

Lithostratigraphy of the Jurassic San Rafael Group from Bluff to the Abajo Mountains, southeastern Utah: Stratigraphic relationships of the Bluff Sandstone

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Key words: Jurassic, Utah, Bluff Sandstone, Entrada Sandstone, Carmel Formation, Summerville Formation, Morrison Formation.

Abstract. Measured sections of Jurassic San Rafael Group strata correlated by lithostratigraphy along an ~60 km transect between Bluff and the Abajo Mountains in southeastern Utah indicate that: (1) the Carmel Formation is continuous and disconformable on the Navajo Sandstone (J-2 unconformity); (2) the Entrada Sandstone (Slick Rock Member) is continuous and conformable on the Carmel; (3) the Summerville Formation is continuous and does not intertongue with the Entrada (its base is the J-2 unconformity); (4) the Bluff Sandstone grades northward into the upper Summerville south of the Abajo Mountains; (5) the Recapture Member of the Bluff is physically continuous with at least part of the Tidwell Member of the Summerville; and (5) the base of the Salt Wash Member of the Morrison Fm. is a pervasive unconformity (J-5) with demonstrable local stratigraphic relief of up to 14 m. These observations counter previous claims of extensive Entrada-Summerville intertonguing in southeastern Utah and do not support recognition of depositional sequence boundaries in the Entrada and Summerville lithosomes. Though Entrada deposition may have been by a wet eolian system, its southeastern Utah outcrops are well to the south/ southeast of any marine and paralic facies with which the Entrada intertongues.

INTRODUCTION

Jurassic strata of the American Southwest include some of the most intensively studied eolian strata on the planet. These strata document several extensive sand seas (ergs) of Jurassic age that covered many thousands of square kilometers, including the largest of all Phanerozoic ergs, the Navajo erg (*e.g.*, Kocurek, Dott, 1983; Blakey *et al.*, 1988). The Jurassic erg history in the southwestern USA begins with the Wingate erg, which covered the Four Corners during the Triassic-Jurassic boundary interval. Next youngest is the Navajo erg, which extended at least from Wyoming to Cali-

fornia and left eolian sandstone up to 660 m thick called in different regions Navajo Sandstone, Nugget Sandstone or Aztec Sandstone. Later, during the Middle Jurassic (Callovian), the Entrada erg extended from Utah to Oklahoma and from New Mexico to Wyoming. The last Jurassic erg, the Bluff sand sea, accumulated during the Middle-Late Jurassic transition and was primarily located in the Four Corners.

The two younger ergs – Entrada and Bluff – accumulated at a time when a Jurassic Cordilleran seaway was present to the northwest, in what is now Idaho and parts of northern and western Utah. The ergs were landward of that seaway and their deposits interfinger to the northwest with its marine and paralic facies. In southeastern Utah, O’Sullivan (1980)

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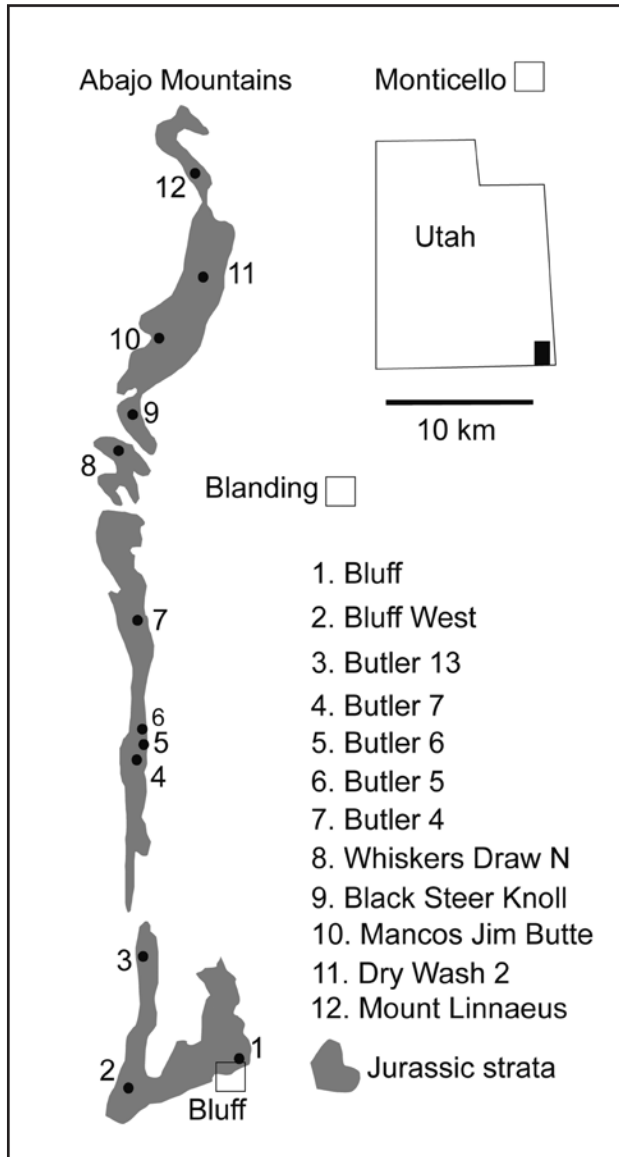


Fig. 1. Map of part of southeastern Utah showing locations of the measured sections of Jurassic San Rafael Group strata along a transect from Bluff to the Abajo Mountains (Fig. 3)

See the Appendix for map coordinates of the measured sections

detailed the stratigraphic relationships between the Entrada and Bluff erg deposits and paralic facies, and Carr-Crabaugh and Kocurek (1998) discussed the significance of these stratigraphic relationships to understanding eolian sedimentation. Here, I present the results of a detailed restudy of the lithostratigraphy of the Entrada-Bluff interval in southeastern Utah (Fig. 1). This research modifies the earlier lithostratigraphy and thus has important implications for sedimentological interpretation.

MATERIALS AND METHODS

In May 2002, I examined the lithostratigraphy of the exposed San Rafael Group strata (Fig. 2) from near Bluff, Utah, to a point southwest of Blanding, Utah, here called the Bluff-Abajo transect (Fig. 1). This is a nearly north-south transect along the strike of the Comb Ridge monocline over a distance of ~60 km (Figs 3–5). In so doing, I restudied all of the stratigraphic sections measured and depicted by O’Sullivan (1980). I measured 12 of those sections in great detail and traced lithostratigraphic units between these sections. In so doing, I produced a lithostratigraphy designed in particular to document the lithostratigraphic relationships of the Entrada Sandstone to adjacent units and the northward pinchout of the Bluff Sandstone and its relationship to adjacent units.

The Jurassic strata I studied were early described by Gregory (1938) and Sears (1956). However, the work of O’Sullivan (1980) first provided significant stratigraphic details of the San Rafael Group strata along the Comb Ridge monocline. My work is thus a careful review of O’Sullivan’s (and that of Carr-Crabaugh, Kocurek, 1998) primarily aimed at documenting the northward pinchout of the Bluff Sandstone along the Bluff-Abajo transect.

LITHOSTRATIGRAPHIC UNITS

The sections presented here extend from the top of the Navajo Sandstone through the base of the Morrison Formation and thus primarily encompass strata of the San Rafael Group (Fig. 2). Here, I briefly review the lithostratigraphic units.

