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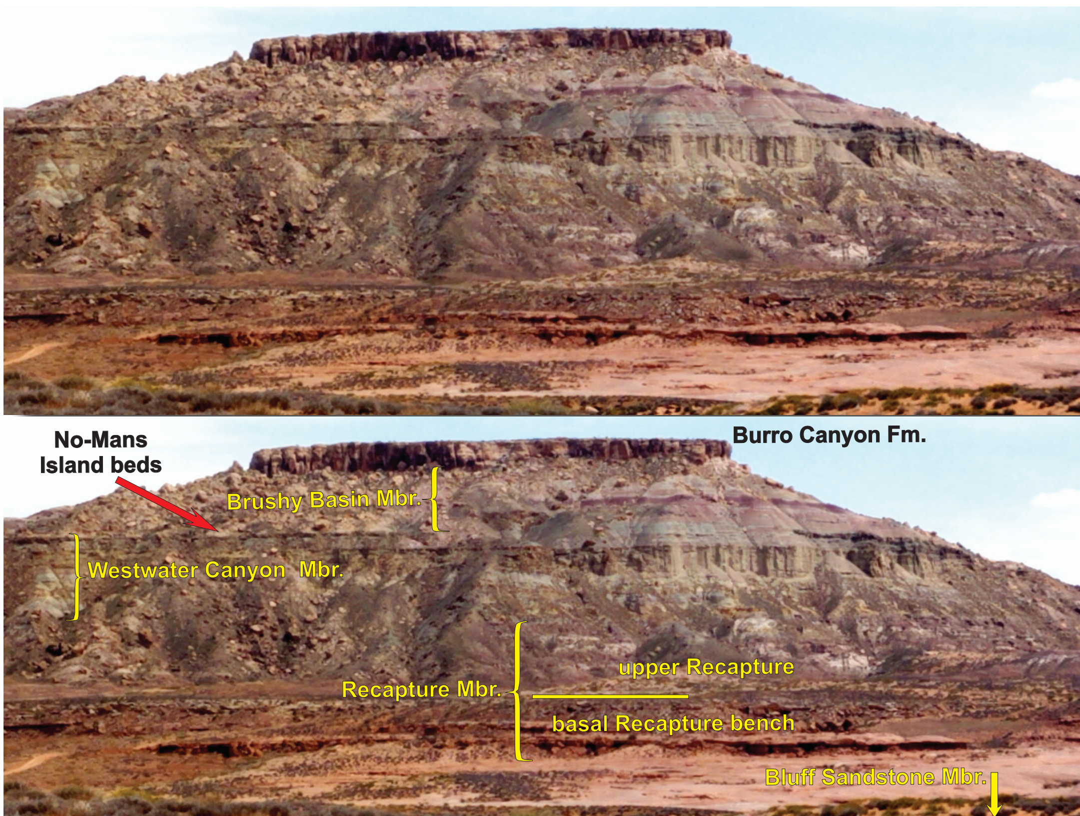

Theme Issue
An Ecosystem We Thought We Knew—
The Emerging Complexities of the Morrison Formation
SOCIETY OF VERTEBRATE PALEONTOLOGY
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Cover

Unannotated (top) and annotated (bottom) photograph of the nearly complete section of Upper Jurassic Morrison Formation exposed on west side of McCracken Point east of the mouth of Recapture Creek, Navajo Nation, Utah.

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The Morrison Formation and its Bounding Strata on the Western Side of the Blanding Basin, San Juan County, Utah

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ABSTRACT

In 2016 and 2017, the Utah Geological Survey partnered with the U.S. Bureau of Land Management to conduct a paleontological inventory of the Morrison Formation south and west of Blanding, Utah, along the eastern margin of the Bears Ears National Monument. The Morrison in this region is critical to understanding Upper Jurassic stratigraphy across the Colorado Plateau because it is the type area for the Bluff Sandstone, Recapture, Westwater Canyon, and Brushy Basin Members of the Morrison Formation, which are the basis for nomenclature in New Mexico and Arizona as well. Researchers have disagreed about nomenclature and correlation of these units, which transition northward in the study area into the Tidwell, Salt Wash, and Brushy Basin Members. Numerous vertebrate localities make inclusion of the Bluff Sandstone and Recapture Members in the Middle Jurassic San Rafael Group, as suggested by some previous workers, unlikely. The Salt Wash Member does not separate the Bluff Sandstone and Recapture Members at Recapture Wash, but sandstone lenses of Salt Wash facies occur higher in northern Recapture exposures. Northward, along the outcrop belt east of Comb Ridge, the Bluff-Recapture interval thins, interlenses, and pinches out into the Tidwell and lower Salt Wash, with the main lower sandstone interval of the Westwater Canyon merging northward into the upper Salt Wash Member.

The partly covered, 1938 type section of the Brushy Basin Member is identified along Elk Mountain Road at the southern end of Brushy Basin. We describe a detailed, accessible Morrison Formation reference section about 11.2 km (7 mi) to the south along Butler Wash. There, 81.68 m (268 ft) of Brushy Basin Member is well exposed along a road between the top of the Westwater Canyon Member and the base of the Lower Cretaceous Burro Canyon Formation. We informally call the upper sandstone bed(s) of the Westwater Canyon Member that cap mesas and benches in the region "No-Mans Island beds." Smectitic mudstones between the No-Mans Island beds and the main sandstone body of the Westwater Canyon suggest that the Salt Wash-Brushy Basin contact to the north may be somewhat older than the base of the Brushy Basin Member as originally defined in its type area. Determining whether the No-Mans Island beds pinch out to the north or are removed by erosion below the regional basal Brushy Basin paleosol requires further research. Several significant fossil vertebrate and plant sites have been documented in the Brushy Basin type area. Newly identified volcanic ashes provided zircons for U-Pb ages of 150.67 ± 0.32 Ma from near the top of the Brushy Basin Member and of 153.7 ± 2.1 Ma and 153.8 ± 2.2 Ma for two zircons in lower part of Recapture Member. At the top of the Brushy Basin Member, ferruginous paleosols commonly overlying conglomeratic sandstone are speculated to be of Early Cretaceous age (detrital zircon age pending) and are assigned herein to the Yellow Cat Member of the Burro Canyon Formation. These iron-rich paleosols suggest wetter climatic conditions during the Jurassic-Cretaceous transition in the Blanding basin.

Citation for this article.
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INTRODUCTION

In 2016, the U.S. Bureau of Land Management (BLM) requested that the Utah Geological Survey (UGS) paleontology team conduct a preliminary inventory of paleontological resources within the Upper Jurassic (mostly Morrison Formation) outcrop belt on the west side of U.S. Highway 191 on the west side of the Blanding basin, Utah, along the eastern margin of Bears Ears National Monument (figures 1 and 2). This area was chosen for survey because the Utah Paleontological Locality Database, managed by the UGS, indicated that few sites had been recorded in the area. Geologic maps showed that fossiliferous rocks of Upper Jurassic Morrison Formation and Lower Cretaceous Burro Canyon Formation (equivalent to the Cedar Mountain Formation to northwest of the Colorado River) crop out in this region. The Morrison Formation in this region is critical for understanding Upper Jurassic stratigraphy across the southern Colorado Plateau because it is the type area for several important stratigraphic units including the Bluff Sandstone, Recapture, Westwater Canyon, and Brushy Basin Members of the Morrison Formation. Additionally, for decades there has been disagreement about stratigraphic nomenclature and correlation of these units (as discussed below).

Utah Geological Surevy personnel recorded more than 50 new fossil localities in the study area. Some sites yielding dinosaur bones were found in the Recapture Member indicating the potential for significant sites in this unit. The Brushy Basin Member is well known for preserving abundant vertebrate fossils and many localities were discovered during this project. Numerous sites contained isolated sauropod bones and a few sites had many bones eroding out over a small area, warranting additional exploration. Several sites have the potential to produce vertebrate microfossils through wet screen washing (Cifelli and others, 1996). One important new site is a multi-meter-thick plant debris bed, likely representing a marsh setting, that preserves numerous compressional plant fossils and petrified wood in addition to bones and bone fragments. This site is quite unusual for the Morrison Formation and resembles deposits better known in the Upper Cretaceous of the western U.S. and Canada. One laterally extensive organic mudstone near the top of the Morrison Formation preserves a 10-cm-thick (4-in) thick volcanic ash that was sampled for palynology and radiometric dating. We spent only limited time prospecting the Burro Canyon Formation and no vertebrate localities were found.

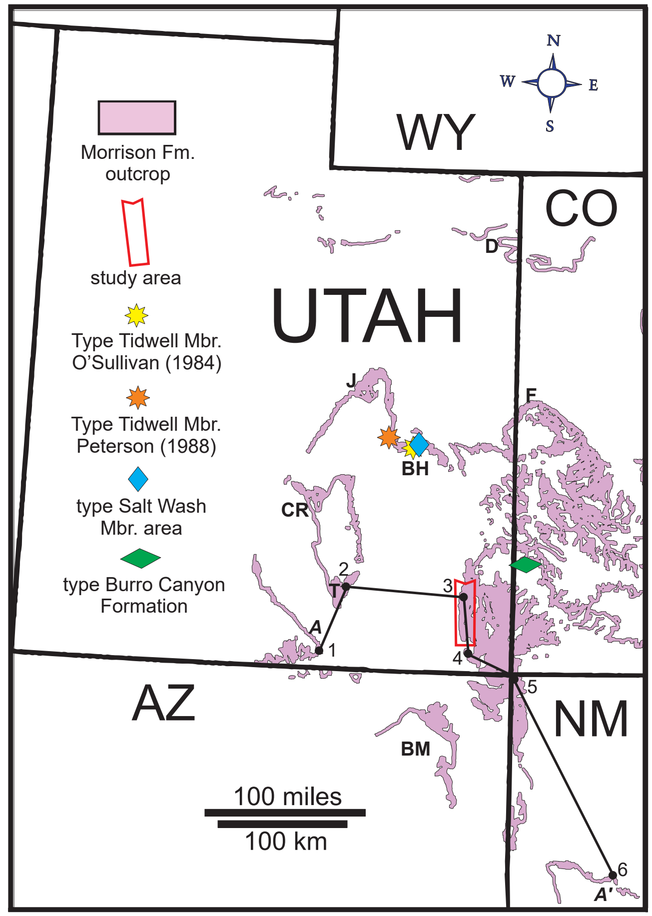

Figure 1. The Morrison Formation outcrop belt in Utah and the Four Corners region with the location of the Blanding basin study area indicated. Line of cross section A–A' for figures 5B amd 5C. BH = Blue Hills area; BM = Black Mesa; CR = northern Capitol Reef area; D = Dinosaur National Monument; F = Fruita Paleontological area; J = Jurassic National Monument (formally the Cleveland-Lloyd Quarry).

The illegal collection of vertebrate fossils has been an ongoing problem in the Morrison Formation outcrops in Utah for many years (e.g., Bertog, 2014; Foster and others, 2016b). Although one site in the Morrison Formation, salvaged by the BLM, had been vandalized by unauthorized excavation, the Morrison Formation in this area appears considerably less vandalized than

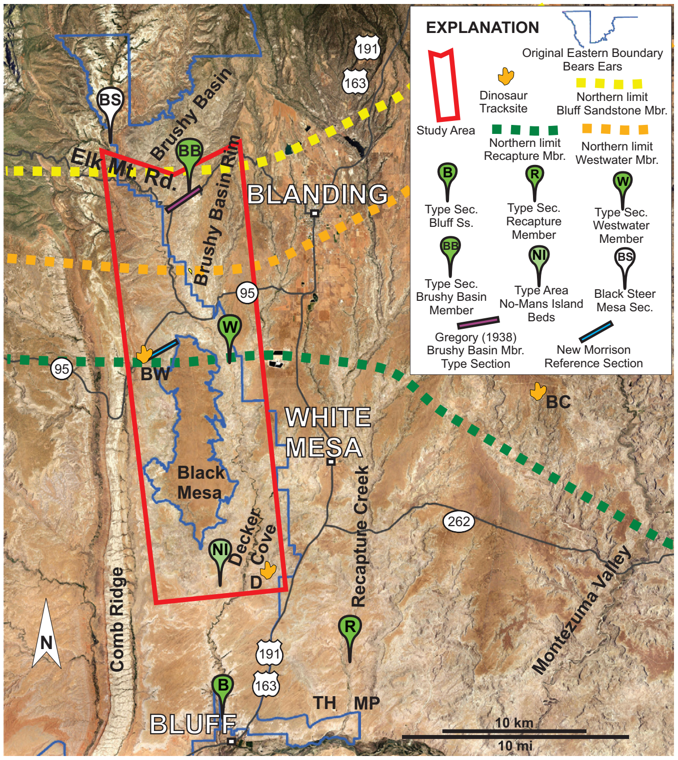

Figure 2. Google Earth© image of study area on the west side of the Blanding basin with locations of type sections of members of the Morrison Formation noted. The Butler Wash (BW) tracksite (Lockley and Mickelson, 1997), the *Deltapodus* (D) site (Milán and Chiappe, 2009), and a unionid bivalve site in the Salt Wash Member in Black Steer Mesa section (BS) (Cadigan, 1955; O'Sullivan, 1980) are the only paleontological localities published on within the study area. Utah's only vertebrate tracksite in the overlying Lower Cretaceous Burro Canyon Formation (BC) is indicated (Milán and others, 2015). Northern limits of lower members of Morrison Formation after O'Sullivan (1998, 2000). MP = McCracken Point, TH = The Horn.

Morrison exposures in other areas of the state (Kirkland and DeBlieux, 2017; Kirkland and others, 2017).

METHODS

During the summer of 2016, Kirkland and DeBlieux spent 10 days prospecting Morrison outcrops for unreported paleontological resources along the west side of the Blanding basin between the south side of Black Mesa and Decker Cove northward to the Elk Mountain Road (figure 2). We followed the standard practice of laterally traversing benches with the least vegetated exposures looking for fossil fragments. When fossil material was located, closer examination was made and additional fossil fragments were traced upslope to determine the source of the fossils. Upon locating the site, photographs were taken, and its location was determined using topographic maps and Global Positioning System device. Additionally, utilizing UGS locality forms as a template, geological data about the site were documented. In general, we followed best practices for mitigation developed by the UGS and the Society of Vertebrate Paleontology (Kirkland and others, 2006; U.S. Bureau of Land Management, 2008; Kirkland and Foster, 2009; Society of Vertebrate Paleontology, 2010; Murphey and others, 2014, 2019). Furthermore, we used taphofacies analysis to identify unusual local environments where rare small vertebrates or plant remains may be found (e.g., Kirkland, 2006). The rarity of taxonomically useful plant and palynomorph sites in the Morrison makes their identification every bit as important, scientifically, as a significant vertebrate locality. During these 10 days we recorded 35 fossil localities. An additional 10 days of prospecting was completed in the fall of 2017 during which we documented an additional 21 fossil localities. Using these methods, most of the more extensive exposures were inventoried for significant fossil sites. We note that even within the areas examined it is not possible to locate every potential site, because a fossil locality may be very subtle, and, in some cases, significant fossils may crumble to dust before becoming exposed on the surface. All locality data have been incorporated into the Utah Paleontological Locality Database maintained by the Office of State Paleontologist at the UGS and are available to permitted paleontologists conducting research in the area or by written consent from the U.S. Bureau of Land Management's Regional Paleontologist.

In preparing for conducting fieldwork in this area, a review of the published literature revealed that there is some dispute as to the appropriate stratigraphic nomenclature to be used on these rocks. This inventory project provided an opportunity to evaluate the various stratigraphic nomenclatures for this area as summarized below. Additionally, we noted that the type section of the most paleontologically significant member of the

Morrison Formation, the Brushy Basin Member, had been inadequately defined by Gregory (1938). Careful reading between the lines resulted in the identification of the largely covered type section along the Elk Mountain Road on the south end of Brushy Basin. In 2017, we described a detailed section of the Morrison Formation 11.2 km (7 mi) to the south of Gregory's type section at a site where the Brushy Basin Member is completely exposed and readily accessible to serve as a primary reference section for this important stratigraphic unit (figures 2 and 3; appendix A).

Additionally, we conducted a parallel paleontological inventory of the Morrison and Cedar Mountain Formations in the Blue Hills region north of Moab, examining the type areas for the Tidwell and Salt Wash Members of the Morrison (figure 1) as summarized by Lupton (1914), O'Sullivan (1984), and Kirkland and DeBlieux (2017). Kirkland has had several opportunities to examine the Tidwell Member of Peterson (1988) in the historic type area at Tidwell Bottoms. Finally, current research on these strata in the northern half of Capitol Reef National Park (figure 1) has resulted in a broader understanding of these rocks. These observations have been important in our developing a general gestalt for these stratigraphic units.

Paleo-Solutions Inc. (Murphey and Zubin-Stathopolos, 2018) conducted inventory work in the lower half of the Morrison Formation (Salt Wash Member in their report) north of Utah State Route (SR) 95 and south of the Elk Mountain Road (figure 2). Their 12 new Morrison fossil localities are incorporated into the Utah Paleontological Locality Database and merged into the stratigraphic framework presented here.

On a two-day field review on October 27 and 28, 2018, Kirkland and DeBlieux with Grant Willis, Program Manager for the UGS Geologic Mapping and Paleontology Program, and Christine Turner, U.S. Geological Survey, retired, reached a general consensus regarding the basal contact of the Recapture Member with the underlying Bluff Sandstone. Additionally, it was decided that the "Yellow Cat facies" at the top of the Brushy Basin Member should be reassigned as the Yellow Cat Member of the Burro Canyon Formation. The Yellow Cat unit was sampled for dating utilizing detrital zircons and for palynology that should validate

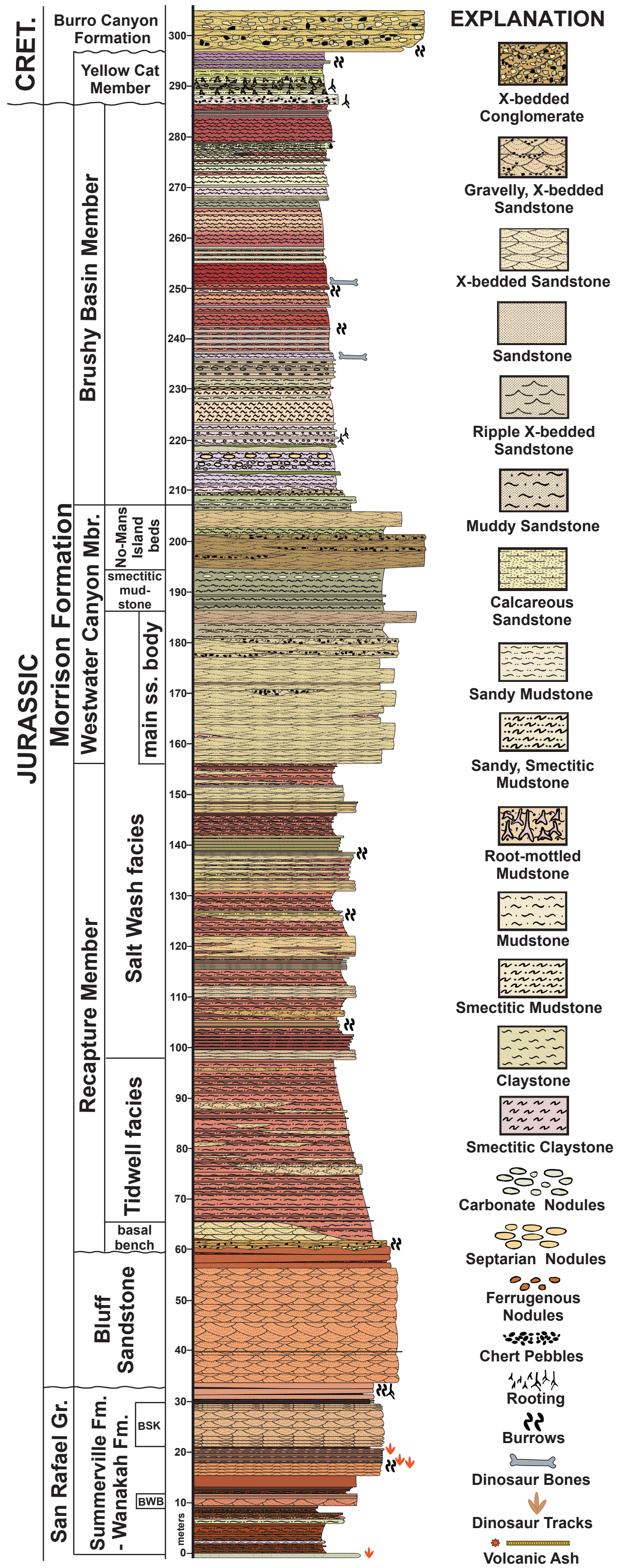

Figure 3. Morrison Formation at measured section on northwest side of Black Mesa (see figure 2 and appendix A).

or refute the reassignment. These decisions were made to facilitate future geological mapping of the Morrison Formation in the region.

Kirkland returned to Recapture Creek in early April 2019 to examine the type area for the Recapture Member of the Morrison Formation considering the new observations south of Black Mesa presented herein. Kirkland observed that the stratigraphic relations of the Recapture Member were consistent throughout the southwestern Blanding basin.

MORRISON FORMATION

The Morrison Formation is probably the most famous Jurassic-age dinosaur-bearing unit in the world, subject of more than 150 years of dedicated paleontological research (Dodson and others, 1980; Morales, 1996; Carpenter and others, 1998; Turner and Peterson, 1999, 2004; Foster, 2003, 2007; Foster and Lucas, 2006). The Morrison was initially named for dinosaur-bearing strata along the Colorado Front Range by Cross (1894). Pipiringos and O'Sullivan (1978) noted that across the Colorado Plateau the Morrison unconformably overlies the San Rafael Group on the J-5 unconformity and is in turn unconformably (K-1 unconformity) overlain by the Lower Cretaceous Burro Canyon Formation in the Blanding basin and the Cedar Mountain Formation farther to the north in central Utah, west of the Colorado River (Stokes, 1952). Additionally, O'Sullivan (1980) noted an angular discordance beneath the J-5 unconformity (bed A) in the type area for the Tidwell and Salt Wash Members (figure 1). However, this feature (figure 4A) may well represent a Gilbert "style" delta formed in the shallow coastal waters of the Summerville sea as sea level rose and fell, much as is exposed in the Summerville west of SR 276 near Ticaboo, Utah (figures 1 and 4B to 4D). Note, that Demko and others (2005) interpreted these specific beds as within the Tidwell Member of the Morrison Formation. Although noting the presence of extensive unconformities above and below the Tidwell on the southwestern margin of the outcrop belt (figures 4E to 4I), we interpret their effect to diminish farther to the north and do not recognize a regional unconformity at the base of the Morrison Formation across the northern Colorado Plateau, but instead interpret the coarser-grained bed A, used by O'Sullivan to define the J-5 unconformity, as representing the transition from shallow subtidal (Summerville Formation) to supratidal in an arid clastic sabkha environment. Although this coastline was apparently low energy, the reported erosional indicator (unconformity) is interpreted to be the result of the winnowing away of finer sediment during storms. In this interpretation, bed A would be regionally diachronous. However, the Summerville Formation is missing on the west side of the Blanding basin, with the strata overlying the Entrada Formation referred to by the U.S. Geological Survey as the Wanakah Formation. Truncation of these coastal strata is evidence for an unconformity in the area toward Comb Ridge at the base of the eolian Bluff Sandstone Member of the Morrison Formation (Turner and Peterson, 2010a).

The Morrison Formation on the west side of the Blanding basin includes a critical series of exposures for understanding Upper Jurassic stratigraphy across the southern Colorado Plateau. Gregory (1938) divided the Morrison Formation into four members in this area. The lower three members—Bluff, Recapture, and Westwater Canyon Members—all either pinch-out or are replaced laterally by other rock units within a few kilometers north of their type sections (figure 2), and these members are important stratigraphic units to the south in northwestern New Mexico and northeastern Arizona. The overlying Brushy Basin Member type section is near the center of its lateral distribution and these brightly variegated strata are readily identified at the top of the Morrison Formation throughout most of the Colorado Plateau region.

The stratigraphic nomenclature in the southern part of the study area is significantly different than that in the northern part of the study area, where the formation consists of the Tidwell, Salt Wash, and Brushy Basin Members. The definitions of these stratigraphic units and their relationship across the area have been a hotly debated issue between two groups of researchers: (1) the U.S. Geological Survey, largely centered around the research of Fred (Pete) Peterson and Christine Turner (Peterson, 1988, 1994; Turner and Fishman, 1991; Turner and Peterson, 2004, 2010a), and (2) a New Mexico group, largely centered around the research of Orin Anderson, New Mexico Bureau of Mines and

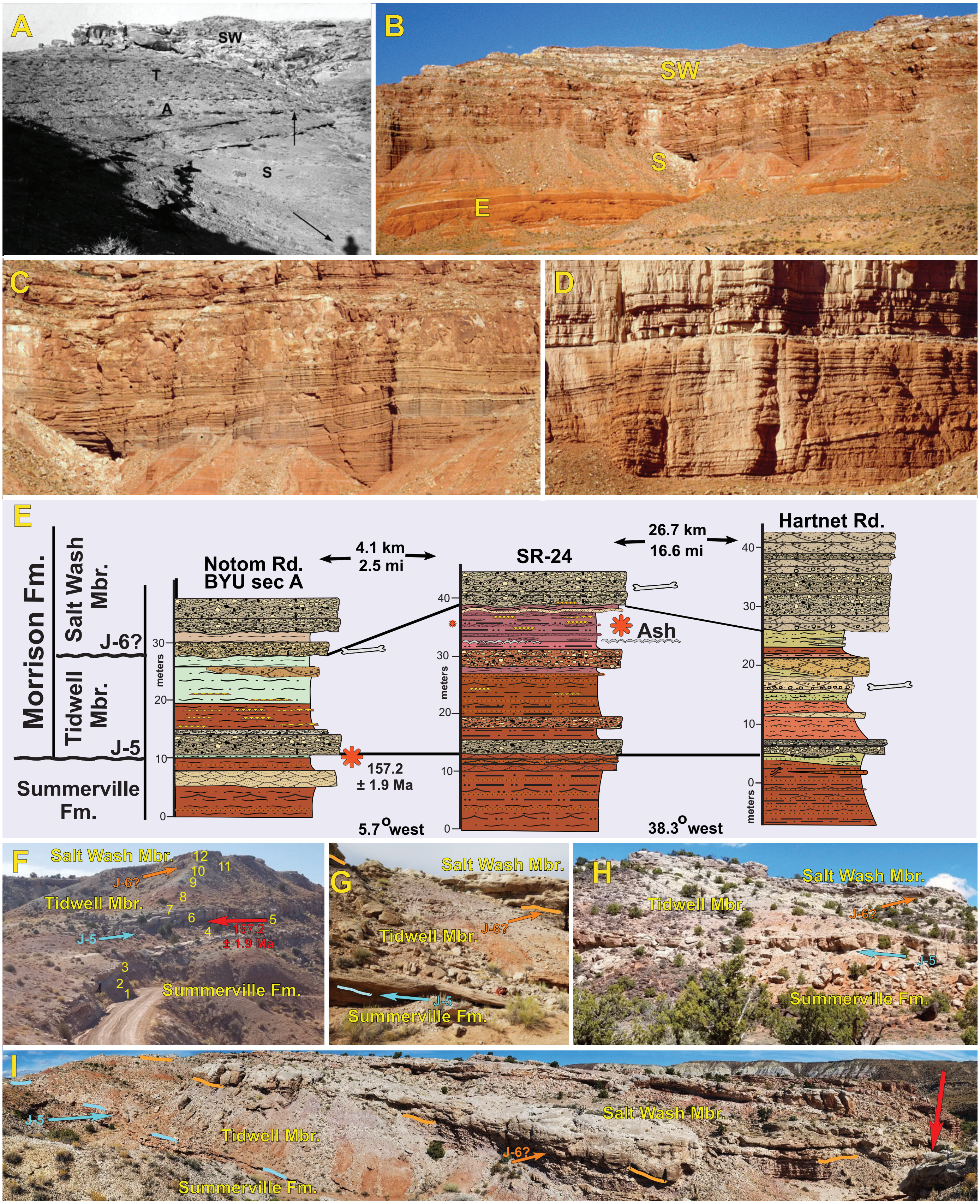

Figure 4. Caption is on the following page.

