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THE JURASSIC SAN RAFAEL GROUP, FOUR CORNERS REGION

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Abstract—The Jurassic San Rafael Group on the Colorado Plateau consists of six formations (in ascending order): Carmel, Entrada, Curtis, Todilto, Summerville and Bluff. Unconformities (J-2 below and J-5 above) bound the San Rafael group, and a within-group unconformity (J-3) separates the Curtis and Todilto Formations from the underlying Entrada. The Page Sandstone is here considered the Page Member of the Navajo Sandstone and not included in the San Rafael Group. The J-2 unconformity is at the Page-Carmel contact, not at the Page-Navajo contact as claimed by some workers. The Dewey Bridge Member of the Entrada Sandstone in Utah-Colorado is correlative to part of the Carmel Formation, and it may correlate to the medial silty member of the Entrada Sandstone in the San Juan Basin, New Mexico. If so, the Iyanbito Member of the Entrada Sandstone in the southern San Juan Basin is older than the J-2 unconformity and a correlative of part of the Glen Canyon Group, probably the Navajo Sandstone. The Entrada Sandstone represents an erg that covered much of the Southwest during late Carmel and post-Carmel time. Early transgression of the Curtis-Sundance seaway across the Entrada erg produced a salina basin in northern New Mexico/southwestern Colorado in which the Todilto Formation was deposited. Continued transgression created a vast paralic facies tract that extended from east–central Utah into southeastern Colorado, northeastern New Mexico and northwestern Oklahoma in which the Summerville Formation was deposited. The Summerville Formation consists of the (lower) Beclabito Member, present throughout the Summerville outcrop belt, and the (upper) Tidwell Member, only present in Utah and southwestern Colorado. The Tidwell Member occupies the same stratigraphic position as and is correlative with the Bluff Sandstone. The Bluff Sandstone (Junction Creek Sandstone is a synonym) consists of the main body (lower) and Recapture Member. The Recapture Member is cyclically bedded sandstones and siltstones strikingly similar to strata of the Summerville Formation. Cow Springs Sandstone is a synonym of Zuni Sandstone. The J-5 unconformity marks the boundary between the youngest San Rafael Group strata and the basal, Salt Wash Member of the Morrison Formation. Fossils, regional stratigraphic relationships and radioisotopic ages support the following age assignments to units of the San Rafael Group: Carmel = middle to late Bajocian; Entrada = Bathonian to early Callovian; Curtis = Todilto = middle Callovian; Summerville = middle Callovian to Oxfordian; and Bluff = Oxfordian.

INTRODUCTION

Gilluly and Reeside (1928), in a classic paper, introduced the term San Rafael Group to encompass four Jurassic formations exposed in the San Rafael Swell and adjacent areas of Utah (in ascending order): Carmel, Entrada, Curtis and Summerville. The San Rafael Group now has been recognized across most of the Colorado Plateau (Fig. 1) and on the southern High Plains of Colorado, Oklahoma and New Mexico (e.g., Baker et al., 1936, 1947; Pipiringos and O'Sullivan, 1978; Lucas et al., 1985; Condon and Peterson, 1986; Anderson and Lucas, 1992, 1994, 1995). Throughout their extent, San Rafael Group strata record shallow marine, paralic and nonmarine eolian and lacustrine environments of Middle–Late Jurassic age. San Rafael Group deposition took place in a vast basin (at least one million km^2) with a paleoslope down to the north and northwest. Here, we review the stratigraphy, depositional environments and age relationships of strata of the San Rafael Group, with emphasis on the Four Corners region.

J-2 UNCONFORMITY

Pipiringos and O'Sullivan (1978) introduced a scheme of widespread unconformities to aid in the organization and correlation of Triassic and Jurassic rocks of the Western Interior. In this scheme, they identified the San Rafael Group as bounded below and above by the J-2 and J-5 unconformities, respectively (Fig. 2). J-3 and J-4 are unconformities within the San Rafael Group and its correlatives.

The J-2 unconformity coincides with the Glen Canyon Group–San Rafael Group contact. This transgressive surface at the base of the Carmel Formation is the base of Sloss's (1963) Zuni sequence, and therefore a long-recognized unconformity of broad regional significance, and this is where we locate the J-2 unconformity.

Work in the Page area of north-central Arizona by Peterson and Pipiringos (1979) located the J-2 unconformity at a surface below the former Navajo–Carmel contact, and some subsequent workers (e.g., Blakey et al., 1996; Evans, 1996) have accepted this placement of the unconformity. This putative J-2 surface lies between the main body of the Navajo Sandstone and the overlying Page Sandstone (Fig. 3A–B), the latter reassigned to the San Rafael Group by Peterson and Pipiringos (1979).

A cliff-forming, crossbedded red or light gray sandstone at the top of and lithogenetically very similar to the Navajo Sandstone was designated the Page Sandstone by Peterson and Pipiringos (1979). Named for the excellent exposures at Page, Arizona, the Page Sandstone was previously included in the Navajo Sandstone (e.g., Gregory and Moore, 1931). At the type section on the north side of Page, the Page Sandstone is 55.8 m thick and consists of moderate reddish brown and locally light gray, fine-grained sandstone. The crossbed sets are mostly large scale, ranging from low to high angle. The uniform grain size, nature of the crossbedding and absence of fluvial indicators suggest an eolian origin.

Peterson and Pipiringos (1979) identified the base of the Page as the J-2 unconformity primarily because the Navajo–Page surface is at least locally marked by angular chert pebbles. However, chert fragments are present throughout the lower half of the Page and thus do not characterize a single surface. Furthermore, the lithologic similarity of the Page and underlying Navajo is striking. Locally, the relationship between the two units appears to be an intra-erg diastem with little lithologic contrast across the depositional break. It is thus difficult to assign them to two separate group-rank units, or to recognize the Page as a separate formation. Therefore, we consider the Page to be a member of the Navajo Sandstone (Fig. 2).

CARMEL FORMATION

The Carmel Formation of Gilluly and Reeside (1928) has its type section at Mount Carmel in Kane County, Utah (Gregory and Moore, 1931). It has long been considered the oldest unit in the San Rafael Group, and we continue to identify it as such. Because the Carmel is a thin unit in only part of the Four Corners region, we provide a brief summary (see Rose, 1996, for a more extensive review).

The Carmel embraces a wide variety of lithologies, including limestone at its base and interbedded sandstone, conglomeratic sandstone, siltstone and bedded gypsum. These strata have been assigned to numerous member-rank units, some of which are not in general use. The limestones occur primarily in the basal part of the Carmel, interbedded with calcareous shale layers. This limestone-dominated interval reaches thicknesses of nearly 76 m. The overlying clastic units may reach a combined thickness of as much as 110 m.

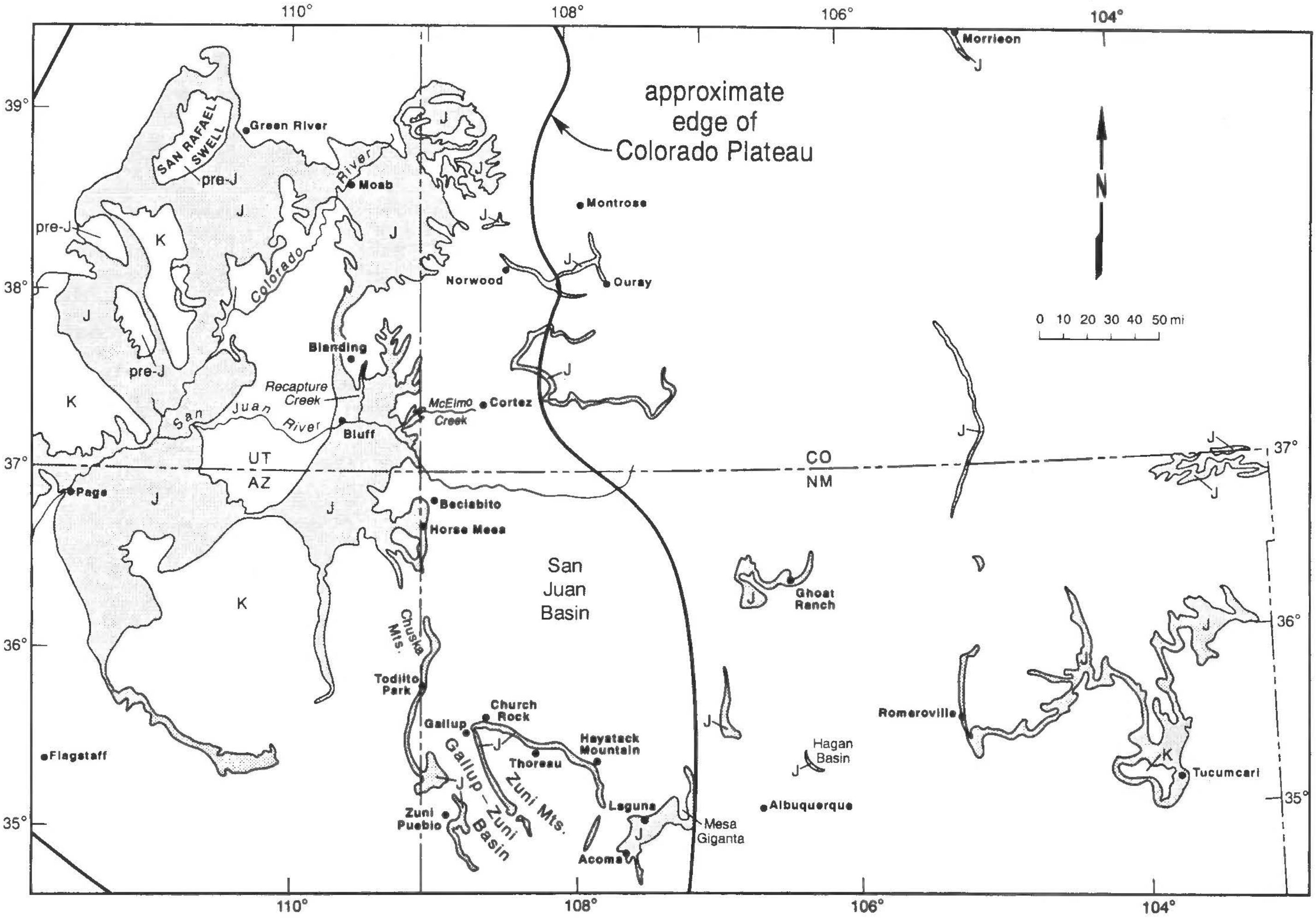


FIGURE 1. Map of part of Colorado Plateau showing distribution of Jurassic rocks.

The Carmel was deposited in an arm of the Twin Creek–Carmel seaway that extended south–southwestward into Utah and Arizona from southwestern Wyoming and southeastern Idaho. Carmel sediments thin eastward from the axis of this arm of the seaway, so the type Carmel strata do not extend through the entire Four Corners region. They represent shallow marine, coastal, fluvial and sabkha environments associated with the Twin Creek–Carmel seaway. To the south and east, erg development persisted as represented by the upper part of the Navajo Sandstone and the Entrada Sandstone. In the areas where no strata associated with this transgression were deposited or preserved, continuous erg deposition and development makes it difficult (in the absence of fossils) to assign eolianites to the younger (San Rafael Group) or older (Navajo) stratigraphic units.

The age of the Carmel has been determined through biostratigraphic correlation—largely based on fossils from the lower limestone beds—and from Ar/Ar ages from thin bentonite beds. The marine invertebrate fauna is mostly bivalves, but includes gastropods, echinoids and colonial corals (Imlay, 1964). The fossils suggest the Carmel is late middle and late Bajocian in age (Peterson and Pipiringos, 1979). Ar/Ar ages from bentonites in the Carmel range from about 166.3 to 167.3 Ma and are close to the Bajocian–Bathonian boundary on the Harland et al. (1990) timescale but older than the Bathonian on the Odin (1994) timescale. Given the poor numerical calibration of the Middle Jurassic portion of the timescale (e.g., Pálfy, 1995), the fossil-based middle to late Bajocian age of the Carmel is the most precise age determination, one consistent with the radioisotopic ages.

Dewey Bridge Member of Entrada Sandstone

In east–central Utah and west–central/southwestern Colorado, McKnight (1940) used the name Carmel Formation to refer to "earthy" siltstones in a stratigraphic position similar to the type Carmel farther west. Wright et al. (1962) questioned this assignment for several reasons. First, these siltstones do not contain the limestone or gypsum beds that are characteristic of the Carmel Formation farther west. Second, and perhaps more important, the "earthy" siltstones are lithologically similar to and laterally continuous with the siltstones of the lower Entrada Sandstone at its type locality in the San Rafael Swell. Third, these "earthy" strata intergrade with the overlying, upper part (Slick Rock Member) of the Entrada Sandstone.

On this basis, Wright et al. (1962) included strata previously mapped as Carmel Formation in eastern Utah–western Colorado in the Entrada Sandstone as the Dewey Bridge Member. Clearly, the Dewey Bridge Member is in part laterally (and temporally) equivalent to the Carmel Formation.