NAVAJO SANDSTONE

In southeastern Utah, the Navajo Sandstone is the stratigraphically highest unit of the Glen Canyon Group. Named by Gregory (1915), the Navajo Sandstone crops out across northern Arizona, and southern and eastern Utah, where it is mostly coarse-grained, trough crossbedded sandstone up to 660 m thick and dominantly of eolian origin (for a review, see Jensen, Morales, 1996). At its base, the Navajo interfingers with the Sinemurian-age Kayenta Formation. At its top, the Navajo Sandstone (including the Page Sandstone as a member: Lucas, Anderson, 1997) is unconformably overlain by the Carmel Formation, forming the J-2 unconformity of Pippingos and O’Sullivan (1978), which is the base of the Zuni sequence of Sloss (1963). It is worth noting that this unconformity (and the J-3 unconformity discussed below) resulted from marine flooding over an erg surface,

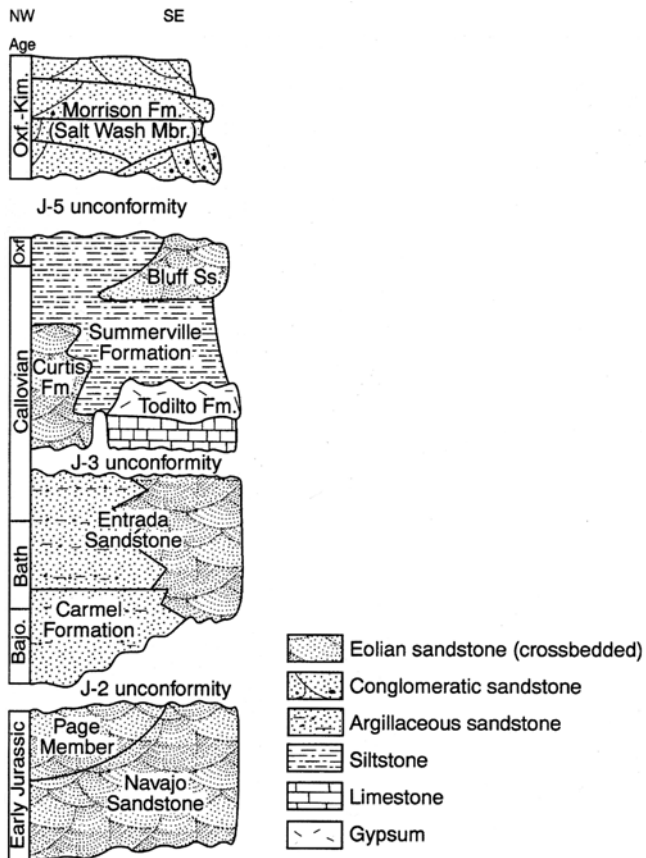


Fig. 2. Summary of regional stratigraphic relationships of San Rafael Group strata (from Lucas, Anderson, 1997)

which must have been a time transgressive event, so that the hiatus represented by the unconformity is of different durations at different locations.

CARMEL FORMATION

The Carmel Formation (of Gilluly, Reeside, 1928) is the lowest stratigraphic unit of the San Rafael Group. It is well known that the Carmel Fm. is the complex of paralic to shallow marine facies of a Bajocian transgression (*e.g.*, Kocurek, Dott, 1983). In southeastern Utah, Carmel strata are usually less than 50 m thick and are siliciclastic red beds of siltstone and fine-grained sandstone, gypsum beds and local beds of limestone and intraformational conglomerate (for a review, see Rose, 1996). The Carmel Formation grades laterally into the Entrada Sandstone to the east and the southeast, and is conformably overlain by the upper part of the Entrada Sandstone in southeastern Utah (Lucas, Anderson, 1997).

ENTRADA SANDSTONE

The Entrada Sandstone of Gilluly and Reeside (1928) is the middle unit of the San Rafael Group and is mostly sandstone of eolian origin (for a review, see Anderson, Lucas, 1996a). As much as ~250 m thick, it crops out from northern Arizona and southeastern Utah across northwestern New Mexico and Colorado to its easternmost outcrops in western Oklahoma. In the Four Corners region the Entrada consists of two members, a lower Dewey Bridge Member, which includes strata equivalent to the Carmel, and an upper Slick Rock Member (Wright *et al.*, 1962). A third, uppermost member, the Moab Member (or Tongue) is sometimes assigned to the Curtis or Summerville formations. Informal subdivisions of the Entrada, largely based on color (*e.g.*, O'Sullivan, 1980, 1996; Robertson, O'Sullivan, 2001) are divisions of the Slick Rock Member, and their utility in lithostratigraphy has been questioned (Lucas *et al.*, 2001). Strata of the Entrada Sandstone studied here pertain to the Slick Rock Member.

In southeastern Utah, the Entrada Sandstone is directly overlain by the Summerville Formation. But, to the northwest, the Curtis Formation separates the Entrada and Summerville formations. And, to the southeast the Todilto Formation is between the Entrada and the Summerville (Fig. 2). The Curtis Formation records a marine transgression across the Entrada erg that produced a vast paralic salina in which the Todilto Formation was deposited. Indeed, the Curtis-Todilto contact with the underlying Entrada Sandstone is a regional unconformity, the J-3 unconformity of Pipiringos and O'Sullivan (1978). I thus consider the base of the Summerville Formation in the sections studied here to be an unconformity.

SUMMERVILLE FORMATION

The Summerville Formation of Gilluly and Reeside (1928) was the original uppermost unit of their San Rafael Group. Usually about 50–100 m thick, the Summerville Formation is mostly thinly (and often repetitively) bedded siltstone, very fine sandstone, silty sandstone, mudstone and some gypsum beds (see Anderson, Lucas, 1996c for a review). It represents paralic facies of the Curtis seaway, and was deposited on an arid, low relief coastal plain in tidal flat, sabkha and shallow water hypersaline environments (*e.g.*, Kocurek, Dott, 1983; Anderson, Lucas, 1994). The lower Summerville Formation is laterally equivalent to the Curtis Formation (Fig. 2).

Lithostratigraphic nomenclature of the Summerville lithosome has been complex, with many synonymous names used (including Wanakah, Red Mesa, Beclabito and Bell Ranch). Indeed, strata I term Summerville Formation here

were termed Wanakah Formation by O'Sullivan (1980) and Carr-Crabaugh and Kocurek (1998). I follow previous work by Anderson and Lucas (1992, 1994, 1996c, 1997; Lucas, Anderson, 1997; Lucas *et al.*, 2006) and include the Tidwell Member (originally of the Morrison Formation: Peterson, 1988) in the Summerville Formation and consider the Recapture Member (originally of the Morrison Formation: Gregory, 1938) to be a member of the Bluff Sandstone.

O'Sullivan (1980) used two terms for bed-level lithostratigraphic units in the Summerville interval, the "bed at Butler Wash" and the "bed at Black Steer Knoll." Here, I formalize these units as the Butler Wash Bed and Black Steer Knoll Bed because both units have value to lithostratigraphic correlation within the Summerville Formation. O'Sullivan (1980) described the "bed at Butler Wash" as a "conspicuous white band in the cliffs along most of the east side of Butler Wash" and noted that Gregory (1938, pl. 14A) and Sears (1956, pl. 20B) had illustrated this bed in the Summerville Formation. I regard units 6–9 of my section Butler 4 (Fig. 3) as the lectostratotype section. Here, the Butler Wash Bed is ~9 m thick and consists of light colored ("white"), trough-crossbedded and ripple-laminated sandstone. It forms a prominent, laterally traceable light-colored ledge/bench that can be correlated for more than 40 km along the Bluff-Abajo transect (Figs 3, 5A).