Figure 4 (figure is on the previous page). Gilbert delta versus angular unconformity in Summerville Formation and Tidwell Member of Morrison Formation at Capitol Reef National Park. (A) Contact between the Summerville Formation and the Tidwell Member of the Morrison Formation (figure 1) northeast of Dellenbaugh Butte (see figure 6 of O'Sullivan, 2010a). Vertical arrow points to position of J-5 unconformity at the base of O'Sullivan's marker bed named bed A. Arrow in lower right corner points to shadow of photographer for approximate scale. (B) Gilbert delta in the Summerville Formation west of SR 276 near Ticaboo, Utah (12 S, 522135.64 m E, 4165396.99 m N). (C) Detail of Gilbert delta from near center of figure B. (D) Another view of Gilbert delta in Summerville Formation laterally along outcrop (12 S, 526116.00 m E, 4178260.75 m N). (E) Stratigraphic sections of the Tidwell Member of the Morrison on the east side of Water Pocket Fold, northern Capitol Reef National Park (figure 1). (F) Notom Road BYU section A (units 1–12 of Peterson and Roylance, 1982; 12 S. 490055.00 m E, 4232678.00 m N). Red arrow position of "Tidwell" age sample (Kowallis and others, 1998) below J-5 unconformity. (G) Tidwell section in canyon southwest of SR 24 (12 S, 489440.00 m E, 4236646.00 m N). (H) Tidwell section on north side of the canyon along the western Hartnet Road (12S, 473110.86 m E, 4257708.98 m N). (I) Panorama of northwest canyon wall southwest of SR 24. Red arrow is position of new bentonitic clay sampled in upper Tidwell (12 S, 489656.00 m E, 4236731.00 m N). A = bed A at base of Tidwell Member, E = Entrada Sandstone, S = Summerville Formation, SW = Salt Wash Member of Morrison Formation, T = Tidwell Member of Morrison Formation. Pale blue arrow labeled J-5 = position of unconformity J-5. Orange arrow labeled ?J-6 = position of possible regional unconformity J-6.

Mineral Resources and Spencer Lucas, New Mexico Museum of Natural History and Science (Anderson and Lucas, 1996, 1997, 1998; Lucas and Anderson, 1997; Lucas, 2014, Dickinson, 2018). Largely, these arguments/questions are (1) should the Bluff Sandstone be separated from the Morrison Formation and included in the San Rafael Group and (2) does (as the U.S. Geological Survey team proposed) the Salt Wash Member directly overlie the Bluff Sandstone Member in its type area and in turn, is it overlain by the Recapture and Westwater Canyon Members as initially described by Stokes (1944) and Craig and others (1955)?

The New Mexico group has argued that the Bluff Sandstone should be included in the San Rafael Group and that it interfingers with the overlying Recapture Member. As such they have proposed that both the Bluff Sandstone and much of Gregory's Recapture Member should be included in the San Rafael Group and that the J-5 unconformity should be placed at the base of the lowest laterally extensive fluvial unit that they assigned to the base of the Salt Wash Member. Additionally, they considered the Westwater Canyon Member to be the upper part of the Salt Wash Member (figure 5).

As discussed below, we consider parts of both stratigraphic interpretations to be correct. We interpret that the upper Recapture and the lower part of the Westwater Canyon Members correlate to the Salt Wash Member in east-central Utah and have identified several vertebrate fossil sites in the lower Recapture Member that support including the basal Recapture in the Morrison Formation. Furthermore, as discussed below, we agree with the U.S. Geological Survey team that recognized coarse sands and gravels at the base of the Bluff Sandstone with considerable erosional relief as representing the J-5 unconformity locally (O'Sullivan, 1980, 2000; Turner and Peterson, 2010a) (figure 6). The Bluff Sandstone Member interfingers with the Tidwell Member to the north (Turner and Peterson, 2010a) and is overlain by approximately 5 m (16 ft) of similar red mudstone of similar character. We therefore retain the Bluff Sandstone Member as the basal member of the Morrison Formation. We disagree with Turner and Peterson's (2010a) acceptance of Craig and others' (1955) interpretation that the Salt Wash underlies the Recapture Member (figure 5B), which resulted in their correlating the Recapture into the basal Brushy Basin Member in the central and northern Colorado Plateau area (Turner and Peterson, 2004, 2010a).

In 2016, we thought we had observed apparent interfingering and interlensing of eolian Bluff Sandstone facies with the lower part of the Recapture Member. On March 4, 2017, Kirkland met with Christine Turner to discuss the stratigraphy in this area. Turner noted that recent observations by O'Sullivan (2010a, 2010b) of the U.S. Geological Survey at the type Recapture section (figures 2 and 4) support the interpretation that in this immediate area the basal Tidwell Member is laterally equivalent to the Bluff Sandstone and that the Salt

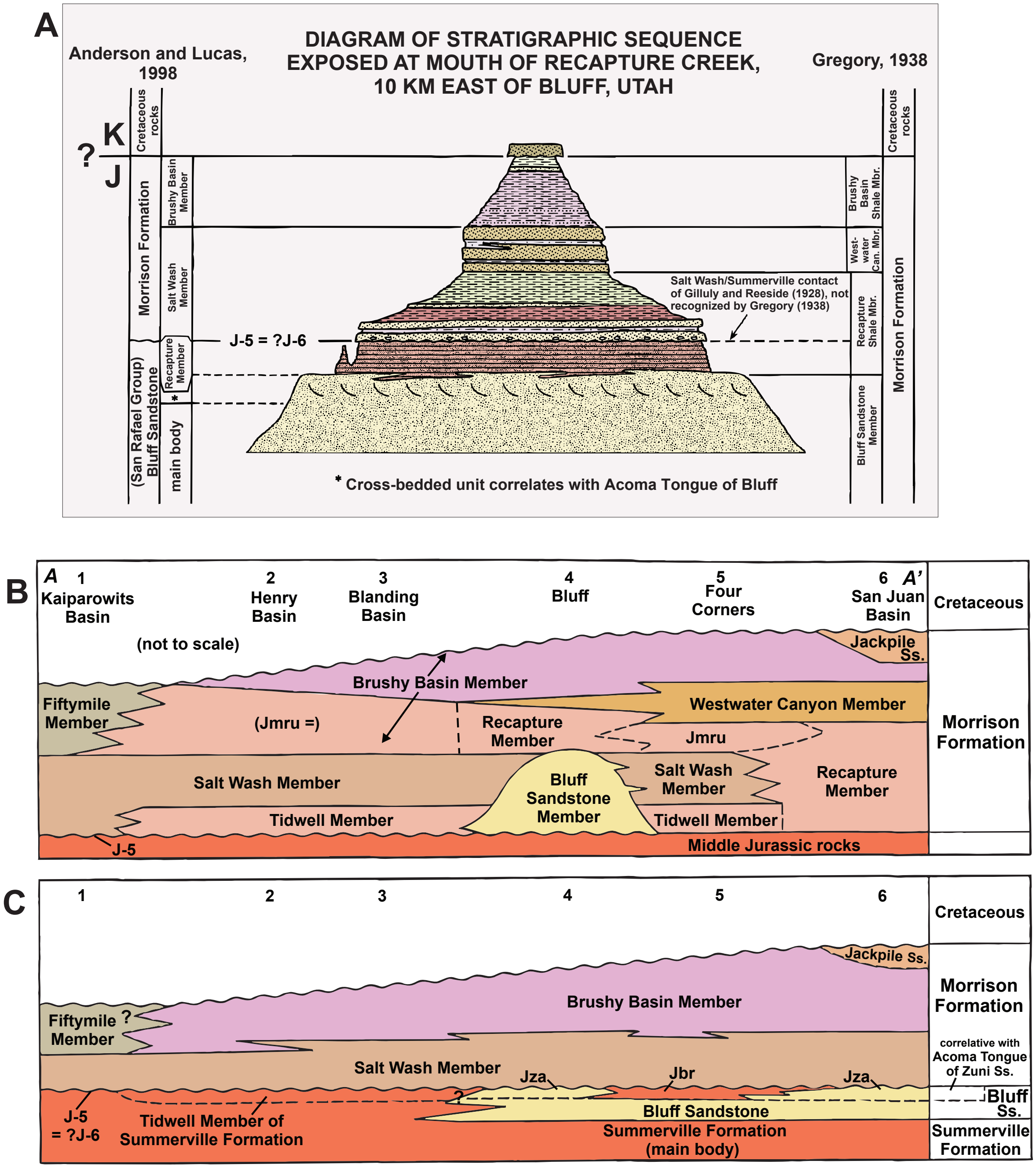

Figure 5. Comparison of stratigraphic interpretations of Gregory (1938), Anderson and Lucas (1996, 1997, 1998) and Peterson and Turner-Peterson (1987) for the Morrison Formation. (A) Gregory (1938) versus Anderson and Lucas (1997, 1998) interpretation of the Upper Jurassic along Recapture Creek. (B) Peterson and Turner-Peterson's (1987) stratigraphic hypothesis across the Colorado Plateau. Interpretation: Jmru = upper part of Recapture Member, (Jmru=) = equivalent to upper part of Recapture Member. Line of correlation as in figure 1. Note correlation developed prior to recognition of clay change in basal Brushy Basin Member. (C) Anderson's revised interpretation of Peterson and Turner-Peterson's (1987) stratigraphic hypothesis. Jza = Acoma Tongue of the Zuni Sandstone, Jbr = Recapture Member of Bluff Sandstone, J-5 = basal Morrison unconformity. J-5 = ?J-6 indicates our interpretation that Anderson and Lucas (1996, 1997, 1998) recognized a younger regional unconformity at the base of the Salt Wash Member and near the base of Gregory's (1938) Recapture Member. Modified from Anderson and Lucas (1997). Generalized figures are not to scale.

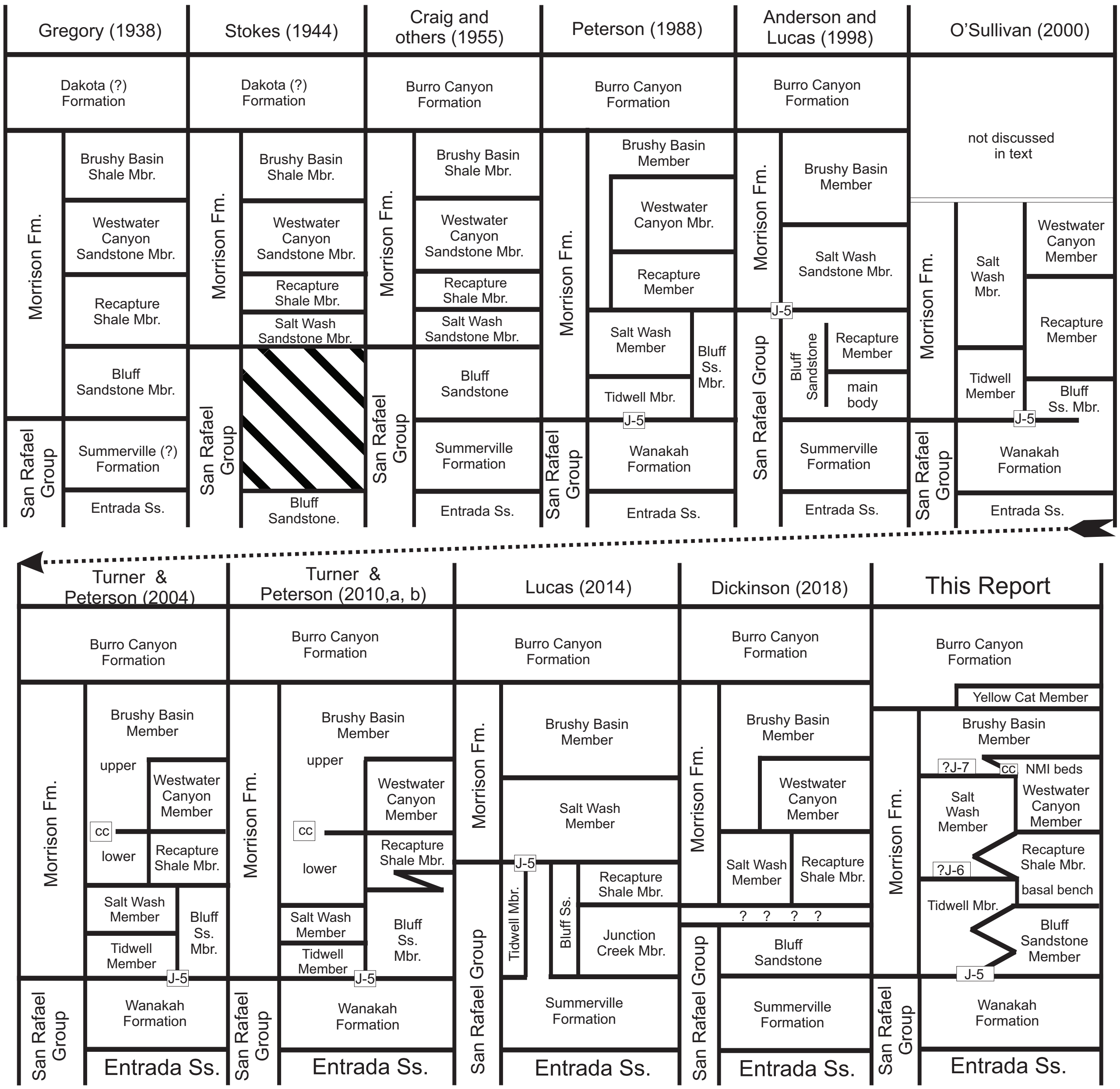

Figure 6. History of nomenclature for the Morrison Formation and bounding strata along east side of Comb Ridge. CC = position of "clay change," J-5 = basal Morrison unconformity, ?J-6 = possible regional unconformity below Salt Wash Member, ?J-7 possible unconformity at the "clay change."

Wash Member does not onlap the Bluff Sandstone as proposed by Stokes (1944), Craig and others (1955), and Turner and Peterson (2004). Instead, Turner noted that the Recapture Member directly overlies the Bluff Sandstone in its type area (Turner and Peterson, 2010a, 2010b; verbal communication, 2017) and continued to propose that the Salt Wash is stratigraphically below the Recapture and, with the underlying Tidwell Member, is laterally equivalent with the Bluff Sandstone and as such both are not identifiable in outcrop across the southwestern Blanding basin. However, O'Sullivan (1980, 1998, 2000, 2010b) proposed that sandstone lenses typical of the Salt Wash appear in the Recapture well above its base north of the Recapture type section in Montezuma Canyon (figure 2), more closely following Anderson and Lucas' (1998) interpretation of Gilluly and

Reeside (1928) (figures 2 and 4). Using Cadigan's (1952) Black Steer Knoll section on the southwest side of the Abajo Mountains north of the Elk Mountain Road, O'Sullivan (1980, 2000) noted that the Tidwell Member is overlain by the Salt Wash Member, forming the base of the Morrison Formation (figures 2 and 6). Utilizing these data points, together with subsurface data, O'Sullivan proposed that the Bluff Sandstone pinches out to the north, where it and the thinning Recapture Member are replaced by the basal reddish mudstones of the Tidwell Member and overlying fluvial-dominated Salt Wash Member (O'Sullivan, 1980, 1998, 2000; Turner and Peterson, 2010a). Both O'Sullivan (1980) and Lucas (2014) documented that the Bluff Sandstone interfingers with the Tidwell Member over a 3 to 5 km (2–3 mi) interval extending north from around Whiskey Draw, with O'Sullivan (1998, 2000) noting that the Bluff Sandstone is not recognizable at the Elk Mountain Road (figure 2). However, Turner and Peterson (2010a, plate 6) illustrated the interfingering of the Bluff Sandstone with the Tidwell Member on the north side of Cottonwood Wash (625381.23 m E, 4168492.67 m N) just south of where the Elk Mountain Road crosses the wash (Turner, verbal communication, October 27, 2018). Taken there by Christine Turner, we were not able to visit the specific site as the Ute Tribe posted numerous no trespassing signs in the area. However, Kirkland noted that approximately an additional 5 to 10 m (16–32 ft) of red mudstone and sandstone overlie this intertonguing interval that can reasonably be interpreted as Tidwell or a northern tongue of the Recapture Member, below what appears to be a series of sandstone ledges typical of the Salt Wash Member.

While we think the strongest evidence supports the hypothesis that the Bluff interfingers with and should be included as a member of the Morrison Formation, we recognize that there is evidence that could result in a somewhat different interpretation. We noted that conglomerate beds separate the Bluff Sandstone from the overlying Recapture Member of the Morrison Formation on the west and south sides of Black Mesa. In fact, even Gregory (1938, section 23, unit 3) noted an unconformity near the base of the overlying Recapture at its type section on Recapture Creek. If this is evidence of a regional unconformity in the basal Recapture, perhaps the Bluff Sandstone is best removed from both the San Rafael Group and the Morrison Formation and elevated to formation status. However, this upper conglomeratic layer has not been documented as extending across the entire outcrop of the Bluff farther to the east and we suspect that it may be reflecting local Mesozoic uplift along Comb Ridge as has been proposed for the San Rafael Reef to the north (Eaton and others, 1990; Kirkland and Madsen, 2007; Kirkland and others, 2016). In conclusion, there is evidence both for and against including the Bluff in the Morrison, but the strongest evidence supports its inclusion.

The general physiographic pattern formed by the Morrison Formation and its bounding strata across the south side of the Blanding basin is a series of three extensive benches. These benches are readily observed where crossed by U.S. Highway 191 between Bluff and White Mesa, Utah (figure 7).

1. The first (southernmost) bench extends along east-west just north of the San Juan River and consists of a dark brownish-red escarpment of the San Rafael Group capped by light brownish-gray eolian Bluff Sandstone Member.
2. The second bench starts with a short step (basal Recapture bench) formed by light brownish-gray fluvial and less commonly eolian sandstone beds at the base of the Recapture Member of the Morrison Formation, and extends up through the steeper cliff formed by fluvial sandstones (No-Mans Island beds) capping the Westwater Canyon Member. The Hovenweep Road (SR 262) extends east from U.S. Highway 191 along the top of this bench.
3. The third bench is made up of the slope-forming Brushy Basin Member of the Morrison Formation capped by resistant Cretaceous fluvial sandstones of the Burro Canyon and Naturita Formations, and forms the "jump off" south of White Mesa.

These benches can also be recognized along the southwest side of Black Mesa as the Morrison outcrop belt narrows and turns north along Comb Ridge (figure 7).

Unfortunately, northward facies changes in the

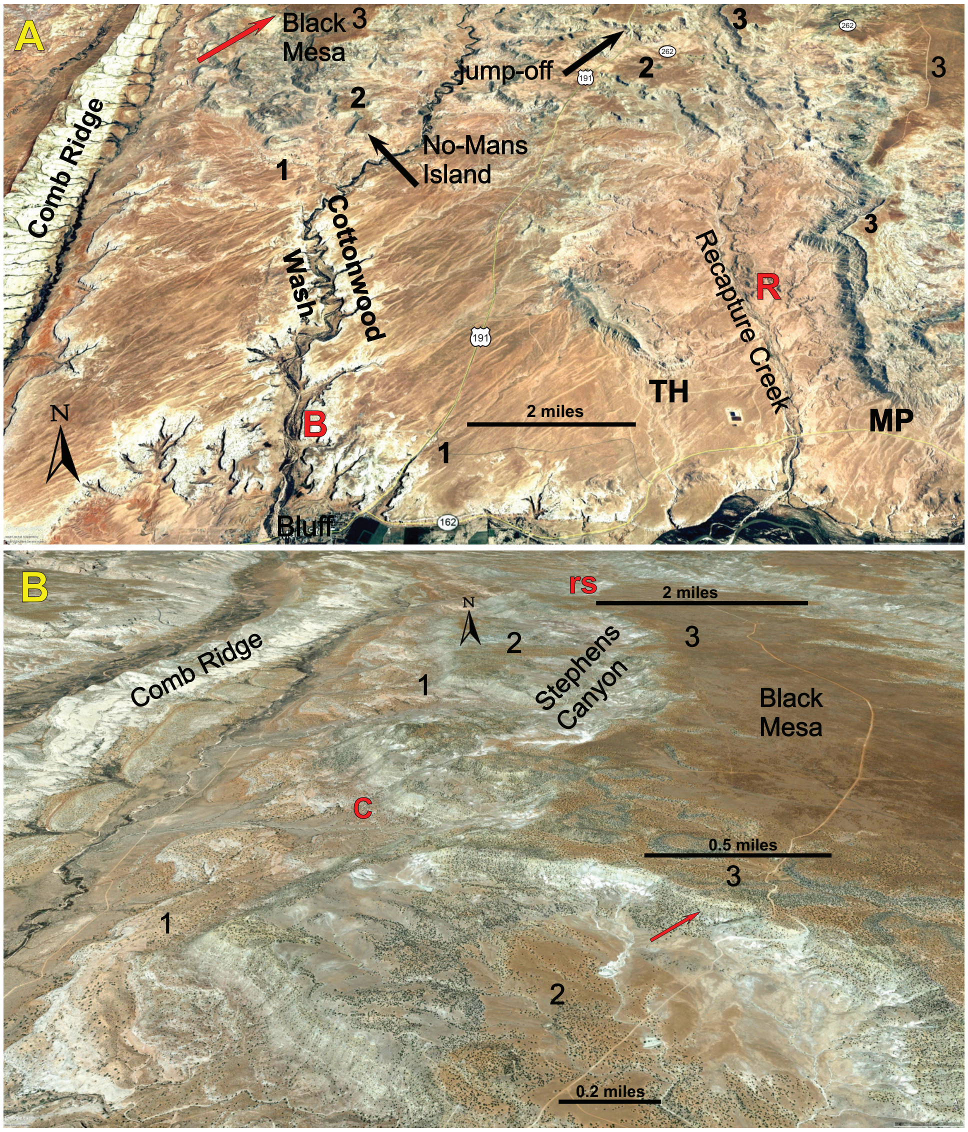

Figure 7. Southwestern Blanding basin (Google Earth©). (A) Oblique view to north into western Blanding basin from near San Juan River. Red arrow on both photos indicates site where dated volcanic ash was collected near top of the Morrison Formation. B = type section of the Bluff Sandstone, R = type section of Recapture Member, MP = McCracken Point, TH = The Horn. (B) Oblique view of Jurassic outcrop between Comb Ridge and Black Mesa from the south. rs = site of Morrison reference section (appendix A). C = site where chert gravel conglomerate was observed at base of Recapture on southwest side of Black Mesa. 1, 2, 3 on tops of benches referred to in text.

