has come from observations regarding the distinctively crossbedded eolianite at the top of the Bluff Sandstone. Noted by Anderson and Lucas (1992) as the Acoma Tongue of the Zuni Sandstone and discussed in terms of regional significance, event stratigraphy, and simplification of nomenclature by Anderson (1993), the Acoma Tongue is now recognized over a much broader area, based partly on observations by Condon (1985) in the Bluff, Utah area. Condon noted a distinctively crossbedded facies with eastward-dipping foresets very similar to the Acoma Tongue of the Zuni. While a revelation in terms of regional correlation of eolian facies in uppermost San Rafael Group rocks, the significance went unrealized when Condon assigned the distinctively crossbedded facies to the Morrison Formation. This left him with the unenviable task of having to identify a group-rank boundary (top of San Rafael Group) in a continuous eolian sandstone sequence, based only on a change in bedform (the crossbedded facies). This approach ignores the lithologic basis of earlier descriptions of the Morrison and is inconsistent with the North American Code of Stratigraphic Nomenclature, which recommends that boundaries of rock-stratigraphic units be placed at positions of lithologic change. Condon and Peterson (1986), in an effort to defend their placement of the basal Morrison contact, referred to it as "an unrecognizable time boundary," presumably because there was no lithologic basis for their decision. One must ask the question: if it is unrecognizable to them, of what utility is it to the geologic mapper? We contend that the distinctly crossbedded facies records the change in wind pattern as this part of the North American continent drifted northward into the zone of prevailing westerlies. As such it is not a lithostratigraphic unit but rather a widely recognized facies, on the basis of bedform, with chronostratigraphic significance. Thus the time boundary need no longer remain "unrecognizable," as it may now be related to that most basic of all tectonic processes, continental drift, and be regarded as an example of event stratigraphy.

We reject the concept of major eolianites in the basal Morrison Formation for the following reasons: (1) the Morrison type section in the Colorado Front Range contains no eolianites; (2) the original definition of the "western Morrison" by Gilluly and Reeside (1928) did not include any eolian strata; (3) the base of the Morrison as described by Gilluly and Reeside (1928) can be projected into the San Juan Basin of New Mexico and is clearly above the crossbedded eolian strata recognized by Condon (1985) and by Anderson and Lucas (1992); and (4) from a lithologic and a paleoclimatic perspective, the eolianites are clearly related to San Rafael Group arid depositional systems rather than to Morrison Formation fluvial systems. Thus we recognize the distinctive crossbedded strata of the Acoma Tongue of the Zuni Sandstone as far northwestward as Bluff, Utah, where it is coeval and intertongues with the Recapture Member of the Bluff Sandstone (Fig. 7). We also recognize that at this geographic locality, remote from the type area of the Acoma Tongue, it may be appropriate to assign a local name to the crossbedded facies that herein correlate with the Acoma Tongue. Perhaps it should be regarded as a local member of the Bluff Sandstone given the nature and subtlety of the bedform contrast between the units. The base of the overlying Morrison by comparison is readily picked by the geologic mapper at the abrupt change in grain size and the presence of fluvial characteristics encountered at a scour surface cut and backfilled by the Salt Wash Member. This regionally traceable surface is the lower bounding surface of the Morrison fluvial sequence.

The area northwest of Bluff and into the San Rafael Swell (Fig. 1), although outside the main area of consideration in this report, is of interest because the pre-Morrison stratigraphy is somewhat different. The Bluff Sandstone is not present in that area, and in addition the upper part of the Summerville Formation contains distinctive grayish-green mudstone beds and bedded gypsum, which Peterson (1988) referred to as the Tidwell Member of the Morrison Formation. Because these lithologies are common to the underlying main portion of the Summerville and bedding characteristics (parallel, thinly bedded strata) are similar, we see little utility in placing the Tidwell Member in the Morrison. The local coarser grained facies at the base of the Tidwell, noted by Peterson (1988), we interpret as wadi deposition (shallow desert arroyos active only during heavy rainstorms) during the latter part of Summerville time. At the type area of the Tidwell Member in sec. 24 T22S R13E, we noted minor wadi-type channel deposits scattered throughout the upper part of the Tidwell in otherwise typically Summerville lithologies. Conversely, the scoured base of the immediately overlying Salt Wash Member defines the horizon above which no Summerville type strata are present. Accordingly, we include Tidwell strata in the Summerville Formation (Fig. 6B).