O'Sullivan's (1980) "bed at Black Steer Knoll" takes its name from the same feature in southeastern Utah (Fig. 1), and I regard units 26–28 of my section there (Fig. 3) as its lectostratotype section. O'Sullivan (1980) describes it here as "a prominent double ledge [of sandstone] 3–4 m thick." The lectostratotype is just such a double ledge, ~4 m thick. The Black Steer Knoll Bed can be correlated over more than 20 km of the Bluff-Abajo transect (Fig. 3).

Finally, I name here the Whiskers Draw Bed of the Summerville Formation for a thin (<1 m thick) but very distinctive bed of gypsiferous, ripple-laminated sandstone with its type section being unit 13 of my Whiskers Draw N section (Fig. 3). This thin bed can be recognized over a north-south transect of at least 18 km and thus is useful to lithostratigraphic correlation.

BLUFF SANDSTONE

Gregory (1938) named the Bluff Sandstone as the basal member of the Morrison Formation, but Goldman and Spencer (1941) and Craig *et al.* (1955) soon questioned the formation assignment. I follow their arguments and those of Anderson and Lucas (1996b, 1997; Lucas, Anderson, 1997) and include the Bluff Sandstone in the San Rafael Group as a formation rank unit. As much as 100 m thick, but generally much thinner, the Bluff Sandstone is mostly fine- to medi-

um-grained quartzose sandstone in crossbeds or tabular beds of evident eolian origin (see Anderson, Lucas, 1996b for a review). These strata are the Junction Creek Member as used by Lucas and Anderson (1997; also see Lucas *et al.*, 2005). They are locally overlain and/or intertongue with a red-bed siltstone-dominated lithofacies, the Recapture Member.

BASE OF MORRISON FORMATION

The base of the Morrison Formation used here is the base of the Salt Wash Member, a readily recognizable contact where crossbedded, conglomeratic sandstone of evident fluvial origin is incised into underlying San Rafael Group strata. This surface has meters of stratigraphic relief and can be traced for long distances – I regard it as the J-5 unconformity as argued by Anderson and Lucas (1994, 1995, 1996d, 1997).

LITHOSTRATIGRAPHY ALONG THE BLUFF-ABAJO TRANSECT

Here, I describe in detail the lithology and thicknesses of the measured sections studied here in southeastern Utah, along what I call the Bluff-Abajo transect (Figs 3–5). Focus is on how each section is correlated to the adjacent sections, as correlation here is purely by lithostratigraphy. I also discuss how my work both resembles and differs from that of O'Sullivan (1980) in terms of lithologic descriptions, choices of lithostratigraphic unit contacts and correlations between the sections.

BLUFF

The section at Bluff begins with the uppermost 3 m of the Entrada Sandstone – pale reddish brown, trough crossbedded sandstone with wind-ripple laminae in the topmost bed. Overlying strata of the Summerville Formation are ~49 m thick and can be divided into lower silty and upper sandy portions. The siltstone-dominated lower portion is 18 m (units 2–5) of red-bed, slope-forming siltstone that is thinly laminated, in places ripple laminated and contains some thin sandy lenses and locally is deformed (folded) due to the expansion/contraction of anhydrite/gypsum beds. The overlying upper part of the Summerville Formation is more sandy, ~30 m thick, and consists of sandstone beds that are typically tabular and ripple laminated, intercalated with siltstone beds similar to the siltstone in the lower part of the formation. One ~5 m thick sandstone bed (unit 8) in the

approximate middle of the upper unit is light-colored ('white'), trough crossbedded, ripple laminated (only the top) and forms a prominent bench. This is the Butler Wash Bed (Fig. 3).

Strata at the base of the Bluff Sandstone are the lower 19 m of a sandstone cliff that is dominantly crossbedded sandstone of evident eolian origin (Fig. 4A). Total Bluff thickness here, in its type area, is about 70 m (Gregory, 1938; Lucas, Anderson, 1997). My section at Bluff is very similar to that of O'Sullivan (1980), except that he recognizes a somewhat thicker Butler Wash Bed (he includes my unit 7).

BLUFF WEST

The Bluff West section is stratigraphically lower than most of the Bluff section. It encompasses the top of the Navajo Sandstone, the entire Carmel and Entrada formations and the base of the Summerville Formation (Fig. 4B). Coarse-

grained, trough crossbedded sandstone is at the top of the Navajo Sandstone. The overlying Carmel Formation is ~31 m thick and is a slope-forming unit, mostly red-bed siltstone with minor interbeds of fine-grained, ripple-laminated sandstone (Fig. 4B).

The base of the Entrada Sandstone (Slick Rock Member) is marked by the stratigraphically lowest, medium-grained, trough-crossbedded sandstone above these silty strata. Here, the Entrada is ~45 m thick and is dominantly sandstone with large scale trough crossbeds and lesser amounts of ripple-laminated sandstone. The base of the Summerville Formation is the beginning of a slope-forming unit of red-bed siltstone above the bench-forming Entrada Sandstone (Fig. 4B). Correlation of the Entrada-Summerville contact between the Bluff West and Bluff sections is unambiguous as it can be physically walked out (Fig. 4B).

O'Sullivan (1980) depicted the interval of my units 23–24 in this section as a siltstone slope, but close examination in the field reveals this interval to be trough-crossbedded