Morrison Formation are hidden as they extend beneath Cretaceous strata forming the center of the Blanding basin. These relationships at the base of the Morrison Formation have been documented in the subsurface by O'Sullivan (1998, 2000). However, the north-south band of Jurassic outcrops along the west side of the Blanding basin on the east side of Comb Ridge exhibits the transition from the southern stratigraphic nomenclature proposed by Gregory (1938) to the terminology used across east-central Utah by Turner and Peterson (2004). The steeper eastward dip imparted to the strata by Comb Ridge has resulted in a complete sequence of the Upper Jurassic extending from the south end of Black Mesa northward until the outcrop becomes largely obscured by vegetation and landslide deposits on the southwest side of the Abajo Mountains (figure 8). The critical transitions in this terminology apparently occur in the outcrops north of where SR 95 crosses this outcrop belt (Miller, 1955a; O'Sullivan, 1998, 2000). Miller (1955a, 1956), on the photogeologic map of the Black Mesa Butte 7.5-minute quadrangle (figure 2), found that north of SR 95 the Recapture Member is no longer recognizable and the Recapture and Westwater Canyon Members were replaced with "lower" Morrison on Millers map; whereas, O'Sullivan (1998, 2000) continued to recognize the Westwater Canyon Member a few kilometers farther north (figure 2), replacing it with Salt Wash Member at the Elk Mountain Road. Our detailed stratigraphic section of the Morrison Formation just south of SR 95 on the northwest side of Black Mesa (appendix

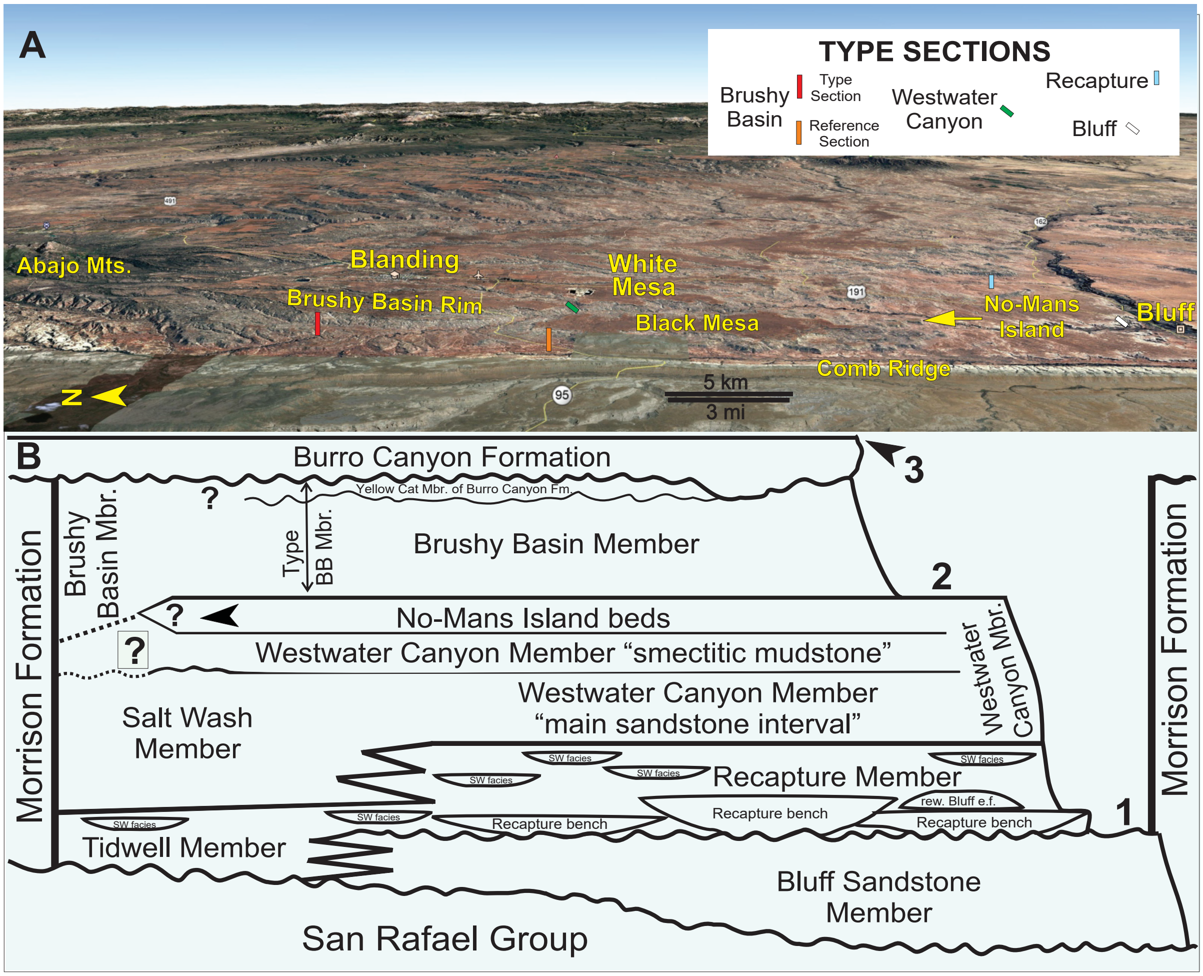

Figure 8. Generalized Upper Jurassic stratigraphic relationships along Comb Ridge. (A) Viewed from the west across Comb Ridge and the Blanding basin (Google Earth©). (B) Simplified diagram of relationships of Morrison Formation units, along with bounding strata, for east side of Comb Ridge. No vertical scale intended. 1, 2, 3 indicate tops of regional benches referred to in text. SW facies = channel sandstone facies of Salt Wash character; rew. Bluff e.f. = reworked Bluff eolian facies.

A) follows along this line of nomenclatural transition critical to interpreting the Morrison Formation on the southern Colorado Plateau relative to its stratigraphic nomenclature across east-central Utah (figure 8).

Basal Contact of the Morrison Formation

We follow the U.S. Geological Survey in recognizing an unconformity below the Bluff Sandstone Member that they interpret as the J-5 unconformity of Pipiringos and O'Sullivan (1978), O'Sullivan (1998, 2000, 2010a, 2010b), and Turner and Peterson (2004, 2010a, 2010b). We suggest that the topographic relief documented at this unconformity, the intrabasinal source of the larger clasts in the conglomeratic beds, and the lateral variability of the units at the top of the San Rafael Group, combined with the local derivation of these clasts (Peterson and Turner, 2010a), supports syndepositional tectonics along the Comb Ridge uplift during the formation of this unconformity, as has been proposed for the San Rafael Swell during the middle Mesozoic (Eaton and others, 1990; Kirkland and Madsen, 2007; Kirkland and others, 2016) and elsewhere on the Colorado Plateau (Peterson, 1969, 1984, 1986; Kirkland 1990, 1991).

Although not the focus of this study, we would have preferred to abstain from committing to a specific terminology for the strata immediately underlying the Bluff Sandstone (figures 3, 6, and 8). Gregory (1938) questioned use of the term Summerville Formation for the strata underlying the Bluff, because the strata are unlike that of the type Summerville Formation. The U.S. Geological Survey recognized the Wanakah Formation below their J-5 unconformity in this area (O'Sullivan 1998, 2000, 2010a, 2010b; Turner and Peterson, 2010a, 2010b), named for the Wanakah mine near Ouray, Colorado, by Burbank (1930). O'Sullivan (1984, 1992) and O'Sullivan and others (2006) noted that it correlates to the lower Curtis and uppermost Entrada Formations, which implies that the J-3 unconformity marking the Entrada-Curtis boundary lies within the Wanakah Formation, possibly at the base of the Butler Wash beds in the southern Blanding basin (O'Sullivan 1998, 2000, 2010b). Complicating the use of the term Wanakah Formation in this area, Grabeau (1917) informally proposed a Devonian Wanakah Shale Member of the Ludlowville Formation in upstate New York, which was formally defined by Cooper (1930). Thus, there has been debate as to whether the Wanakah Formation is a valid term for these strata or if another name should be applied (Armstrong, 1995, p. 5). Burbank (1930) was aware of the duplication of names and felt there would be no confusion, given the vastly different age of the strata in different regions of the country. The North American Stratigraphic Code (NASC) allows the duplication of nomenclature if there is no chance of confusion. O'Sullivan (2010a, p. 99) noted that the NASC's discouraging the duplication of names was published after Wanakah was applied to these strata in both areas and that "the continued use of the name Wanakah Formation is highly preferable to the use of Summerville Formation, which is absent in the Four Corners area" (O'Sullivan, 1980, 1984, 1992, 1998, 2000, 2010a; Condon and Hoffman, 1988). Summerville Formation has been applied incorrectly to these more complex strata most recently by Lucas (2014) and Dickinson (2018). Resolving this ongoing debate is beyond the scope of this paper and Wanakah Formation is used without implying a preference over Summerville.

Several subdivisions of the Wanakah Formation have been proposed and have variably been applied to these rocks in the Blanding basin (O'Sullivan, 1980, 1984, 1992, 1998, 2000, 2010a; Condon and Hoffman, 1988; Lucas, 2014). We found that it is difficult to recognize some of these units in outcrop and that different authors have applied different terms to the same beds over the years. For example, near the top of the Wanakah a prominent pair of sandstone ledges were referred to as the bed at Black Steer Knoll (O'Sullivan, 1980). Subsequently, O'Sullivan (1997, 1998, 2000) discontinued using this nomenclature in favor of the Horse Mesa beds (erected for sandstone beds near the top of the Wanakah in northern Arizona by Condon and Hoffman [1988]). However, in describing these strata as Summerville Formation, Lucas (2014) used the Black Steer Knoll bed for this same pair of sandstone beds. In describing the Wanakah Formation at the base of the Morrison reference section, we found it nearly impossible to be certain which of the previously described subdivisions within the Wanakah preserved the Butler Wash dinosaur tracksite (figure 3), although the tracksite is well below the base of the Bluff Sandstone (Lockley and Mickelson, 1997).

West of Bluff, Utah, Turner and Peterson (2010a, figure 1.25, p. 16) noted angular red chert fragments in the basal contact of the Bluff Sandstone Member that were derived from dark red chert lenses in the uppermost part of the Wanakah Formation that are cut out by an unconformity which has tens of meters of relief locally (figure 9A). Similarly, to the north of SR 95, where the Bluff Sandstone Member interfingers with the Tidwell Member, O'Sullivan (1980, 2000) and Turner and Peterson (2010a, plate 7, p. 79) recognized coarse sandstone bed A representing the J-5 unconformity. This contact was also followed in Carr-Crabaugh and Kocurek's (1998) examination of the San Rafael Group as a complex, wet eolian system in this area.

In addition to the J-5 unconformity at the base of the Bluff Sandstone Member, we note that there is another unconformity at the top of the Bluff below a fine-grained, fluvial and eolian bench-forming facies. We interpret these beds to represent eolian sands reworked across this unconformity from the underlying Bluff Sandstone Member into the basal Recapture Member of the Morrison Formation. Thus, we do not interpret these sandstones as representing intertonguing between the Bluff and Recapture Members or as fluvial sandstones pertaining to the Salt Wash Member.

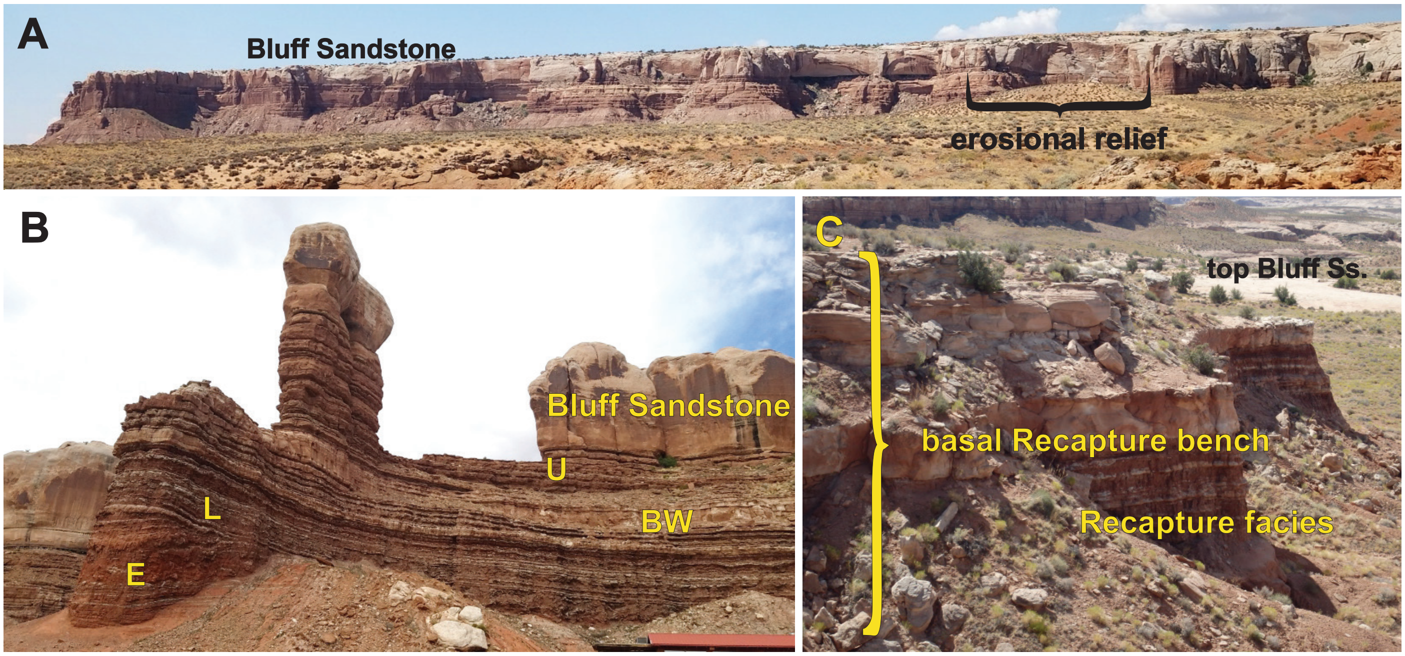

Figure 9. Upper San Rafael Group and Bluff Sandstone and basal Recapture Members of the Morrison Formation in the western Blanding basin in the Bluff and southern Black Mesa areas. (A) Upper San Rafael Group capped by Bluff Sandstone viewed to west from Bluff, Utah, toward Comb Ridge. Bracket denotes clearly expressed erosional base of Bluff Sandstone discussed by Turner and Peterson (2010a, figure 1.25). (B) Upper San Rafael Group and Bluff Sandstone bench at Bluff, Utah, as described by O'Sullivan (2010a). BW = bed at Butler Wash of the Wanakah Formation, E = Entrada Sandstone, L = lower member of Wanakah Formation, U = upper member of Wanakah Formation. (C) Basal fluvial bench of Recapture Member of Morrison Formation sitting above regional bench 1 formed by top of the Bluff Sandstone southwest of No-Mans Island looking south.

Bluff Sandstone Member

Following the usage of Baker and others (1936), Gregory (1938) described the Bluff Sandstone Member as the basal member of the Morrison Formation from outcrops at the top of the Middle Jurassic "Summerville Formation" of the San Rafael Group on either side of the San Juan River near Bluff, Utah. We interpret the type section to be in an alcove to the northeast of Bluff, Utah, (figure 2) based on the photograph of the team surveying the Bluff Sandstone Member (Gregory, 1938, plate 3C). Gregory described the Bluff as follows:

> "The Bluff sandstone member is white, brown-stained, commonly cross-bedded, and made up of medium to coarse quartz grains. Typically it is one massive bed 200 to 350 feet thick that here and there includes aggregates of large quartz grains, clay balls, and short thin lenses of red mudstone. In some places it is arranged as long overlapping sandstone wedges bordered by a little red shale, and in other places as poorly defined beds 20 to 40 feet thick. Traced eastward, the Bluff sandstone that forms the top of Tank Mesa is less persistently massive. Near the mouth of Montezuma Canyon 10 to 20 feet of bedded white sandstone are incorporated in red sandy shale that thins, thickens, bunches up, or flattens out along the strike. Traced northward along Butler Wash and Cottonwood Canyon the Bluff sandstone is represented in places by three or more beds."

Lower Contact

Workers have had varied interpretations of how the Bluff relates to other units and the nature of the basal contact. Stokes (1944) considered the Bluff a formation and correlated the Bluff Sandstone with the Entrada Sandstone, resulting in an apparent unconformity between the Bluff Sandstone and Morrison Formation. Craig and others (1955) noted that it interfingers with both the underlying Summerville Formation and the overlying Salt Wash Member of the Morrison Formation, and thus is transitional between the two stratigraphic units. Likewise, Dickinson (2018) recently reported intertonguing between the underlying Summerville and the Bluff Sandstone, reflecting the complexities in the transition in the upper San Rafael Group in this area. O'Sullivan and Maberry (1975) identified trace fossils (interpreted as having marine origins) in the Bluff Sandstone Member near the Arizona border and indicated that this supported a genetic link with the underlying San Rafael Group. These observations preclude the presence of a J-5 unconformity either above or below the Bluff Sandstone. Anderson and Lucas (1996, 1998) removed the Bluff Sandstone from the Morrison Formation and elevated it to a formation in the underlying San Rafael Group. They correlated the Bluff Sandstone to similar eolian units (Zuni and Cow Springs Sandstones) to the south in New Mexico and Arizona that occur at the top of the Middle Jurassic San Rafael Group. The basal unit A of the Bluff Sandstone preserving "marine" burrows south of the San Juan River (O'Sullivan and Maberry, 1975) was referred to as the Horse Mesa Member of the Wanakah Formation by some workers (Condon and Hoffman, 1988; O'Sullivan, 2010b). Peterson (1994) interpreted the Bluff Sandstone to represent a coastal eolian unit.

In contrast, Turner and Peterson (2004, 2010a) reported that the Bluff Sandstone unconformably overlies the San Rafael Group, where they document a basal gravel and several tens of meters of relief on the regional scoured contact west of Bluff, Utah. Where the upper San Rafael Group is thinly bedded, this basal contact of the Bluff Sandstone Member is easily recognized (figures 9A and 9B). O'Sullivan (1980) reported that the Black Steer Knoll bed, a distinctive marker bed near the top of the Wanakah Formation north of SR 95, is truncated by an angular unconformity at the base of the Bluff Sandstone to the south. Researching these same sections, Lucas (2014) interpreted the Bluff Sandstone as interfingering northward of SR 95 into the Tidwell Member, which put in the Summerville Formation, but did not speculate on the loss of the underlying Black Steer Knoll bed to the south.

Dickinson (2018) noted that the provenance as indicated by the suite of ages determined for detrital zircons in the Bluff Sandstone is comparable to that of the underlying eolian Entrada Sandstone and laterally underlying the marine Curtis Formation and as such, the Bluff should be considered part of the San Rafael Group. Surprisingly, Entrada eolian sands were transported by Middle Jurassic paleowinds from the north and north-northeast and those in the Bluff Sandstone Member from Late Jurassic paleowinds from the southwest as reported by Dickinson (2018). Given the erosional relief at the base of the Bluff Sandstone Member (Turner and Peterson, 2010a), reworking sand grains (including zircons) from the underlying formations of the San Rafael Group could well account for the similarity in provenance data as determined by detrital zircons.

Upper Contact

The top of the Bluff Sandstone Member forms a broad bench across the south side of the Blanding basin north of the San Juan River (figure 8). On the south and west sides of Black Mesa, a distinct second bench 5 to 15 m (16–50 ft) thick is formed by flat-bedded, reddish-brown mudstone and sandstone beds, or simply softer sandstone capped by fine, light brownish-gray fluvial and eolian sandstone beds apparently derived from reworking of the upper Bluff Sandstone Member. This lower bench is at the base of a steep slope-forming interval that extends through the overlying Recapture Member and steeper Westwater Canyon Member (figures 9C and 10). Our documentation of coarse chert clasts up to 10 cm in diameter at the base of these fluvial sandstones precludes these beds from being part of the Bluff Sandstone Member as mapped by Miller (1955b) and supports the observation that the Bluff is bounded above and below by unconformities at least locally in the southwestern Blanding basin.

Given that Gregory (1938, section 23, unit 3) noted an unconformity near the base of the overlying Recapture Member at its type section on Recapture Creek east of the study area (figure 2), it was critical to reexamine this section. We found that Gregory's unit 3 was a channel sandstone lens cutting down into the lower Recapture strata and that unit 3 was the same sandstone interpreted by Anderson and Lucas (1996, 1997, 1998)

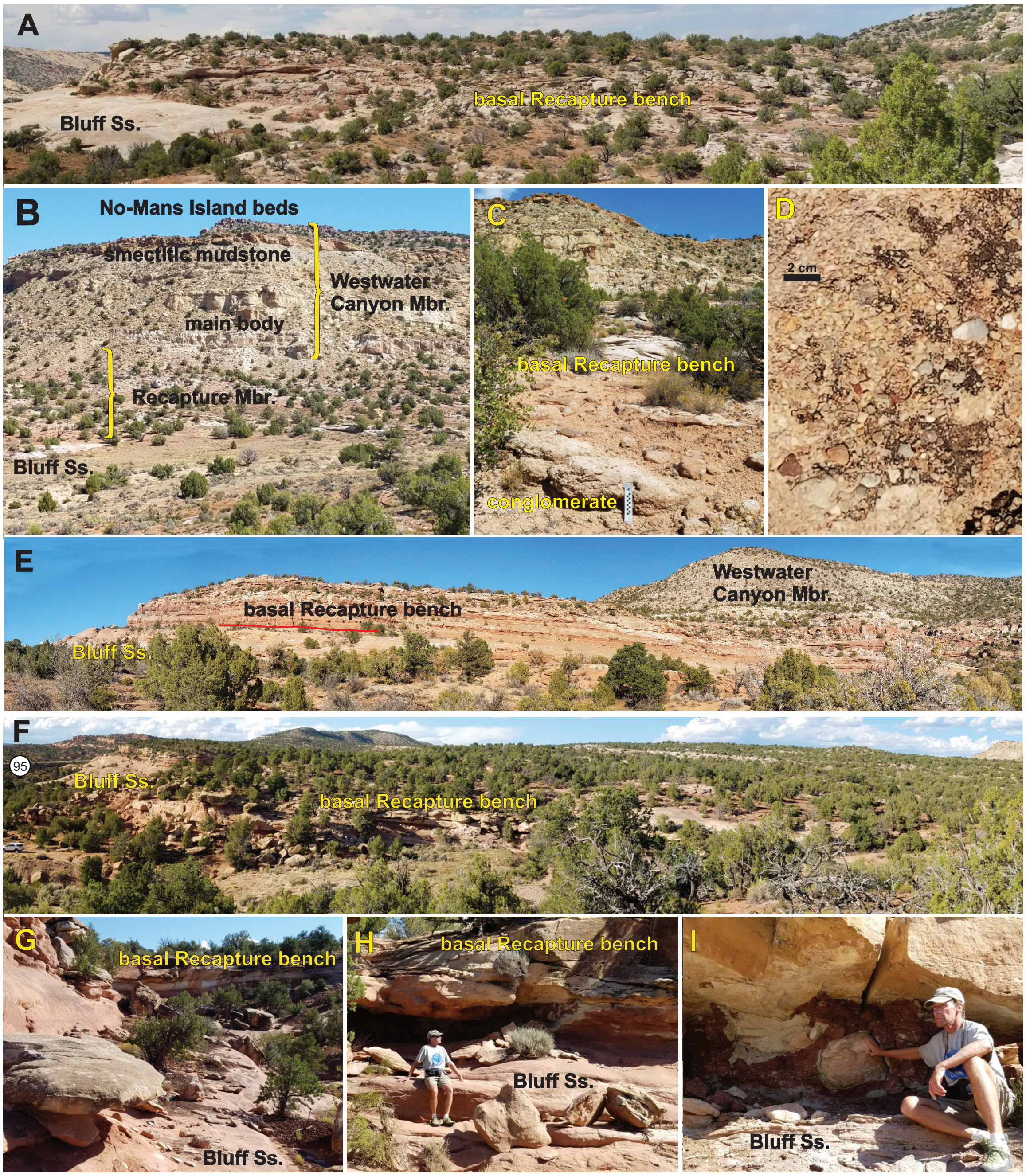

Figure 10. Lower Morrison Formation (Bluff Sandstone, Recapture, and Westwater Members) west of Black Mesa. (A) Northern margin of alcove at base of Morrison Formation just northwest of ash site (figures 2 and 5) on the southwest side of Black Mesa. (B) Recapture and Westwater Canyon Members on northwest escarpment of alcove on southwest side of Black Mesa. (C) View up exposure in B from conglomerate unit between Bluff Sandstone and reworked lenses of Bluff Sandstone facies in Basal Recapture Member. (D) Basal conglomerate unit above Bluff Sandstone (C in figure 5). (E) Exposure on west side of Black Mesa from Butler Wash Road (at about 621854.36 m E, 4153612.63 m N) with thick fluvial sequence at the base of the Recapture Member overlying eolian Bluff Sandstone. (F) Transition between Bluff Sandstone and basal Recapture Member of Morrison Formation at reference section for Brushy Basin Member. (G) Upper Bluff Sandstone west of Butler Wash Tracksite at 12 S 0622447 E, 4154912 N. (H) Contact between Bluff Sandstone and base of Recapture Member at 12S 0622624 E 4155098 N. (I) Intraformational conglomerate at contact between Bluff Sandstone and Morrison Formation in same area.

as representing the base of their Salt Wash Member capping their Recapture Member of the Bluff Sandstone. This area is described in more detail below in the Recapture Member section.

O'Sullivan (1998) and Turner and Peterson (2010a) documented that the Bluff Sandstone Member pinches out into the Tidwell Member of the Morrison north of SR 95 above the marker bed formed by the underlying Horse Mesa Member of the Wanakah Formation (figure 2). Inexplicably, Dickinson (2018) included the Horse Mesa Member (Black Steer Knoll bed) of the Wanakah Formation as the basal unit in the Bluff Sandstone. Turner and Peterson (2004, 2010a) noted that the Bluff Sandstone Member interfingers with and is overlain by the Tidwell Member in some areas and is overlain by the Salt Wash Member in others. This interpretation follows Stokes' (1944) and Craig and others' (1955) view that the Recapture Member overlies rather than underlies the Salt Wash Member. Subsequently, Turner and Peterson (2010a, 2010b; verbal communication, 2017) revised this interpretation following O'Sullivan (1998, 2010a, 2010b) in recognizing that the Recapture Member directly overlies and intertongues with the Bluff Sandstone Member in the area around Recapture Creek and the south side of Black Mesa. This suggests that both the Tidwell and Salt Wash Members are laterally equivalent to the Bluff. We observed that the isolated eolian lenses (dunes) were much less common than similarly appearing fine-grained fluvial units in the lower part of the overlying Recapture Member on the south side of Black Mesa, which supports the observation that the Bluff Sandstone Member of the Morrison Formation appears to be genetically associated with the basal Recapture Member (Anderson and Lucas, 1996, 1998; Turner and Peterson 2010a, 2010b).

We noted that along the west side of Black Mesa conglomerate is at least locally present at the base of the lower Morrison slope at the top of the Bluff Sandstone. On the southwest side, we noted a gravel conglomerate overlying the Bluff Sandstone Member about 30 cm (1 ft) thick with white and gray chert grains with diameters up to 2 cm (1 in) (figures 10C and 10D). To the north, south of SR 95 in our new Morrison reference section (appendix A), we observed a largely intraformational clast conglomerate with clasts up to 50 cm (1.5 ft) across above the Bluff Sandstone Member (figures 10H and 10 I). At both sites light-colored, fine-grained fluvial and minor eolian sandstones less than 10 m (30 ft) thick are also present at the base of the Recapture Member.

The presence of these conglomerates a few meters above the contact between the Bluff Sandstone Member and the Recapture Member indicates that a more careful reconnaissance of the contact throughout the area is called for to establish if these conglomerates extend farther across the Blanding basin. The present evidence supports the hypothesis that the Bluff Sandstone Member does not interfinger with the Recapture Member of the Morrison Formation, at least on the southwest side of the Blanding basin, but that the basal sandstone units of the Recapture are composed mainly of fine sands reworked from the underlying Bluff Sandstone Member across this unconformity. We expect that at most sites, where this fine sandstone interval is fluvial in nature and directly overlies the basal conglomeratic bed, an interpretation that these sandstones represent the Salt Wash Member of the Morrison Formation (Stokes, 1944; Craig and others, 1955) is completely understandable.