The base of the Morrison in the San Juan Basin is similarly placed at the scoured base of a prominent, cliff-forming sandstone that since Craig et al. (1955) has been called "Westwater Canyon Sandstone Member" (Fig. 7). This scour surface also marks an abrupt change in grain size and sedimentary characteristics. Most diagnostic is the appearance of pebbly sandstones, clay clasts, rip-up clasts, fluvial crossbedding, and smectitic clay in the interbedded mudstone (overbank) deposits. As such the scour surface is everywhere recognizable, commonly has a thin, irregular pedogenic carbonate unit, and can be correlated with the base of the distinctive Salt Wash Member into the Four Corners area. Just south of Beclabito, New Mexico (Fig. 1), near the Four Corners, the ☞

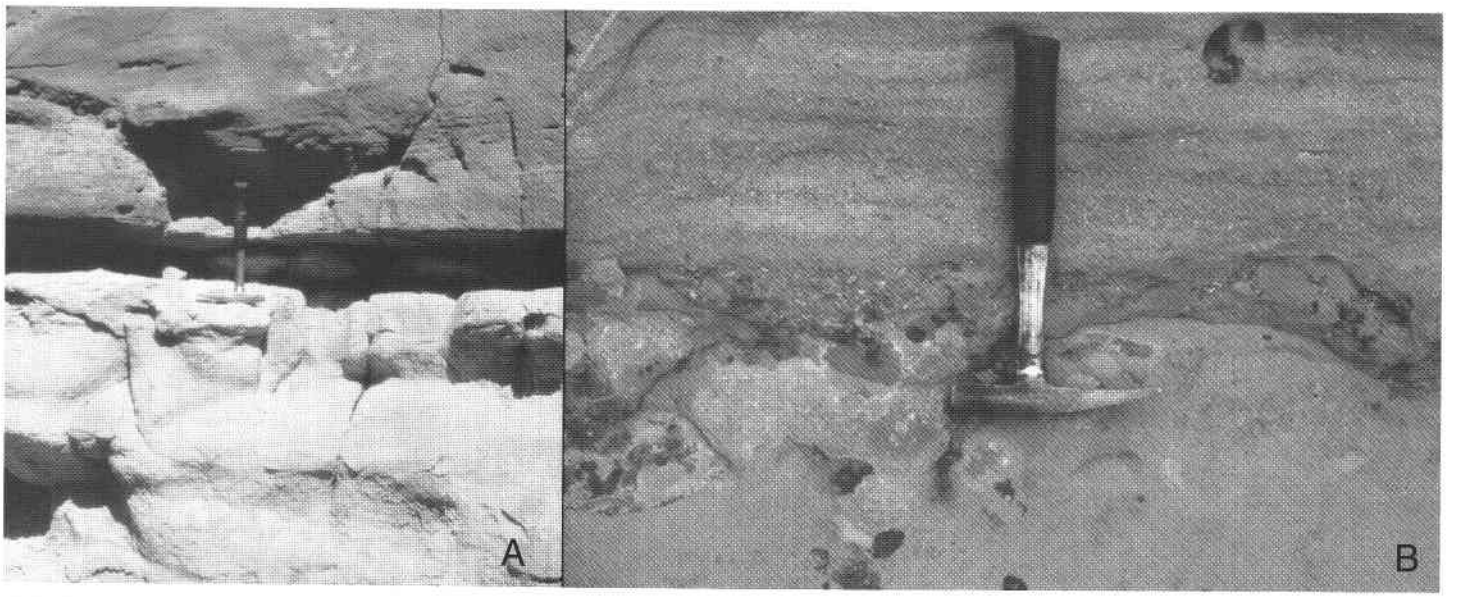

FIGURE 7—Scour surface at base of Salt Wash Member of Morrison Formation (**A**) near Church Rock, New Mexico, and (**B**) in hogback south of Gallup, New Mexico.

so-called three-part Salt Wash Member (William Chenoweth, oral comm., 1993) apparently includes a relatively fine grained basal unit up to 30 ft (9 m) thick and showing oxidized (red) colors. This unit likely correlates with the reddish, parallel-bedded unit that formed the base of Gregory's "Recapture Shale Member" and is here reassigned to the San Rafael Group. Thus, the middle part (crossbedded, pebbly sandstone) of the so-called three-part Salt Wash is the actual base of the Salt Wash Member, in the corrected stratigraphy presented here, and it is that horizon or stratum that we correlate with the base of what has been called "Westwater Canyon Sandstone" in the San Juan Basin.