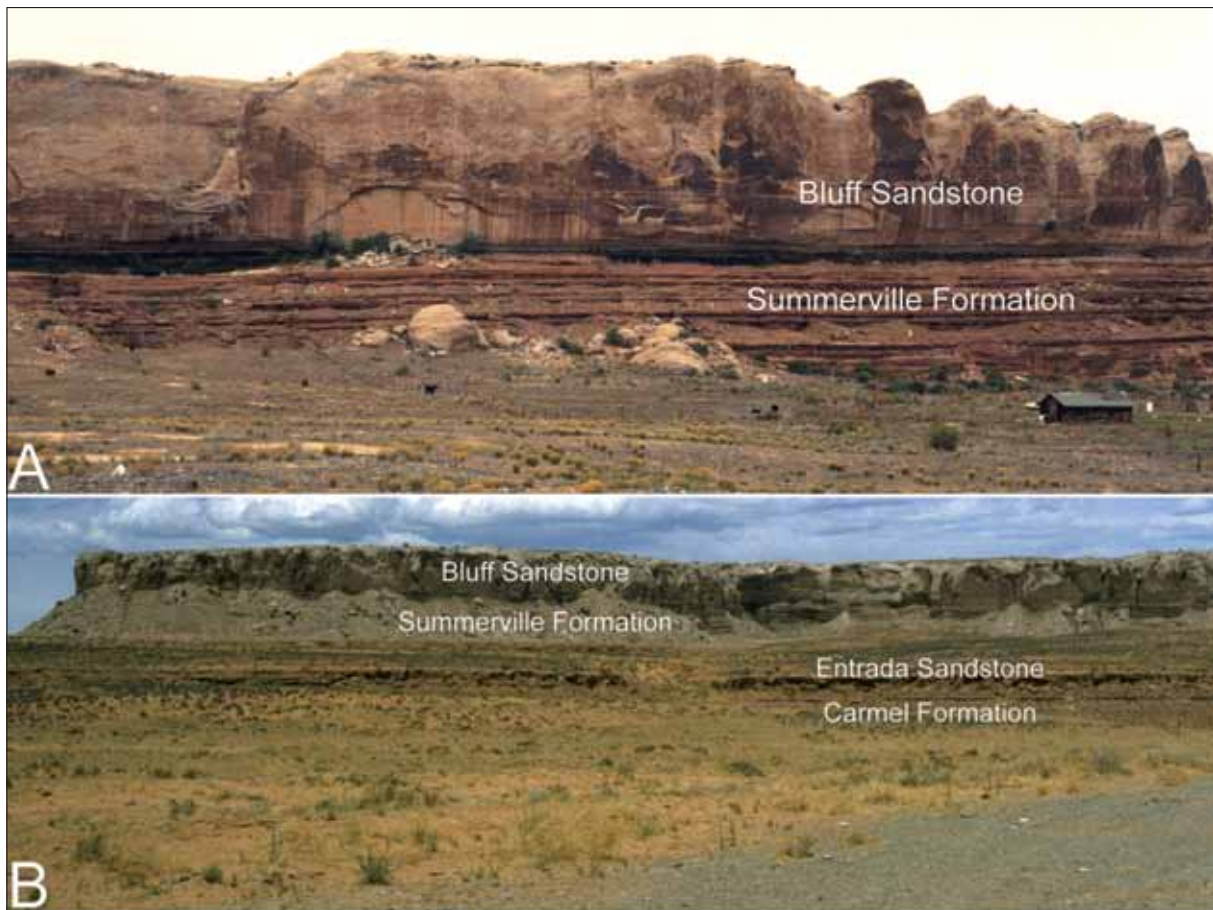


Fig. 4. Selected outcrops of San Rafael Group strata at the Bluff (A) and Bluff West (B) sections

sandstone covered locally by weathered siltstone colluvium. This is an important amendment, as the red-bed siltstones O'Sullivan (1980) perceived in the Entrada section induced him to divide the Entrada into three, primarily color-based informal units: middle sandstone (my units 17–21), upper red (my units 22–26) and salmon sandstone (my unit 27).

BUTLER 13

The Butler 13 section is a complete section of the Summerville Formation that also encompasses the base of the overlying Bluff Sandstone and the top of the underlying Entrada Sandstone. The uppermost Entrada Sandstone is trough-crossbedded sandstone capped by a thin (~2 m thick) interval of ripple-laminated gypsiferous sandstone.

To the south, I identify the base of the Summerville Formation as the base of a slope-forming, siltstone-dominated interval that here is variegated red, green and brown. Total Summerville thickness at the Butler 13 section is ~54 m, the lower 30 m of which are mostly slope-forming, red-bed siltstone with minor interbeds (especially in the uppermost part) of ripple-laminated sandstone. Units 9–13 of the section are an ~6-m-thick interval of light-colored, mostly crossbedded sandstone that is the Butler Wash Bed. The overlying upper part of the Summerville Formation is a mixture of siltstone and ripple-laminated sandstone. The base of the Bluff Sandstone is at the base of the cliff-forming, crossbedded tan sandstone. My descriptions and lithostratigraphic contacts in this section well match those of O'Sullivan (1980).

BUTLER 7

At the Butler 7 section, only the upper two-thirds of the Summerville and the base of the Bluff Sandstone were measured (Fig. 3). The Butler Wash Bed here (units 2–5) is relatively thick, ~10 m, but otherwise is very similar to the Butler Wash Bed in adjacent sections. My descriptions and lithostratigraphic contacts in this section well match those of O'Sullivan (1980).

BUTLER 6

The Butler 6 section extends from the top of the Navajo Sandstone to the base of the Bluff Sandstone (Fig. 3). Correlation of formation rank contacts to the sections to the south are unambiguous. Thus, relatively coarse-grained, trough crossbedded sandstone at the top of the Navajo Sandstone is overlain by slope-forming, dark reddish-brown siltstone with thin interbeds of ripple-laminated sandstone of

the Carmel Formation. This contact is thus essentially identical lithologically to the Navajo-Carmel contact at the Bluff West section (Fig. 3).

Carmel thickness is ~16 m, somewhat less than at the Bluff West section. I place the base of the Entrada Sandstone at a 3.5-m-thick bed of ripple-laminated sandstone overlain by trough-crossbedded sandstone. Entrada Sandstone thickness at Butler 6 is 55 m, and the Carmel-Entrada contact is readily correlated to the contact at Bluff West, which it closely resembles. Summerville strata are ~38 m thick and readily divided into a lower, slope-forming, siltstone-dominated interval (~28 m thick) overlain by an upper, sandier interval. The Butler Wash Bed is more heterogenous than to the south, locally containing a medial siltstone between ripple-laminated sandstone (below) and trough crossbedded sandstone (above) with a total thickness of ~7 m.

My descriptions and contacts in this section are the same as those of O'Sullivan (1980), though some of our unit thicknesses differ somewhat. Note that at the Butler 6 section O'Sullivan again divided the Entrada into informal middle sandstone (my units 10–19), upper red (my unit 20) and salmon sandstone (my unit 21) units.

BUTLER 5

This is a thin section not far from Butler 6 that encompasses the upper part of the Summerville Formation and the base of the overlying Bluff Sandstone (Fig. 3). It is very similar to the upper part of the Butler 6 section and readily correlated to it. My descriptions and lithostratigraphic contacts in this section are similar to those of O'Sullivan (1980). However, an important difference is that he considers my unit 9 to be the Black Steer Knoll Bed and shows it truncated southward by an unconformity at the base of the Bluff Sandstone. Instead, this unit appears to me to be typical Summerville sandstone readily correlated to beds it resembles to the south that are below the base of the Bluff (units 40–41 of the Butler 6 section).

BUTLER 4

This section encompasses the top of the Entrada Sandstone through the base of the Morrison Formation. The Entrada top is a "slick rock" unit of trough-crossbedded sandstone capped by a very thin (0.2 m thick) bed of ripple-laminated sandstone that is likely a water reworked eolianite. The overlying Summerville Formation is virtually the same thickness and lithology as the Summerville Formation at the Butler 6 section. Thus, a lower, slope-forming, red-bed siltstone-dominated interval (~23 m thick) is overlain by a more sand-



Fig. 5. Selected outcrops of San Rafael Group strata at the Butler 4 (A) and Whiskers Draw N (B) sections

stone rich upper Summerville interval that is ~19 m thick. In this upper interval, the lower 7 m is the Butler Wash Bed, two, light-colored crossbedded sandstones split by a thin (0.5-m-thick) siltstone notch (Fig. 5A). The Whiskers Draw Bed, ~0.6 m of gypsiferous, ripple-laminated sandstone, is about 1.3 m above the Butler Wash Bed.

At Butler 4, the base of the Bluff Sandstone is at the base of a cliff of thick-bedded and trough crossbedded sandstone (Fig. 5A). This means that the base of the Bluff Sandstone is the Black Steer Knoll Bed, a double ledge of trough-crossbedded and ripple-laminated sandstone ~3 m thick. Total Bluff thickness is ~36 m, and the formation is mostly crossbedded sandstone and, in the lower part, contains some ripple-laminated sandstone. The Bluff is overlain by ~5 m of silty sandstone with thin siltstone partings that weathers to spheroidal forms. I assign these strata to the Recapture Member of the Bluff Sandstone based on lithology and stratigraphic position shared with the type Recapture Member section at Recapture Creek east of Bluff (Anderson, Lucas, 1997). The base of the Salt Wash Member of

the Morrison Formation above the Recapture Member is a trough-crossbedded conglomeratic sandstone that has local stratigraphic relief (incision into underlying strata) of about 1 m.