Given that the Bluff Sandstone Member, as we interpret it, is bounded by unconformities just above the top, and at its base, and given the distinctiveness of its much lighter color relative to the underlying strata of the San Rafael Group, it is tempting to consider it as a distinct formation lying between the underlying San Rafael Group and overlying Morrison Formation. We agree with Turner and Peterson (2004, 2010a) and O'Sullivan (1980, 2010a, 2010b; Lucas, 2014) that the Bluff Sandstone Member interfingers into the lower part of the Tidwell Member of the Morrison Formation to the north of Whiskey Draw (12 S, 620605.59 m E, 4162400.38 m N) and extending to the Elk Mountain Road. However, the conglomerates at the top of the Bluff Sandstone have only been identified on the southwest side of the Blanding basin and until the lateral extent of these coarse units can be determined, we retain the Bluff Sandstone as the basal member of the Morrison Formation at this time (figures 3, 6, and 8).

Paleontology

No fossils were observed in the Bluff Sandstone

Member during this study, although these strata likely preserve invertebrate trace fossils and perhaps even dinosaur tracks elsewhere. The Butler Wash Dinosaur Tracksite (figure 2) on the northwest side of Black Mesa was described as being immediately below the Bluff Sandstone (Lockley and Mickelson, 1997). However, we find no genetic association of the tracksite with the Bluff at the base of our new Morrison Formation reference section (appendix A). We identify the tracksite as near the middle of the Wanakah Formation (O'Sullivan, 1980, 1992, 1998, 2000, 2010a, 2010b), but cannot tie this site to a specific bed in any previously measured sections in the area (O'Sullivan, 1980; Lucas, 2014).

Tidwell Member

History and Lithology

The term "Tidwell Member" has had a complicated history of usage. The Tidwell Member was named for Tidwell Bottoms along the San Rafael River in Emery County, Utah, and was first used on a number of unpublished geological maps produced by Robert Young over several decades for the Atomic Energy Commission and subsequently the U.S. Department of Energy (Peterson, 1988). The first formal description was published by O'Sullivan (1984), who defined the Tidwell Member of the Morrison Formation as the relatively thin (about 10 m [32 ft]) interval of light-gray-colored sandstone and sandy shale beds spanning the slope from the J-5 unconformity up through the base of the first laterally extensive fluvial sandstone (figures 1, 4A, and 11) of the overlying Salt Wash Member, with a section on the west side of Dumas Point in Grand County, Utah (NE1/4NE1/4SW1/4 and SE1/4SE1/4NW1/4, section 30, T. 23 S., R. 18 E, Salt Lake Base Line and Meridian). O'Sullivan (1984) described the lithology of the Tidwell Member as:

> "…. somewhat varied. Siltstone is the dominant rock type. Chert beds as much as 1.5 m thick, rounded limestone nodules, and gray limestone beds are conspicuous lithologic features of the Tidwell Member. Gypsum is also present in some abundance from the San Rafael Swell to just east of the Green River. Gray ledge-forming sandstones as much as 2 m thick, in which bedding is absent or not apparent, crop out at many localities; light-gray crossbedded channel sandstone beds typical of the overlying Salt Wash Member are absent at most places, but where present form a minor lithology in the slope-forming Tidwell Member. At places, the Tidwell contains persistent thin ledge-forming sandstone beds, generally less than 1 m thick, which are blocky, ripple marked, and commonly carry coarse grains of chert. A widespread sandstone, termed for convenience bed A, marks the base of the Tidwell Member at most places. Throughout large areas of east-central Utah, bed A is generally less than 0.5 m thick but locally is as much as 2.5 m thick. Here and there the bed contains coarse grains, is ripple marked, and tends to form a resistant ledge that overhangs the J-5 unconformity and underlying rocks."

Complicating the story, Peterson (1988) defined the Tidwell Member using a section to the west in Emery County located 5 to 8 km (3–6 mi) south of Tidwell Bottoms and 24 km (15 mi) southwest of Green River, Utah. In this area, gypsum beds with authigenic chert characterize the lower few meters of the section, instead of bed A, which O'Sullivan (1984) used to mark the J-5 unconformity across much of eastern Utah. Stratigraphically, O'Sullivan's (1984) and Peterson's (1988) type sections are essentially correlative and so do not confuse the use of the term Tidwell in this area. Interestingly, Peterson (1988) did not reference O'Sullivan (1984) regarding the Tidwell Member, but acknowledged O'Sullivan's paper in the discussion of the type section of the overlying Salt Wash Member.

We observed stromatolites (figure 11C) preserved in dark-gray limestone beds that are associated with the surface of the basal sandstone bed (bed A) of the Tidwell Member in a broad area between the Blue Hills westward to Duma Point (Kirkland and DeBlieux, 2017). Similar algal limestone beds appear to cap some of the thin, red sandstone beds in the upper part of the underlying Summerville Formation as well. Given the presence of extensive gypsum beds along the Summerville-Tidwell contact to the west, such as at Tidwell Bottoms (Peterson, 1988) southwestward to the east side of Capitol Reef National Park, we interpret this transition

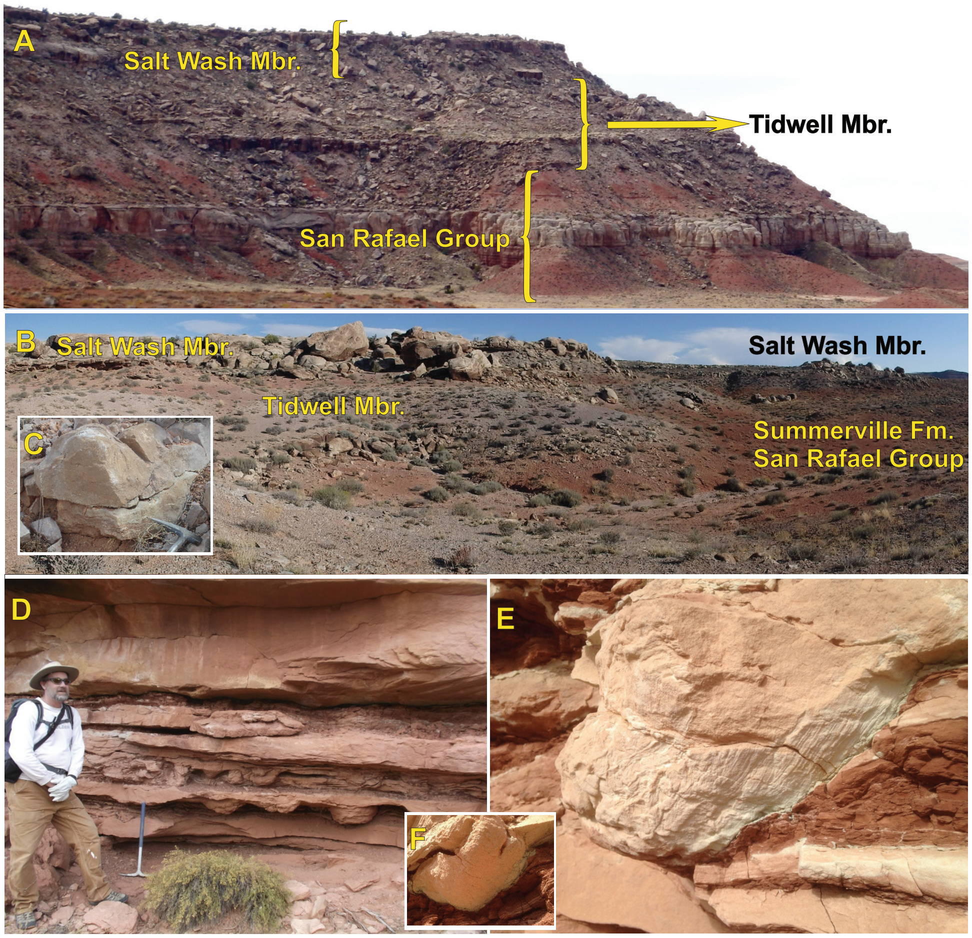

Figure 11. Tidwell Member and its fossils. (A to C) Tidwell Member in O'Sullivan's (1984) type area (figure 1). (A) Photo of a bluff along the Ten-mile Wash road on the west side of the Blue Hills showing the contact of the Morrison Formation with the San Rafael Group. (B) The Tidwell-Salt Wash Member contact along Ten-mile Wash road. (C) Stromatolite in the basal Tidwell Member. (D to F) Dinosaur tracksite (Sa1445) where Bluff Sandstone interfingers with, and is overlain by, Tidwell Member (O'Sullivan, 1980) north of SR 95 discovered by John Foster during Paleo Solutions paleo-inventory (Murphey and Zubin-Stathopoulos, 2018). (D) Overview of site with natural casts of sauropod tracks, (E) detail of sauropod track displaying scratch marks from scales, (F) detail of natural cast of three-toed dinosaur track.

between the San Rafael Group and the Morrison Formation to represent the "higher" energy shoreline of a clastic "sabkha" (Thompson and Meadows, 1997; Saleh and others, 1999; Kirkland, 2006) and not necessarily the presence of a regional J-5 unconformity (O'Sullivan, 1984; Turner and Peterson, 2004). Sedimentary features such as stromatolites and evaporites are all consistent with a clastic sabkha interpretation of the transition between the Summerville Formation and the overlying Tidwell Member of the Morrison Formation. We interpret O'Sullivan's (1984) bed A as representing the normally quiet-water sabkha's waterline, occasionally agitated by storms such that coarser grains are winnowed out of the sediment forming a diachronous bed A. Wind deflation may have also served to concentrate these coarser grains given a depositional hiatus in these flat-ripple bedded, coastal sediments.

Anderson and Lucas (1996,1998) reported that the Salt Wash Member unconformably overlaid the Tidwell Member marking the position of the J-5 unconformity and the base of the Morrison Formation in this area. We identified large Tidwell or Summerville stromatolite clasts in the basal Salt Wash Member here, further supporting the presence of a significant unconformity at the base of the Salt Wash Member. At Capitol Reef (figures 1 and 4E to 4I) we recognized a 2 to 3 m (6–10 ft) pebble conglomerate extending over more than 50 km (30 mi) across the north end of the park along the basal contact of the Tidwell Member marking the J-5 unconformity (figures 4E to 4I). O'Sullivan (1984) noted that the upper contact of the Tidwell Member may be difficult to place because of intertonguing between the Salt Wash and Tidwell Members. We observed that less laterally extensive sandstone channels of Salt Wash aspect occur in the upper half of the Tidwell Member in nearly all sections examined in Utah.

The conglomeratic Salt Wash Member likewise marked a major regional unconformity across this region as well, with meters of relief at its lower contact (figures 4E to 4I). Perhaps in the future we should consider the Tidwell-Salt Wash contact to represent a J-6 unconformity. Thus we have concluded that across most of central and southern Utah, an unconformity marks the top and bottom of the Tidwell. Maidment and Muxworthy (2019) proposed that the Tidwell Member be excluded from the Morrison Formation as a separate sequence bounded by unconformities. These unconformities were not identified in the basal Morrison Formation in the area around Dinosaur National Monument (figure 1, Sprinkel and others, 2019; D.A. Sprinkel, UGS, verbal communication, 2019). Thus, we suggest that these unconformities are subsumed within complexities of the marginal marine to terrestrial facies shift marking the base of the Morrison Formation as the Sundance sea continued to retreat to the north.

Demko and others (2004) suggested that the regional paleosol at the base of the Brushy Basin Member reflected a regional unconformity. Kirkland (2006) agreed with their conclusion and furthermore noted that such an unconformity would explain the dramatic change from illitic to smectitic clays noted at this level across the Colorado Plateau (Peterson and Turner-Peterson, 1987; Turner and Peterson, 2004, 2010a). Therefore, as the three members of the Morrison Formation spanning the central and northern Colorado Plateau preserve large dinosaur remains and are bounded by unconformities there is no reason to separate the Tidwell Member from the rest of the Morrison Formation.

Paleontology

Though not examined extensively, no fossils were found in the Tidwell Member at the base of the Morrison Formation in the northern part of the study area. However, farther to the north, the Tidwell is known to preserve the oldest Morrison vertebrate fossil sites, including the oldest associated sauropod dinosaur body fossil in North America, *Dystrophaeus* (Gillette, 1996a, 1996b; Turner and Peterson, 1999; Foster, 2007; Trujillo and Kowallis, 2015; Foster and others, 2016a; Kirkland and DeBlieux, 2017). This important dinosaur site is approximately 57 km (35 mi) north-northeast of Gregory's (1938) Brushy Basin type section on the Elk Mountain Road and is in the middle of an 8-m (26-ft) Tidwell Member section. Any identifiable fossils from the Tidwell Member are of considerable significance.

Paleo-Solutions Inc., as part of their inventory of paleontological sites within the mapped lower Morrison Formation (Salt Wash Member of Miller [1955b]) between SR 95 and the Elk Mountain Road (Murphey and Zubin-Stathopoulos, 2018), discovered a dinosaur tracksite. The tracksite consists of natural casts of sauropod tracks and one track of a three-toed dinosaur from a couple of meters above the Bluff Sandstone Member (figures 11D to 11F). This site is in the interval north of SR 95 where the Bluff begins to interfinger with the Tidwell Member and may be the oldest known Morrison dinosaur tracksite.

Recapture Member

History and Lithology

The type section of the Recapture Member is on Recapture Creek northeast of Bluff, Utah (figures 2, 7A, and 12). These strata are well exposed across the southern portion of the study area (figures 12 to 14). Gregory (1938) initially referred these rocks to the Recapture Shale Member summarized as follows:

> "The interval between the Bluff sandstone member and the lowermost bed characteristic of the Westwater Canyon sandstone member is occupied by a series of strongly colored shales and sandstones 100 to 300 feet thick. They appear in many places as sloping platforms at the base of cliffs and are particularly well displayed near the mouth of Recapture Creek, from which the name is derived. The shales are prevailingly dark red, but some are variegated pink, ash, brown, and gray. Many of them include firm, strongly calcareous beds that break into slabs and friable, imbricated gypsiferous beds that weather as tiny cliffs. The sandstones are white beds of glistening quartz cemented by lime, few of them more than a foot thick or continuous for more than 1,000 feet….The shales and sandstones combine to form slopes, low mesas, and platforms, and the edges of sandstone beds appear as shelves and small benches. The outcrops are attractively color-band-

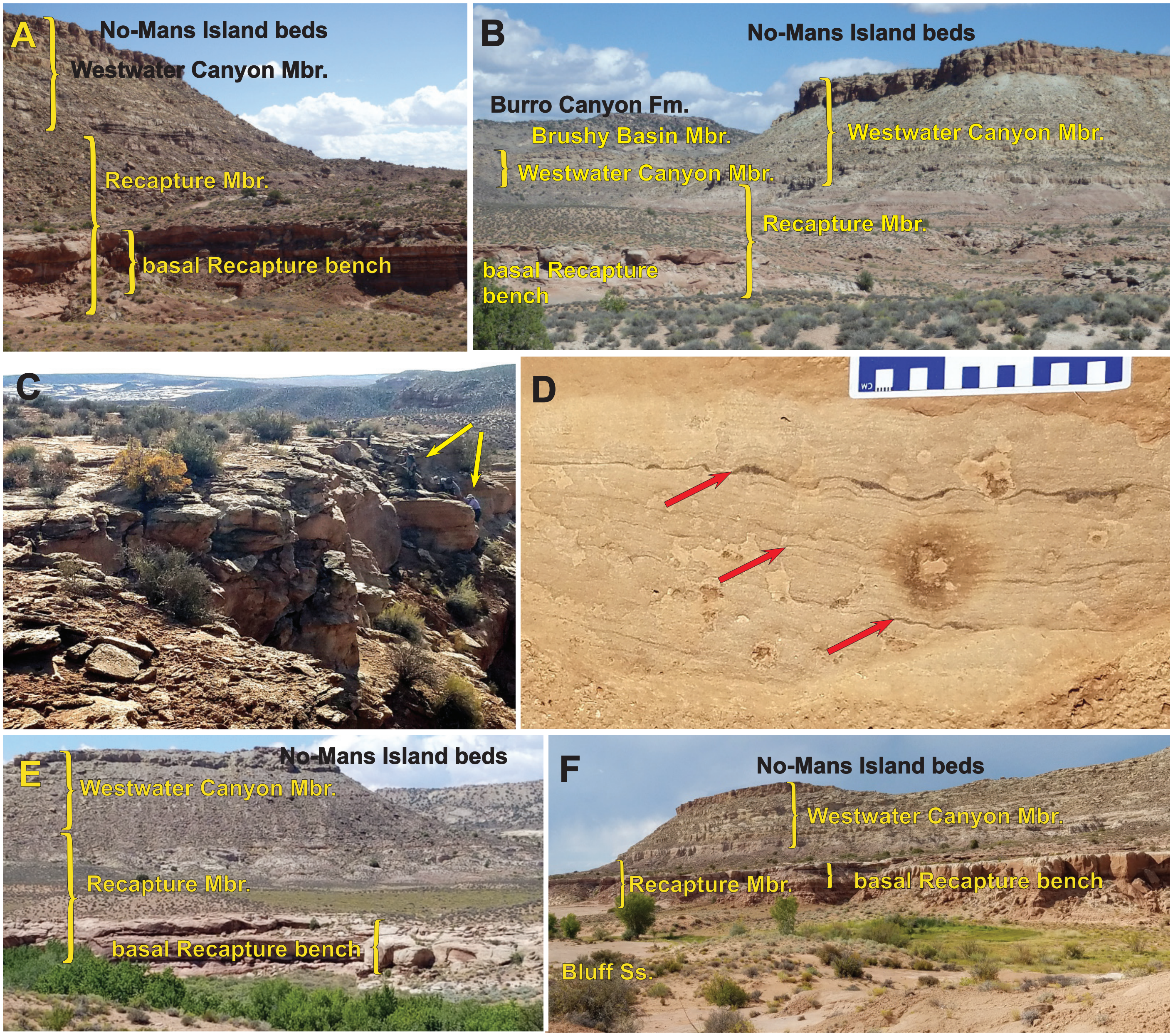

Figure 12. Basal Recapture bench on south side of Black Mesa. (A) Lower units in Morrison Formation on southwest side of No-Mans Island viewed to east. Note continuation of basal Recapture bench from figure 9C. (B) Morrison Formation through Burro Canyon Formation strata viewed toward north on east side of Decker Cove along west side of No-Mans Island and northward to south end of Black Mesa. (C) Geologists (yellow arrows) climbing through fluvial sandstone forming basal Recapture bench south of No-Mans Island. (D) Dark layers (red arrows) formed by heavy mineral concentrations typical of Recapture Member in fluvial sandstone forming basal Recapture bench. (E) Lower Morrison Formation strata at the south end of Black Mesa. View toward west. (F) Lower Morrison Formation strata at the southwest end of Black Mesa farther to the west than in E.

ed, but as the shale and sandstone feather out and replace each other along the strike the arrangement of sections 1,000 feet apart is quite different."

Gregory (1938) recorded that the Recapture Member averages about 60 m (200 ft) thick throughout the region. At its type section along Recapture Creek, Gregory (1938, section 23) measured 67 to 88 m (220–290 ft) of

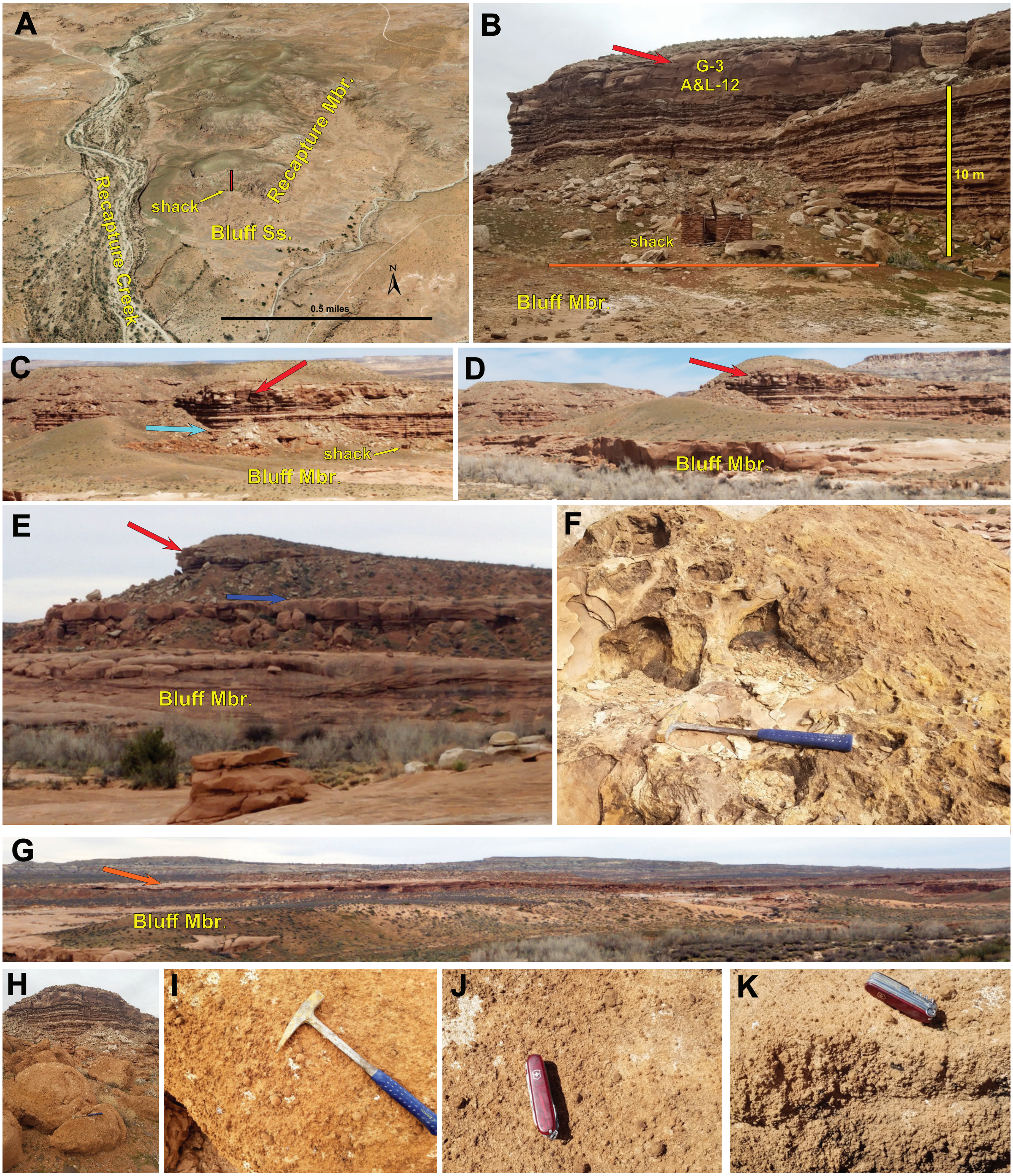

Figure 13. Caption is on the following page.

Figure 13 (figure is on the previous page). Lower Recapture Member along Recapture Creek. (A) Oblique view from south of the type section of the Recapture Member following Gregory (1938) and Anderson and Lucas (1997, 1998) (Google Earth©). (B) Lower Recapture section on Recapture Creek described by Anderson and Lucas (1998) as Recapture Member of the Bluff Formation from southeast; compare with Lucas and Anderson (1997, figure 11E). G-3 = Gregory's (1938, section 23) unit 3 and A&L-12 = Anderson and Lucas' (1998) "Type section of Bluff Formation," unit 12 as base of Salt Wash Member (red arrow indicates this channel sandstone). Orange line indicates approximate position of upper contact of Bluff Sandstone Member. Height of door frame in shack is 1.8 m (6 ft) with total height of shack 2 m (6.5 ft). (C) Same area in B from southwest across Recapture Creek. Light blue arrow indicates level of H and I. (D) Same area in B from the west across Recapture Creek. Red arrow indicates position of channel sandstone (Gregory's [1938], section 23, unit 3; Anderson and Lucas' [1998], unit 12). (E) Correlative section as viewed to southwest across Recapture Creek. Red arrow indicates position of correlative channel sandstone (Gregory's [1938], section 23, unit 3; Anderson and Lucas' [1998], unit 12). Dark blue arrow indicates position of coarse-grained strata in J and K. (F) Basal surface of channel cutting down into lower bench of Recapture Member. Rock hammer head about 18 cm (7 in). (G) Escarpment formed by basal bench of Recapture Member to northwest across Recapture Creek. Orange arrow indicates top of bench. (H) Overview of coarse-grained sandstone as indicated in C. (I) Detail of carbonate-cemented sandstone and mudstone grains in H. (J) Top view of coarse-grained sandstone as indicated in E. (K) Oblique view of coarse-grained sandstone as indicated in E.

Recapture in five lithologic units. Unfortunately, while noting that the Morrison section along Recapture Creek was based on correlating six sections, Gregory did not record on which stratigraphic units these correlations were made (Gregory, 1938). In reevaluating Gregory's type section, Anderson and Lucas (1996, 1998) marked the top of the Recapture at the base of Gregory's (1938, section 23) unit 3, 34.14 to 77.42 m (112–254 ft) below the top of the section of the Recapture Member (see figure 11E and 11F of Lucas and Anderson, 1997). Gregory (1938) identified an unconformity at the base of unit 3 represented by voids, where weathered, and jumbled fragments of green and red clay (rip-up clasts) 5 to 15 cm (2–6 in) across at the base of the sandstone (figure 13F) that was used to define the base of Salt Wash Member by Anderson and Lucas (1996, 1998). Kirkland examined the section on Recapture Creek and discerned that the sandstone is a lenticular, low sinuosity channel sandstone extending across Recapture Creek from the southwest cutting down into the basal Recapture bench (figures 13A to 13E).

Gregory (1938) noted that the Recapture Member resembles beds 13 km (8 mi) south of Woodside, Utah, which were placed at the base of the Salt Wash Member by Gilluly and Reeside (1928), apparently noting a similarity to the Tidwell Member as it is currently used. Gregory compared these basal Morrison strata near Woodside as like the Recapture Shale Member for the dominance of red mudstone characterizing the rocks (figures 12 and 13), although subsequent authors have used Recapture Member. Stokes (1944) noted that laterally the Recapture interfingers with, and is underlain by, the Salt Wash Member. Craig and others (1955) recognized that the Recapture Member thickens to the south and, based on the local presence of granite pebbles, appears to have been sourced from the south, as is the overlying and genetically related Westwater Canyon Member. An apparent Salt Wash tongue was thought to split the Recapture into upper (Recapture Member) and lower (Tidwell Member) members in the southern part of the study area (Peterson and Turner-Peterson, 1987; Turner and Peterson, 2004), based on a laterally extensive channel sandstone near the middle of the member. Thus, in the area of the southwestern Blanding basin, Turner and Peterson (2004) divided the Morrison Formation into: (1) Bluff Sandstone Member, (2) Tidwell Member, (3) Salt Wash Member, (4) Recapture Member, (5) Westwater Canyon Member, and (6) Brushy Basin Member (figure 6).