ENTRADA SANDSTONE

Introduction

The Entrada Sandstone was named by Gilluly and Reeside (1928) for exposures at Entrada Point in the San Rafael Swell, east–central Utah. In the type area, the Entrada consists of as much as 95 m of fine-grained, moderate to deep red, quartzose sandstone, with argillaceous (originally described as "earthy") facies. The more typical, well-sorted eolian facies are better expressed eastward and southward into Colorado, New Mexico, Arizona and Oklahoma. Thicker sections are present to the west on the western flank of the San Rafael Swell, where the unit may be in excess of 250 m thick, and in the Henry Mountains south of Hanksville, where Hintze (1988) illustrated a thickness of as much as 136 m. Southward, the unit thins so that in the Four Corners region near Kayenta and westward to Cow Springs the Entrada is 88 m and 100 m thick, respectively (Harshbarger et al., 1957).

The Carmel Formation conformably underlies the Entrada in the type area, and the two units make up the lower part of the San Rafael Group. The Entrada is unconformably overlain by the Curtis Formation in the type

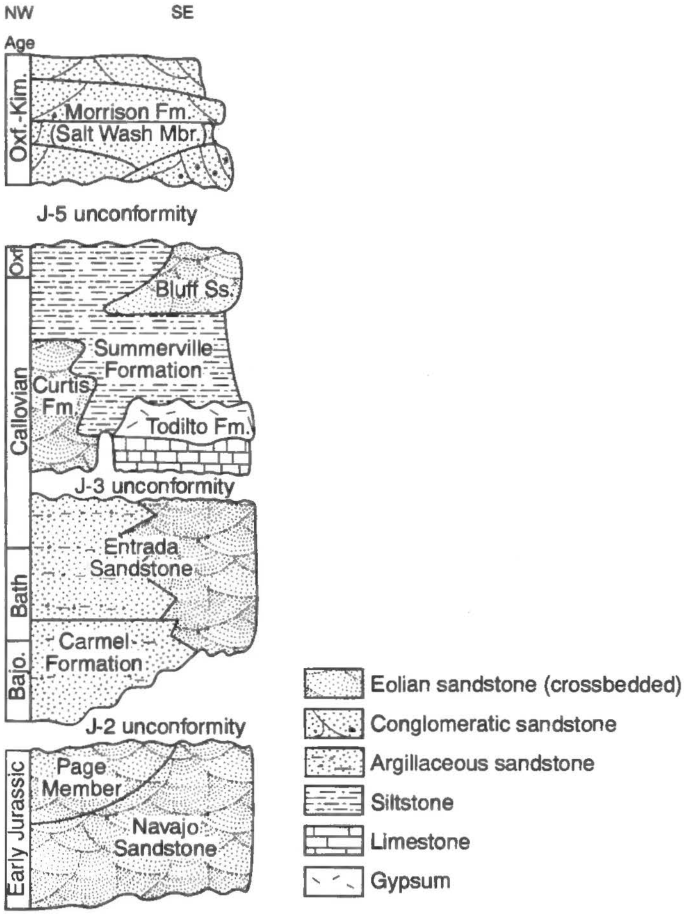


FIGURE 2. Summary of stratigraphy and age relationships of the San Rafael Group.

area, the unconformity being marked by a pebbly zone as much as 1 m thick, which in turn represents a transgressive lag deposit. This is the J-3 unconformity of Pipiringos and O'Sullivan (1978).

As both the underlying (Carmel) and overlying (Curtis) units contain marine fossils, the Entrada has been envisioned as a vast erg which developed on an emergent arid coastal plain during a regression of the shallow, epicontinental, Curtis–Sundance seaway (Fig. 4). The strata in the type area of the Entrada and northward contain evidence of aqueous deposition (Gilluly and Reeside, 1928), and thus are thought to be marginal marine, tidal flat, supra–tidal, and erg–marginal in origin (Kocurek and Dott, 1983). In the Four Corners region, the Curtis Formation is not present, and the Entrada is disconformably overlain by the Summerville Formation, which partly overlaps the Curtis in age (see below).

History of stratigraphic nomenclature

Use of the name Entrada Sandstone to designate a lithostratigraphic unit in the lower part of the San Rafael Group became widespread following its introduction and definition by Gilluly and Reeside (1928). The Entrada was not, however, controversy–free in terms of regional correlations during this early period. It was not recognized southward and southeastward from the Four Corners into New Mexico and Arizona, even though reconnaissance work had indicated its presence in north–central New Mexico. This perception was due primarily to the work of Baker et al. (1936), who were of the opinion that strata of the older Glen Canyon Group (Early Jurassic) could be correlated into the San Juan Basin of New Mexico. A section of well-exposed, highly crossbedded sandstone near Gallup, New Mexico, had been named the Wingate Sandstone (from nearby Fort Wingate) by Dutton (1885). This sandstone was miscorrelated by Baker et al. (1936) with the basal part of the Glen Canyon Group in northeastern Arizona, and thus the name Wingate Sandstone came into general usage regionally.

However, Baker et al. (1947) realized their earlier miscorrelation and proceeded to extend the name Entrada Sandstone southward into New Mexico to be used for strata they had previously called Wingate. Although the name Wingate had precedence, it was abandoned as a formal stratigraphic name for Jurassic rocks. It was only following this remedial action that the San Rafael Group was generally recognized in New Mexico and Arizona.

Hoover (1950) recognized the Entrada Sandstone in extreme northeastern Arizona. He, moreover, identified the finer-grained, parallel-bedded unit overlying the Entrada and in the stratigraphic position of the Summerville Formation as part of the Entrada—the Red Mesa Member. Also included in the Entrada was the eolianite above the fine-grained Red Mesa Member. This upper eolianite was recognized as the Bluff Sandstone, a unit which Gregory (1938) had included in the Morrison Formation, but which Hoover now regarded as the upper member of the Entrada Sandstone. Hoover apparently concluded that eolianites and associated sabkha or arid-cycle deposits along the southwest margin of the Middle Jurassic depositional basin should all be included in one lithostratigraphic or lithogenetic unit—the Entrada Sandstone.

O'Sullivan (1978) also regarded the fine-grained, parallel-bedded strata overlying the Entrada in northeastern Arizona to be associated with the Entrada Sandstone rather than with the Summerville Formation. In O'Sullivan's stratigraphy, however, the Bluff Sandstone was regarded as a post–Entrada depostional event, or more specifically as a post–Cow Springs Sandstone event. Other authors (e.g., Craig, et al., 1955) had considered the Bluff to be merely a northward extending tongue of the Cow Springs Sandstone.

Peterson (1988) discussed the stratigraphy and nomenclature of Middle Jurassic rocks of the western Colorado Plateau. In much of this area he recognized three informal members of the Entrada Sandstone (lower, middle, and upper) and considered the Cow Springs Sandstone equivalent to the upper two members at Black Mesa, Arizona (south of Kayenta), which is the type area of the Cow Springs Sandstone. Peterson illustrated the Cow Springs as a pre–Curtis, pre–Summerville unit (his figure B–2), beneath a regional unconformity, and therefore related it to the lower part of the San Rafael Group. The Cow Springs was accordingly reduced by Peterson to a member of the upper Entrada Sandstone. Nonetheless, in the text he conceded that the Cow Springs is correlative with the unit of the same name (but also called Zuni Sandstone) in the southwestern San Juan Basin, near Zuni, New Mexico. In the Zuni area, the Cow Springs Sandstone (=Zuni Sandstone: Anderson, 1993) is demonstrably equivalent to the undivided Summerville and Bluff Formations, and thus is associated with the upper part of the San Rafael Group. Peterson further conceded that the type Cow Springs can be traced northeastward into strata which have been designated Wanakah Formation in southwestern Colorado. As the Wanakah strata are demonstrably equivalent to and associated with the upper San Rafael Group (Curtis and Summervile Formations), there are thus two independent correlations recognized by Peterson that do not support his illustration that the Cow Springs is pre–Curtis, pre–Summerville in age.

Our observations in the type area of the Cow Springs are consistent for the most part with those of Harshbarger et al. (1957). We recognize, as they did, a distinctive sandstone unit, approximately 100 m thick, consisting of light greenish gray, fine-grained, crossbedded, quartzose sandstone (the type "Cow Springs") overlying a reddish brown, more thinly bedded Entrada Sandstone. We are also in agreement with Harshbarger et al. (1957) in recognizing a persistent, 7 to 8 m thick, red to grayish red or maroon, siltstone-dominated unit separating the Entrada from the overlying Cow Springs Sandstone. Whereas Harshbarger et al. (1957) included the red siltstone-dominated unit with the overlying Cow Springs, we tentatively correlate this siltstone with the unit O'Sullivan (1978) termed the "beds at Baby Rocks" 22 km east of Kayenta, Arizona. The "beds at Baby Rocks" lie at the top of the Entrada Sandstone in the stratigraphic position of the Summerville Formation. On the basis of these lateral relationships, we (as did Harshbarger et al., 1957) recognize the strata called Cow Springs Sandstone (=Zuni Sandstone) as a lithologic unit distinct from and younger than the Entrada Sandstone, and would associate it with the upper part of the San Rafael Group. We do not accept Peterson's (1988) contention that the type Cow Springs is merely the upper part of the Entrada Sandstone.

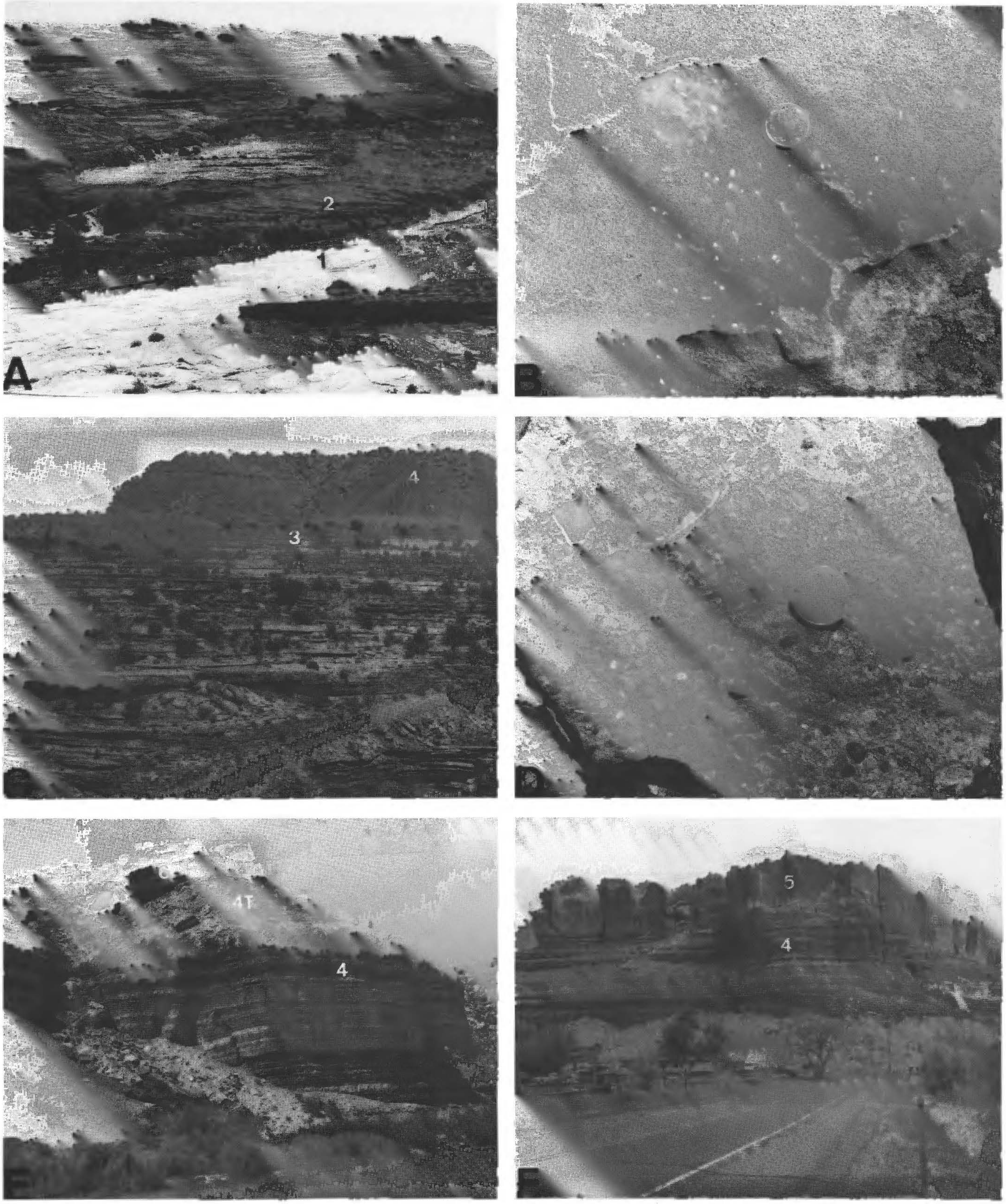


FIGURE 3. Photographs of selected outcrops of Jurassic rocks in the Four Corners region. A, Type section of Page Sandstone (2) showing surface (arrow) separating it from underlying main body of Navajo sandstone (1). B, Close-up view of chert pebbles on surface at Navajo–Page contact. C, Overview of Dry Mesa, Utah, reference section of Summerville Formation showing Curtis (3), Summerville (4) and base of Morrison (5) Formations. D, Siliceous conglomerate at base of Curtis Formation at Dry Mesa that marks the J-3 unconformity. E, Summerville–Morrison section near Dry Mesa showing Beclabito (4) and Tidwell (4T) Members of Summerville Formation overlain by basal Salt Wash Member of Morrison Formation (5). F, Bluff Sandstone (5) overlying Summerville Formation (4) at Bluff, Utah.