Three marker beds in this section are critical to lithostratigraphic correlation along the Bluff-Abajo transect:

1. The Butler Wash Bed is trough-crossbedded sandstone, up to 7 m thick (Fig. 5A).
2. The Whiskers Draw Bed is 0.6 m of gypsiferous, ripple-laminated sandstone that forms a thin but traceable ledge.
3. The base of the Bluff Sandstone is the Black Steer Knoll Bed, 2.7 m thick, a double ledge of sandstone (Fig. 5A).

O'Sullivan (1980) measured a much thicker section at Butler 4 than did I – his section extends all the way down to the Navajo Sandstone. His depiction of this lower part of the section is very similar to the lower part (Navajo-Summerville interval) of my Butler 6 section. Higher in the section, O'Sullivan (1980) recognized a slightly thicker Butler

Wash Bed than I do. A larger difference between his interpretation and mine is his much higher placement of the base of the Bluff Sandstone (~contact of my beds 22 and 23). I reject this placement as it excludes ~10 m of cliff-forming, crossbedded and tabular sandstone below the base of bed 22 from the Bluff Sandstone (Fig. 5A). Note that O'Sullivan (1980) included the ~5 m thick siltstone interval in the Bluff Sandstone (my bed 27, here assigned to the Recapture Member of the Bluff Sandstone).

WHISKERS DRAW N

The lower part of this section is very similar to and readily correlated to the Butler 4 section. Above the Entrada Sandstone, the lower, siltstone-dominated and slope-forming Summerville interval is ~27 m thick. It is overlain by an upper, sandy Summerville interval that is ~16 m thick. The Bluff Sandstone has largely pinched out at this section. Its basal strata – the Black Steer Knoll Bed—persist as an ~4 m thick double sandstone ledge (Fig. 5B). Strata laterally equivalent to the Bluff are a slope-forming interval ~28 m thick that is ~70% slope-forming, red-bed siltstone (Fig. 5B). Within this slope-forming interval, ripple-laminated and trough crossbedded sandstone beds (units 22, 24, 26, 28) are of Bluff lithology and I regard them as tongues of the Bluff Sandstone (Fig. 3). Trough crossbedded, conglomeratic sandstone at the base of the Salt Wash Member of the Morrison Formation is scoured into the top of this siltstone-dominated interval.

O'Sullivan's (1980) Whiskers Draw N section only encompasses the Summerville to Salt Wash interval of my section (essentially equivalent to my units 11–30). His correlation of this section to the Butler 4 section is the same as mine, but his base of the Bluff Sandstone at Whiskers Draw N is much higher than mine (only my units 26–28 are Bluff according to O'Sullivan, 1980).

O'Sullivan (1980) assigned my unit 24 to his informal "bed A", which he regarded as the base of the Morrison Formation – the base of his "lower beds" of the Morrison, later named Tidwell Member by Peterson (1988). O'Sullivan thus identifies my units 26–28 as a tongue of the Bluff Sandstone between Tidwell strata. I agree with the basic lithostratigraphic relationships O'Sullivan depicts here – the Bluff Sandstone does pinch out northward into Tidwell strata. However, I place the base of the Morrison Formation much higher at a mappable contact between trough-crossbedded conglomeratic sandstone (base of Salt Wash Member) and underlying siltstone-dominated strata. Instead, O'Sullivan's Morrison base is at the base of a 0.8-m-thick sandstone in a siltstone slope, not what I consider a mappable, formation-rank boundary (Fig. 5B).

BLACK STEER KNOLL

The Black Steer Knoll section is very similar to the section at Whiskers Draw N. Above water-reworked eolian sandstone at the top of the Entrada Sandstone, the lower siltstone-dominated interval of the Summerville Formation (units 2–25) is ~50 m thick and ends at the Black Steer Knoll Bed. Strata above that are more sandy Summerville strata that are ~23 m thick. In this interval, other than the Black Steer Knoll Bed, remnant tongues of the Bluff Sandstone are thin to nonexistent. The base of the Salt Wash Member is conglomeratic sandstone scoured into underlying siltstone with as much as 6 m of local stratigraphic relief.

O'Sullivan's (1980) section at Black Steer Knoll extends down to the top of the Navajo Sandstone. Here, his section of the upper Navajo, Carmel and Entrada formations is very similar to my sections at Butler 6 and Mancos Jim Butte (Fig. 3). At Black Steer Knoll, O'Sullivan (1980) identified the Butler Wash Bed as 22 m thick, consisting of massive sandstone (my units 5–16), a correlation I do not endorse because of the great lithologic differences (indeed units 5–16 are in an interval of much siltstone by my observations) and the thickness changes it accepts. O'Sullivan's Black Steer Knoll Bed in this section is the same as mine (this is the bed's type section).

O'Sullivan (1980) also identifies an informal "bed A" (my units 32–34) as a marker bed that he correlates to his Bluff base to the south (my Bluff base is the Black Steer Knoll Bed, a northward persistent tongue of the Bluff), and he calls the siltstone-dominated interval above "bed A" the "lower beds of the Morrison Formation," later named Tidwell Member by Peterson (1988). Because O'Sullivan's Bluff base is higher than mine, his Salt Wash base is drawn higher at Black Steer Knoll than he draws it at Whiskers Draw N. Interestingly, O'Sullivan's correlation shows the same magnitude of stratigraphic relief on the Salt Wash base as do my sections, but he draws the correlation lines between the sections as if this is an intertonguing, not a disconformable contact.

MANCOS JIM BUTTE

My section at Mancos Jim Butte extends from the upper part of the Navajo Sandstone through the base of the Morrison Formation, so it includes complete sections of the Carmel, Entrada and Summerville formations. The upper part of the Navajo Sandstone here is ~32 m of relatively coarse-grained and mostly trough-crossbedded sandstone. The Carmel Formation has a sharp basal contact of red siltstone on sandstone at the top of the Navajo Sandstone. Total Carmel thickness is ~12 m of slope-forming silty sandstone with some intercalated beds of siltstone and gypsiferous sandstone.

I pick the base of the Entrada Sandstone at the base of a slick rock cliff of trough crossbedded and ripple-laminated sandstone that is ~21 m thick. The stratigraphic section between the top of the Entrada Sandstone and the base of the Morrison Formation is ~66 m thick and is mostly slope-forming siltstone. The Whiskers Draw and Black Steer Knoll beds are identifiable in the section and readily correlated to the section at Black Steer Knoll, ~3 km to the southwest. This correlation indicates that the base of the Morrison Formation has substantial stratigraphic relief between Mancos Jim Butte and Black Steer Knoll – it is 14 m lower at Mancos Jim Butte – which I take to indicate substantial downcutting of the Morrison fluvial system into underlying San Rafael Group strata.

O’Sullivan’s (1980) section at Mancos Jim Butte almost totally overlaps mine but embodies what I regard as a serious mis-correlation. Thus, his Carmel Formation and middle sandstone unit of the Entrada Sandstone are actually the upper part of the Navajo Sandstone. Thus, note that at Mancos Jim Butte strata O’Sullivan assigned to the Carmel Formation are mostly trough-crossbedded sandstone, unlike any Carmel strata to the south. The chert pebble zone he identifies as the top bed of the Navajo Sandstone is unit 2 of my section, about 27 m below where I place the Navajo-Carmel contact. O’Sullivan’s “upper red sandstone” of the Entrada at Mancos Jim Butte is the interval I term Carmel Formation, and his “salmon sandstone” here is the entire Entrada Sandstone of my section.