As noted above, a low (about 10 m [30 ft]) bench largely capped by light-brown to gray to nearly white fluvial sandstone is present along the west and across the south side of Black Mesa makes up the base of the Recapture Member, which Miller (1955a) mapped as the top of the Bluff Sandstone (figures 8, 9C, 10, and 12). These sandstone beds do not seem to pertain to the Salt Wash Member because they include heavy mineral concentrations along bedding planes (figure 12D) that

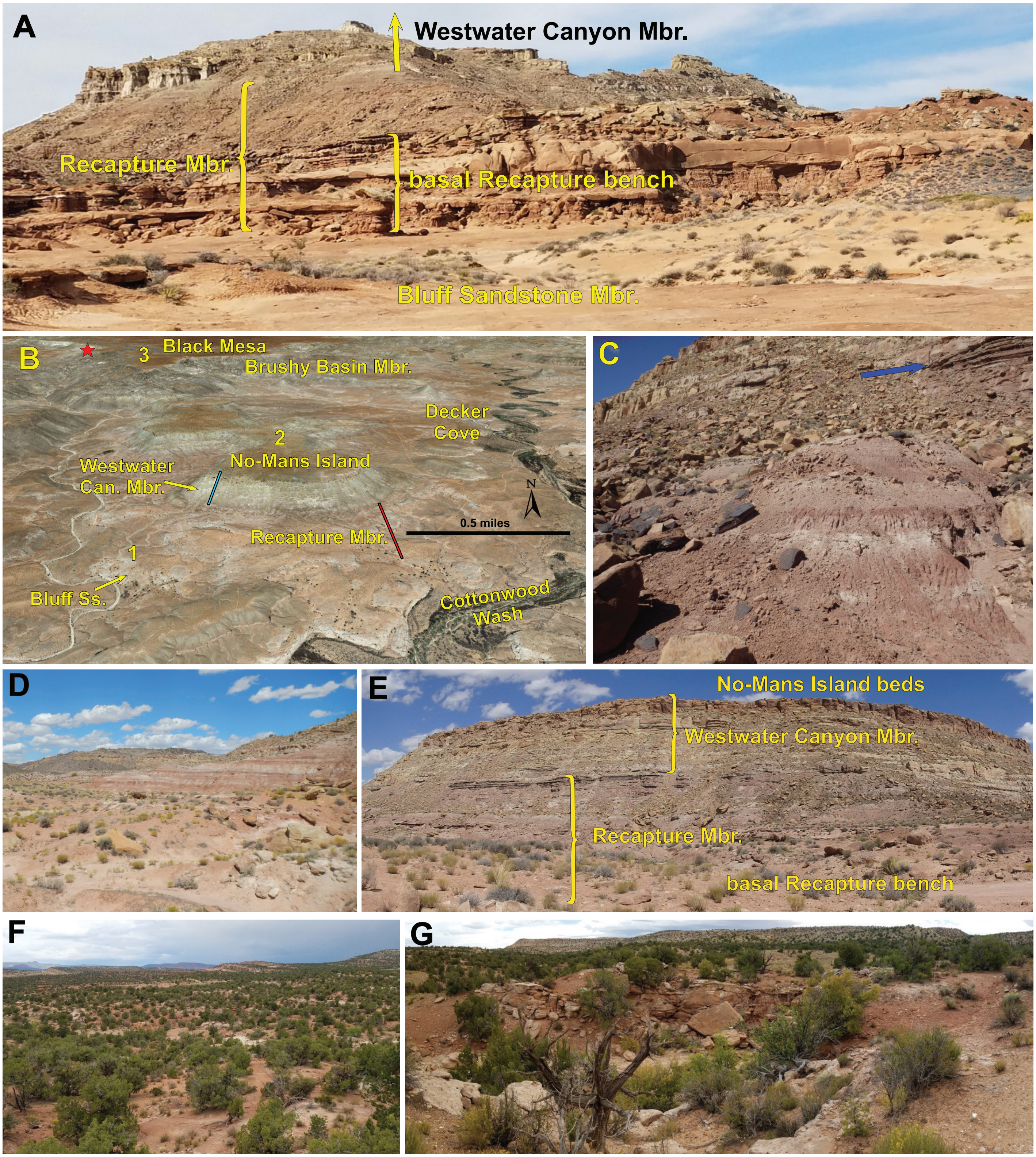

Figure 14. Caption is on the following page.

Figure 14 (figure is on previous page). Recapture Member of the Morrison. (A) Exposure of total Recapture Member and its bounding strata at The Horn on the west side of Recapture Creek (figure 2). Note the long slope of red Recapture mudstones and thin sandstones overlying the lower Recapture bench. (B) Oblique view from south of Upper Jurassic outcrops south of Black Mesa (Google Earth©). Blue bar stratigraphic extent of Westwater Canyon Member. Red bar stratigraphic extent of Recapture Member. Red star is the Brushy Basin dated ash site. Number 1 is the lower bench, number 2 is the middle bench, and number 3 is the upper bench. (C) Recapture Member on the west side of No-Mans Island viewed toward north. Blue arrow denotes basal contact of the Westwater Canyon Member. (D) Typical exposures of the Recapture Member northwest of No-Mans Island. (E) Lower Morrison Formation strata on south side of No-Mans Island looking north. (F) Overview of Recapture exposures described for Morrison reference section on the northeast side of Black Mesa (appendix A). (G) Salt Wash-style channel sandstone in Recapture Member, Morrison reference section on the northeast side of Black Mesa (appendix A).

are only characteristic of the fluvial sandstones in the Recapture Member (Christine Turner, verbal communication, October 27, 2018). Thus, identifying that this bench is made up of the basal-most beds of the Recapture Member is an important contribution of this project. The basal Recapture bench extends east of Black Mesa to the type section of the Recapture Member on Recapture Creek (figure 13) where it thickens and includes more than one coarse-grained, ledge-forming unit. In this area, each of these ledge-forming units are commonly conglomeratic, composed largely of small (0.5 to 2 cm [0.2–1.0 in]) carbonate-cemented intraclasts of mudstone and fine sandstone (figures 13H to 13K).

Anderson and Lucas (1996, 1998) restricted the Recapture Member to the lower bench-forming interval, assigned it as a member of the Bluff Sandstone of the San Rafael Group, and included the upper more fluvial interval in an expanded Salt Wash Member (figure 5). In their description of the Recapture type section Anderson and Lucas (1996, 1998) described only the lower 17.9 m (55 ft) as Recapture Member, stopping at a "reddish" sandstone bench that they interpreted as the base of their Salt Wash Member. We found that this sandstone is lenticular and cuts down into the top of the lower Recapture bench (figures 13B to 13E). Even if we identified this bed as a Salt Wash-style channel sandstone, we would follow Gregory (1938) in extending the Recapture Member in the southern Blanding basin for another 35 to 70 m (115–230 ft) up the red slope to the base of drab, yellowish-gray sandstones and sandy mudstones characteristic of the basal Westwater Canyon Member (figure 14). This is in keeping with Gregory's (1938, section 23, p. 76) type section of 67 to 88 m (220–290 ft) thickness in which it was noted that shale constituted more than 85% of this upper Recapture interval.

However, we want to point out that both Turner and Peterson (e.g., 2010a) and Anderson and Lucas (1996, 1998) identified important breaks in depositional history in this area. We tentatively suggest that unconformity below the Bluff Sandstone Member represents the J-5 and the unconformity associated with the lower Recapture bench tentatively represents our J-6 unconformity at the base of the Salt Wash Member (figure 6). The distinctive feldspathic, red-bed sequence in the type area of the Recapture, does not support assigning these strata to the Salt Wash as in so doing would obscure the depositional history of these important stratigraphic units.

In Anderson and Lucas' (1997, 1998) system, the Morrison Formation is restricted to a lower fluvial-sandstone-dominated Salt Wash Member and an upper variegated-mudstone-dominated Brushy Basin Member. To some degree this followed the way Craig and others (1955) split the Morrison for their analysis of the distribution of facies and sedimentological properties, although they never proposed combining these rock units or changing names.

In their 2004 overview of Morrison paleoenvironments, Turner and Peterson (2004) indicated that above the Bluff Sandstone Member at Recapture Creek, both the Tidwell and the Salt Wash Members underlie the Recapture Member, apparently following Anderson and Lucas (1996, 1998) in identifying the fluvial sandstone bench in the lower part of Gregory's (1938) type Recapture section as pertaining to the Salt Wash Member. In 2010, Turner and Peterson (2010a, plate 6b, verbal discussion, 2017) revised their interpretation and followed

O'Sullivan (1998, 2000, 2010a, 2010b) in recognizing that the Recapture Member along the southwest side of the Blanding basin rests directly on, and intertongues with, the Bluff Sandstone Member of the Morrison Formation (figures 6 and 8). However, they also noted that both the Salt Wash and Tidwell Members correlate laterally with the lower Bluff Sandstone Member. This is in keeping with their correlation of the Recapture with the basal Brushy Basin Member above the Salt Wash Member to the north (Turner and Peterson, 2004). In this scenario, the entire Westwater Canyon Member pinches out between the Recapture Member and the overlying Brushy Basin Member to the north.

Miller (1955a) mapped the northern limit of the Recapture Member on the northwest side of Black Mesa south of SR 95 at about the latitude of the Butler Wash Tracksite (figure 2). This is approximately along the line of our Morrison reference section (figure 3; appendix A). Additionally, on the east side of Black Mesa, Miller (1955a) mapped its northern limit in Cottonwood Wash only about 1 km (0.6 mi) north of the type section of the overlying Westwater Canyon Member of the Morrison Formation. Gregory (1938) and Anderson and Lucas (1996, 1998) noted that no recognizable Recapture is below the lowest described beds of the Westwater Canyon Member at its type section. To the north beyond our Morrison reference section (figure 3), Miller (1955a, 1956) mapped the combined Recapture and Westwater Canyon Members as the lower Morrison Formation. O'Sullivan (1998, 2000) replaced the Recapture Member with the Salt Wash Member at approximately this same position but extended the Westwater Canyon Member several kilometers farther north. To the east of the study area, O'Sullivan (2000, 2010a) recognized several prominent sandstone channels within the Recapture Member at Montezuma Creek east of Black Mesa considered to be of Salt Wash morphology. Likewise, we recognize that the red mudstone in the upper two-thirds of the Recapture Member is replaced over a relatively short distance by ledge-forming sandstones typical of the Salt Wash Member on the north end of Black Mesa. Thus, we follow O'Sullivan (1980, 1998, 2000, 2010b) in recognizing the interfingering of the upper part of the Recapture with the Salt Wash Member and the correlation of the lower part of the Recapture with the upper Tidwell Member, with the northward pinch-out of the last tongues of Bluff Sandstone Member into the Tidwell and regional thinning of the basal Recapture beds overlying the northernmost expression of the Bluff (figure 8).

Given its southern source area, we recognize the Recapture Member as thinning to the north. We expect that the more westerly derived Salt Wash Member represents a distributive fluvial system (Owen and others, 2015, 2017) that onlaps the southerly derived Recapture such that Salt Wash fluvial sandstones would progressively interlense diachronously with the wedge of mostly finer-grained Recapture sediments as both members thicken and expand their distribution to the north and east. To the north is a fining of southern-sourced materials in the Recapture, with a loss of both the granitic materials and the eolian beds noted as characteristic of the member in northern Arizona (Dickinson, 2018). With the northern pinch-out of the Bluff Sandstone Member, the lower part of the Recapture Member merges with the Tidwell Member and fluvial sandstones of the eastward-prograding Salt Wash Member (figure 8).

We conclude that the Recapture in its type area on the southwest side of the Blanding basin does not overlie the Salt Wash Member as stated by Turner and Peterson (2004, 2010a). We propose that the Salt Wash distributary megafan expanded to the east over the coastal Tidwell deposits, where it onlapped and interfingered with the coarsening upward, southerly sourced, distributary megafan formed by both the Recapture and overlying Westwater Canyon Members. Herein, we use the term distributary megafan in the sense of Miall (1966) rather than distributive fluvial system (Owen, 2015, 2017), noting that they essentially mean the same thing. Our model largely supports the conclusions reached by Dickinson (2018), supplemented by additional observations of the interactions of these two important sedimentary packages (Hurd and others, 2006). Additionally, our model suggests that strata referred to the Salt Wash Member, below the Recapture Member in the region of the Four Corners and in northern New Mexico (Tyler and Ethridge, 1983; Peterson, 1994, Turner and Peterson, 2004; Lucas, 2018), represent fluvial systems associated with a distributary megafan farther east than the Salt Wash Member in its type area of central Utah.

While examining strata lateral to vertebrate locality Sa1115v in the lower Recapture Member above the lower Recapture bench south of Black Mesa, thin smectitic clay layers a few mm thick were identified interspersed with thin layers of mudstone and sandy shale. This interval was sampled for detrital zircons resulting in a mixing of these thin clastic layers. The resulting zircons included some fine, clear, and elongate crystals that might well have be derived from a near contemporaneous ash (appendix B). The youngest single grain in the dataset is 145.9 ± 1.6 Ma, which is younger than any ash date known for the Morrison Formation (Trujillo and Kowallis, 2015). The next youngest single grain for which discordance is <20% is 150.2 ± 2.1 Ma, which is close to our new age for the top of the Brushy Basin Member in this area (appendix C). The next two youngest grains that pass the discordance filter are 153.7 ± 2.1 Ma and 153.8 ± 2.2 Ma, which are approximately 1.5 million years older than ages for the base of the Brushy Basin Member. Even these ages seem a bit young for the lower Recapture and would suggest as much as 130 m (about 430 ft) (figure 3; appendix A) would have had to be deposited in 1.5 million years. Maidment and Muxworthy (2019) have suggested the lower Morrison Formation was deposited as rapidly as the Brushy Basin Member with a larger, previously unidentified unconformity spanning 2 to 3 million years separating the Tidwell Member from the overlying Salt Wash Member. Our initial laser ablation data for the lower Recapture lends credence to their hypothesis, but further analysis of the zircons from this site is needed.

Paleontology

One fossil site was recognized in the basal Recapture bench, Sa0918t. It is identified as a trace fossil produced by social insects, in this case, termites (e.g., Bown, 1982; Hasiotis and Bown, 1992; Thorne and others, 2000; Hasiotis, 2004, 2008; Bromley and others, 2007) (figures 15A and 15B). We identified several dinosaur sites in the Recapture Member above the basal Recapture Bench (figures 15C and 15D) adding credence to its inclusion within the Morrison Formation, as no dinosaur remains are known from the San Rafael Group. It is noteworthy that the lower "Recapture" portion of the Morrison Formation preserves most of the known dinosaur and invertebrate remains to the southwest at Black Mesa in northern Arizona, where the Brushy Basin Member has been stripped off the Westwater Canyon Member below the regional angular unconformity on the rift shoulder of the Mogollon Uplift at the base of the Cretaceous unconformity (Harshberger and others, 1957; Kirkland 1990, 1991). This pattern seems to be like that in the southwestern Blanding basin, where we identified several vertebrate sites in the Recapture Member and few sites in the overlying Westwater Canyon Member. The abundance of dinosaur bones a short distance above the Bluff Sandstone Member adds to the evidence leading us to reject the Anderson and Lucas (1996, 1998) hypothesis that the Recapture Member should be included within the San Rafael Group.

Most fossil sites in the lower Recapture Member to the south and west of No-Mans Island consist of scattered small bone chips associated with thin (<0.6 m [<2 ft]), light-gray-colored, sandy intervals about 10 to 20 m (32–65 ft) above the top of the Bluff Sandstone (e.g., Sa1131v, Sa1132v, figures 13H and 13I). One locality (Sa1115v; figures 14C, 15C, and 15D) preserved several bones along a single bedding plane and appears to be deserving of additional scientific examination. Previously, the only Morrison locality that has been published from the study area is a natural cast of a stegosaur track referred to the ichnogenus *Deltapodus* by Milán and Chiappe (2009). Their study was the first report of this track type in the Jurassic of North America. This locality, Sa448t (figure 15E), is in an area that we did not investigate in the extreme southeastern part of the study area (figure 1). However, we were able to determine that the locality is in the Recapture Member.

Salt Wash Member

History and Lithology

Lupton (1914) first described the Salt Wash Member from the west side of Salt Wash, Grand County, Utah (NW1/4, section 19, T. 23 N., R. 18 E., Salt Lake Base Line and Meridian). Gregory (1938) provided an excellent summary:

"In reports on the geology of the region north of

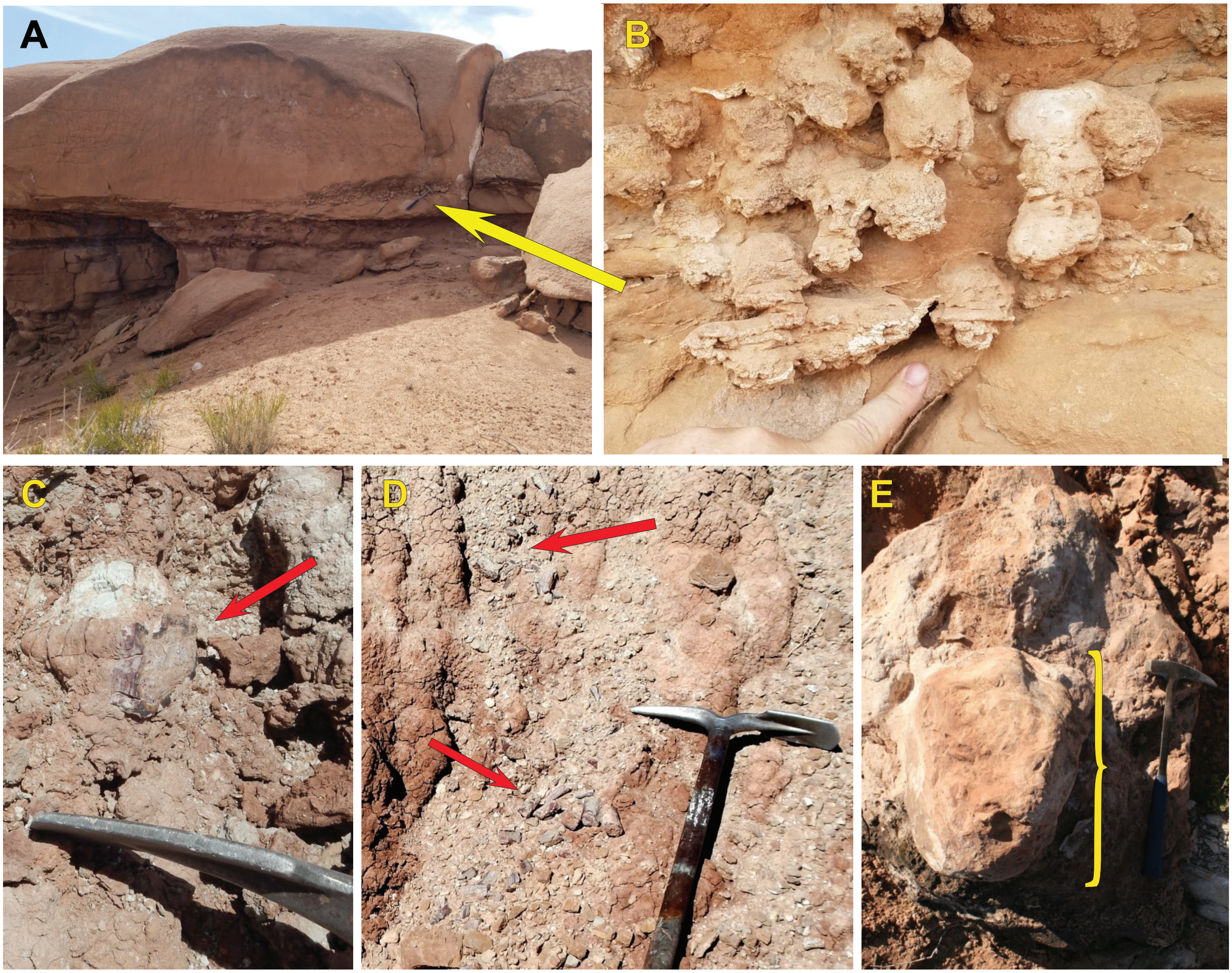

Figure 15. Fossils in the Recapture Member. (A) Possible termite traces in lower Recapture bench west of Recapture Creek Sa0918t. Yellow arrow points to close-up view shown in B. (B) Detail of Sa0918t showing individual galleries in larger scale structure. (C, D) Close-ups of dinosaur bone (red arrows) in situ at Sa1115v. (E) Natural cast of *Deltapodus* ("stegosaur" track) from the Recapture Member below the southeast margin of White Mesa at Sa448t (Milán and Chiappe, 2009).

Moab and other places in east-central Utah Lupton (1914) described a coarse-grained 'gray conglomeratic sandstone', in places lenticular and cross-bedded, that forms cliffs about 350 feet from the top of the Morrison strata sufficiently uniform and persistent to serve as a datum plane for mapping. For this sandstone he proposed the name 'Salt Wash member of the McElmo formation.' As classified by Gilluly and Reeside (1928) the Salt Wash sandstone member lies at the base of the Morrison and includes not only gray conglomeratic sandstones but also clay, limestone, and gypsum. Baker (1933) defines this member as 'white conglomeratic sandstones interbedded with red sandy mudstones and red shale' that occupy the lower half of the Morrison south of Moab."

Craig and others (1955) followed Stokes (1944) in extending the Salt Wash Member into the Recapture

Member as defined by Gregory (1938) across the Four Corners region of the Colorado Plateau as summarized below:

> "Gregory (1938) did not recognize the Salt Wash member in the southeastern corner of Utah, but subsequently Stokes (1944) recognized the member in the lower part of Gregory's Recapture member in this area as well as in the Carrizo Mountains area of northeastern Arizona. The extension of the Salt Wash member as a recognizable unit through southeastern Utah and into northeastern Arizona and northwestern New Mexico constitutes a restriction of Gregory's original definition of the Recapture member."

O'Sullivan's (1984) plot (figures 1, 14A and 14B) of the type section of the Salt Wash Member is in the same location noted by Lupton (1914). However, the proposed site of the type section by Anderson and Lucas (1998) is about 3 km (2 mi) farther north. Kirkland and DeBlieux (2017) documented large, isolated, cobble-sized, stromatolitic limestone clasts in the basal sandstone of the Salt Wash Member in its type area (figures 16C to 16F). These large clasts appear to have been sourced from the base of the Tidwell Member and similar beds toward the top of the Summerville Formation (figures 11B and 11C). This supports the view that the J-5 unconformity is at the base of the lowest Salt Wash channel sandstone (Anderson and Lucas, 1996, 1998). However, isolated channel sandstones in the upper Tidwell Member are present at other sites, below the more obvious break formed by the first set of continuous, ledge-forming channel sandstones that are generally picked as the base of the Salt Wash Member. Thus, in many areas, the Tidwell appears to be gradational with the overlying Salt Wash with a decrease in coastal fine-grained facies and an increase in fluvial channel sandstones. We propose that these large stromatolite clasts are reworked from the underlying Tidwell Member, maybe a result of local Late Jurassic salt tectonics within the Paradox Basin such as has been documented in the Lower Cretaceous, or a phase of uplift along the San Rafael Reef during the Late Jurassic (Kirkland and Madsen, 2007; Kirkland and others, 2016; Kirkland and DeBlieux, 2017). Given the recognition of a significant unconformity above and below the Tidwell in the Capitol Reef area (figures 4E to 4I), we suggest that once again Anderson and Lucas (1996, 1998) have recognized a possible J-6 unconformity (figure 6). As another example of evidence of this uplift during the Late Jurassic, Demko and others (2004) documented the pinch-out of both the Tidwell and the Salt Wash Members between the Summerville Formation and the Brushy Basin Member on the southwest side of the San Rafael Swell along the Last Chance monocline.

In discussing the Salt Wash Member, it is important to note that Peterson (1988) and Turner and Peterson (2004) interpreted the Salt Wash Member of the Morrison Formation in the western Blanding basin as separating the Tidwell and the overlying Recapture (figure 6). Turner and Peterson (2010a, 2010b; verbal communication, 2017) now interpret the Salt Wash to onlap the Bluff Sandstone Member from the north, such that around the southern end of Black Mesa, the Recapture Member directly overlies the Bluff Sandstone Member and that both the Salt Wash and underlying Tidwell Members are lateral equivalents to the Bluff Sandstone unlike what we propose here for the Salt Wash (figures 3, 6, and 8). O'Sullivan (1998) plotted the Salt Wash Member as overlying the Tidwell Member in the Black Steer Mesa section at the north end of the study area (figure 2). O'Sullivan (2000) noted that isolated sandstone lenses of Salt Wash character within the Recapture Member just to the east of the study area in the Montezuma Valley provide evidence that the Salt Wash indeed interfingers with the Recapture Member, as noted by Stokes (1944) and Craig and others (1955). Miller (1955a, 1956) noted on the photogeological maps that the Recapture and overlying Westwater Canyon Members could not be separated below the Brushy Basin Rim within the Brushy Basin (figure 2), and from about the current position of SR 95 northward mapped these beds as lower Morrison Formation. A nearly continuous line of outcrops extends from this line northward to the Black Steer Mesa section (Cadigan, 1955; O'Sullivan, 1980, 1998), and provides an opportunity to rigorously document the interfingering of the Salt Wash and Recapture Members in this area (figure 2). We follow O'Sullivan (1998, 2000) in recognizing that the lower Morrison Formation in this area consists of the Tidwell Member overlain by the Salt Wash Member. We also find it noteworthy that reddish mudstone beds interspersed between sandstone benches of the Salt Wash Member in east-central Utah are nearly identical to similar mudstones that form the bulk of the Recapture Member in the southwestern Blanding basin (figures 13 and 14).

Paleontology

The Salt Wash Member was not examined for fossils during this study. However, within its type area, Kirkland and DeBlieux (2017) found it to be fossiliferous with numerous sites preserving natural casts of dinosaur tracks and several sites with bone fragments on the surface.

A single invertebrate fossil locality has been noted at the Black Steer Mesa section in the Salt Wash Member from an exposure in the wash to the northeast of that section (Cadigan, 1952). This locality (Sa0083I) as listed in the Utah Paleontological Locality Database is based on a passing reference to bivalve shells "in the eastern wall of Cottonwood Wash east of the Indian school." It is the most northern Morrison fossil site recorded along Comb Ridge.

From October 16 to 20, 2017, Paleo Solutions Inc. conducted an inventory of paleontological sites largely within the Salt Wash Member (mapped as lower Morrison Formation by Miller, 1955b, 1956) between SR 95 and the Elk Mountain Road (Murphey and Zubin-Stathopoulos, 2018). During this study, two fossil plant sites, one sauropod dinosaur tracksite, and seven dinosaur bone localities were documented (figures 16G to 16N). The surficial skeletal materials observed at the surface were fragmentary.