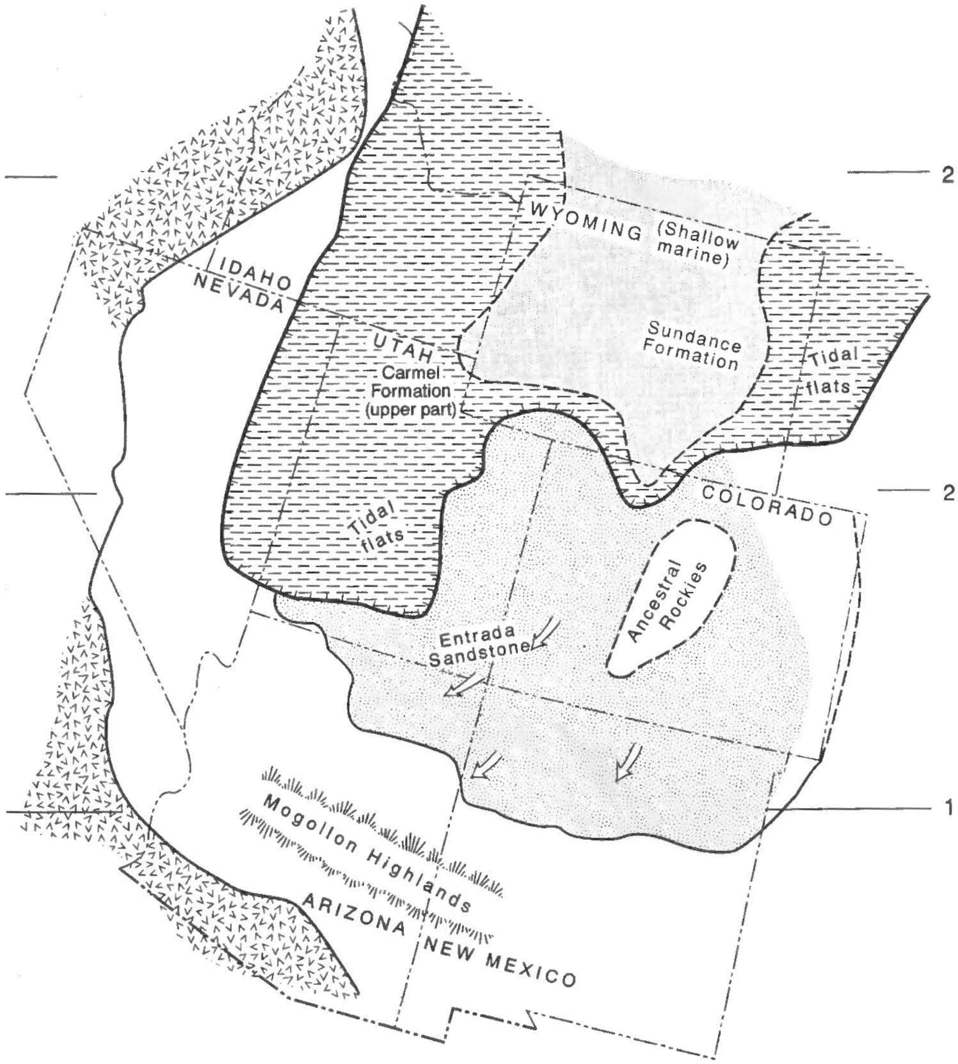


FIGURE 4. Paleogeographic map (generalized) depicting major depositional systems during the Bathonian–early Callovian. Entrada deposition took place in large, well-defined erg, directly influenced by northeast trade winds, with a source area in coastal plains-tidal flats to north.

Members of the Entrada Sandstone

The Entrada Sandstone has been divided into members in eastern Utah–western Colorado and in the San Juan Basin, New Mexico. Wright et al. (1962), as indicated above, named the Dewey Bridge, Slick Rock and Moab members of the Entrada in Utah–Colorado. In the San Juan Basin, the Iyanbito, medial silty and upper sandy members of the Entrada are recognized (Harshbarger et al., 1957; Green, 1974; Condon and Peterson, 1986). The latter two members have also been identified off of the Colorado Plateau in the Hagan basin of north–central New Mexico (Lucas et al., 1995).

These members of the Entrada are local/regional units of stratigraphic utility. Their correlation to each other—from Utah–Colorado to the San Juan Basin—poses an interesting problem, still not solved. As noted above, the Dewey Bridge Member is correlative to at least part of the Carmel Formation (Wright et al., 1962), so it is above the J-2 unconformity. Wright et al. (1962, p. 2062) raised the possibility that the lithologically similar Dewey Bridge and medial silty members may be correlative. If this correlation is correct (and it remains to be established), then the Iyanbito may lie below the J-2 unconformity. This would mean that the Iyanbito Member correlates with part of the Glen Canyon Group, probably the Navajo Sandstone. Further work is needed to evaluate this possibility.

Depositional environments

In the type area, the Entrada Sandstone is a fine- to medium-grained, parallel and even-bedded sandstone, with significant silty or siltstone facies. It is regarded as a water laid deposit (Gilluly and Reeside, 1928; Baker et al., 1936), but lacks fossils that indicate marine influence. Elsewhere, particularly to the east and south, bedding planes are less conspicuous bedding features, and crossbedding becomes more common and distinct; in these areas the unit is considered to be largely eolian in origin (Harshbarger et al., 1957; Poole, 1962; Kocurek and Dott, 1983; Peterson, 1988; Blakey et al., 1988), and represents deposition in a large dune field or erg.

These lateral relationships considered in the context of the vertical facies relationships (marine influenced strata both above and below) allow a moderately well-constrained depositional model for the Entrada (Fig. 4). Strata in the type area apparently were deposited in a marginal marine setting during a regression of the Sundance seaway system; specific environments likely included tidal flats, supra-tidal, shallow playa, and erg-marginal conditions with considerable clastic input from eolian processes (Kocurek and Dott, 1983). This depositional setting gave way southward and eastward to major erg development influenced directly by the northeasterly trade winds characteristic of the subtropical zone. This is supported by the fact that the crossbedded facies generally indicate southward and southwestward paleotransport directions (Poole, 1962). Erg development continued until southward expansion of the Sundance–Curtis seaway system produced a marine transgression that vastly reduced the source area for eolian materials and that inundated the type area of the Entrada in east–central Utah. Landward from the shallow seaway, a broad, featureless arid coastal plain existed upon which was developed the sabkha, playa, and supra-tidal environments that gave rise to the fine grained, gypsiferous, horizontally-bedded strata of the overlying Summerville and related formations.

Paleontology and age

One body fossil of a reptile—the crocodyliform *Entradasuchus spinosus* Hunt and Lockley, 1995—has been reported from the Entrada Sandstone. Numerous dinosaur footprints, mostly of theropods, are also known, especially from southeastern Utah (Lockley, 1991a,b). These fossils indicate that tetrapods lived in the Entrada erg, but they are under-represented as body fossils in Entrada strata.

These fossils from the Entrada suggest a Jurassic age, but are not more precise age indicators. Stratigraphic relationships and the ages of vertically adjacent units (underlying Carmel, overlying Curtis) suggest the Entrada is of Bathonian to early Callovian age (Imlay, 1980).

CURTIS FORMATION

Introduction

The Curtis Formation disconformably overlies the Entrada Sandstone (J-3 unconformity), is laterally equivalent to the lower part of the Summerville and is gradationally overlain by the middle-upper part of the Summerville Formation (Figs. 2, 3C). At its type section in the San Rafael Swell, the Curtis is 93 m thick and is mostly greenish gray, crossbedded and ripple-laminated fine-grained sandstone and minor glauconitic clay. Its erosional base on the Entrada Sandstone is marked by as much as 15 m of stratigraphic relief and by siliceous conglomerates of chert and flint pebbles (Fig. 3D). In the type area, the Curtis grades upward into finer-grained, more evenly and cyclically-bedded red beds of the Summerville Formation. The Curtis Formation is not present in the Four Corners region; it extends to the southeast of the San Rafael Swell only as far as the Green River Desert northwest and west of Moab, Utah (Fig. 1). However, lateral correlation of the Curtis into the Four Corners region is of some interest.

Sedimentation and age

The base of the Curtis Formation is a transgressive unconformity, and the unit represents marine flooding of the central and western portions of the San Rafael Group basin (Caputo and Pryor, 1991). In other words, the Curtis Formation is much of the transgressive systems tract of the unconformity-bounded Curtis–Summerville sequence.

The Curtis has produced a sparse marine invertebrate fauna of shallow water bivalves of limited biostratigraphic value. Northward and northeastward from Utah, the Curtis can be traced directly into the lower Stump Sandstone of Idaho–Wyoming, which rests directly on the Preuss Sandstone of well-established early Callovian age. For this reason, the Curtis is usually assigned a middle Callovian age (Imlay, 1980).

Correlation of the Curtis and Todilto

The Curtis can be traced eastward from the San Rafael Swell to the Green River Desert and shown on physical stratigraphic evidence to grade into the lower part of the Summerville Formation (e.g., McKnight, 1940). However, to the east and the southeast—in the Four Corners region and San Juan Basin—correlation of the Curtis cannot be demonstrated so directly.

Regional stratigraphic relationships indicate that the Todilto is homotaxial with the marine Curtis Formation in Utah (Anderson and Lucas, 1992, 1994). Both units are between the Entrada and Summerville formations, and both have pebbly zones (transgressive lag deposits) at their bases. The regional rise in base level that led to transgression of the Curtis seaway and the resultant highstand produced a paralic salina in northern New Mexico–southwestern Colorado, immediately southeast of the seaway (Imlay, 1980; Anderson and Lucas, 1994; Kirkland et al., 1995).

TODILTO FORMATION

Introduction

One of the most distinctive Jurassic lithostratigraphic units in the American Southwest is the Todilto Formation of northern New Mexico and southwestern Colorado. This relatively thin (>75 m) unit is almost totally carbonates and evaporites in a thick section otherwise dominated by siliciclastic eolianites (Fig. 2). The Todilto Formation is extremely significant economically as a source rock for petroleum (Vincelette and Chittum, 1981) and uranium (Chenoweth, 1985); it also provides all the gypsum mined in New Mexico (Weber and Kottlowski, 1959). Because of its economic importance,

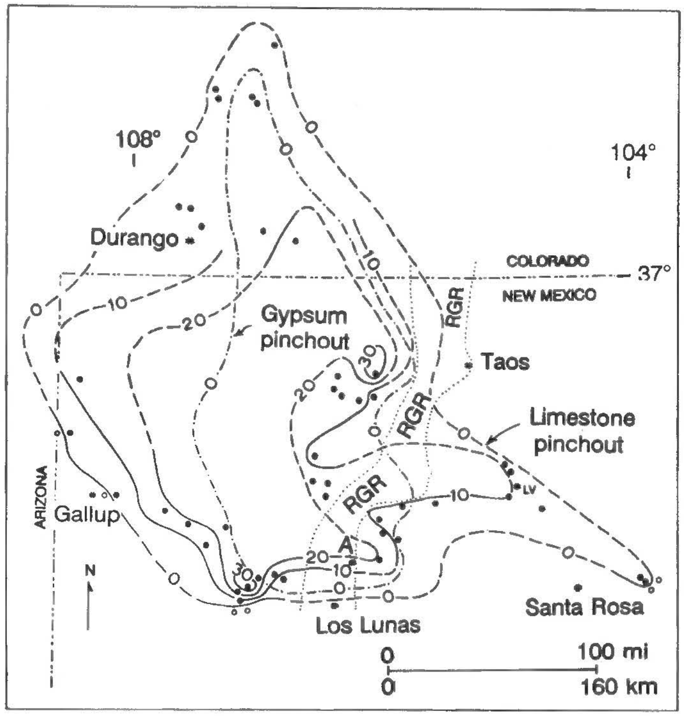


FIGURE 5. Isopach map of Todilto Formation based on Kirkland et al. (1995). A= Albuquerque, LV = Las Vegas and RGR = Rio Grande rift.

much study of the Todilto has been undertaken, and a vast literature exists (see reviews by Lucas et al., 1985; Kirkland et al., 1995).

Some earlier workers regarded the Todilto as having been deposited in a marine embayment of the Middle Jurassic Curtis seaway (e.g., Harshbarger et al., 1957; Ridgley and Goldhaber, 1983), but more recent studies of stratigraphy, paleontology and geochemistry indicate that any marine connection to the Todilto basin was short-lived and/or intermittent (Lucas et al., 1985; Kirkland et al., 1995). Todilto deposition took place in a paralic salina culminated by a gypsiferous evaporitic lake.

Stratigraphy

The Todilto Formation crops out and is present in the subsurface across most of northern New Mexico and southwestern Colorado (Fig. 5; Lucas et al., 1985; Kirkland et al., 1995; Lucas and Kietzke, 1986). Throughout its extent, the Todilto rests on the Entrada Sandstone with minor disconformity and is overlain disconformably to conformably by the Summerville Formation (Fig. 2).