This may seem a surprising mis-correlation by as experienced a student of Jurassic stratigraphy as O’Sullivan. But, note that O’Sullivan (1996) published a similar mis-correlation of the Navajo-Entrada interval (Lucas *et al.*, 2001). Thus, at Church Rock in southeastern Utah (sec. 24, T31S, R23E, San Juan County), the unit O’Sullivan (1996) identified as the “red member” of the Entrada actually is the Carmel Formation, and the unit he labelled “middle sandstone” is the Navajo Sandstone (*e.g.*, Weir, Dodson, 1958).

Furthermore, at Mancos Jim Butte, O’Sullivan (1980) continues to identify a thick (~34 m), massive sandstone interval (~my units 31–38) as the Butler Wash Bed, a lithostratigraphic assignment not supportable by lithology or thickness (see above). His Black Steer Knoll Bed is the same as mine, and his “bed A” is my unit 49.

DRY WASH 2

The section at Dry Wash 2 encompasses the top of the Entrada Sandstone through the base of the Morrison Formation. The Black Steer Knoll Bed is identifiable stratigraphically high in this section, and provides a direct correlation to the section at Mancos Jim Butte, and this is the northernmost section where this tongue of the Bluff

Sandstone can be identified (Fig. 3). This indicates that there is about 5 m less stratigraphic relief on the Morrison Formation base than at Mancos Jim Butte. I could not identify the Whiskers Draw Bed at the Dry Wash 2 section.

O’Sullivan’s (1980) Dry Wash 2 section begins in the Entrada Sandstone and extends to the base of the Morrison Formation. His interpretation of the Dry Wash 2 section is very similar to that at Mancos Jim Butte. Thus, his “salmon sandstone” is the Entrada Sandstone. O’Sullivan shows most of the lower Summerville as sandstone, but my observations indicate significant siltstone beds. His Black Steer Knoll Bed is my bed 27, his “bed A” is my bed 29 and his Salt Wash basal bed is the same as mine.

MOUNT LINNAEUS

The northernmost section, at Mount Linnaeus, is just south of the Abajo Mountains southwest of Monticello (Fig. 1). This section extends from the top of the Entrada Sandstone to nearly the base of the Morrison Formation. The Entrada-Summerville contact is readily correlated to Dry Wash 2, but no internal correlation of beds between the two sections is evident. Post-Entrada Summerville strata here are at least 68 m thick and are siltstone-dominated strata without any obvious sandstone marker beds. Thus, I cannot identify the Black Steer Knoll Bed at Mount Linnaeus. The Morrison base is not exposed but must be stratigraphically somewhat higher than at Dry Wash 2.

O’Sullivan’s (1980) section at Mount Linnaeus extends from strata he assigned to the Navajo Sandstone to high in the Summerville interval. His section, however, bears little resemblance to mine. The interval that unambiguously correlates his section to mine is my beds 11 (cherty sandstone) and 12 (trough-crossbedded sandstone) that correlate to two beds near the top of his section, thus indicating that my section extends at least 30 m higher than does his. If his Entrada top is correlated to my Entrada top, and if his correlations of the Black Steer Knoll Bed and “bed A” are correct, then the entire Summerville section below them must be extremely condensed between Mount Linnaeus and Dry Wash 2. I reject these correlations, but cannot resolve the evident contradictions. The important point is that there are no tongues of the Bluff Sandstone as far north as Mount Linnaeus. The Bluff has pinched out into the Summerville (including Tidwell) lithosome.

LITHOSTRATIGRAPHIC CORRELATION

The sections correlated here (Fig. 3) document the following:

1. From south to north, the Carmel Formation is continuous, but thins from ~30 to ~12 m thick and becomes more sandy.

2. The Entrada Sandstone (Slick Rock Member) is also continuous and thins northward, from 55 m to 21 m over the transect, but does not change lithologic character as a unit mostly of trough-crossbedded sandstone.

3. O'Sullivan subdivided the Entrada Sandstone along the Bluff-Abajo transect into three informal units, largely based on color. I did not find these useful subdivisions. Indeed, I encourage the reader to examine closely the outcrop photograph of the Entrada Sandstone near Bluff published by O'Sullivan (2003, fig. 5) that labels these three informal subdivisions of the Entrada Sandstone. That photo makes it clear that these subdivisions are not based on lithology. Given the great regional color variation in Entrada outcrops, much of it likely post-depositional and even post-diagenetic (perhaps weathering related?), stratigraphic subdivisions of the Entrada Sandstone based primarily on color appear to be of little lithostratigraphic value (Lucas *et al.*, 2001; Lucas, Heckert, 2003).

4. Where overlain by the Bluff Sandstone, the Summerville Formation is of nearly constant thickness (it ranges from about 42 to 54 m thick) divisible into a lower, slope-forming, siltstone-dominated interval (about two-thirds of the formation) overlain by an upper, more sandstone-dominated interval.

5. Within the sandstone-dominated interval of the Summerville Formation, the Butler Wash Bed is a distinctive, light-colored, mostly trough-crossbedded sandstone unit—likely a laterally persistent eolianite. It can be correlated from near Bluff to the north to Whiskers Draw N, a distance of ~51 km.

6. Thickness of the Bluff Sandstone decreases northward from the type section at Bluff (~70 m) to the Butler 4 section, where it is about 36 m thick (or 41 m if the Recapture Member is included).

7. The Bluff Sandstone pinches out rapidly north of the Butler 4 section, over a distance of less than 10 km. Thus, the massive cliff of eolianite sandstone at Butler 4 interfingers northward with a siltstone-dominated section that resembles the underlying strata of the Summerville Formation. Some of these strata have been assigned to the Tidwell Member of Peterson (1988), and the uppermost part of this siltstone-dominated interval is homotaxial with the Recapture Member of the Bluff Sandstone. The units named Recapture and Tidwell are thus part of the Summerville lithosome that are laterally equivalent to the Bluff Sandstone where it pinches out northward.

8. Correlation north of the last outcrop of cliff-forming Bluff Sandstone is achieved by correlation of the Black Steer Knoll Bed, which is the base of the Bluff Sandstone at the Butler 4 section. This correlation is reinforced by correlation of the underlying Whiskers Draw Bed from Butler 4 to Manco Jim Butte.

9. The northernmost recognizable tongue of the Bluff Sandstone is the Black Steer Knoll Bed at the Dry Wash 2 section.

10. The base of the Salt Wash Member of the Morrison Formation has stratigraphic relief of as much as 14 m incised into underlying San Rafael Group strata. I take this as evidence of the regional J-5 unconformity at the Salt Wash base.

WET EOLIAN SYSTEM

Building on an earlier study in northeastern Utah (Craabaugh, Kocurek, 1993), Carr-Craabaugh, Kocurek (1998) presented a sedimentological study of the Entrada Sandstone along the Bluff-Abajo transect (and farther northward), inferring that demonstrates that the Entrada Sandstone was deposited in a “wet eolian system” (an eolian system with a shallow [rising] water table). They presented their own lithostratigraphy of the transect (Fig. 6) that differs in various ways from that presented by O'Sullivan (1980) and presented here, though it more resembles O'Sullivan's lithostratigraphy than mine. Thus, for example, Carr-Craabaugh and Kocurek (1998) identify the Black Steer Knoll Bed as far south as Bluff, contrary to the observations of O'Sullivan (1980) and myself. However, given the lack of detail in the lithostratigraphy of Carr-Craabaugh and Kocurek (1998) – their figure 3 (here reproduced as Fig. 6) is the only presentation of their stratigraphic data – I do not attempt to review their lithostratigraphy in detail.