Westwater Canyon Member

History and Lithology

Recognizing that the Westwater Canyon Member may be partially or even wholly correlative to the Salt Wash Member to the north in Grand County, Utah, Gregory (1938) established the Westwater Canyon Sandstone Member for the sandstone cliffs in the lower to middle part of the Morrison because he was uncertain as to the exact correlation of these rocks. He noted that the Westwater Canyon Member caps the mesas in the southern part of the study area across the southern part of Black Mesa and around Decker Cove as later documented on the photogeological map of this area (Miller, 1955b) (figures 2, 6, and 9). Gregory (1938) summarized the properties of the Westwater Canyon Member as follows:

> "This member is essentially a series of white sandstones composed of rounded medium to coarse grains of quartz, cemented by calcium carbonate and arranged in lenticular, irregular beds 1 to 30 feet thick. They include conglomeratic bands and stringers composed of quartz aggregates, colored chert, concretionary masses of compact green-white clay, and rare fragments of petrified wood and dinosaur bones. Interbedded with the sandstones are red earthy soft fine-grained sandy shales perhaps better called 'mudstones' that thin, thicken, or disappear in short distances. With them are associated a few thin short lenses of gray limestone conglomerate. These mudstones, which make up 8 to 20 percent of measured sections, are extremely irregular.
>
> …Unconformable contacts at the base of the Westwater Canyon member were observed at several places. Features that indicate exposure of the top beds before the Brushy Basin shale was laid down were noted in McElmo Canyon, but generally the sandstone grades upward through a series of gray sandy shales and merges into the variegated shales at different horizons….The thickness of eight measured sections of the Westwater Canyon sandstone member ranges from 222 to 295 feet."

As with the Recapture Member, the term Westwater Canyon Member was applied to correlative strata across the Four Corners area, northeastern Arizona, and northern New Mexico. Whereas, the U.S. Geological Survey has maintained Gregory's (1988) usage, Anderson and Lucas (1997, 1998) proposed that the Westwater Canyon Member be dropped in favor of the Salt Wash Member. They identified Gregory's (1938) type section where Westwater Canyon joins Cottonwood Canyon (figures 17A and 17B) and provided a redescription (Anderson and Lucas, 1997, 1998), noting, as have we, that the basal contact with the underlying

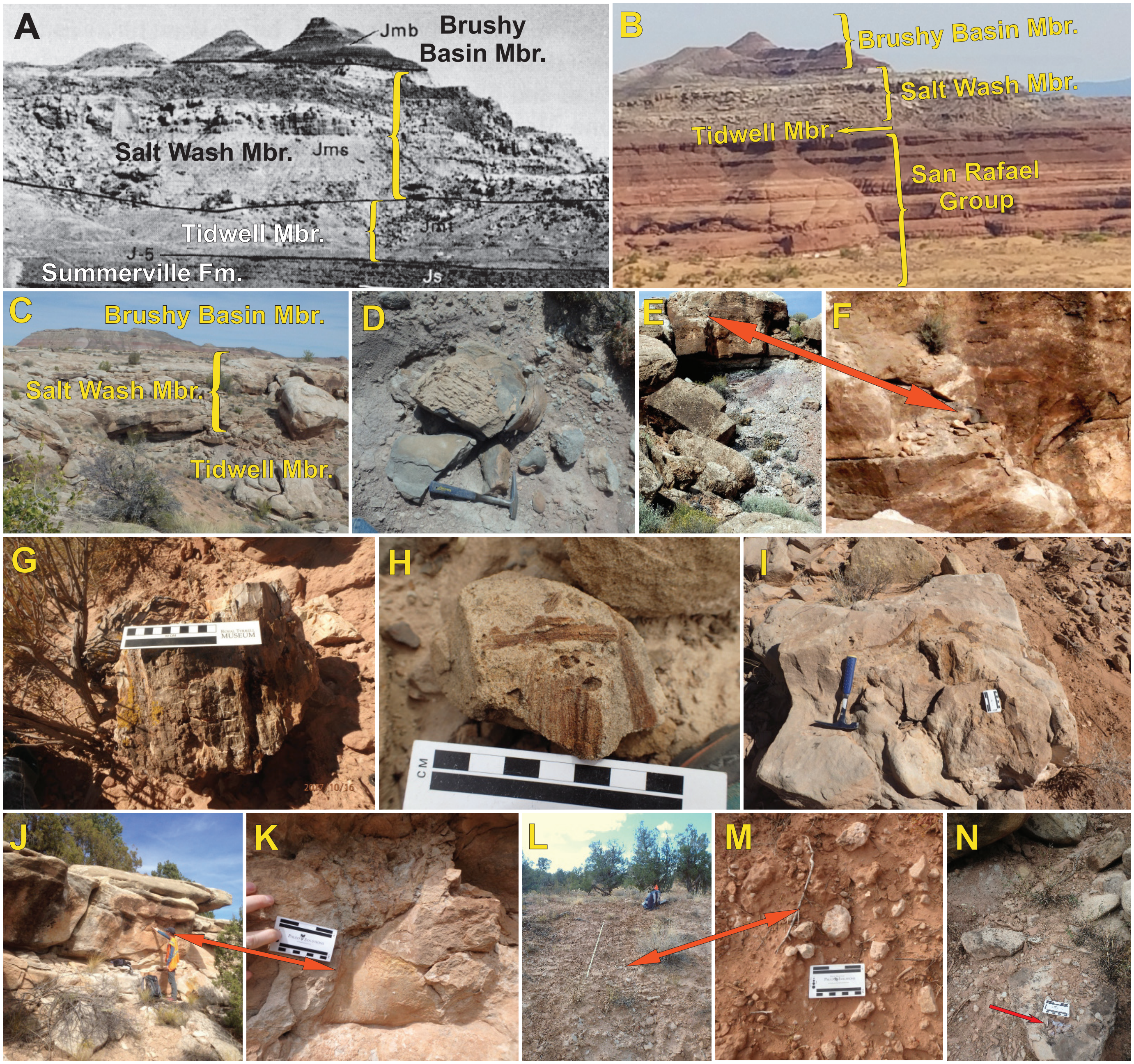

Figure 16. Salt Wash Member. (A to F) Salt Wash Member in its type area (figure 1). (A) Type section of Salt Wash Member on the south end of Duma Point as modified from O'Sullivan (1984). Stratigraphic units are written out. (B) Type area of the Salt Wash Member around Duma Point as viewed from the west with stratigraphic units labeled. (C) Salt Wash Member northwest of Duma Point. (D) Stromatolite fragments on slope of Tidwell reworked from overlying Salt Wash Member. (E) Stromatolite clast in basal sandstone of the Salt Wash reworked from top of Summerville or base of Tidwell as indicated by double-headed arrow. (F) Detail of stromatolite clast in basal sandstone of the Salt Wash Member as indicated by double-headed arrow. (G to N) Typical fossils in the Salt Wash Member north of SR 95 (lower Morrison of Miller [1955a] from paleo-inventory of Paleo Solutions [Murphey and Zubin-Stathopoulos, 2018]). (G) Petrified log from Sa1450. (H to I) Fossil plant impressions from Sa1466. (J) Overview of Sa1447. Double-headed red arrow indicates position of sauropod vertebra in K. (K) Sauropod vertebra external impression of centrum below scale with cross section of highly pneumatic bone above scale. (L) Overview of bone scatter at Sa1441. Double-headed red arrow indicates position of bone scatter on slope. (M) Detail of bone scatter. (N) Dinosaur bone fragments at Sa1444 as indicated by red arrow.

Recapture Member is not exposed in the floor of the canyon.

In Craig and others' (1955) discussion of the Morrison Formation, the Westwater Canyon Member was shown to be a wedge of coarse strata, both thickening and coarsening directly south of the study area. The presence of granitic fragments and detrital zircons indicates it was derived directly from the south where Protorozoic granites were becoming exposed along the central Arizona rift shoulder of the Mogollon Highlands on the north side of the Bisbee Basin (e.g., Kirkland, 1990, 1991; Dickinson and Gehrels, 2008, 2010). Genetically, these rocks can be considered a distributary megafan similar to the coarse, westerly sourced sandstone wedge (Fifty Mile Member) that is interpreted to replace the Brushy Basin Member to the southwest in the southern Kaiparowits Basin (Peterson, 1988). However, the genetic similarity does not presuppose equivalence as has been proposed by others (Turner and Peterson, 2004; Dickinson, 2018). We suggest that the Westwater Canyon is somewhat older and is only correlative with the lower part of the Brushy Basin Member to the north. In fact, we have observed (2019, research in progress with Grant Willis, UGS) that the Lower Cretaceous Buckhorn Conglomerate Member of the Cedar Mountain Formation cuts the entirety of the Brushy Basin Member such that the Buckhorn rests directly on the similar appearing Salt Wash Member in the northern part of Capitol Reef National Park (figures 1, 5B, and 5C) south of Cathedral Valley (12S., 472691.00 m E , 4258154.00 m N). It is now thought that the Fifty Mile Member of the Morrsion Formation may represent the Buckhorn Conglomerate on the south end of the Straight Cliffs, where it has cut out the Brushy Basin Member in this area. There are no outcrops where the lateral relationships of the Fifty Mile Member with other strata may be observed. Provenance studies will be needed to test the identity of these sedimentary packages.

In our limited explorations in the southern part of the study area around Decker Cove (figure 2), we note that the lower half of the member forms a main cliff formed by stacked sandstones of the Westwater Canyon Member that is separated from a smaller upper cliff that caps the mesas (following Miller, 1955b) by an appreciable slope of pale-greenish mudstone that we initially identified, at a distance, as the overlying Brushy Basin Member (figure 17C). Turner and Peterson (2004, figure 3) correlated the upper half of the Westwater above the main cliff with the lower part of the Brushy Basin Member in its type area in Brushy Basin, ignoring Gregory's (1938) description of the type section, but in keeping with our correlation with the Brushy Basin farther to the north (figure 8). A sharp break between mudstones without smectitic clays to highly smectitic mudstones has been used as a marker horizon to separate a basal "lower Brushy Basin" from the bulk of the Brushy Basin Member across the Colorado Plateau region and is referred to as the "clay change" (Peterson and Turner-Peterson, 1987; Turner and Peterson, 2004, 2010a). Turner and Peterson (2004) correlated the "clay change" to the base of the mudstone slope dividing the Westwater Canyon Member (figure 6).

The main cliff ("main body") of the Westwater Canyon Member appears as a series of closely spaced sandstone ledges in naturally weathered outcrop. This lower half of the Westwater Canyon Member is nearly all sandstone in composition with the weathered ledges appearance related mainly to induration and percent clay content. Overall, even the most mudstone-appearing partings are, at best, muddy sandstone intervals. Gravel-sized chert and limestone grains make up conglomerate lenses mostly in the upper third of this unit. This interval is well-expressed along a steep dugway on the west side of Stephens Canyon (figure 7B) on the west side of Black Mesa (12 S, 623450.00 m E, 4148459.00 m N). The pale mudstones overlying these sandstones are moderately smectitic (figure 8). The presence of these mudstones is similar to those in the Brushy Basin Member because smectitic clays are completely absent in the Salt Wash Member to the north in east-central Utah (Keller, 1962). We agree with Turner and Peterson (2004) that this interval must correlate with the lower portion of the smectitic upper Brushy Basin farther to the north (figure 8). One or two well-cemented conglomeratic sandstones overlie this smectitic mudstone interval and cap a series of mesas and cuestas along the south side of Black Mesa, and form the top of the second bench described below (figures 5, 6, and 8), which can be traced east across the southern Blanding basin nearly to Colorado (e.g., figure 17C and 17E). Miller

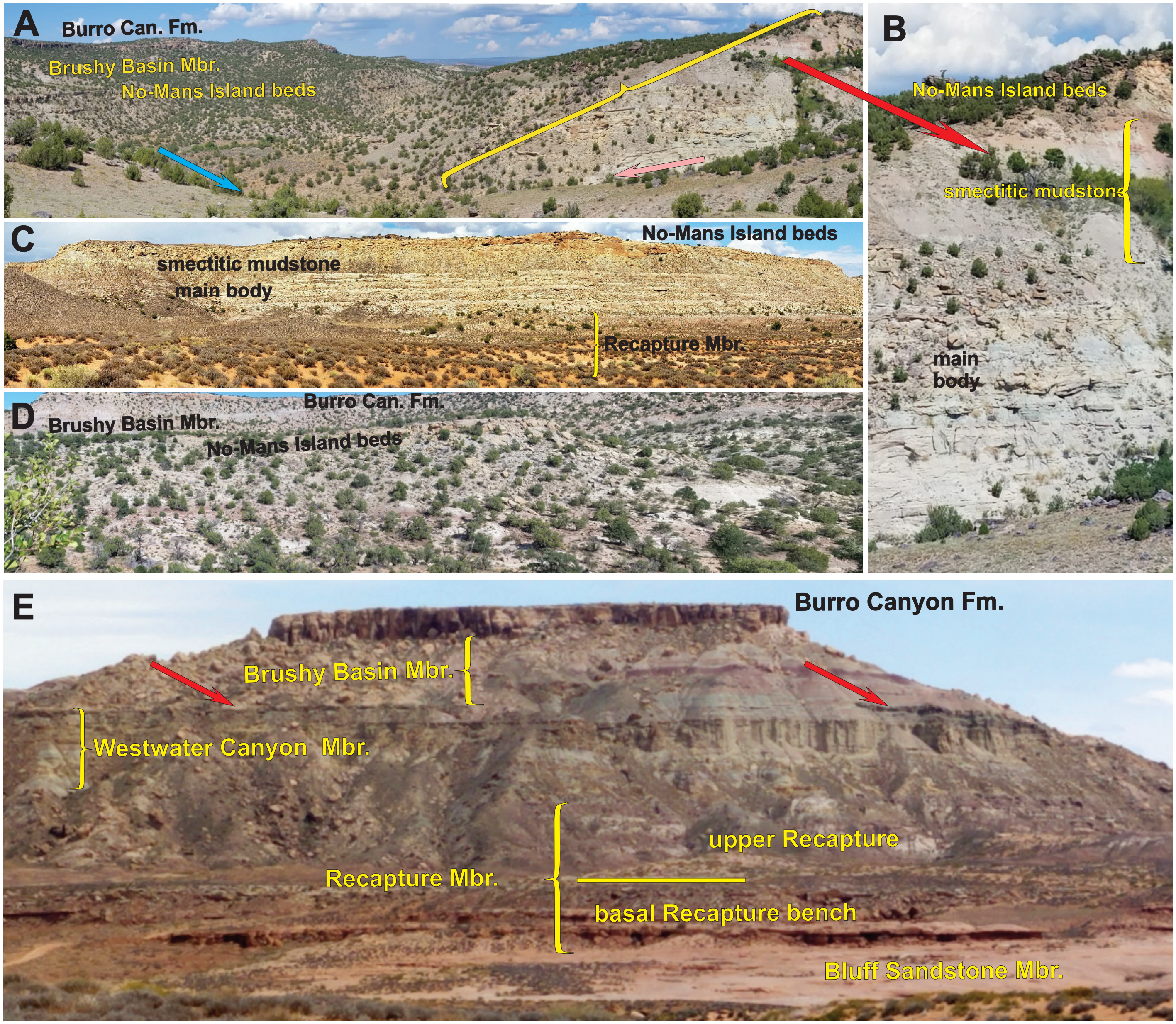

Figure 17. Westwater Canyon Member of the Morrison Formation. (A) Overview of type area of Westwater Canyon Member, where Westwater Canyon joins Cottonwood Wash. Pink arrow indicates Westwater Canyon as viewed from south. Blue arrow indicates Cottonwood Wash. Yellow bracket shows extent of type section. (B) Detail of exposure of type section of Westwater Canyon Member near mouth of Westwater Canyon. Red arrow shows position of B in A. (C) Extensive exposure of Westwater Canyon Member on southwest side of White Mesa (figure 2). (D) Exposures of Westwater Canyon Member along route of Morrison reference section (appendix A), below southwest side of Black Mesa. (E) Nearly complete section of Morrison Formation exposed on west side of McCracken Point southeast of basal Recapture type section (figure 2). Red arrows indicate position of the No-Mans Island beds at top of the Westwater Canyon Member.

(1955a, 1955b) used this surface to define the top of the Westwater Canyon Member in the photogeological maps and as the top of the lower Morrison Formation along the Elk Mountain Road (Miller, 1956). We informally refer to these beds as the No-Mans Island beds as they are well developed capping No-Mans Island (figures 2, 7, 8, 12B, 12F, and 14E).

Miller (1955a, 1956) only mapped the Westwater Canyon Member south of the northern limit of the Recapture Member. Thus, on Miller's (1955a) photogeological map the usage of Westwater Canyon Member only extends north of its type section for approximately 0.8 km (0.5 mi), with the Morrison Formation from this point northward divided into a "lower Morrison Formation" and an upper Brushy Basin Member. However, O'Sullivan (2000) recognized the Westwater as extending several kilometers farther north.

Prospecting for fossils below the Brushy Basin Rim north of SR 95, we noted that the lower Brushy Basin Member is very sandy and largely devoid of significant vertebrate fossils, and we initially concluded that Turner and Peterson's (2004) correlation of the upper interval of the Westwater Canyon with the lower Brushy Basin Member was probably correct. However, we have subsequently examined the upper contact of the Westwater Canyon Member farther north along the Elk Mountain Road and noted that in Gregory's (1938) type section, the No-Mans Island beds are present at the top of the Westwater Canyon Member and below the base of the type section of the Brushy Basin Member (Gregory, 1938, section 25, p. 77). Thus, we now recognize that this unfossiliferous interval is actually the upper smectitic mudstone near the top of the Westwater Canyon Member. The complexities in correlating the southern and northern portions of the study area are daunting, but we believe correlating this interval from south to north along the west side of the Blanding basin by using the resistant No-Mans Island beds as a marker bed is key; these beds can indeed be traced north from the south end of Black Mesa to the southwest side of the Abajo Mountains using aerial imagery (figure 8).

Paleontology

During our paleontological inventory no significant fossils were noted in the Westwater Canyon Member. Gregory (1938) reported that the member preserves dinosaur bone and petrified wood. We found the remains of a shattered dinosaur limb bone on the west side of Decker Cove (Sa1135v) near the base of the Westwater Canyon (figures 18C to 18E) and dinosaur bone fragments in the upper Westwater Canyon Member north of SR-262 (Hovenweep Road) in Recapture Canyon. Additionally, we identified a sandstone bed preserving abundant carbonaceous plant detritus (figures 18A and 18B) in the upper Westwater Canyon in a rather densely vegetated area west of the north end of Black Mesa (Sa1126p). None of the plant remains appeared identifiable. Similar fossils were noted by Paleo Solutions Inc. (figures 16G to 16N) where they examined the correlative Salt Wash strata mapped by Miller (1955a) as "lower" Morrison Formation below the Brushy Basin Rim (Murphey and Zubin-Stathopoulos, 2018).

Brushy Basin Member

In establishing the Brushy Basin Shale Member for the variegated mudstone interval that forms the upper part of the Morrison Formation across the Colorado Plateau region, Gregory (1938) did not state the specific location for the type section. Gregory (1938) however, titled section 25 solely as "Morrison Formation in Brushy Basin." In *Utah Place Names*, Van Cott (1990, p. 52), reported:

> "BRUSHY BASIN (San Juan [County]) is on the southern slopes of the Abajo Mountains six miles south of Mount Linnaeus. It drains south into the Brushy Basin Wash and is named for its heavy growth of upland desert shrubs. S7, 18, T35S, R22E, SLM; ca. 7500' (2,286m)."

Although not describing the lateral extent of Brushy Basin, on the geological map, Gregory (1938, plate 1) indicated that the Brushy Basin physiographic feature extends from the southwest side of the Abajo Mountains along Brushy Basin Wash to its confluence with Cottonwood Wash west of Brushy Basin Rim and north of SR 95. In the 1930s, a dirt road extended westward from Blanding, across the southern part of Brushy Basin, and through the Bears Ears to Natural Bridges National Monument (Gregory, 1938, plate 1). This road is now referred to as the Elk Mountain Road (BLM 092). We assume that Gregory measured the section along this road. Less than 1 km (0.6 mi) south of the road are excellent, deeply dissected exposures of the Brushy Basin Member (figures 19A and 19D); however, Gregory

Figure 18. Fossils from Westwater Canyon Member. (A) Overview of plant debris bed in the upper Westwater Canyon Member below northwestern Black Mesa (Sa1126p). (B) Detail of fine sandstone fragments preserving carbonaceous plant debris at Sa1126p. (C) Overview of shattered dinosaur limb bone site near base of the Westwater Canyon Member on northwest side of Dexter Cove (Sa1135v). View from south. (D and E) Limb bone fragments at Sa1135v.

(1938) noted in the description of a 68-m-thick (224-ft) unit 18 that the unit is partially concealed by landslides, which indicates that the section would have been closer to the road. We noted a wooden culvert under the road at the top of the No-Mans Island beds that could date to the 1930s. On thoroughly investigating the transition between the Westwater Canyon Member and the Bushy Basin Member, we interpret Gregory's (1938)unit 13 at the top of the underlying Westwater Canyon Member as also representing the top of the No-Mans Island beds (figures 6, 8, and 19). Further support for this interpretation came from driving up the Elk Mountain Road following a rain storm and finding it impossible to continue up the slope formed by Gregory's (1938) unit 12 because of the swelling clays, which first appear beneath the No-Mans Island beds (figure 3). A complete section of the Brushy Basin can be pieced together utilizing the exposures south of the Elk Mountain Road (figure 19A). However, this section would be difficult to access in the more deeply dissected and vegetated terrain of this area.

The Brushy Basin type section of Gregory (1938) is as follows:

25. *Section of Morrison formation in Brushy Basin*

Dakota (?) sandstone.
Unconformity.
Morrison formation:
Brushy Basin shale member:

28–24. Shale, red and white, sandy, and white lenticular coarse grained porous sandstone, in alternating beds; forms stepped slope.......61 ft

23. Sandstone, white and greenish yellow,

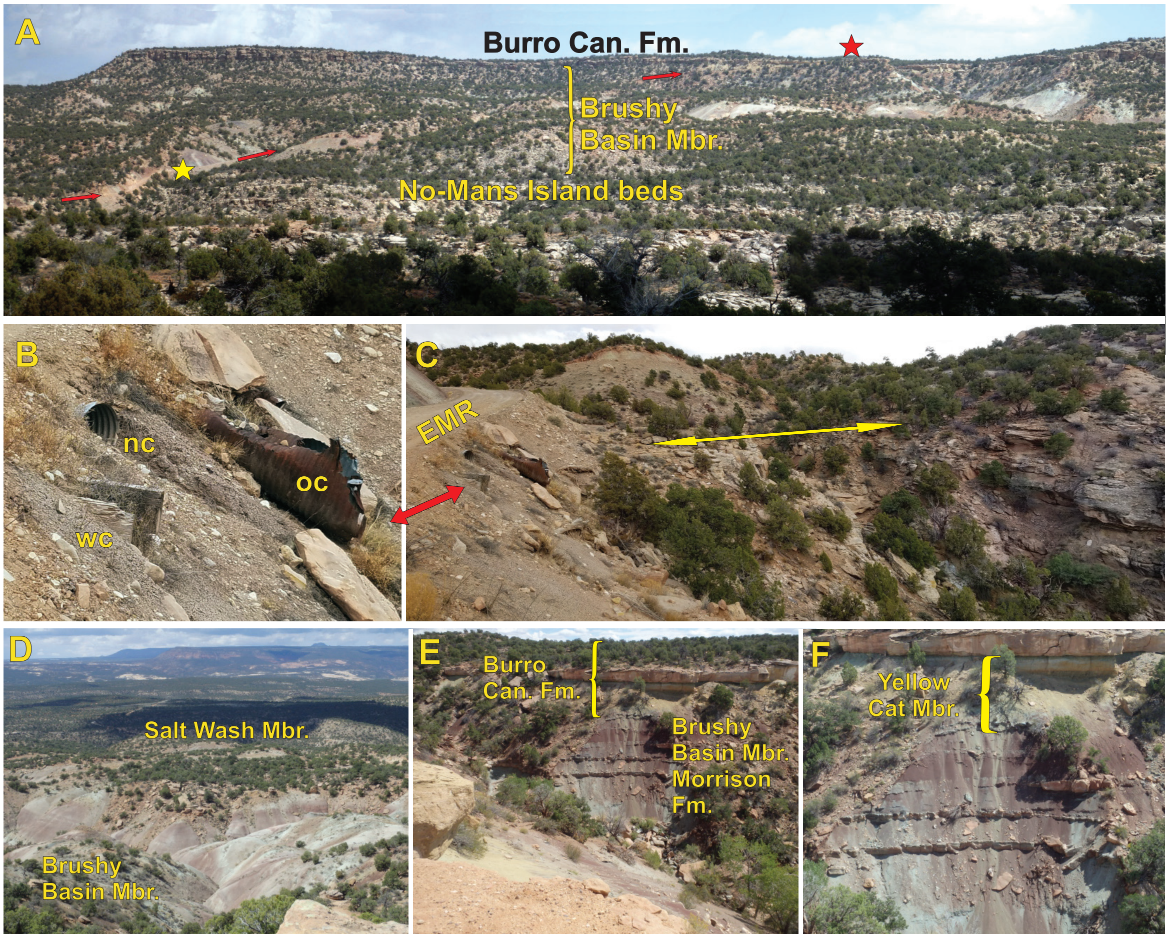

Figure 19. Gregory's (1938) type section of the Brushy Basin Member of the Morrison Formation. (A) Central portion of Brushy Basin viewed to the east toward the Brushy Basin Rim. Red arrows indicate Elk Mountain Road (BLM 0620. Red star indicates where the Elk Mountain Road crosses onto the Brushy Basin Rim. Yellow star indicates site of culverts in B and C. (B) Three generations of culverts. nc = new culvert, oc = old abandoned culvert, wc = wooden culvert. (C) Detail of the contact between the No-Mans Island beds at the top of the Westwater Canyon Member and the overlying Brushy Basin Member as indicated by double-headed yellow arrow (12 S, 625171.42 m E, 4166584.89 m N). EMR = Elk Mountain Road. Double-headed red arrow position of the culverts detailed in B. (D) View toward west from Elk Mountain Road on Brushy Basin Rim across Brushy Basin toward Bears Ears on horizon. (E and F) View east across small canyon from Elk Mountain Road on Brushy Basin Rim at exposure at the top of Gregory's (1938) type section of the Brushy Basin Member. Note that the Yellow Cat Member of Burro Canyon Formation was initially within the top of Gregory's (1938) type section of the Brushy Basin Member.

coarse, very lenticular, in part cross-bedded; lenses of conglomerate consist chiefly of red and black chert, fragments of green sandstone, and clay balls; includes round white aggregates of quartz and elongated brown concretions of iron and sand; forms cliff....................................27 ft

22–20. Shale, red, ash gray, yellow, and green, sandy, and lenses of white sandstone; forms color-banded slope............................59 ft

19. Sandstone, dark green, hard, very fine grained, persistent ledge...............................2 ft

18. Shale, red, yellow, green, purple, and white; color distributed in regular bands and in blotches to form variegated slope; beds include lenses of pink, purple, and white limestone, white and brown sandstone, and limestone conglomerate con-

sisting of concretionary balls, chert, and bone fragments; weathers to form loose, fluffy, marl-like material, partly concealed by landslides ....224 ft

17. Sandstone, dark green, resistant, like no. 6 ... 1 ft
16. Sandstone, brown; appears as massive ledge but weathers readily to shale-like beds...12 ft
15. Shale, dark red, unevenly bedded; thin band of white powder-fine sandstone at top and base..15 ft
14. Shale, red and slate-colored...........................29 ft

Total Brushy Basin member....................................450 ft

Westwater Canyon sandstone member:

13. Sandstone, white and greenish yellow, with lenticular partings of greenish shale; top surface hardened and uneven......24 ft
12. Shale, banded red and greenish white, flaky, and thin white sandstone, in overlapping lenticular beds..................................30 ft
11. Sandstone, white, thin-bedded, and red shale, irregularly interfoliated; forms broad platform ....16 ft
10. Sandstone like no. 1 but coarser-grained; forms strong ledge ....20 ft
9. Shale, red, streaked greenish white ....3 ft
8. Sandstone like no. l..22 ft
7. Shale, red; forms bench...................................8 ft
6. Sandstone like no. 1; base firmly cemented mass of fragments of sandstone, red shale, and white mud shale; rests in hollows and about ridges at top of no. 5............25 ft
5. Sandstone, greenish-white, and lumpy mudshale; contains lime concretions and fragments of carbonaceous material....... 5 ft
4. Shale, red; forms platform ....3 ft
3. Sandstone like no. 1 ....23 ft
2. Shale, red, unevenly bedded, imbricated; weathers to leaf-like chips ....30 ft
1. Sandstone, white; weathers yellowish white, most of it cross-bedded and lenticular; lenses of conglomerate made up chiefly of lozenges and scales of greenish-white clay, chert, and fragments of shale; a few very thin short lenses of red shale; weakly cemented with lime; round holes and slots give weathered cliff face a spongy appearance ....46 ft

Total Westwater Canyon member exposed ....255 ft

Gregory (1938) summarized the characteristics of the Brushy Basin shale member as follows:

> "The upper part of the Morrison of the San Juan country consists of the well-known variegated shales (Morrison shales, McElmo shales) that generally in Utah and western Colorado lie immediately below the Dakota (?) sandstone. In fact, they owe their preservation to the resistant Dakota cover. Directly beneath cliffs of Dakota (?) sandstone they stand in almost vertical walls; where the sandstone has been stripped back, they form slopes that continue outward into mounds and ridges spread over a platform of Westwater Canyon sandstone. Their appearance is everywhere the same brightly variegated masses that are exceeded in beauty of coloring only by the Chinle "marls." The dominant beds are white, gray, green, purple, and red sandy shales and sandstones. …Subordinate beds are gray, pink, blue, and gray limestones; conglomerates of red, green, and white cherts; and buff hard sandstones. The buff sandstone is more abundant near the base and seems to increase in amount eastward toward the Colorado line."