Two members of the Todilto Formation are recognized—Luciano Mesa (limestone) and Tonque Arroyo (gypsum) (Fig. 6). The Luciano Mesa Member has a maximum thickness of 13.3 m and is mostly microlaminated, kerogenic limestone. It crops out over an area of 88,000 km^2 in northern New Mexico and southwestern Colorado. The unit can be divided at most outcrops into a lower, thinly laminated limestone and an upper massive limestone. The lower limestone has fine (mm-scale) laminations that are locally microfolded and contorted. It typically overlies Entrada eolianite sandstone with erosional unconformity marked by a thin (20 cm or less) interval of limey sandstone that is often pebbly. This is the J-3 unconformity.

The upper, massive limestone is a ledge-forming, poorly laminated carbonate containing numerous vugs filled with secondary carbonate. The vugs are selectively located in rounded, "algal"-like structures, and some contain thin needles of secondary gypsum. The structures, however, lack the finely laminated texture typical of most algal stromatolites. Anderson and Kirkland (1960) suggested the microlaminae of the Luciano Mesa Member form varved couplets and counted these couplets to estimate a duration of about 14,000 years for their deposition.

The Tonque Arroyo Member of the Todilto Formation is as much as 61 m thick and mostly massive and brecciated white gypsum. In its lower part the Tonque Arroyo Member contains some 1–2–mm–thick carbonate lay-

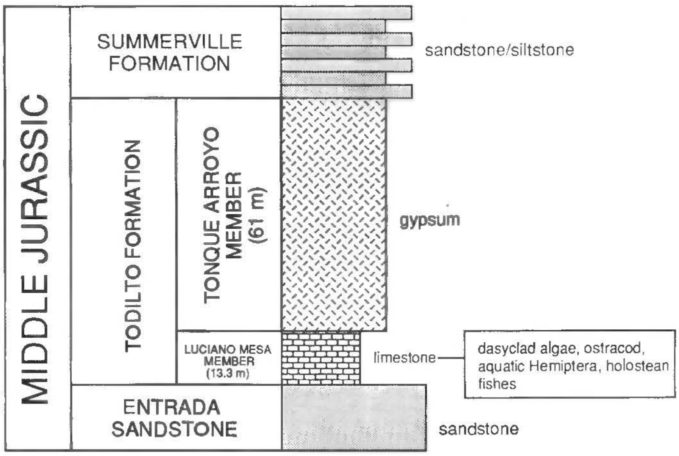


FIGURE 6. Summary of the stratigraphy and paleontology of the Todilto Formation.

ers. The Luciano Mesa Member has a much broader distribution than the Tonque Arroyo Member, and is a continuous unit across the Todilto depositional basin (Fig. 7). The Tonque Arroyo Member has a more limited outcrop belt, widely varying thickness and numerous local pinchouts.

Tectonics and sedimentation

The Todilto basin developed in a tectonically passive downwarp between two east–west oriented positives, the Mogollon highland of east–central Arizona and west–central New Mexico and the Uncompaghre highland of north–central New Mexico and south–central Colorado (Kirkland et al., 1995). Laterally persistent laminae of calcite and organic matter in the Luciano Mesa Member of the Todilto Formation suggest deposition in quiet water with no bioturbating benthos. Kirkland et al. (1995) estimated the Todilto waterbody to have been stratified and less than 91.5 m deep.

A regional drop in base level cut the Todilto depositional basin off from waters in the Curtis seaway to the northwest and initiated evaporite deposition (Lucas et al., 1985). The sub–Todilto paleotopography of Entrada dunes controlled evaporite deposition, confining it largely to brine pools that developed in inter–dunal lows (Vincelette and Chittum, 1981).

Paleontology, age and correlation

Fossils are not abundant in the Todilto Formation. No megafossil plants are known, and attempts to extract identifiable palynomorphs have failed (Anderson and Kirkland, 1960). Algal structures are present, as are dascycladacaean algae at one locality in west–central New Mexico (Armstrong, 1995). Invertebrate fossils are limited to the ostracod *Cytheridella* and aquatic Hemiptera, including *Xiphenax jurassicus* (Cockerell, 1931; Kietzke, 1992; Kirkland et al., 1995). Fossil vertebrates

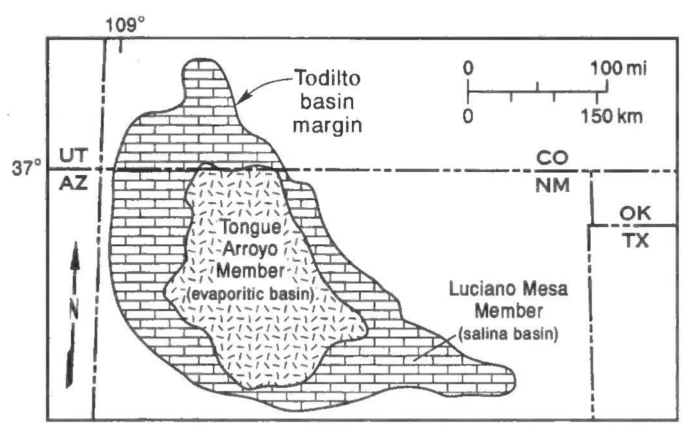


FIGURE 7. Location and distribution of the two members of the Todilto Formation in northern New Mexico and southwestern Colorado. The distribution of the Luciano Mesa Member essentially defines the extent of the Todilto depositional basin.

are the holostean fishes *Hulettia americana*, *Todiltia schoewei* and *Caturus dartoni* (Koerner, 1930; Dunkle, 1942; Schaeffer and Patterson, 1984; Lucas et al., 1985).

If the Todilto is correlative to the Curtis, then the Todilto is of middle Callovian age. Certainly, its position above the Bathonian–early Callovian Entrada and below the Callovian–Oxfordian Summerville is consistent with a middle Callovian age assignment.

Only the fossil fishes provide a possible paleontological basis for correlation of the Todilto Formation. Nevertheless, one of the fossil fishes from the Todilto Formation—*Hulettia americana* (Eastman)—is also known from the Canyon Springs Sandstone and the Stockade Beaver Shale Members of the Sundance Formation of South Dakota-Wyoming, units of Bathonian age (Schaeffer and Patterson, 1984). The age discrepancy this creates has to be explained away ad hoc—*Hulettia americana* has a longer temporal range (Bathonian–Callovian) than is recorded in either area, South Dakota/Wyoming or New Mexico/Colorado.

Salina deposition

Several lines of evidence suggest that the Todilto depositional basin had little connection to the Jurassic seaway and instead was a vast, paralic salina:

1. No direct stratigraphic continuity of Todilto strata and marine Jurassic strata exists, either on outcrop or in the subsurface. The Todilto pinches out around its preserved basin periphery into eolianites (Lucas et al., 1985; Anderson and Lucas, 1992).

2. No clearly marine fauna or flora are known from the Todilto Formation. Instead, a very low diversity fish fauna, characteristic of saline lakes, is known from the Todilto (Barbour and Brown, 1974; Lucas et al., 1985). Indeed, the low diversity fish and invertebrate fauna of the Todilto is strikingly similar to that of Quaternary salinas in Australia (e.g., Warren, 1982; Warren and Kendall, 1985). Armstrong (1995) claimed that the dascyclad algae found in the Todilto near Grants, New Mexico indicate a marine environment, but today these algae tolerate a wide range of salinity from fresh to hypersaline waters.

3. Carbon and sulfur isotope ratios calculated for Todilto limestones have a wide range of values compatible with a nonmarine, marine or mixed waterbody (Kirkland et al., 1995). However, strontium isotope ($^{87}Sr/^{86}Sr$) ratios for the Todilto do not match those of sediments deposited from normal marine Callovian seawater (Kirkland et al., 1995).

Reconstructing the Todilto paleoenvironment as a salina is consistent with all data. Todilto deposition began with initial flooding of marine waters during transgression of the Curtis–Sundance seaway. After the initial flooding, the Todilto basin was separated from the seaway by coastal ergs (Fig. 8). Freshwater stream runoff, influx of seawater by seepage through the erg and possible short-lived overtopping of the erg maintained the Todilto salina. Increased aridity promoted evaporation, which eventually produced a smaller, evaporitic basin in which gypsum precipitated.

SUMMERVILLE FORMATION

Introduction

The Summerville Formation was named for exposures at Summerville Point in the San Rafael Swell by Gilluly and Reeside (1928). In that area (east–central Utah), the Summerville forms the uppermost unit of the San Rafael Group. It consists of a sequence of thinly bedded, very fine-grained silty sandstone and lesser mudstone, generally reddish, grayish red, or "chocolate" in color, as much as 50 m thick in the type area (Fig. 9). To the south in the Four Corners region it is thinner, being approximately 23 m thick (Baker et al., 1936) near Bluff and thinning into northeastern Arizona.

Underlying the type Summerville with a gradational and laterally intertonguing relationship is the Curtis Formation (Fig. 3C). Thus, the Summerville and the Curtis partly overlap in age. The Curtis contains molluscan fossils indicative of a marine depositional environment (Gilluly and Reeside, 1928), but the unit is areally restricted. It is not present in areas south of the San Rafael Swell and hence not present in the Four Corners area. Nonetheless, it is important to recognize the proximity of marine influence to the basin of Summerville deposition for several reasons. Many authors have attributed the Summerville to deposition on an arid coastal plain in sabkha, tidal flats, or shallow water hypersaline environments (Stanton, 1976; Kocurek and Dott, 1983; Anderson and Lucas,

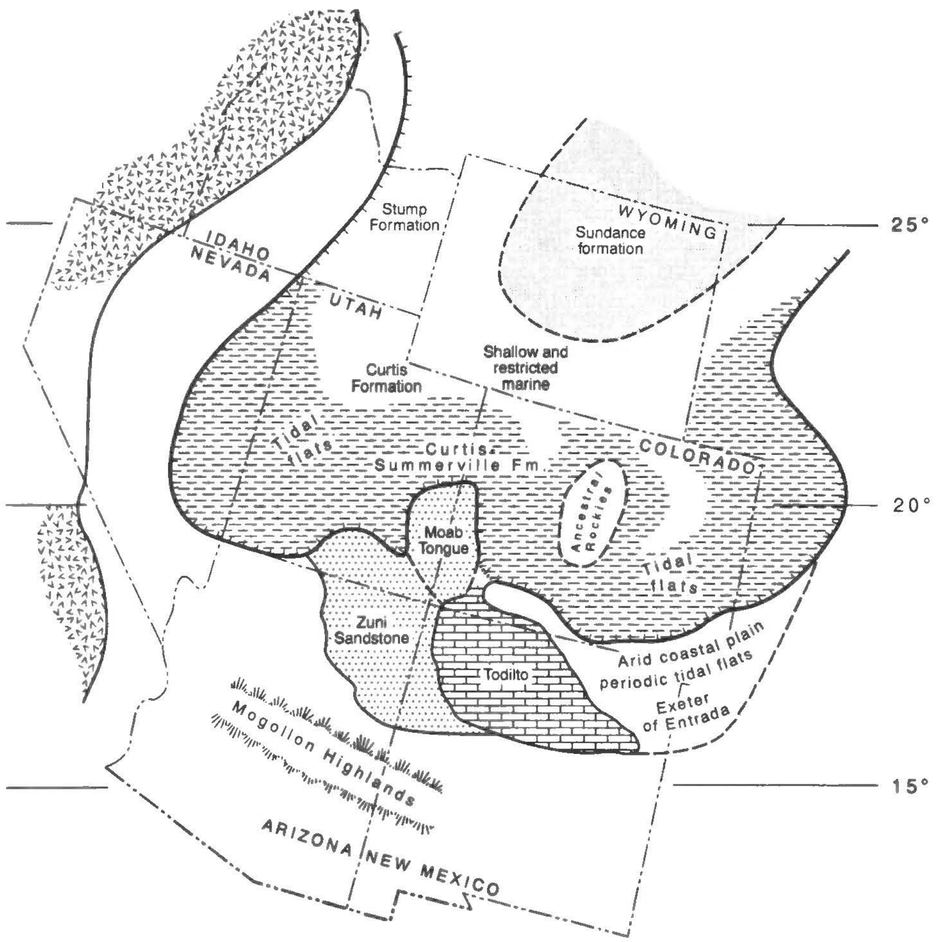


FIGURE 8. Paleogeographic map showing major depositional systems during middle Callovian–earliest Oxfordian time, representing maximum extent of the tidal flats-sabkha environment in which the Summerville Formation was deposited; the Zuni Sandstone is only partly contemporaneous with Summerville deposition.

1992). Without direct evidence of incursion of marine waters into the general area, the interpretation of arid coastal plain–sabkha–tidal flats environments becomes highly speculative. Even so, very broad, flat coastal plains underlain by permeable strata saturated with marine or hypersaline groundwater far inland are necessary to defend the depositional setting hypothesized for Summerville strata (Fig. 8).

In areas where neither the Curtis or the Todilto are present, such as in southeastern Utah and northeastern Arizona, the Summerville rests with disconformity on the Entrada Sandstone. In that same area as well as in adjacent northwestern New Mexico, the Summerville is overlain by the Bluff Sandstone (Fig. 3F). In areas north of Bluff, Utah, the Summerville is unconformably overlain by the Salt Wash Member of the Morrison Formation.