Instead, I focus on Carr-Craabaugh and Kocurek's (1998) identification of four unconformity-bounded sequences in the San Rafael Group strata along the Bluff-Abajo transect (Fig. 6). The base of their sequence 1 is the base of the Carmel Formation, the regional J-2 unconformity. The base of their sequence 3 is the base of the Summerville Formation, the regional J-3 unconformity (see above). Their sequence 2 base is within the Entrada Sandstone (base of O'Sullivan's “upper red”), and their sequence 4 base is within the Summerville Formation (top of Butler Wash Bed).

Thus, these latter two sequence boundaries (unconformities), not recognized by O'Sullivan or myself, are the top beds of eolianites, and each was envisioned by Carr-Craabaugh and Kocurek (1998) as a super surface above dune/interdune deposits that is “characteristically corrugated, polygonally fractured or featureless” (Carr-Craabaugh, Kocurek, 1998, p. 215). My fieldwork indicates that such surfaces are locally present, but not as pervasive as is indicated by Carr-Craabaugh and Kocurek (1998). Indeed, I see no lithostratigraphic evidence for the sequence 2 and 4 boundaries posited by Carr-Craabaugh and Kocurek (1998). Sequence boundary 2 is supposed to be within the Slick Rock

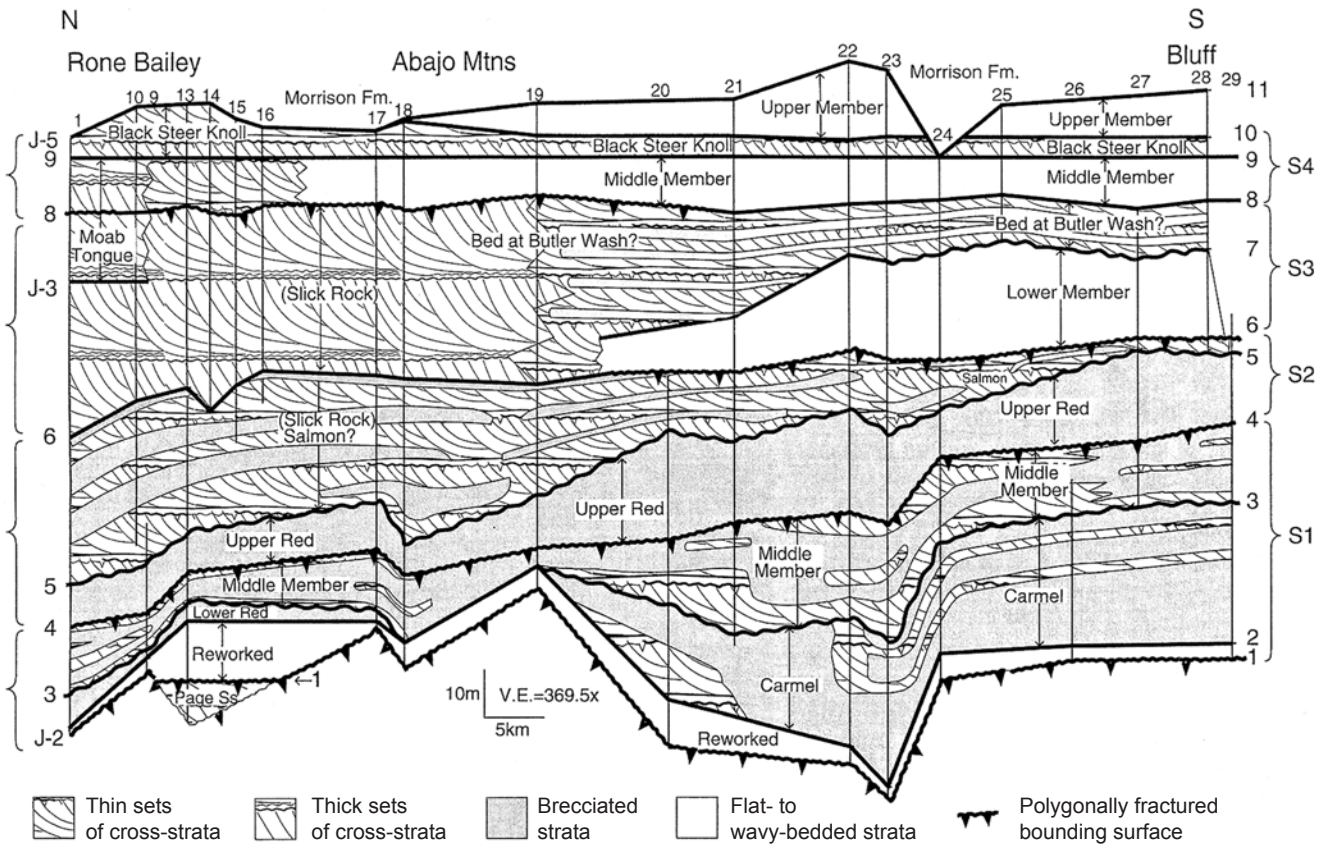


Fig. 6. Sequence stratigraphy of the San Rafael Group along the Bluff-Abajo transect and northward from the Abajo Mountains (modified from Carr-Crabaugh, Kocurek, 1998).

Member of the Entrada Sandstone and I suspect it is little more than local reactivation surfaces (set breaks) conflated into a much more extensive surface than is represented. Sequence boundary 4 is where Summerville siltstone rests on sandstone and appears to be little more than a lithologic contact, surely a paraconformity, but lacking evidence of a significant sedimentary break.

Furthermore, their conclusion that the Entrada Sandstone along the transect is correlative to marine and sabkha facies to the south contradicts extensive data that identify a persistent, eolian Entrada Sandstone all the way to Zuni Pueblo in west-central New Mexico (e.g., Harshbarger *et al.*, 1957; Condon, Peterson, 1986; Lucas, Anderson, 1997, 1998; Lucas, Heckert, 2003; Lucas *et al.*, 2005). Indeed, the lithostratigraphy presented here demonstrates no obvious intertonguing or lateral facies relationship between the Entrada Sandstone and marine or paralic facies. These facies (Carmel and Summerville formations) bound the Entrada, but there is no demonstrable lateral equivalence.

It may be that the Entrada Sandstone represents a wet eolian system, but the sequence stratigraphic analysis of the Entrada Sandstone along the Bluff-Abajo transect presented by Carr-Crabaugh and Kocurek (1998) is not well supported. The southeastern Utah outcrops of the Entrada Sandstone are well to the south and southeast of any marine and paralic facies with which the Entrada intertongues, so any relationship between their deposition and rising sea level remains to be demonstrated.

CONCLUSIONS

This article reports a detailed lithostratigraphic study of San Rafael Group strata along an ~60 km transect from Bluff to the Abajo Mountains in southeastern Utah. It indicates continuity with minor thickness and lithologic changes of the Carmel, Entrada and pre-Bluff Summerville formations across this transect. The Bluff Sandstone is shown to pinch

out northward over a relatively short distance into siltstone-dominated strata that (in part) have been termed Tidwell Member, and are clearly part of the Summerville lithosome.