The Brushy Basin Member is well exposed across the southern Blanding basin (figure 17E) and in the southward-draining canyons cutting through the third bench formed by the Burro Canyon Formation (figures 7 and 8). Some of the most continuous, non-vegetated sections are along the west side of Black Mesa above Stephens Canyon (figure 20A) and on the south side of Black Mesa where Black Mesa Road cuts down through the Brushy Basin section (figures 20B to 20H) at the escarpment formed south of the third bench (12 S, 624213.94 m E, 4144247.69 m N). About 200 m (700 ft) northeast of the Black Mesa Road, we identified an organic-rich mudstone layer that extends across this entire portion of the outcrop (figures 20B to 20H) that we

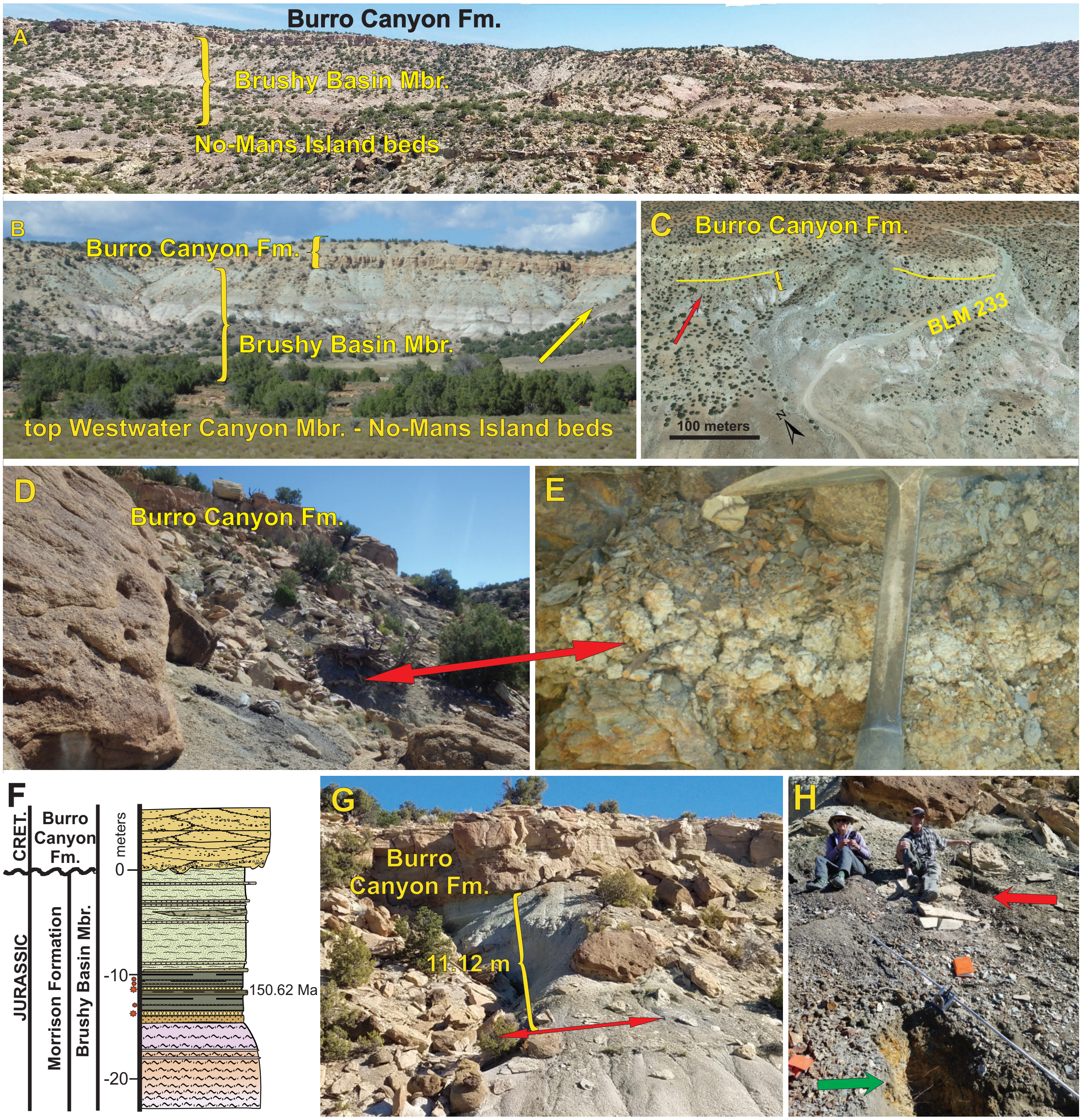

Figure 20. Brushy Basin Member of the Morrison Formation on west and south sides of Black Mesa. (A) Overview of Brushy Basin exposures on west side of Black Mesa as viewed east across Stephens Canyon. (B to E) Brushy Basin Member on the south side of Black Mesa (figure 7B). (B) Brushy Basin exposures west of Black Mesa Road (BLM 233) as viewed from south. Yellow arrow indicates Sa1133vp, where productive palynomorph sample was taken. (C) Brushy Basin exposures near Black Mesa Road (BLM 233) as viewed obliquely from south (Google Earth©). Red arrow = position of dated volcanic ash. Yellow line indicates basal contact of Burro Canyon Formation. (D) Overview of pollen-ash site Sa1114. Red double headed arrow indicates position of ash sample (appendix B). (E) Close-up view of volcanic ash layer at Sa1114p. Rock hammer head about 18 cm (7 in). (F) Section across Morrison-Burro Canyon transition 110 m (360 ft) N 104° E from Sa1114 with dated ash indicated. (G) Morrison-Burro Canyon transition. Double-headed red arrow indicates stratigraphic position of dated ash 11.12 m (36.48 ft) below base of Burro Canyon Formation. (H) Organic interval preserving volcanic ashes near top of the Brushy Basin Member. Green arrow indicates lower undated ash. Red arrow indicates position of dated ash.

sampled for palynomorphs (Sa1133p). It was processed under the direction of Carol Hotton at the Smithsonian Institution, who initially found it to be barren of palynomorphs. This fine-grained, organic-rich bed extends for hundreds of meters west (figure 20B; locality Sa1114vp) from where a colleague, Nina Baghai-Riding, extracted a palynoflora dominated by *Exisipollenites*, with lesser amounts of conifer and ginkophyte pollen, and with many fewer spores of mosses, horsetails, and ferns (Baghai-Riding and others, 2018).

Within the organic layer we identified a 20-cm-thick (5-in) volcanic ash (figures 20D to 20E) that was processed by one of us (KCT), with Kevin Chamberlain, at the University of Wyoming, who reported that it preserves pristine needles of zircon (appendix B) that yielded a highly-resolved uranium-lead age following chemical abrasion to remove the altered rind on the crystals. Chamberlain reported an age that incorporates both the $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ data, of 150.67 ± 0.32 Ma (95% confidence limits) from this sample (appendix B). This is one of the most highly resolved ages for the top of the Brushy Basin Member of the Morrison Formation (Kowallis and others, 2007; Trujillo and Kowallis, 2015; Chamberlain and Trujillo (verbal communication, 2017). This ash is situated only 11.12 m (36.5 ft) below the erosional contact with the overlying Burro Canyon Formation (figures 20F to 20H). More recently, an age of 149.45 ± <0.10 Ma was determined from a volcanic ash a couple of meters below the top of the Morrison Formation in western Colorado south of Fruita (Galli and others, 2018). Our new Morrison age appears to weakly support Galli and others (2018) and Maidment and Muxworthy (2019) hypotheses that the top of the Morrison is older to the west as a result of tectonic beveling.

Forested cover is extensive over the Brushy Basin outcrop belt north of SR 95. However, Gregory (1938, plate 13D) illustrated typical exposures of the Brushy Basin on the northwest corner of Black Mesa, where some of the most extensive exposures of the Morrison Formation in the area are located (figure 21). The dirt road (BLM 233) from SR 95 to the top of Black Mesa now traverses the entire section of the Brushy Basin Member, making it one of the most accessible Brushy Basin exposures in the region. This exposure is only 11.2 km (7 mi) due south of Gregory's original 1938 type section. Given the paleontological significance of the Brushy Basin Member of the Morrison Formation, we decided that this is a good site to designate as an accessible reference section for the Brushy Basin Member (figures 3 and 18; appendix A).

The Brushy Basin Member is noticeably thicker in the Brushy Basin area than in other areas on the Colorado Plateau. Gregory's (1938) measured section along the Elk Mountain Road, gave a thickness of 137.25 m (450 ft). He found 108 to 132 m (360–440 ft) on Recapture Creek (Gregory, 1938, section 23). However, we measured only 77.50 m (254.2 ft) at our reference section along the Black Mesa Road. We also recognize that there are few conglomeratic channel sandstones in the Brushy Basin Member along Comb Ridge. Such "ribbon" sandstones are present in most other areas of Brushy Basin exposure, reflecting deposition on a floodplain dominated by low-sinuosity anastomosing rivers (e.g., Kirkland, 2006). In fact, there is not a single channel sandstone in the Brushy Basin reference section we measured on the northwest side of Black Mesa (figures 3, 21, and 22). A large proportion of sand-sized material is characteristic of approximately the lower 18 m (59 ft), with beds of sandstone, muddy sandstone, and smectitic sandy mudstone. Gregory (1938) also noted that sandstone beds are most apparent in the lower Brushy Basin Member. Dark-green, ledge-forming sandstones (units 58, 61, and top of 63) may be colored by vanadium oxide, and units 61 and 63 form local marker beds (figures 22 and 23A to 23D).

Up section, the mudstones are much richer in smectitic clays. These swelling clays give the slope the typical convex natural weathering profile characteristic of the Brushy Basin Member (figures 19 and 20D to 20G). On the surface these clays display characteristic "popcorn" weathering typical of smectitic mudstone beds (Keller, 1962). These smectitic clays formed from the natural decomposition of volcanic glass (ash) initially mixed throughout the fine sediments of the Brushy Basin floodplain. These volcanic ashes erupted from large caldera-forming eruptions in the magmatic arc to the west (Christiansen and others, 2015). Within the mudstone intervals of units 66, 76, and 82 are intervals colored a distinctive orange-pink (figures 22 and 23D to 20G)

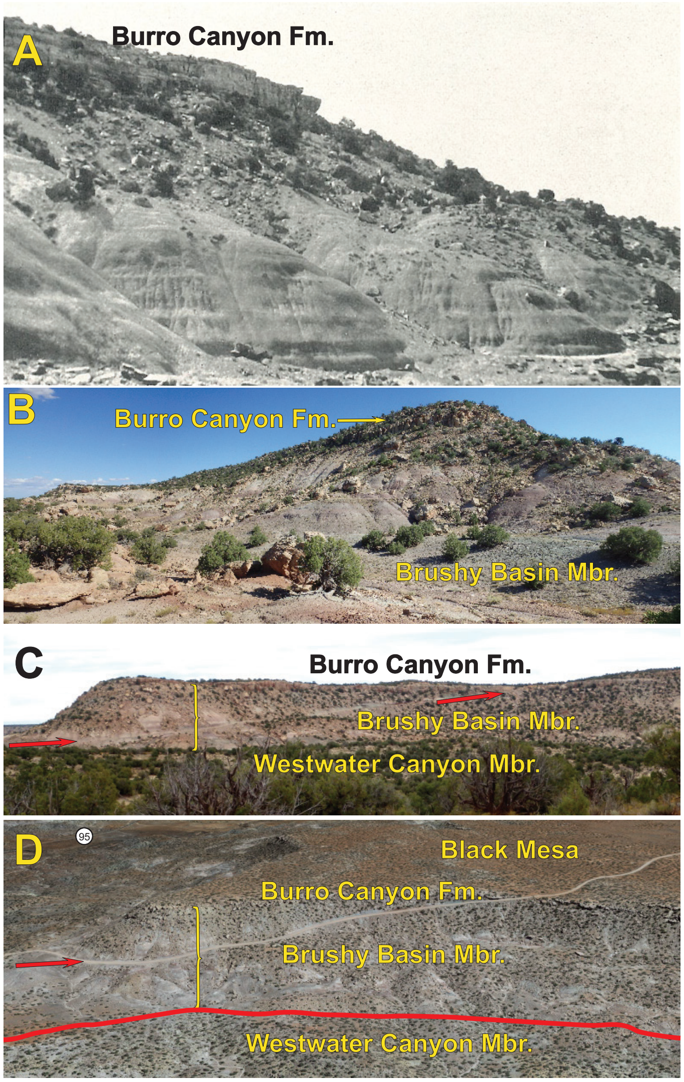

Figure 21. Brushy Basin Member of the Morrison Formation at its newly proposed reference section. (A) Gregory's (1938, plate 13D) photograph of typical exposures of the Brushy Basin Member on "west" side of Black Mesa. (B) Northwest corner of Black Mesa viewed from north. (C) Northwest corner of Black Mesa viewed from west with BLM 233 angling up across the Brushy Basin exposure to the top of Black Mesa. (D) Northwest corner of Black Mesa viewed from above and west (Google Earth©) with BLM 233 angling up across the Brushy Basin exposure to the top of Black Mesa. Red line is approximate contact between Brushy Basin and Westwater Canyon Members. Red arrows indicate the Black Mesa Road, (BLM 233).

that look like clinoptilolite diagenetic mineral zones described by C. Turner (Turner and Fishman, 1991, 1998; Dunagan and Turner, 2004; Turner and Peterson, 2010a, plate 5) for alkaline-saline wetland deposits of ancient "Lake" T'oo'dichi'. In the Montezuma Creek area, Turner (2010) noted tawny brown beds that contain authigenic albite characteristic of a more central "Lake" T'oo'dichi' setting. Such beds in the reference section may include units 74, 80, 95, and 97, but a detailed analysis of the minerals in these beds would be needed to identify the presence of these alteration products. Additionally, it is noteworthy that the zeolites in the Morrison Formation have also been interpreted as to be purely a diagenetic phenomenon (Tanner and others, 2014).

Well-developed paleosols are not typical of the Brushy Basin Member (Demko and others, 2004). Carbonate nodules with associated root traces, which may reflect pedogenic or paludal processes, are present in the upper portion of the lower sandy interval in units 62 and 64. Kirkland (2006) proposed that the basal Brushy Basin paleosol documented by Demko and others (2004) farther north represents an unconformity that explains the dramatic clay change across the central and northern Colorado Plateau (Turner and Peterson, 2004). Could this also explain the apparent loss of at least the upper Westwater Canyon Member beneath the Brushy Basin to the north? Tracing this contact along the west side of the Abajo Mountains would be an important test of this hypothesis versus a simple pinch-out of the No-Mans Island beds to the north (figure 8).

Additional incipient paleosols may also be recognizable near the middle of the Brushy Basin Member. Unit 69 is a bed of coalesced septarized carbonate nodules 23 cm (9 in) thick. The highest stratigraphic unit associated with abundant carbonate nodules is unit 71. Fragments of sandstone from the interspersed sandstone beds together with carbonate fragments armor the mudstone outcrop for several meters downslope. Small carbonate nodules are present toward the top of unit 74. Only a more detailed analysis by a specialist in paleosols would distinguish if these carbonate-bearing intervals represent paleosols. Unit 77 is 65 cm (25 in) of pale grayish-yellow mudstone with burrows and root traces overlain by 22 cm (8.5 in) of very well indurated, blackish-red, perhaps siderite-cemented, muddy sandstone with additional root traces. Perhaps this distinct horizon represents a wetter incipient paleosol (Tabor and others, 2017).

Much of the upper Brushy Basin Member exposed

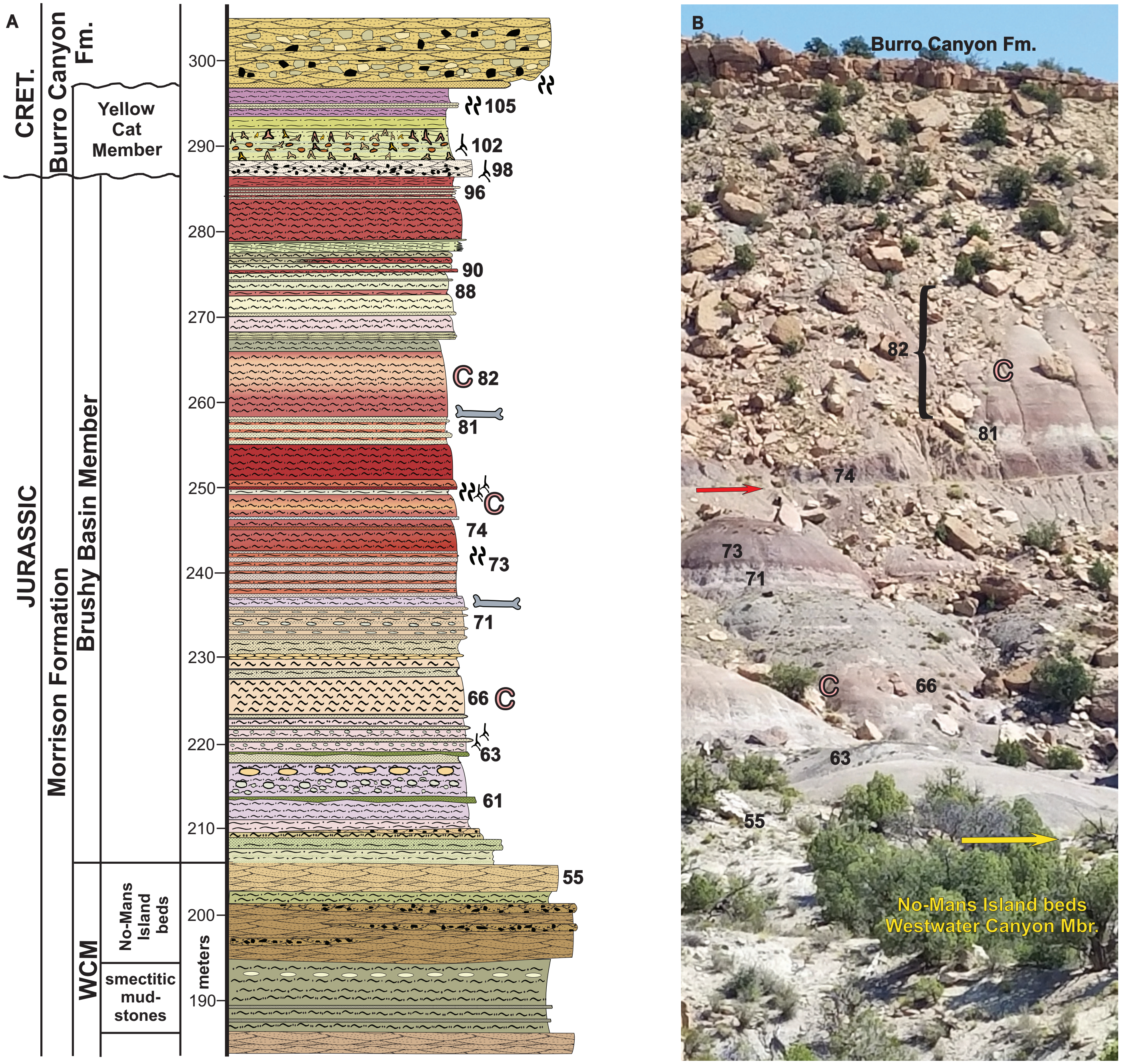

Figure 22. Brushy Basin Member reference section on northwestern Black Mesa. (A) Brushy Basin reference section on and below Black Mesa Road (BLM 233) on northwest side of Black Mesa. WCM = upper part of Westwater Canyon Member. (B) Brushy Basin reference section below Black Mesa Road (BLM 233 as noted by red arrow) and extending up to Burro Canyon Formation on northwest side of Black Mesa as viewed from sandstone-capped ridge to west. Yellow arrow indicates the basal contact of the Brushy Basin Member. Pink Cs indicate zones of clinoptilolite after Turner and Fishman (1991) and Turner and Peterson (2010a). Black numbers indicate stratigraphic units in appendix A and noted in figures 19 to 21. See figure 3 for explanation of symbols shown on A.

Figure 23. Exposures of Brushy Basin Member along Morrison reference section. (A) Deeply weathered uppermost sandstone of the No-Mans Island beds at top of the Westwater Canyon Member. (B to F) Lower half of the Brushy Basin Member downslope below Black Mesa Road (BLM 233 as noted by red arrows in C, F, and G). (G to K) Upper Brushy Basin Member along Black Mesa Road (BLM 233 as noted by red arrow). Pink Cs indicate zones of clinoptilolite after Turner and Fishman (1991) and Turner and Peterson (2010a). Black numbers indicate stratigraphic units in appendix A.

along the Black Mesa Road above unit 82 is less brightly variegated, although it includes several thin, dark-red mudstone units that tend to be obscured by debris from the surrounding drably colored mudstones. However, units 95 to 97 form a dark reddish-brown band (figure 20K) more than 7 m (23 ft) thick near the top of the Brushy Basin Member that is apparently widespread across the study area.

Overlying this smectitic red-bed interval at the top of the Brushy Basin Member is a marked change in deposition that we initially referred to as the "Yellow Cat facies" (Kirkland and others, 2018), but is herein recognized as the Yellow Cat Member of the Burro Canyon Formation and lithologically preserves iron-rich paleosols and mudstone-supported conglomeratic lenses typical of the "lower" Yellow Cat Member of the Cedar Moutain Formation northwest of the Colorado River (Kirkland and others, 2016).

The upper contact of the Brushy Basin Member is generally marked by a conglomeratic sandstone or mudstone with dispersed pebbles that is overlain by nonsmectitic mudstones, which may include zones of ferruginous nodules. The absence of smectitic clays gives the Yellow Cat Member a straight to concave slope profile as opposed to the convex weathering profile characteristic of the Brushy Basin interval. Where present, the overlying Yellow Cat Member is generally no thicker than 10 to 15 m (30–45 ft). Elsewhere, coarse, cliff-forming conglomeratic sandstones of the main body of the Burro Canyon Formation directly overlie the Brushy Basin Member that exhibits basal Cretaceous aquifer bleaching of the uppermost Jurassic mudstones to a pale green. Such a Jurassic–Cretaceous contact is present at the south end of Black Mesa on either side of the Black Mesa Road (figures 20B to 20H) and at the Los Angeles County Museum's dinosaur tracksite in the central Blanding basin (Milán and others, 2015; figure 2).

Paleontology

At present more than 65 fossil localities have been documented in the Morrison Formation within the study area; approximately 50 of these are in the Brushy Basin Member. We found that the Brushy Basin fossil sites in the western Blanding basin are mostly in the middle and upper portions of the member. To the north, in the Blue Hills area, fossil sites appear to be more evenly distributed within the Brushy Basin but may be most abundant in the lower part as documented for the member in general by Turner and Peterson (1999).