History of nomenclature

Following the introduction and widespread usage of the name San Rafael Group (Gilluly and Reeside, 1928) for Middle Jurassic strata in east–central Utah, additional regional studies were initiated. Baker et al. (1936) discussed correlation of the San Rafael Group within Utah and adjacent states. They contended that the Summerville could not be correlated into New Mexico, but this contention was based largely on the misapprehension that the underlying Entrada Sandstone did not extend into New Mexico. An interesting observation of Baker et al. (1936, p. 21) is that in some areas where the Bluff Sandstone is present the Morrison strata immediately overlying the Bluff were noted to be "not greatly different" from the Summerville Formation. This is consistent with Anderson and Lucas (1995), who found that the strata overlying the Bluff in its type area are similar to Summerville lithologies and should therefore be associated with the San Rafael Group.

Gregory (1938, p. 57–58), in his studies in southeastern Utah, suggested the Summerville is conformable on the Entrada Sandstone in most places. He, however, attempted to define the top of the Summerville as an unconformity, based on some distorted bedding, which was in turn overlain by the "Bluff Sandstone Member of the Morrison." Then, he hedged on this observation, contending that the contact he picked was ambiguous: "similar breaks in continuity of sedimentation appear above and below the contact," meaning his Summerville–Morrison contact. He further stated that "the division plane may prove to lie at one of several horizons within 500 ft of Summerville? or Morrison sediments." These "horizons" were probably distorted or irregularly bedded zones, locally common in the Summerville and probably related to dewatering, soft sediment deformation, or gypsum formation and dissolution. One of the "horizons" might even have been the unconformity above the Bluff Sandstone that marks the general onset of fluvial (Morrison) deposition in the region.

Baker et al. (1947) recognized that the Summerville and underlying Entrada Sandstone had broader areal extent than they had previously believed. This permitted the extension of San Rafael Group units into southwestern Colorado and particularly into northern New Mexico, and carried significant implications for regional correlation of Middle Jurassic rocks. Unfortunately, Baker et al. reduced the significance of their own work by emphasizing instead the fact that the San Rafael Group–Morrison contact "is not yet definitely known in New Mexico." As a result, they advocated use of the name "Wanakah Formation," a parochial, preoccupied name from southwestern Colorado, for "these upper beds of the San Rafael Group" in New Mexico. This did little to solve the basic lithostratigraphic problem involved, i.e., the placement of a mappable contact between arid-cycle San Rafael Group strata and the overlying fluvial sequence, the Morrison Formation.

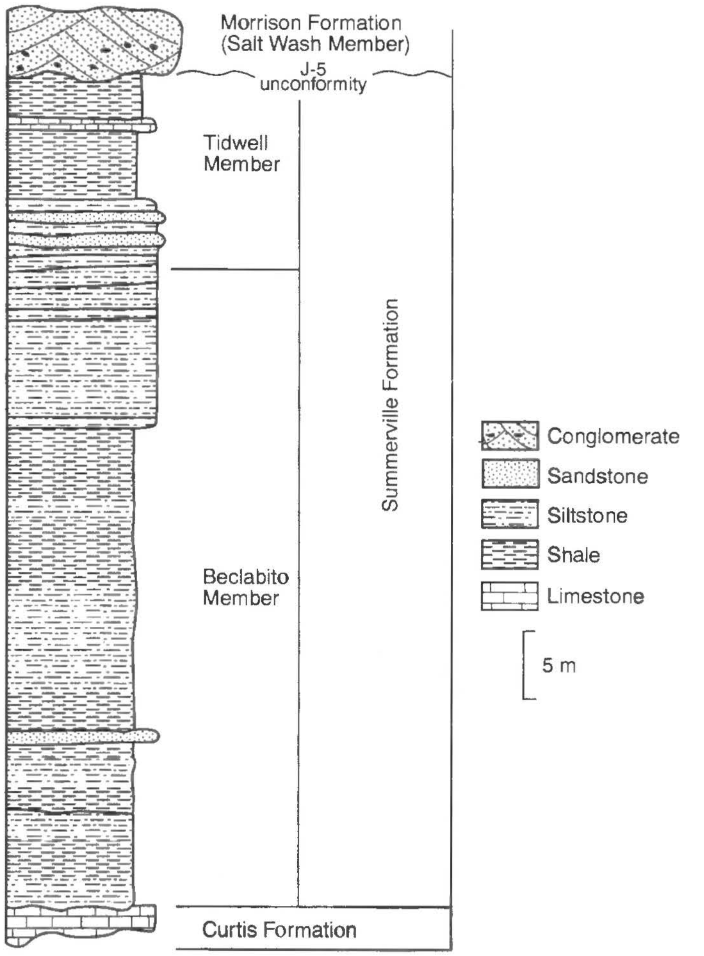


FIGURE 9. Dry Mesa, Utah, reference section of the Summerville Formation. See Appendix for description of the numbered stratigraphic units.

Additional nomenclature was provided by Hoover (1950). He recognized a crinkly (distorted) bedded unit in the stratigraphic position of the Summerville Formation near Red Mesa in northeastern Arizona, 27 km west of the Four Corners. He designated this unit the Red Mesa Member and regarded it as part of the Entrada Sandstone. His justification for yet another name was that the Red Mesa Member differed in lithologic character and color from the type Summerville. Moreover, he doubted continuity northward of his new unit with the Summerville Formation.

It is likely that the configuration of the sabkha–playa depostional system of Summerville time was highly irregular and embayed (based on thickness variations). This would allow local variations in subenvironments and salinity. However, the strata deposited in this post–Entrada system have a unifying characteristic; they are all very fine grained (low energy), horizontally-parallel bedded, thinly bedded, and gypsiferous (the latter to varying degrees). Physically and lithogenetically they are related and occur in similar stratigraphic position. Perhaps Hoover could have made a stronger case by relating his Red Mesa Member to the Summerville Formation. As it was, his name Red Mesa never gained widespread usage. He did, however, recognize the overlying Bluff Sandstone as part of the San Rafael Group as an upper member of the Entrada Sandstone. Had this perception of the stratigraphy been given serious and proper attention it might have removed any further temptation to include the Bluff Sandstone in the Morrison Formation.

Hoover, very significantly, noted that the Bluff locally graded southward into his Red Mesa Member. This is at odds with a later interpretation by O'Sullivan (1978), who illustrated the Bluff as a post–Summerville (=Red Mesa Member) unit, and even more significantly as a post–Cow Springs Sandstone unit.

Craig et al. (1955) noted that the strata between the Entrada and the Morrison Formation in the Four Corners area may be complicated by many facies changes and that perceptions have been further complicated by several formation and member names. Nonetheless, they recognized the Summerville as a marginal marine deposit formed in relatively quiet shallow water, and as a lithostratigraphic unit extending into northwestern New Mexico. Their work, coming on the heels of an intense uranium exploration effort on the Colorado Plateau, provided much of the basis for extending San Rafael Group and Morrison Formation units into the San Juan Basin of northwestern New Mexico.

O'Sullivan (1978) correlated Summerville strata into northeastern Arizona to a point approximately 32 km east of Kayenta. From this area westward and southward, the fine-grained facies in this stratigraphic position were assigned the informal name "beds at Baby Rocks" from the locality of the same name on U. S. Highway 160, approximately 22 km east of Kayenta. In this area, the "beds at Baby Rocks" weather to rounded, spheroidal forms termed "hoodoos" or stone babies, but the unit, nonetheless, exhibits the ribbed weathering profile so characteristic of Summerville strata, and forms nearby vertical cliffs. The "beds at Baby Rocks" consist of a relatively thin-bedded succession of very fine-grained sandstone and silty sandstone, as much as 28 m thick; the succession reportedly exhibits less distorted or crumpled bedding than the correlative Summerville strata (particularly the lower Summerville) to the east (O'Sullivan, 1978). Apparently for this and perhaps other reasons related to nomenclatural preferences, O'Sullivan considered these strata to be part of the Entrada Sanstone, but we assign them to the Summerville Formation. The extent to which strata in this part of the section are contorted or crumpled may be related to gypsum content, which tends to be higher in a basinward (northward and eastward) direction. Bedded gypsum, present as a basinal facies in the type area, is not present in Summerville strata of northeastern Arizona (O'Sullivan, 1978).

Members of the Summerville Formation

The Summerville Formation can be divided into two members, for which formal names already exist (Figs. 3E-F, 9). These are the Beclabito Member (lower) and Tidwell Member (upper). The Beclabito Member (Condon and Huffman, 1985) is mostly sandy shale and siltstone that is pale brown, grayish red and brownish gray. Dominant bedforms are parallel laminations and ripple laminations. Numerous thin beds and nodules of gypsum are characteristic. In contrast, the Tidwell Member (Peterson, 1988) is mostly olive gray and greenish gray and a slope former, not a cliff former. Though bedforms and lithologies of the two Summerville Members are very similar, the Tidwell generally has more shale and limestone than the Beclabito.

Regional lithostratigraphic correlation (Fig. 10; Anderson and Lucas, 1992) indicates that (1) the Beclabito Member is most of the Summerville Formation across its outcrop belt in Utah, Colorado, Arizona, New Mexico and western Oklahoma; (2) the Tidwell Member is only present in Utah and southwestern Colorado; (3) in the Four Corners region, the Bluff Sandstone rests directly on the Beclabito Member, thus occupying the same stratigraphic position as the Tidwell Member; and (4) the upper Recapture member of the Bluff is cyclically bedded siltstones and fine sandstones similar lithologically to the Tidwell Member; farther to the southeast, in the San Juan Basin, New Mexico, the Bluff Sandstone and a paleoweathering profile between it and the base of the Morrison Formation is correlative to the Tidwell Member (Anderson and Lucas, 1995).

Depositional environments

The Summerville Formation was deposited in rather quiet, ephemeral shallow water on an arid coastal plain of very low slope and relief (e.g., Gilluly and Reeside, 1928; Baker et al., 1936; Craig et al., 1955; Kocurek and Dott, 1983; Peterson, 1988; Anderson and Lucas, 1992). Proximity to a Middle Jurassic seaway is provided by the marine strata of the Curtis Formation, the upper part of which grades laterally into the Summerville. The Summerville is thus associated with the transgression, highstand and eventual regression of the Curtis seaway. The lack of fossiliferous strata or other marine indicators in the Summerville suggest that at no time did the seaway extend into the area of Summerville deposition. The thinly and evenly bedded nature of the unit, the bedded gypsum locally, the fine-