The base of the Salt Wash Member of the Morrison Formation above the Bluff Sandstone and above the Summerville strata north of the Bluff pinchout is a surface with substantial stratigraphic relief. The bases of the Carmel, Summerville and Morrison formations are recognized as the J-2, J-3 and J-5 regional Jurassic unconformities, respectively. There is no compelling evidence for substantial unconformities within the Entrada and Summerville lithosomes. The Entrada Sandstone may represent a wet eolian system, but the lithostratigraphy underpinning the sedimentological analysis of Carr-Crabaugh and Kocurek (1998) is not well supported by this study.

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Appendix

MAP COORDINATES OF MEASURED SECTIONS (Figs 1, 3)

All GPS derived coordinates are in zone 12, datum NAD 27. Township and range coordinates are for San Juan County, Utah.

- Bluff** (= O’Sullivan, 1980, section 52) – base at 628856E, 4127496N; at base of unit 8 offset to 629141E, 4127837N; at base of unit 17 offset to 629740E, 4128504N; top at 629918E, 4128806N. Measured in the NW ¼ NW ¼ sec. 30 and SW ¼ and SW ¼ NE ¼ sec. 19, T40S, R22E.
- Bluff West** (= O’Sullivan, 1980, section 51) – base at 620393E, 4125840N, top at 621338E, 4126465N. Measured in the SE ¼ sec. 30 and SW ¼ sec. 29, T40S, R21E.
- Butler 13** (= O’Sullivan, 1980 section 49) – base at 621884E, 4133591N; top at 622088E, 4133764N. Measured in the NE ¼ sec. 5, T40S, R21E.
- Butler 7** (= O’Sullivan, 1980, section 43) – base and top at 621291E, 4149975N. Measured in the SE ¼ sec. 8, T38S, R2E.
- Butler 6** (= O’Sullivan, 1980, section 42) – base at 620893E, 4151941N; top at 621537E, 4152319N. Measured in the SE ¼ sec. 5, T38S, R21E.
- Butler 5** (= O’Sullivan, 1980, section 41) – base and top at 622013E, 4154235N. Measured in the NW ¼ NW ¼ sec. 33, T37S, R21E.
- Butler 4** (= O’Sullivan, 1980, section 40) – base at 621276E, 4157206N; top at 621695E, 4157325N. Measured in the NE ¼ sec. 20, T37S, R21E.
- Whiskers Draw N** (= O’Sullivan, 1980, section 35) – base at 620112E, 4166478N; top at 620359E, 4166551N. Measured in the SW ¼ sec. 20, T36S, R21E.
- Black Steer Knoll** (= O’Sullivan, 1980, section 33) – base at 620645E, 4169949N; top at 620802E, 4170173N. Measured in the NW ¼ SE ¼ sec. 8, T36S, R21E.
- Mancos Jim Butte** (= O’Sullivan, 1980, section 29) – base at 621610E, 4175065N; top at 622240E, 4175203N. Measured in the SE ¼ sec. 21, T35S, R21E.
- Dry Wash 2** (= O’Sullivan, 1980, section 28) – base at 625958E, 4177653N; top at 626076E, 4177760N. Measured in the NW ¼ NW ¼ sec. 13, T35S, R21E.
- Mount Linnaeus** (= O’Sullivan, 1980, section 26) – base at 624284E, 4185572N; top at 624369E, 4185778N. Measured in the NW ¼ sec. 23, T34S, R21E.

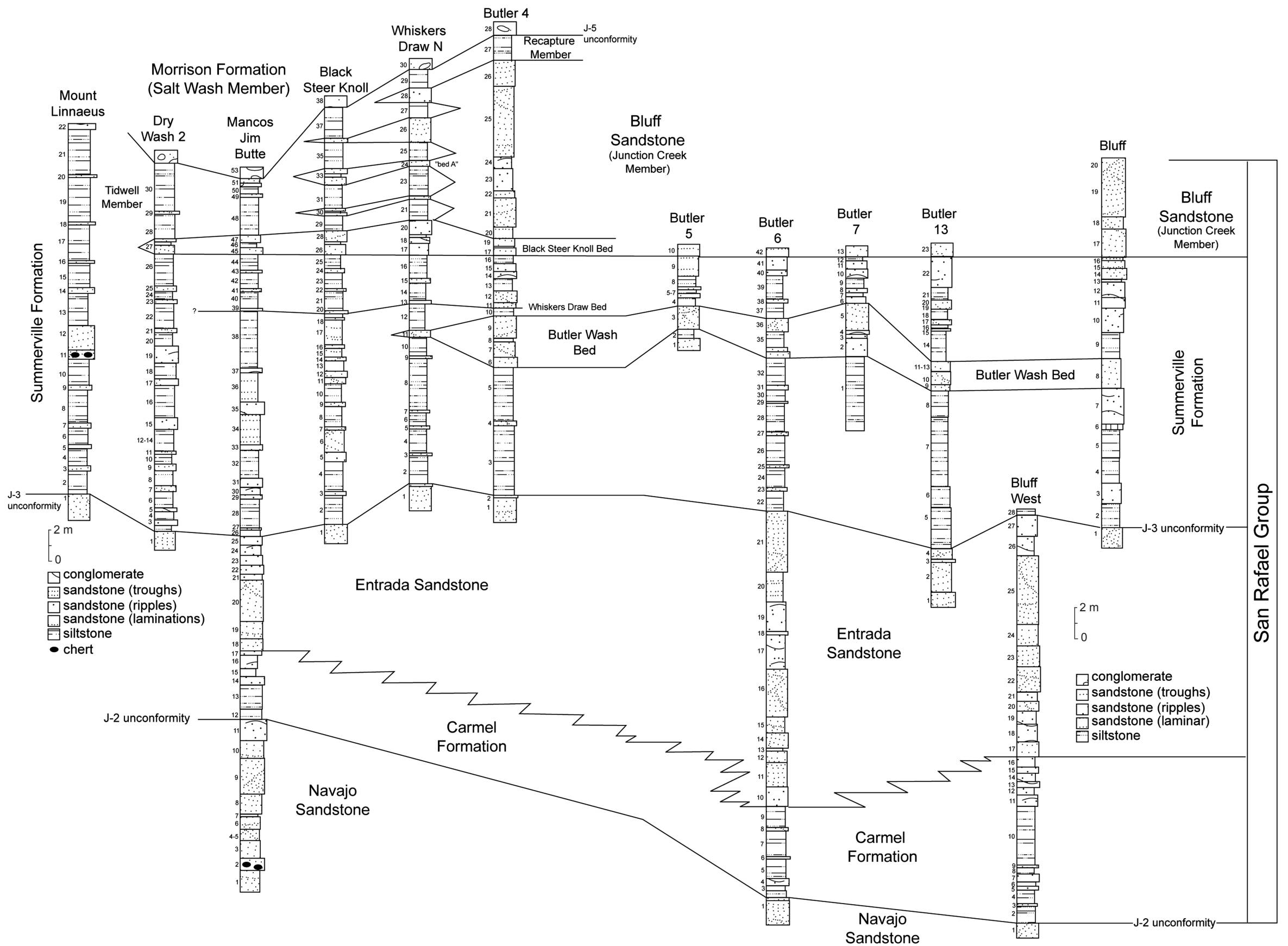


Fig. 3. Measured sections of San Rafael Group strata along the Bluff-Abajo transect (Fig. 1)

See the Appendix for map coordinates of the measured sections