Although the name "Westwater Canyon Sandstone" was recognized as duplicative earlier in this paper and consequently recommended for abandonment, we nonetheless point out that the unit referred to as "Westwater Canyon" in the San Juan Basin is coarser grained and does not correlate directly with the "Westwater Canyon" Member designated in Gregory's reference section at the mouth of Recapture Creek. The two may be correlative in part, but the base of the San Juan Basin unit is stratigraphically lower and hence perhaps older than the base of the "Westwater Canyon" designated at the Recapture Creek section by Gregory. This is significant; most workers use the Recapture Creek reference section as the basis for correlations southward into the San Juan Basin primarily because (1) the type "Westwater Canyon Sandstone" did not have an exposed base and was more difficult to access, and (2) exposures are not so good or extensive as they are at the mouth of Recapture Creek.

Having said this, the logical stratigraphic procedure would be to apply the name Salt Wash to the basal Morrison sandstone in the San Juan Basin. We adopt this nomenclature but do not ignore the fact that the basal Morrison in the San Juan Basin has a different source area than the Salt Wash Member. Source area for the Salt Wash was inferred to be to the west in south-central Utah (Craig et al., 1955). Source area for the "Westwater Canyon", considered to be an "alluviating distributary system of braided channels" (Craig et al., 1955) was inferred to lie to the west and southwest in adjacent Arizona. These observations are supported in a general way by paleoflow interpretations of crossbedded strata and geometry of the sandbodies.

In addition to the different source area is the fact that the Salt Wash has a somewhat different weathering profile than the basal Morrison of the San Juan Basin. This is primarily due to a lower ratio of channel-deposit thickness to floodplain-deposit thickness in the type Salt Wash; in other words, the basal Morrison sandstone in the southern San Juan Basin characteristically has thicker channel sandstone deposits than the Salt Wash.

For these reasons, a case could be made to recognize the basal Morrison sandstone of the San Juan Basin as a separate member as Smith (1954) advocated, and correlate it with the Salt Wash Member. Smith, working on the Thoreau 7½-min quadrangle in the southern San Juan Basin, recognized 189 ft (57 m) of crossbedded, pebbly sandstone with at least three significant finer-grained intervals (up to 15 ft [5 m]) in the lower part of the Morrison. These lithologies are not dissimilar to those of the Salt Wash Member. We, accordingly, have chosen to simplify the nomenclature and here term the basal Morrison sandstones of the San Juan Basin the Salt Wash Member pending further study of their internal stratigraphy and lithology.

The Salt Wash Member thins gradually though nonuniformly southwestward to a wedge edge. South of Gallup, along the hogback near latitude 35°22′, the Salt Wash is beveled off by pre-Dakota erosion, and from this latitude southward the Dakota rests on Zuni sandstone or older Mesozoic rocks. Eastward from the Thoreau–Grants area the Salt Wash also thins, though not uniformly, and at Mesa Gigante, 30 mi (48 km) west of Albuquerque at longitude 107°15′, the Salt Wash is sporadically present. The significant aspect of the Morrison Formation in this eastward direction is that the fine-grained upper member, the Brushy Basin, persists all the way out to the southern High Plains. Thus the extent of the Brushy Basin Member approaches 500 mi (800 km) in an east-west direction, greater than has heretofore been acknowledged in the literature. This is significant to any undertaking of a basin analysis study of the upper Morrison.

In the few areas of the southeastern San Juan Basin where a basal Salt Wash Member is not present, the mapping contact may be based on the lithologic contrast between the greenish, variegated smectitic claystones of the Morrison and the underlying reddish, silty sandstones of the San Rafael Group. In addition, dinosaur bone fragments are relatively abundant in the Morrison of this area, but none have been reported locally in the San Rafael Group.

Conclusions

We recognize a two-part Morrison Formation throughout northwestern New Mexico and southeastern Utah. Previous attempts to recognize and correlate Gregory's (1938) four divisions of the Morrison in Utah and New Mexico were met with failure for the following reasons: (1) his

basal Bluff Sandstone Member is basically a fine-grained eolianite with affinities to the San Rafael Group, and it demonstrably lies below a regional unconformity and/or paleosol that signals the onset of fluvial deposition under a more mesic climatic regime; (2) his type "Recapture Shale Member" included sabkha deposits at the top of the San Rafael Group, the unconformity at the base of the Salt Wash Member, and the entire Salt Wash Member; (3) his type "Westwater Canyon sandstone member" is demonstrably correlative with the Salt Wash Member, so the name "Westwater Canyon Member" is superfluous; and (4) most of the type "Recapture," by original definition, lies above the regional unconformity, whereas the Recapture unit that was correlated into the San Juan Basin lies demonstrably and entirely below this regional unconformity and hence is part of the San Rafael Group.