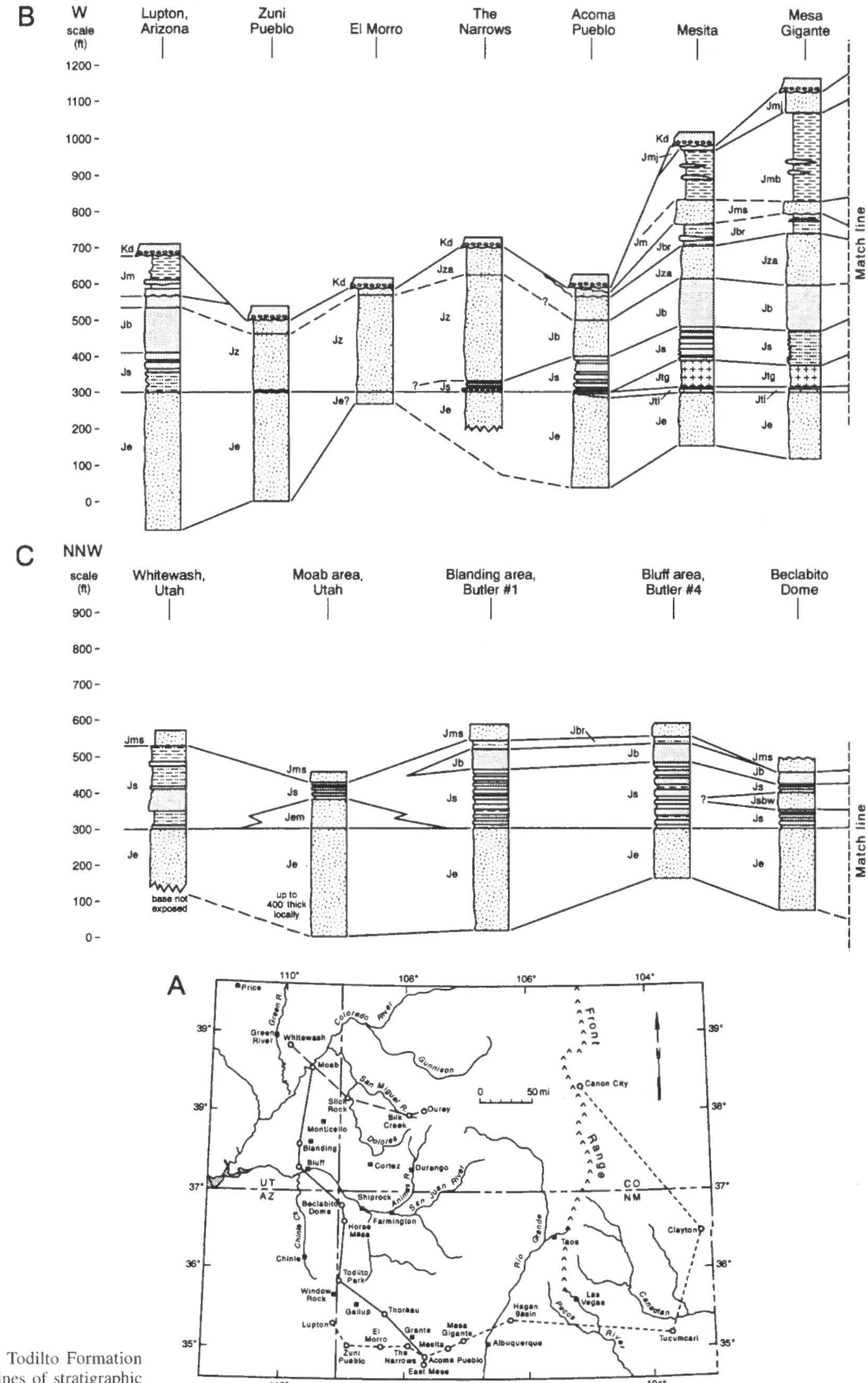
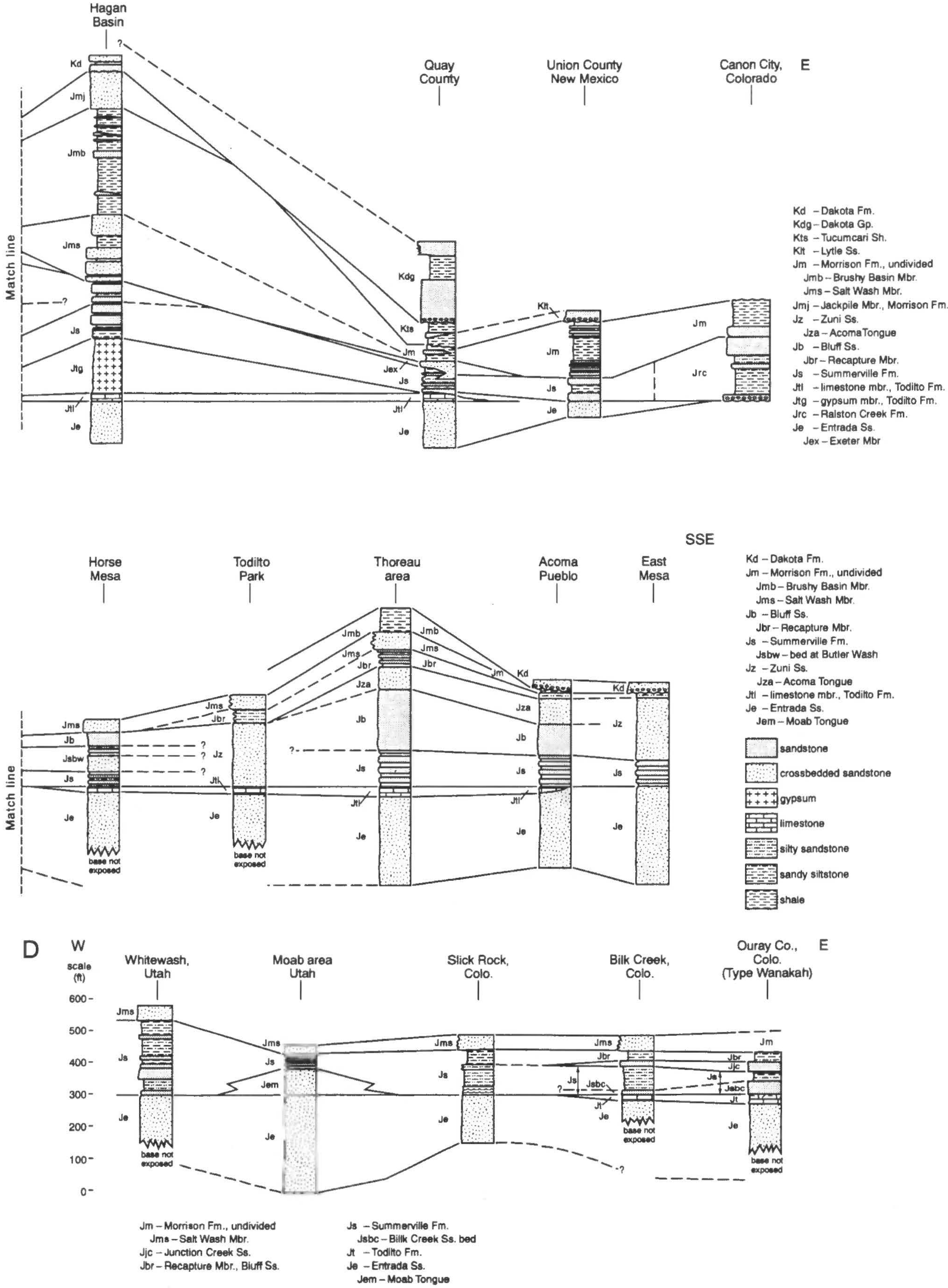


FIGURE 10. Regional correlation of the Todilto Formation and other San Rafael Group strata. A—Lines of stratigraphic cross sections shown in B-D. B—Lupton, Arizona to NE New Mexico. C—Whitewash, Utah to Acoma Pueblo, New Mexico. D—Whitewash, Utah to Ouray, Colorado.


Hagan Basin
Quay County
Union County New Mexico
Canon City, Colorado
E
Match line
Kd
Jmj
Jmb
Jms
Js
Jtg
Jtl
Je
Kdg
Kts
Jm
Jex
Klt
Jrc
Kd – Dakota Fm.
Kdg – Dakota Gp.
Kts – Tucumcari Sh.
Klt – Lytle Ss.
Jm – Morrison Fm., undivided
Jmb – Brushy Basin Mbr.
Jms – Salt Wash Mbr.
Jmj – Jackpile Mbr., Morrison Fm.
Jz – Zuni Ss.
Jza – Acoma Tongue
Jb – Bluff Ss.
Jbr – Recapture Mbr.
Js – Summerville Fm.
Jtl – limestone mbr., Todilto Fm.
Jtg – gypsum mbr., Todilto Fm.
Jrc – Ralston Creek Fm.
Je – Entrada Ss.
Jex – Exeter Mbr
SSE
Horse Mesa
Todilto Park
Thoreau area
Acoma Pueblo
East Mesa
Jb
Jsbw
Jbr
Jz
Jza
base not exposed
Kd – Dakota Fm.
Jm – Morrison Fm., undivided
Jmb – Brushy Basin Mbr.
Jms – Salt Wash Mbr.
Jb – Bluff Ss.
Jbr – Recapture Mbr.
Js – Summerville Fm.
Jsbw – bed at Butler Wash
Jz – Zuni Ss.
Jza – Acoma Tongue
Jtl – limestone mbr., Todilto Fm.
Je – Entrada Ss.
Jem – Moab Tongue
sandstone
crossbedded sandstone
gypsum
limestone
silty sandstone
sandy siltstone
shale
D
W
scale (ft)
600
500
400
300
200
100
0
Whitewash, Utah
Moab area Utah
Slick Rock, Colo.
Bilk Creek, Colo.
Ouray Co., Colo. (Type Wanakah)
E
Jem
Jsbc
Jt
Jjc
base not exposed
Jm – Morrison Fm., undivided
Jms – Salt Wash Mbr.
Jjc – Junction Creek Ss.
Jbr – Recapture Mbr., Bluff Ss.
Js – Summerville Fm.
Jsbc – Bilk Creek Ss. bed
Jt – Todilto Fm.
Je – Entrada Ss.
Jem – Moab Tongue

grained aspect, and the lack of fluvial features strongly suggest sabkha, large shallow playa, and perhaps tidal flat depositional environments, with clastic input from eolian processes acting on the adjacent ergs.

Paleontology and age

Dinosaur body fossils—mostly fragmentary or isolated bones of sauropods—have been collected from the Summerville Formation at localities in Utah and New Mexico (e.g., Lucas et al., 1995, 1996). The type locality of the sauropod dinosaur *Dystrophaeus viaemalae* is in the Tidwell Member of the Summerville Formation in San Juan County, Utah (Gillette, 1993, 1996). Theropod dinosaur footprints and pterosaur tracks are found in the Summerville Formation at many localities (Lucas et al., 1990; Anderson and Lucas, 1996; Lockley et al., 1996). These fossils are consistent with either a Middle or Late Jurassic age, but are not more precise age indicators.

Imlay (1980) assigned the Summerville Formation a late Callovian age based on regional stratigraphic relationships. However, charophytes and ostracods suggest an Oxfordian age for the Tidwell Member (Schudack et al., 1997). A radioisotopic age (Ar-Ar) of 154.9 ± 1.5 Ma from the Tidwell Member suggests an Oxfordian age on the Harland et al. (1990) numerical time scale (Peterson et al., 1993) and is consistent with the microfossils. The Summerville thus apparently straddles the Callovian–Oxfordian boundary.

BLUFF SANDSTONE

Introduction

The Bluff Sandstone was formally named by Gregory (1938) for exposures at Bluff, Utah (Fig. 11A), where it forms prominent cliffs at the top of the San Rafael Group (Baker et al., 1936, noted that the name "Bluff sandstone" had been used locally as an informal term). It reaches a maximum thickness of approximately 100 m in the area immediately south of Bluff (O'Sullivan, 1978), but thins northward (nonuniformly), southward and eastward from that point. Eastward it is the same unit called the Junction Creek Sandstone (Goldman and Spencer, 1941; Craig et al., 1955; Poole, 1962), an eolianite which in southwestern Colorado locally exceeds the Bluff in thickness (Figs. 11C, 12). Westward and southwestward the Bluff Sandstone as well as the closely related, underlying Summerville Formation grade into a distinctive eolianite called the Cow Springs Sandstone (Harshbarger et al., 1951, 1957; O'Sullivan, 1978). The Cow Springs Sandstone (Harshbarger et al., 1951) is a junior synonym for the Arizona portion of the lithostratigraphic unit named the Zuni Sandstone by Dutton (1885) for the excellent exposures near Zuni, New Mexico.

History of nomenclature

Although the Bluff Sandstone was originally assigned to the Morrison Formation as its basal member (Gregory, 1938), that perception of stratigraphy was soon questioned by Goldman and Spencer (1941) and by Craig et al. (1955). Both of these works recognized the Bluff and its correlative units as pre-Morrison lithotypes.

Three problems plagued the Bluff Sandstone from the beginning of its recognition as a formal lithostratigraphic unit: (1) the Bluff is not present at the type locality of the San Rafael Group in east–central Utah, so Gregory (1938) was predisposed to include any strata overlying the uppermost unit of the type San Rafael Group in the younger Morrison Formation; (2) Gregory provided no criteria for defining the base of the Morrison Formation once he included the Bluff Sandstone in it as the basal member; and (3) a fine-grained, flat-bedded, red-bed unit at the top of and intertonguing with the Bluff Sandstone is lithologically and lithogenetically similar to strata underlying the Bluff (i.e., Summerville Formation); therefore the Bluff Sandstone lies encased in San Rafael Group strata in the type area of the Bluff (Figs. 11A, E). Gregory unquestioningly assigned the red beds at the top of the Bluff to the Morrison Formation, and, because of the intertonguing relationship with the Bluff, was compelled to include both units in the Morrison.

Lacking criteria and a lithostratigraphic basis for defining the San Rafael Group–Morrison contact, the stage was set for stratigraphic controversy that continues to the present. Some recent work on these rocks continues to advocate inclusion of part or all of the Bluff Sandstone in the Morrison Formation (O'Sullivan, 1980; Condon, 1985; Condon and Peterson, 1986), or inclusion of the eastward correlative of the Bluff, the Junction Creek Sandstone, in the Morrison (O'Sullivan, 1995). Based on lithology and regional correlations, Craig et al. (1955) assigned the Bluff to the San Rafael Group; Saucier (1967) recognized the laterally equivalent Cow Springs Sandstone as a pre-Morrison unit, albeit with some intertonguing of the two units (he did not, however, diagram them that way). Contending that the regionally-traceable lithologic contact (and associated unconformity) that defines the base of the fluvial Morrison Formation lies above the Bluff Sandstone, Anderson and Lucas (1992, 1995) included the Bluff Sandstone in the San Rafael Group. The basal Morrison contact defined by Anderson and Lucas is consistent both stratigraphically and lithologically with the definition of the base of the Morrison by Gilluly and Reeside (1928). Moreover, this contact (Figs. 10, 11B, D–F) provides a good regional mapping surface.

Depositional environments

The Bluff Sandstone is an upper fine- to lower medium-grained, quartzose sandstone. Both crossbedded and flat to low-angle crossbedded facies are present. It is generally considered to be an eolian unit (e.g., Poole, 1966; O'Sullivan, 1978; Anderson and Lucas, 1992), but other lithotypes or depositional environments are locally represented. Interdunal deposits, recognized as finer grained redbeds, are common in the Four Corners area. Basal as well as lateral intertonguing with the Summerville Formation is apparent in outcrops from northeastern Arizona to the Grants–Gallup area of the southern San Juan Basin (Fig. 13). Lacking throughout much of the unit, however, are the large scale, typically eolian, crossbed sets characteristic of older Jurassic eolianites of the Colorado Plateau. Thus, more variable wind patterns, lower sedimentation rates, smaller dune forms, and more reworking of sediments by other processes may be indicated by the prevalent bedforms in the Bluff.

In many areas, the top of the Bluff can be seen to grade upward into a more prominently crossbedded sandstone (Condon, 1985; Anderson, 1993; Anderson and Lucas, 1995) with more uniform dip directions. The dip directions indicate predominantly eastward paleotransport directions.

We interpret this prominently crossbedded sandstone to represent a marked change in wind pattern related to the continued northward drift of the North American continent throughout the Jurassic Period (Dickinson, 1989). Anderson and Lucas (1995) have related this crossbedded unit to the arrival of the region into the zone of prevailing westerlies (Fig. 14), and regard it as a good example of event stratigraphy. Event stratigraphy can be a useful correlation tool in relatively unfossiliferous rocks such as the arid-cyle San Rafael Group.

In the southern San Juan Basin of New Mexico, the Bluff and the underlying Summerville Formation grade southward into an undivided eolianite named the Zuni Sandstone (Fig. 13) by Dutton (1885). Inasmuch as the upper Zuni Sandstone exhibits prominent eastward–dipping crossbed forms similar to those present at the top of the Bluff, a tongue of the Zuni Sandstone has been interpreted as extending northward (Anderson, 1993) to include strata that have been previously recognized in the San Juan Basin as Zuni Sandstone by Maxwell (1976, 1979). Maxwell's designation of the Zuni as a mapping unit was based more on bedform than on lithologic distinction. This bedform has been recognized in the same stratigraphic position from Zuni, New Mexico (Anderson, 1993) northward as far as Bluff, Utah (Condon, 1985). In recognition of the fact that Zuni Sandstone is a valid stratigraphic name, that it has been used in detailed geologic mapping, and that the uppermost facies may have utility in terms of event stratigraphy, it was designated the Acoma Tongue of the Zuni by Anderson (1993), though it may not be mappable or present everywhere. Both units are nonetheless shown on the paleogeographic map (Fig. 15). (See additional comments on the Zuni below).

From the type area at Bluff, the Bluff Sandstone grades southwestward into the lithologically similar Cow Springs Sandstone. The Cow Springs Sandstone (Harshbarger et al., 1951, 1957) was named for exposures along the north side of Black Mesa, south of Kayenta, Arizona, where it forms white to very light gray cliffs. Crossbedding is the dominant sedimentary structure, but because of the lack of fluvial characteristics the unit may be eolian in origin (Harshbarger et al., 1957). It is generally thicker bedded and somewhat thicker overall than the Bluff, but at the type locality it is 104 m thick , similar to the Bluff. Elsewhere, primarily southeastward, it may be as much as 128 m thick (Harshbarger et al., 1951); regionally it thins northward and, more gradually, southward against the paleobasin margin.

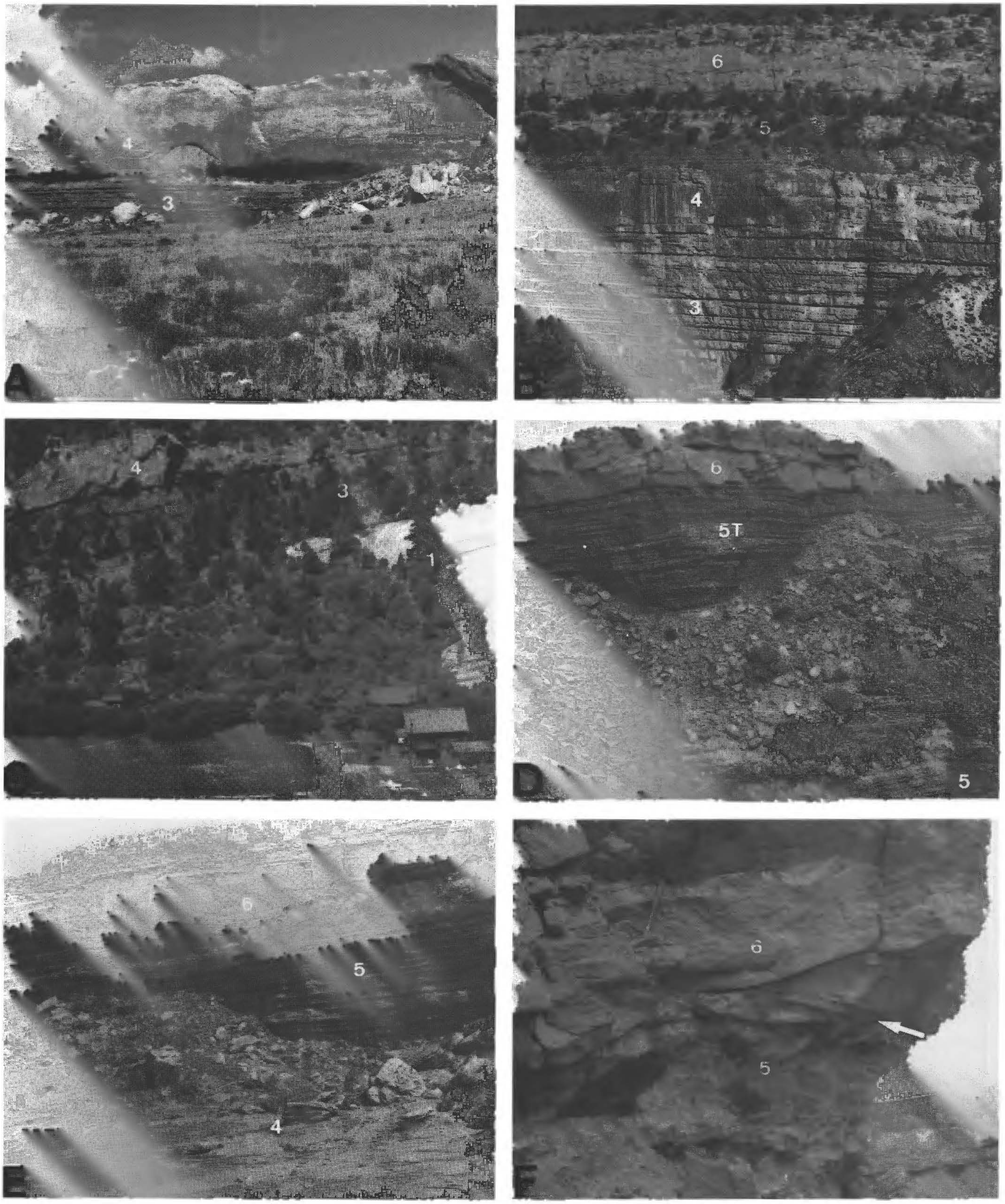


FIGURE 11. Photographs of selected Jurassic strata in the Four Corners region. A, View of Bluff Sandstone (4) overlying thinly bedded Summerville Formation (3) just east of Bluff, Utah. Note bedform change within Bluff from flat-bedded (lower) to crossbedded/massive (upper). B, Summerville Formation (3), main body of Bluff Sandstone (4), Recapture Member of Bluff Sandstone (5) and Salt Wash Member of Morrison Formation (6) at Sanostee Canyon, New Mexico. C, Entrada Sandstone (1), Todilto Formation (2), Summerville Formation (3) and main body of Bluff sandstone (4) at Junction Creek, Colorado. D, Type section of Tidwell Member of Summerville Formation at Tidwell Bottoms, Utah, showing Beclabito (5) and Tidwell (5T) Members of Summerville Formation overlain by Salt Wash Member of Morrison Formation (6). E, Type section of Recapture Member of Bluff Sandstone showing main body of Bluff Sandstone (4), Recapture Member of Bluff Sandstone (5) and Salt Wash Member of Morrison Formation (6). F, Close-up view of J-5 unconformity (arrow) in Recapture Creek, Utah between Recapture Member of Bluff Sandstone (5) and Salt Wash Member of Morrison Formation (6).

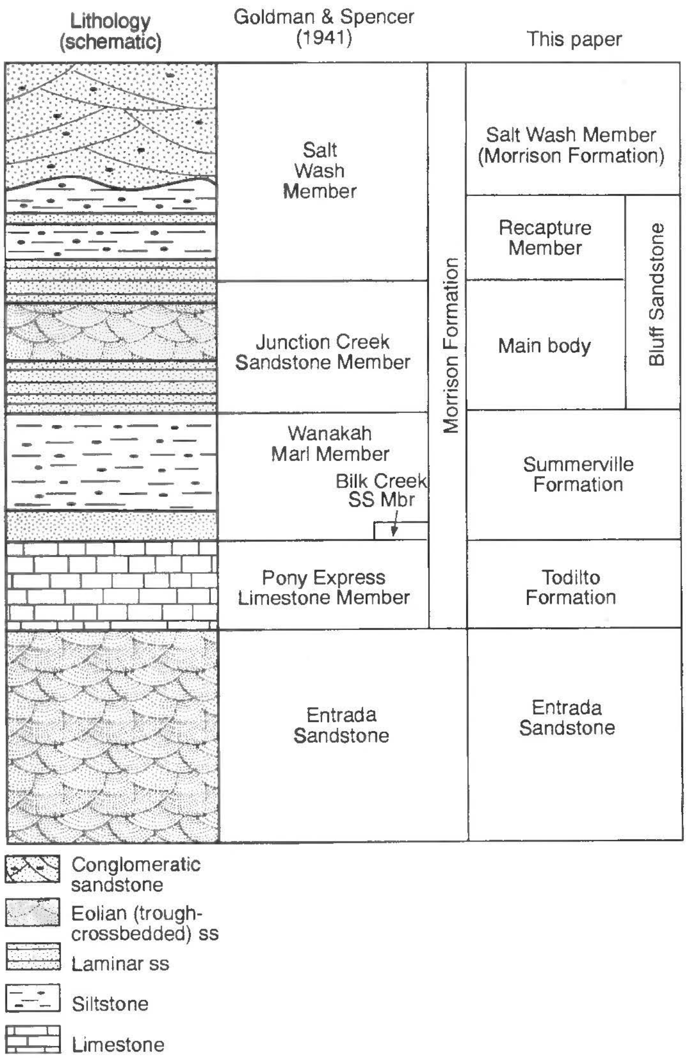


FIGURE 12. Section of Jurassic strata at Junction Creek comparing stratigraphic nomenclature of Goldman and Spencer (1941) and that advocated here. See Appendix for description of the section.

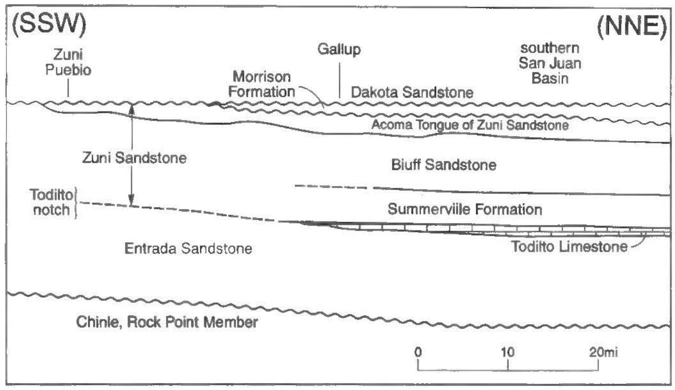


FIGURE 13. Diagrammatic cross section showing relationship of the Bluff and Summerville Formations southward into the Zuni Sandstone; transition occurs between Gallup and Zuni, New Mexico.

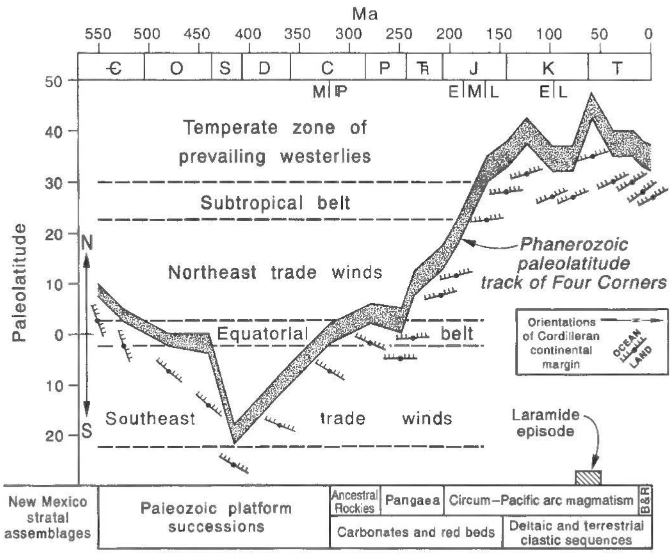


FIGURE 14. Graph of the paleolatitude (stippled area) of the Four Corners (Colorado Plateau) region through the Phanerozoic (from Dickinson, 1989). Note the arrival of this area into the zone of prevailing westerlies during late Middle to early Late Jurassic time.

In its eastern area of distribution the Cow Springs is unconformably overlain by the Morrison Formation, however, in the type locality near Kayenta and areas west, the Dakota Sandstone (Cenomanian) overlies it with more profound unconformity.