Recapture and Westwater Canyon are thus superfluous names as members of the Morrison Formation in northwestern New Mexico. The valid name Salt Wash Member pertains to the prominent pebbly sandstone at the base of the Morrison Formation throughout its area of western distribution, and it is overlain by and intertongues with the distinctive, claystone-dominated (smectitic) Brushy Basin Member. In the more distal areas such as at Mesa Gigante in the southeastern San Juan Basin, the Salt Wash Member is not present, and the Brushy Basin Member rests on a more profound unconformity marked by a well-developed paleosol.

The name Recapture Member is retained as a subdivision of the Bluff Sandstone in southeastern Utah to define a 40–55-ft-(12–17-m-)thick, fine-grained, parallel-bedded silty sandstone. This sandstone represents local sabkha conditions at the close of San Rafael Group deposition. As so defined the Recapture Member represents nothing more than an upper unit of the Summerville Formation. However, because these strata formed the base of Gregory's type Recapture Member, we have chosen to perpetuate the name.

The distinctively crossbedded upper part of the Bluff Sandstone contains thick sets of east-dipping foresets and has an intertonguing relationship with the Recapture Member. The crossbedded unit is recognized in the southern San Juan Basin in similar stratigraphic position, where it is designated as the Acoma Tongue of the Zuni Sandstone. This unit is more significant in terms of event stratigraphy than as strictly a lithostratigraphic unit, and thus we will leave the matter of nomenclature for this unit in Utah to local mappers or investigators. We cannot accept the proposal by previous workers (Condon and Peterson, 1986) that the gradational base of this crossbedded sandstone represents an unrecognized time boundary that defines the base of the Morrison Formation. The event stratigraphy alluded to above relates to the concept that this part of the North American continent drifted into the zone of prevailing westerlies at the close of San Rafael Group deposition (late Middle Jurassic) and eolianites of that age reflect this in the prominent east-dipping foresets.

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References

Anderson, O. J., 1993, Zuni Sandstone and Acoma Tongue defined: New Mexico Geology, vol. 15, no. 2, pp. 38–39.

Anderson, O. J., and Lucas, S. G., 1992, The Middle Jurassic Summerville Formation, northern New Mexico: New Mexico Geology, v. 14, no. 4, pp. 79–92.

Anderson, O. J., and Lucas, S. G., 1994, Middle Jurassic stratigraphy sedimentation and paleogeography in the Colorado Plateau and Southern High Plains; *in* Caputo, M. V., Peterson, J. A., and Franczyk, K. (eds.), Mesozoic Systems of the Rocky Mountain region, U.S.A.: Rocky Mountain Section, SEPM (Society for Sedimentary Geology), pp. 299–314.

Brenner, R. L., 1983, Late Jurassic tectonic setting and paleogeography of Western Interior, North America; *in* Reynolds, M. W., and Dolly, E. D. (eds.), Mesozoic paleogeography of west-central U.S.: Rocky Mountain Section, Society of Economic Paleontologists and Mineralogists, pp. 119–132.

Chenoweth, W. L., 1953, The Variegated Member of the Morrison Formation in the southeastern part of the San Juan Basin, Valencia County, New Mexico: Unpublished M.S. thesis, University of New Mexico, Albuquerque, 86 pp.

Condon, S. M., 1985, Lithologic descriptions of the selected intervals of Jurassic rocks in southeastern Utah, northeastern Arizona, and northwest New Mexico: U.S. Geological Survey, Open-file Report 85-223, 100 pp.

Condon, S. M., and Huffman, A. C., Jr., 1984, Stratigraphy and depositional environment of Jurassic rocks, San Juan Basin, New Mexico, with emphasis on the south and west sides: Rocky Mountain Section of Geological Society of America, Field Trip Guidebook, 37th Annual Meeting, Durango, Colorado, pp. 93–148.

Condon, S. M., and Huffman, A. C., Jr., 1988, Revision in nomenclature of the Middle Jurassic Wanakah Formation, northwestern New Mexico and northeastern Arizona: U.S. Geological Survey, Bulletin 1633–A, 12 pp.

Condon, S. M., and Peterson, F., 1986, Stratigraphy of Middle and Upper Jurassic rocks of the San Juan Basin; historical perspectives, current ideas and remaining problems: American Association of Petroleum Geologists, Studies in Geology no. 22, pp. 7–26.

Craig, L. C., et al., 1955, Stratigraphy of the Morrison and related formations, Colorado Plateau region, a preliminary report: U.S. Geological Survey, Bulletin 1009–E, pp. 125–168.

Dickinson, W. R., 1989, Tectonic setting of Arizona through time; *in* Jenney, J. P., and Reynolds, S. J. (eds.), Geologic evolution of Arizona; Arizona Geological Society Digest, no. 17, pp. 1–16.

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

Goldman, M. I., and Spencer, A. C., 1941, Correlation of Cross' La Plata Sandstone, southwestern Colorado: American Association of Petroleum Geologists, Bulletin, v. 25, pp. 1745–1767.

Gregory, H. E., 1938, The San Juan Country: U.S. Geological Survey, Professional Paper 188, 123 pp.

Hackman, R. J., and Olson, A. B., 1977, Geology, structure, and uranium deposits of the Gallup 1° x 2° quadrangle, New Mexico and Arizona: U.S. Geological Survey, Map I-981, 1:250,000.

Harshbarger, J. W., Reprenning, C.A., and Irwin, J. H., 1957, Stratigraphy of the uppermost Triassic and the Jurassic rocks of the Navajo country: U.S. Geological Survey, Professional Paper 291, 71 pp.

Harshbarger, J. W., Repenning, C. A., and Jackson, R. L., 1951, Jurassic stratigraphy of the Navajo country; *in* Smith, C. T., and Silver, C. (eds.), San Juan Basin: New Mexico Geological Society, Guidebook 2, pp. 95–99.

Hintze, L. F., and Stokes, W. L., 1964, Geologic map of southeastern Utah: University of Utah, 1:250,000.

Imlay, R., 1954, Summary of Jurassic history in the western interior of the U.S.: Billings Geological Society, Third Annual Field Conference, pp. 79–85.

Kocurek, G., and Dott, R. H., Jr., 1983, Jurassic paleogeography and paleoclimate of the central and southern Rocky Mountains; *in* Reynolds, M. W., and Dolly, E. D. (eds.), Mesozoic paleogeography of west-central United States, Rocky Mountain Section, Society of Economic Paleontologists and Mineralogists, pp. 101–116.

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

Lupton, C. T., 1912, Oil and gas near Green River, Grand County, Utah: U.S. Geological Survey, Bulletin 541.

Moench, R. H., 1963, Geologic map of the Laguna quadrangle, New Mexico: U.S. Geological Survey, Map GQ–208.

O'Sullivan, R. B., and Beikman, H. M., 1963, Geology, structure, and uranium deposits of the Shiprock Quadrangle, New Mexico and Arizona: U.S. Geological Survey, Map I–345, 1:250,000.

Peterson, F., 1988, Stratigraphy and nomenclature of Middle Jurassic rocks, western Colorado Plateau, Utah, and Arizona: U.S. Geological Survey, Bulletin 1633–B, pp. 17–56.

Peterson, F., and Turner–Peterson, C. E., 1987, The Morrison Formation of the Colorado Plateau; recent advances in sedimentology, stratigraphy, and paleotectonics: Hunteria, v. 2, no. 1, 18 pp.

Rappaport, I., Hadfield, J. P., and Olson, R. H., 1952, Jurassic rocks of the Zuni uplift: U.S. Atomic Energy Commission, Rept. RMO–642, 55 pp.

Ridgley, J. L., 1989, Trace fossils and mollusks from the upper member of the Wanakah Formation, Chama Basin, New Mexico—evidence for a lacustrine origin: U.S. Geological Survey, Bulletin 1808–C, pp. C1–C16.

Saucier, A. E., 1967, The Morrison Formation in the Gallup region; *in* Trauger, F. D. (ed.), Defiance, Zuni, Mt. Taylor Region: New Mexico Geological Society, Guidebook 18, pp. 138–144.

Smith, C. T., 1954, Geology of the Thoreau quadrangle, McKinley and Valencia Counties, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 31, 36 pp.

Stokes, W. L., 1944, Morrison and related deposits in an adjacent to the Colorado Plateau: Geological Society of America, Bulletin, v. 55, pp. 951–992.

Thaden, R. E., Santos, E. S., and Ostling, E. J., 1967, Geologic map of the Dos Lomas quadrangle, New Mexico: U.S. Geological Survey, Map GQ–680.

Turner–Peterson, C. E., 1986, Fluvial sedimentology of a major uranium-bearing sandstone—a study of the Westwater Canyon Member of the Morrison Formation, San Juan Basin, New Mexico: American Association of Petroleum Geologists, Studies in Geology no. 22, p. 60.

Waldschmidt, W. A. and LeRoy, L. W., 1944, Reconsideration of the Morrison Formation in the type area, Jefferson County, Colorado: Geological Society of America Bulletin, v. 55, pp. 1097–1114. □