Harshbarger et al. (1957) traced the Cow Springs Sandstone into New Mexico where they correlated it with the Zuni Sandstone. The Zuni Sandstone, named by Dutton (1885) for the post-Entrada eolian sandstone well exposed at Zuni, New Mexico, has clear precedence over the name Cow Springs. Harshbarger et al. (1957) never sought to resolve the nomenclatural problem they created, choosing instead to discuss the intertonguing red beds in the upper part of the Cow Springs unit as evidence that it was closely related to and coeval with the Recapture Member of the Morrison Formation. These redbeds are now associated with San Rafael Group arid-cycle depostion (Anderson and Lucas, 1995), and thus no intertonguing of Cow Springs (=Zuni) and Morrison strata exists.

In view of these nomenclatural relationships, we regard the name Cow Springs Sandstone as a junior synonym of Zuni Sandstone, and by rule of precedence the name Cow Springs should be abandoned. This clarifies and unifies the lithostratigraphic approach to regional correlations of Upper San Rafael Group units. It also simplifies the nomenclature and permits regional correlations of these rocks without the encumbrance of having to explain at what point one unit arbitrarily becomes known by another name.

Paleontology and age

No fossils have been reported from the Bluff or Zuni Sandstones, although we have observed large-diameter trace fossils (burrowing) in the latter unit near Gallup in the southern San Juan Basin. Lacking age diagnostic body fossils, the age of the Bluff and correlative eolianites must be inferred from the ages of the subjacent and superjacent units. The Bluff conformably overlies, and, in many areas, intertongues with the Summerville Formation which is of probable Callovian–Oxfordian age. The top of the Bluff is identified by an unconformity with a poorly constrained time value. Above the unconformity rests the Morrison Formation of Kimmeridgian to Tithonian age. The Bluff is thus of Late Jurassic age, perhaps late Oxfordian or even close in age to the Oxfordian–Kimmeridgian boundary. The base of the laterally adjacent Zuni Sandstone (=Cow Springs in Arizona) is older than the base of the Bluff, because the Summerville Formation grades southward and westward into the Zuni; the Zuni should thus be regarded as of probable Oxfordian age.

J-5 UNCONFORMITY

Pipiringos and O'Sullivan (1978) identified the break between the San Rafael Group and the Morrison Formation on the Colorado Plateau as the J-5 unconformity. We identify the unconformity at the same position, between the basal Salt Wash Member of the Morrison Formation and the

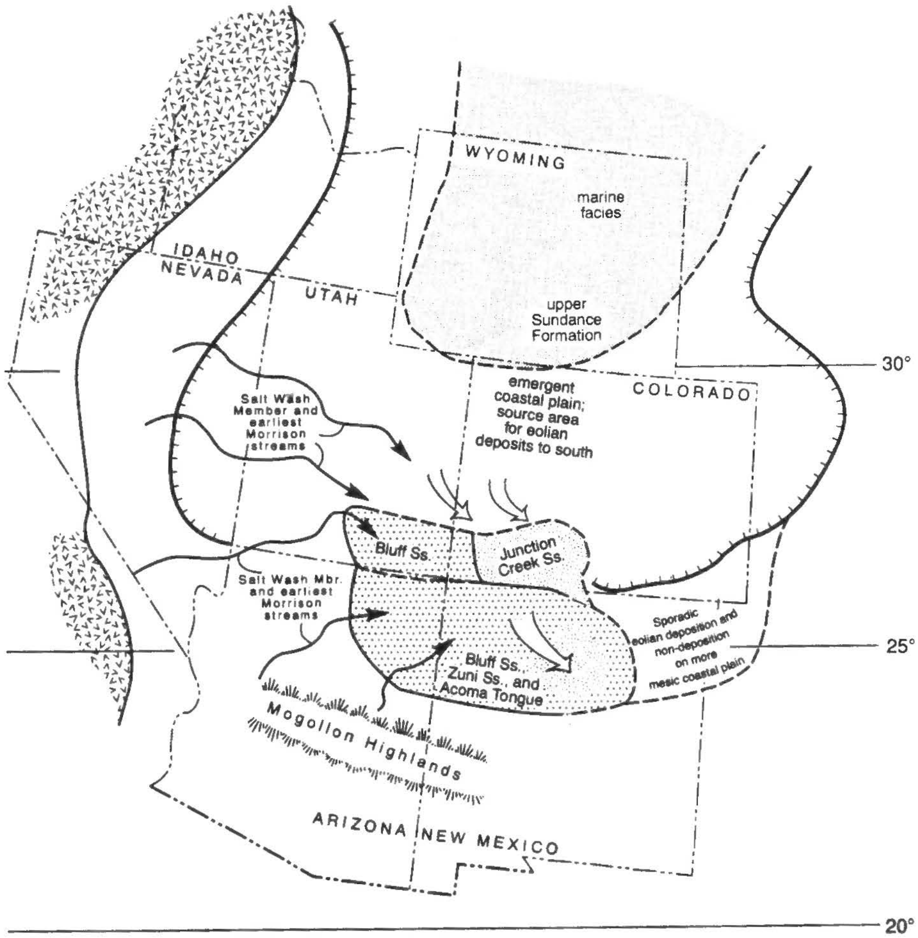


FIGURE 15. Paleogeographic map showing depositional basins at the close of Bluff Sandstone, Zuni Sandstone (=Cow Springs), and Junction Creek (= Bluff) Sandstone time; the earliest Morrison streams are shown originating on the west side of the terrestrial depositional basin, in a compressed time frame.

underlying Bluff Sandstone or Summerville Formation (Figs. 11B, D–F). Anderson and Lucas (1992, 1995) explained why there is no evidence for a regional unconformity lower in the section at the contact between the Beclabito and Tidwell Members of the Summerville Formation, as advocated by Peterson (1988).

The J-5 unconformity we identify is a tectonosequence boundary that corresponds to a significant tectonic reorganization of the Jurassic Western Interior basin. At this boundary, San Rafael eolian and sabkha deposits with source areas to the northeast and southwest are overlain by Morrison Formation fluvial deposits derived from a volcanically active uplift to the west.

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The New Mexico Museum of Natural History and Science and New Mexico Bureau of Mines and Mineral Resources supported this research. Adrian Hunt and Charles Maxwell provided helpful reviews of an earlier version of this article.

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APPENDIX-MEASURED STRATIGRAPHIC SECTIONS

Reference Section of Summerville Formation

Measured at Dry Mesa in the San Rafael Swell in the NE¼ NE¼ sec. 16, T19S, R13E, Emery County, Utah. Strata are essentially flat-lying.

Unit	Lithology	Thickness (m)
Morrison Formation:		
Salt Wash Member:		
20.	Sandstone and conglomeratic sandstone; with (N9) to yellowish gray (5 Y 8/1); sandstone is silty, very fine to coarse grained, poorly sorted, subrounded-subangular subarkose; conglomerate clasts are quartzite and chert up to 8 mm in diameter; trough crossbedded; forms a bench.	not measured
J-5 unconformity		
San Rafael Group:		
Summerville Formation:		
Tidwell Member:		
19.	Sandy shale; same colors and lithology as unit 17.	3.0
18.	Limestone; light olive gray (5 Y 6/1); nodular micrite; forms a prominent ledge.	0.2
17.	Sandy shale; olive gray (5 Y 4/1); not calcareous; limestone ledges are olive gray (5 Y 4/1) and greenish gray (5 GY 6/1), calcareous and silty; forms a slope.	4.9
16.	Sandy siltstone/silty sandstone; same colors and lithology as unit 12; forms a ledge.	0.9
15.	Silty sandstone; same colors and lithology as unit 13.	0.4
14.	Sandy siltstone/silty sandstone; same colors and lithology as unit 12.	0.4
13.	Silty sandstone; light olive gray (5 Y 6/1); fine grained; moderately sorted; subrounded; micaceous litharenite; calcareous; trough crossbedded and hummocky.	0.3
12.	Sandy siltstone; light greenish gray (5 GY 8/1), weathers to moderate yellowish brown (10 YR 5/4)and dark yellowish brown (10 YR 4/2); contains biotites; very calcareous; some agate; hummocky; forms a thick ledge.	0.3
11.	Muddy siltstone; light olive gray (5 Y 6/1); very calcareous; pedogenically altered.	0.5

Unit	Lithology	Thickness (m)
Beclabito Member:		
10.	Sandy siltstone; same colors and lithology as unit 6; three ripple-laminated ledges with interbeds of siltstone of unit 9 lithology.	0.8
9.	Siltstone; grayish red (10 R 4/2) to pale brown (5 YR 5/2); calcareous; laminated.	2.1
8.	Sandy siltstone; same colors and lithology as unit 6; bioturbated and ripple laminated in 2–8–cm–thick sets; forms a ledge.	0.3
7.	Siltstone; light brownish gray (5 YR 6/1) to pale yellowish brown (10 YR 6/2); some biotites; very calcareous; ripple laminated.	7.0
6.	Sandy siltstone; pale brown (5 YR 5/2); very calcareous; ripple laminated; forms a persistent ledge.	0.3
5.	Sandy shale (same color and lithology as unit 2) with interbeds of sandy siltstone, which is pale brown (5 YR 5/2), calcareous and laminated; unit about 80% shale.	22.2
4.	Sandstone; pale brown (5 YR 5/2); fine grained; subangular; well sorted; micaceous quartzarenite; very calcareous; ripple laminated; ledgy.	0.3
3.	Sandy shale and siltstone; same colors and lithology as unit 2 but more sandy and greener; forms a slope.	4.6
2.	Sandy shale and siltstone; shale is grayish red (10 R 4/2), calcareous, slope-forming and contains layers of gypsum nodules every 0.3–0.9 m; siltstone is light brown (5 YR 6/4) and light olive gray (5 Y 6/1), calcareous, bioturbated and ledgy.	7.3
Curtis Formation:		
1.	Limestone; light olive gray (5 Y 5/2); micrite; contains much pale reddish brown (10 R 5/4) chalcedony; forms a ledge.	not measured

Animas City Mountain (Junction Creek)

Measured in the NE¼ sec. 5, T35N, R9W, La Plata County, Colorado, at Animas City Mountain (Junction Creek) north of Durango. Strata dip 14° to the NW.

Unit	Lithology	Thickness (m)
Morrison Formation:		
Salt Wash Member:		
21.	Sandstone; pinkish gray (5 YR 8/1); very fine and medium grained; angular; poorly sorted; subarkose; not calcareous; clay-ball ripups at base; trough crossbedded; forms a cliff.	not measured
J-5 unconformity		
San Rafael Group:		
Bluff Sandstone:		
Recapture Member:		
20.	Muddy sandstone; same color and lithology as unit 16.	2.5
19.	Sandstone; light brownish gray (5 YR 6/1); medium grained; angular; moderately sorted; litharenite; not calcareous; very indurated; trough crossbedded; forms a ledge.	0.8
18.	Muddy sandstone; same color and lithology as unit 16; contains some sandstone lenses of unit 15 lithology.	6.8
17.	Sandstone; same color and lithology as unit 15.	2.3
16.	Muddy sandstone; reddish brown (10 R 4/4); very fine grained; moderately sorted; subangular; litharenite; calcareous; ripple laminated; forms a slope.	1.7
15.	Sandstone; grayish orange pink (5 YR 7/2); very fine and fine grained; subangular and subrounded; moderately sorted; subarkose; clayey; calcareous; laminated.	1.9

Unit	Lithology	Thickness (m)
main body:		
14.	Sandstone; pale red (5 R 6/2); very fine and fine grained; subrounded; moderately sorted; subarkose; calcareous; laminated to massive.	6.1
13.	Sandstone; very light gray (N8) with moderate brown (N4) spots; very fine to medium grained; subrounded; poorly sorted; subarkose; calcareous; trough crossbeds dipping to E.	20.2
12.	Sandstone; same colors and lithology as unit 13; lower part is laminated, upper part is massive; 18 m above base a few trough crossbeds; units 12–14 form a bold cliff.	29.3
Summerville Formation:		
11.	Sandy siltstone; same colors and lithology as unit 7.	1.1
10.	Sandstone; pale red (10 R 6/2); same lithology as unit 14; ripple laminated; ledge.	1.3
9.	Sandy siltstone; same colors and lithology as unit 7.	3.2
8.	Sandstone; very pale orange (5 YR 8/2) and grayish orange pink (5 YR 7/2); same lithology as unit 15; trough crossbedded and ripple laminated.	1.9
7.	Sandy siltstone; pale grayish red (10 R 5/2); not calcareous.	4.6
6.	Sandstone; yellowish gray (5 Y 8/1); very fine grained; subangular; moderately sorted; subarkosic; calcareous; clayey; trough crossbedded to ripple laminated; ledge.	1.2
5.	Sandstone; grayish orange pink (5 YR 7/2); very fine grained; well sorted; subrounded; litharenite; calcareous; ripple laminated; some cover; forms a slope.	19.5
4.	Sandstone; same color and lithology as unit 5, but more poorly sorted and coarser grained; trough crossbedded; forms a ledge; this is the Bilk Creek Sandstone of Goldman and Spencer (1941).	0.3
3.	Sandstone; same color and lithology as unit 5; ripple laminated; forms a slope.	1.2
Todilto Formation:		
2.	Limestone; medium dark gray (N4); finely laminated.	1.3
Entrada Sandstone:		
1.	Sandstone; pinkish gray (5 YR 8/1); medium grained; subrounded to subangular; well sorted; feldspathic quartzarenite; calcareous; trough crossbedded; forms a cliff.	not measured