The Brushy Basin Member is generally the most fossiliferous member of the Morrison Formation and preserves more significant dinosaur fossil remains than nearly any other rock unit in North America (Carpenter and others, 1998; Turner and Peterson, 1999; Foster and Lucas, 2006; Foster, 2007). The most common fossils recognized in the Brushy Basin Member are fragmentary dinosaur bones eroded out onto the surfaces of the mudstone intervals and as bone chip lags at the toes of steeper slopes. This is the setting that produced the few identified tooth fragments. The smectitic mudstones of the Brushy Basin are notorious as swelling clays. Rainwater will quickly destroy the dinosaur bones that are partially uncovered by wetting and expanding the surrounding mudstone, which then shrinks again on drying. Repeating this process quickly shatters even relatively well-preserved dinosaur bones. Experience shows that to preserve any bones left in situ requires that they be protected by waterproof tarps. But even with the use of a tarp, the condensation of moisture under the tarp may still damage the bone. Therefore, uncovering bones in the Brushy Basin Member should not be done unless the intent is to immediately document the position of the bones and collect them. Most bones encountered during the course of the project appear to represent isolated bones or, at most, a few associated bones (figures 24E to 24H). Only limited test excavations were conducted at a few bone sites, so it is conceivable that in a few cases more extensive accumulations of bone may have been obscured by debris weathered down slope. A few laterally extensive bone accumulations were encountered (figures 24I to 24N) that may represent bone bed accumulations (e.g., Rogers and others, 2007) or large associated skeletal elements like the *Diplodocus* caudal vertebrae identified by our team (JRF, DDD, RKH-F) at Sa1232v (figures 24L to 24N). A number of these sites warrant additional research that is beyond the scope of this project.

Fragments of petrified wood, logs, and stumps are also relatively common (figures 24C and 24D), but not as common as dinosaur bone. Trace fossils and rooting are present, but are not as ubiquitous as one might suppose, and are generally restricted to specific horizons and zones (figures 24A and 24B).

Susannah Maidment reported to the BLM the only dinosaur site (Sa1155v) in the entire study area that we are aware of that has clearly been uncovered by unper-

Figure 24. Examples of fossils in the Brushy Basin Member. (A) Trace fossils preserved on underside of crevasse splay block below Sa1127t. (B) Possible termite nest(?) associated with vertebrate remains at Sa1122v. (C) Tree stump preserved in situ at Sa1130p. (D) Section of petrified log (red arrow) at Sa1108p. (E) Broken up sauropod vertebra at Sa1129v. (F) Broken up dinosaur bone at Sa1128v 100 m to east. (G) Nearly complete dinosaur bone in situ at Sa1110v. (H) Bone fragments at Sa1112v. (I) Extensive scatter of dinosaur bones within the red outline at Sa1113v. (J) Caudal vertebral centrum at Sa1113v. (K) Laterally extensive bone site at Sa1229v. Red arrows point to bones. (L and M) Possible *Diplodocus* skeleton at Sa1232v. (L) Broken caudal vertebra. (M) John Foster examines another caudal vertebra (red arrow). (N) A naturally weathered limb bone. (O) Overview of vandalized dinosaur bone locality Sa1155v. View looking north. (P) Telephoto view of Sa1155v from the same location shown in O. Rock hammer in D, E, and F is 30 cm (12 in) long. Hoe pick head in G, H, K, and N is about 40 cm (16 in).

mitted excavation (figures 24O and 24P). We assumed that it had been worked by individuals with experience excavating bones in the Brushy Basin Member as it had been covered by a blue tarp and reburied. Salvaged by the BLM, the site consisted only of a couple of large bone fragments. Farther to the north, in the Blue Hills area northwest of Moab, Utah, vandalism of fossil sites is much more widespread with nearly all evidence of isolated bones, petrified logs, and even agate removed in some areas (Kirkland and DeBlieux, 2017; Kirkland and others, 2017, 2018).

Less than 15 total sites in the Morrison Formation of Utah are on file in the Utah Paleontological Locality Database with any identifiable leafy plant fossils. Many of the strata in the Morrison Formation are highly alkaline such that leafy vegetation and palynomorphs are rare, with less than 10% of the identified pollen and spore types represented by macroscopic plant remains (Parrish and others, 2004; Kirkland 2006). Therefore, we search for these sites as carefully as we would for those preserving vertebrate remains. Toward the south end of the study area an organic layer approximately 15 m (50 ft) below the Burro Canyon Formation and below the "Yellow Cat facies" preserves a significant palynomorph assemblage (Baghai-Riding and others, 2018) associated with a dated volcanic ash as described above (figure 20C to 20H).

Toward the northern end of the study area near the middle of the Brushy Basin Member about 50 m (165 ft) below the Burro Canyon Formation (figure 2), we identified a thick organic plant debris bed (Sa1134vp). Several meters thick, this site appears to cross the valley floor for approximately 100 m (330 ft). The site preserves copious amounts of carbonaceous plant material with petrified driftwood and isolated bones through its lower 2 m (6 ft) (figure 25). This bed is very different than other plant-bearing beds in the Morrison Formation on the Colorado Plateau, which are generally dark-gray mudstones with more disseminated plant material (Parrish and others, 2004; Kirkland, 2006). The main bed resembles the plant debris beds in the Lower Cretaceous Wessex Formation of England, which are famous for the abundance and diversity of the flora and fauna they preserve (Martill, 2001; Sweetman and Insole, 2010). The UGS obtained a permit to conduct a test excavation in May 2017 to evaluate the paleontological potential of this locality. This resulted in the recognition of a paleobotanical site preserving abundant *Czekanowskia*, ginkgoes, ferns (dominated by *Coniopteris*), conifer shoots, coprolites, less common conchostracans, a giant water bug (Lara and others, 2020), and impressions of possible salamander bones, in a finely laminated shale at the top of the exposure overlying a 10-cm-thick (4-in) volcanic ash (sampled). Tentatively identified were possible impressions of small bones and insects. Additionally, this is a rare example of a compressional plant site that also preserves pollen (Baghai-Riding and others, 2018). This compressional plant horizon is considered to be highly significant and was given its own locality number Sa1212p (figure 25). We have come to consider this complex site to have so much paleontological potential that we classify it as a small "Paleontological Site Complex" (Kirkland and Foster, 2009). Paleontological Site Complexes (PSCs) are areas having microvertebrate sites, bonebeds, and areas with dense concentrations of individual sites that require comprehensive and long-term management—potentially in perpetuity. As such, we have been putting together a team of paleontologists to excavate and research this "marsh/pond deposit." The results of this research will be presented elsewhere.

BURRO CANYON FORMATION

Yellow Cat Member

History and Lithology

The uppermost Brushy Basin Member at its reference section (figures 22 and 26), as originally defined, includes ferruginous paleosol(s) (units 100 to 103 appendix A) indicating a wetter climate than has been previously interpreted for the Morrison Formation (Demko and others, 2004; Kirkland and others, 2016). These ferruginous paleosols were first recognized at the top of the Brushy Basin slope by Turner and Peterson (2010a), who suggested that they may represent an interval of Cretaceous-age strata. Because these paleosols are underlain by a distinctive conglomeratic sandstone (unit 98), we also interpret the paleosols to be within basal Cretaceous strata resting on the Jurassic-Cretaceous unconformity (K-1 unconformity). When com-

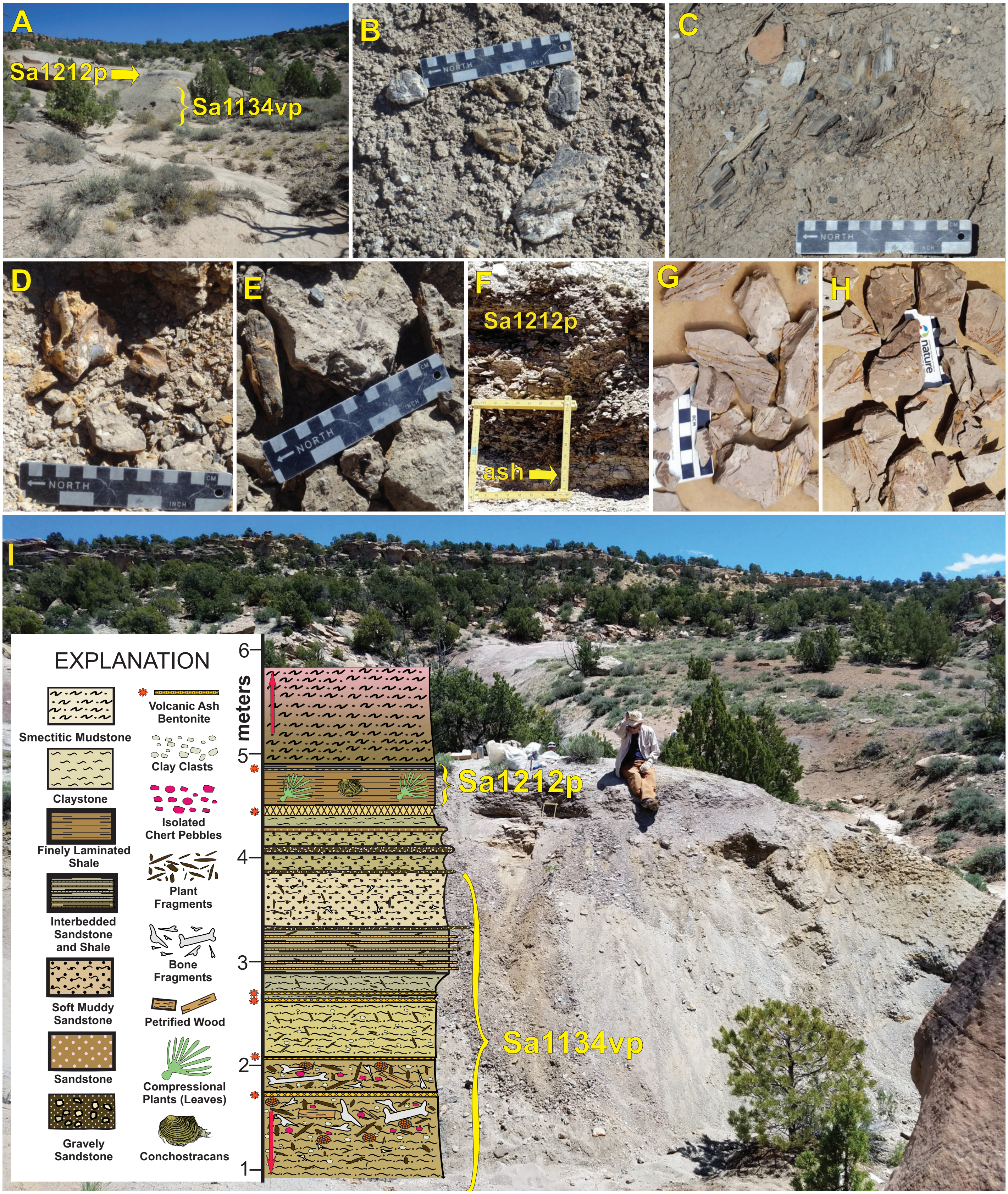

Figure 25. Caption is on the following page.

Figure 25 (figure on the previous page). Fossiliferous marsh/pond deposit. (A) Overview of plant debris bed at locality Sa1134v and overlying compressional fossil plant locality Sa1212p. (B) Close-up of bone fragments initially found at Sa1134v. (C) Petrified wood exposed at Sa1134v. (D and E) Bone and plant fragments near base of Sa1134v. (F) Close-up of volcanic ash underlying Sa1212p. (G and H) Typical compressional plant fossils preserved in Sa1212p. (I) Stratigraphic section of Paleontological Site Complex geometrically estimated at about 50 m (164 ft) below top of Brushy Basin Member.

pared to correlative strata farther to the north, this sequence compares well with the interfluvial Yellow Cat facies that laterally interfingers with the Buckhorn Conglomerate of the Cedar Mountain Formation (Lower Cretaceous) on the western San Rafael Swell and with the lower Yellow Cat Member of the Cedar Mountain Formation in the northern Paradox Basin (Kirkland and others, 2016). As with the Yellow Cat Member of the Cedar Mountain to the north, the mudstones of this interval do not appear to be smectitic and form a flat to concave slope as opposed to the convex slope formed by the underlying smectitic mudstones of the Brushy Basin Member (Kirkland and others, 2016).

However, at this time, no radiometric or biostratigraphic ages exist for these strata so a latest Jurassic age cannot be completely ruled out; sediment samples have been collected that will hopefully remedy this situation. Given that these beds were included within Gregory's (1938) type section of the Brushy Basin Member (figures 19E and 19F), and that this thin sequence of rock is rarely exposed below the sandstone rubble from the overlying Burro Canyon Formation, we initially chose not to separate these possible Cretaceous strata from the Brushy Basin Member. However, we now agree with the U.S. Geological Survey and separate the Yellow Cat interval from the underlying Morrison Formation (Aubrey, 1998) as the basal interval of the Cedar Mountain Formation as a member of the Burro Canyon Formation in the Blanding basin.

In addition to also being recognized at the top of the type section of the Brushy Basin Member along the Elk Mountain Road (figures 19E and 19F), Yellow Cat strata are recognized in road cuts along paved roads in the region, where further study may be readily undertaken. Kirkland and others (2016) recognized these facies at Gregory's (1938) "jump-off" on U.S. 191 south of White Mesa (figures 7A, 27A, and 27B) for which, given our new observations, we provide an updated interpretation. The "jump off" exposures differ in that the upper dark-red mudstone interval is strongly mottled, suggesting the beginning of soil modification prior to the deposition of the Yellow Cat Member. Additionally, the upper part of the Yellow Cat Member appears to be so organic-rich that it was initially interpreted as being part of the Naturita Formation (Kirkland and others, 2016). These beds have been sampled for palynology. It would be informative to test if they preserve a pre-angiosperm palynomorph flora. An exceptional exposure (figures 27C to 27G) of the Yellow Cat Member is on the north side of SR 95 near mile post 120 on the eastern margin of the study area. At this site, the conglomeratic basal unit contains larger chert pebbles that are more varied than those observed in unit 98 in the Brushy Basin reference section. In addition, the ferruginous paleosol is well developed at this site. Finally, dark-green claystones preserving plant fragments are present near the top of the sequence and have also been sampled for palynomorphs. None of these samples yielded palynomorphs or enough zircons to substantiate a maximum age.

The upper contact of the Yellow Cat Member is sharp with the scoured base of the fluvial sandstones at the base of the main body of the Burro Canyon Formation (figures 16E, 16F, 21G to 21J, and 22). This is like the unconformity between the Yellow Cat Member and overlying fluvial sandstones at the base of the Poison Strip Member of the Cedar Mountain Formation in the northern Paradox Basin (Kirkland and others, 2016). The Yellow Cat Member and the main body of the Burro Canyon Member do not appear to intertongue, such as has been observed in the western San Rafael Swell between the interfluvial Yellow Cat facies and the Buckhorn Conglomerate Member of the Cedar Mountain Formation (Kirkland and others, 2016).

The Yellow Cat Member is notably absent at several sites in the Blanding basin. It is not present at the Los Angeles County Museum's Burro Canyon dinosaur tracksite (Milán and others, 2015), which has several meters of relief documented where the basal conglom-

Figure 26. Morrison reference section, Yellow Cat Member of Burro Canyon Formation at top of the Brushy Basin Member. Black numbers indicate stratigraphic units in appendix A. (A and B) Contact of red mudstone unit 97 with conglomeratic sandstone at base of Burro Canyon Formation, unit 98. Double-headed red arrow indicates position of 30-cm-long rock hammer. (C) Close-up of unit 98 showing light-colored pebbles of chert and quartzite. (D) Overview of Yellow Cat Member of Burro Canyon Formation viewed to south along BLM 233. (E) Lower part of Yellow Cat Member of Burro Canyon Formation. Orange double-headed arrow indicates greatest concentration of ferruginous nodules in paleosol. (F) Ferruginous nodules in unit 102. (G) Transition from top of Yellow Cat Member with fluvial facies of Burro Canyon Formation. Yellow double-headed arrow indicates location of burrows in H. (H) Burrows in unit 105. (I) Basal fluvial sandstone ledge of Burro Canyon Formation. (J) Burrows in unit 107 at base of fluvial Burro Canyon Formation.

eratic sandstone unit is incised directly into the Brushy Basin Member of the Morrison Formation. Likewise, on the south end of Black Mesa, where the Black Mesa Road cuts down through the Brushy Basin Member, a fluvial sandstone characteristic of the Burro Canyon Formation directly overlies the Brushy Basin Member (figures 17B to 17H). In both areas the upper Brushy Basin Member apparently has been bleached to a pale green below the unconformity.

We were tempted to retain the "Yellow Cat facies" in the Brushy Basin Member for the following reasons:

1. The "Yellow Cat facies" was included by Gregory (1938) as part of the type section of the Brushy Basin Member (figures 19E and 19F).

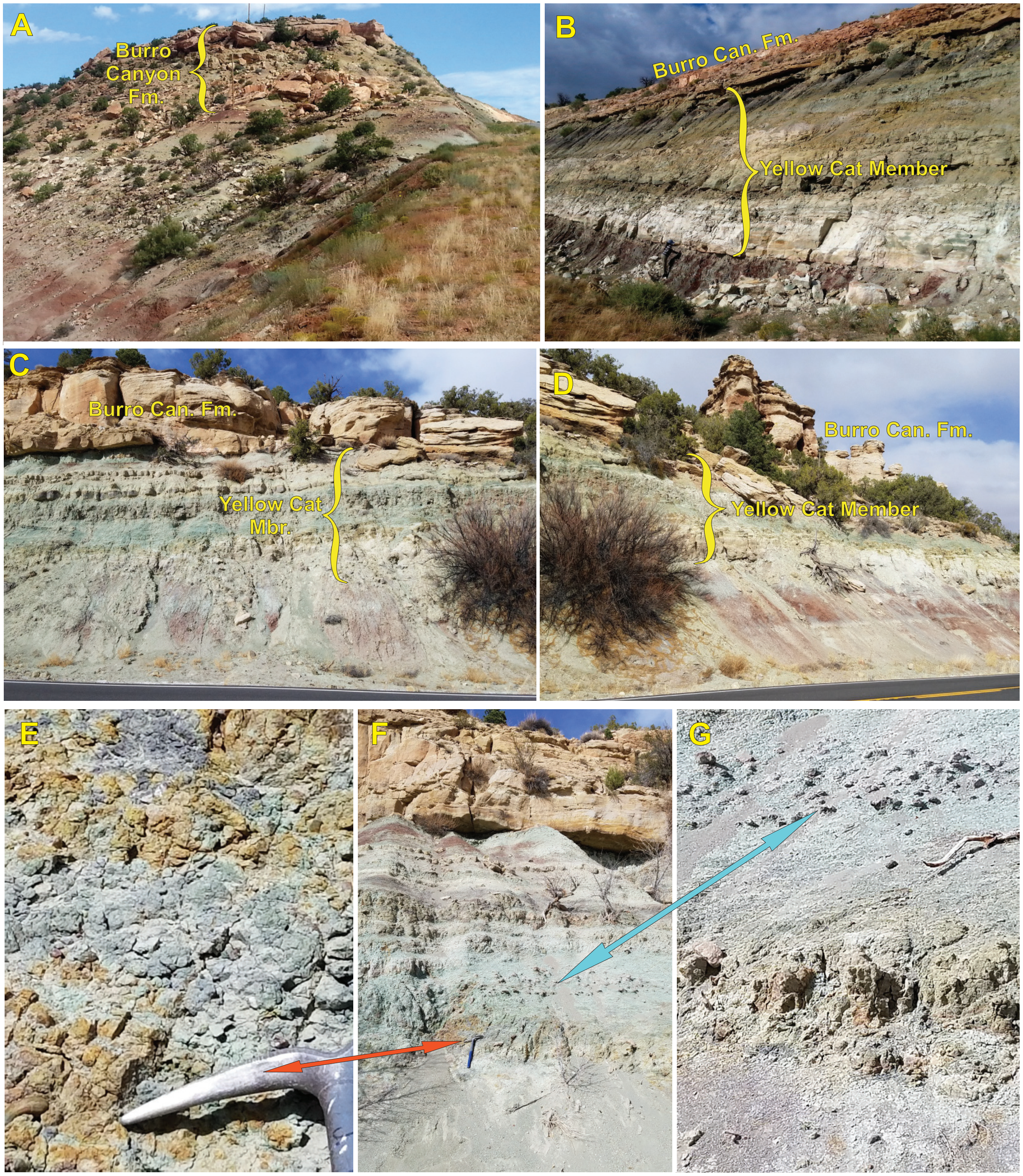

Figure 27. Yellow Cat Member of Burro Canyon Formation along paved roads in the western Blanding basin. (A and B) Upper Brushy Basin, Yellow Cat Member and main body of Burro Canyon Formation at the 'jump off' on west side of U.S. Highway 191 at mile marker 37, between Bluff and Blanding, Utah (12S, 635214.22 m E, 4160060.00 m N). (A) Exposure from the south, and (B) exposure at north end of cut from the northeast. (C to G) Top of the Brushy Basin Member of Morrison Formation and lower Burro Canyon Formation on north side of SR 95 at mile marker 120 (12 S, 631151.75 m E, 4160060.65 m N). (C and D) Exposure from the south of eastern part of roadcut. (E to G) Exposure toward west end of outcrop. (E) Detail of basal conglomerate at base of Yellow Cat Member. (F) Overview of Yellow Cat Member. Double-headed red arrow indicates position of conglomerate in E. Double-headed blue arrow indicates position of ferruginous nodules in G. (G) Ferruginous nodules above conglomeratic sandstone at base of Yellow Cat Member of the Burro Canyon Formation.

2. Doing so would preserve the long-established break between the mudstone-dominated Brushy Basin Member and the overlying sandstone-dominated Burro Canyon Formation that is clearly recognized throughout the Burro Canyon outcrop belt. In contrast, to the north, the Cedar Mountain Formation contains a large percentage of mudstone. Even the overlying Poison Strip Member (initially the Poison Strip Sandstone) may not include any sandstone units locally (Kirkland and others, 1997, 2016).
3. In places, the resistant sandstone ledge at the base of the main body of the Burro Canyon Formation completely overhangs the "Yellow Cat facies," such that the Yellow Cat is not visible in map view.
4. The "Yellow Cat facies" and the unconformity are commonly obscured by sandstone rubble armoring the upper slopes, which masks the difficult-to-map contact.

In the end, a consensus developed to recognize these strata as part of the overlying Burro Canyon Formation for the following reasons:

1. It is preferable to restrict the Morrison to Upper Jurassic strata below the K-1 unconformity.
2. The same criteria used to define the K-1 unconformity in the northern Paradox Basin in the type area of the Yellow Cat Member of the Cedar Mountain Formation can be used here (Kirkland and others, 2016).
3. It is preferable for future geological mapping in the region to maintain the use of the map symbol Jm for the Morrison Formation and Jmb for the Brushy Basin Member of the Morrison Formation, instead of JKm and JKmb, respectively.
4. Coarse fluvial sandstones at the base of the main body of the Burro Canyon Formation apparently cut out the Yellow Cat Member in some areas of the Blanding basin, such that the main basal ledge of the Burro Canyon Formation immediately overlies the Brushy Basin Member.
5. The ferruginous paleosols in the lower Yellow Cat Member indicate that wetter climatic conditions (Demko and others, 2004) appear to be characteristic of the transition between the underlying Morrison Formation and basal conglomeratic sandstone beds at the base of the cliff-forming Burro Canyon Formation in this area (figures 13A to 13D). Similar beds in this position to the north in the basal Cedar Mountain Formation were found to be Cretaceous based on dinosaur remains (Kirkland and others, 2016).

Paleontology

Sandstone unit 105 near the top of the Yellow Cat Member at the Brushy Basin reference section is notable in preserving distinctive traces attributed to insects (figure 26H), as does the basal sandstone of the Burro Canyon Formation (figure 26J). Abundant invertebrate traces are characteristic in the overlying fluvial facies within the Poison Strip Member of the Cedar Mountain Formation in the northern Paradox Basin (Kirkland and others, 2016; Kirkland, 2017).

Main Body of the Burro Canyon Formation

History and Lithology

The Burro Canyon Formation was not a major focus of this study because it is not known to contain many vertebrate fossils, but this was also true of the correlative (and highly fossiliferous) Cedar Mountain Formation until the last 25 years (e.g., Kirkland and others, 2016). In 1948, Stokes and Phoenix (1948) described the Burro Canyon Formation in Burro Canyon, San Miguel County, west-central Colorado (figures 1; UTM 12S., 685639.00 m E, 4213275.00 m N) as a mappable relatively thin (45 to 80 m [148–262 ft]) Lower Cretaceous unit of:

> "alternating conglomerate, sandstone, shale, limestone and chert ranging from 150-260 feet in thickness. The sandstone and conglomerates are gray, yellow, and brown, and the shales are faintly varicolored mainly purple and green. …The lower contact

is at the base of the lowest resistant, light-colored, conglomeratic sandstone above the varicolored Brushy Basin shale member of the Morrison; the upper boundary is placed above the highest varicolored beds so as to exclude any carbonaceous shales or sandstones in which plant materials are abundant. This contact has no topographic expression but is remarkably persistent and useable over a wide area in and adjoining Gypsum Valley. The Burro Canyon shows a slight thinning in passing over the crests of the Dolores anticline and the Gypsum Valley anticline; this may indicate a slight upgrowth of these structures during the early Cretaceous."

The sandstone making up the bulk of the main body of the Burro Canyon Formation is distinguished based on thickness, pebble size, and paleocurrent directions (Craig, 1981). According to Stokes (1952), the Burro Canyon Formation accumulated atop the Upper Jurassic Morrison Formation and formed a broad alluvial plain deposited by rivers flowing from highlands to the south. Young's (1960) proposal that the correlative Burro Canyon Formation be considered as simply a southern and eastern extension of the Cedar Mountain Formation has not been adopted. The Colorado River has been used as the defining line in Lower Cretaceous rocks between the Burro Canyon Formation and the Cedar Mountain Formation to the northwest.

Paleontology

No vertebrate body fossil sites are known or were found in the Burro Canyon Formation in Utah during this study, although two of us (JRF, RKH-F) have noted a large sauropod dinosaur humerus fragment in these beds on Recapture Creek. Recently, a diverse dinosaur tracksite (Milán and others, 2015) was revealed by road construction in these beds east of the study area (figure 2). The tracks were salvaged and are now housed at the Natural History Museum of Los Angeles County. These natural track molds document a minimum of six to seven dinosaur taxa divided among three theropods, one to two sauropods, one to two ornithopods, and one thyreophoran that is possibly a stegosaur (first Cretaceous example in North America). A sample of the track-bearing sandstone was collected to extract detrital zircons to provide an estimate of the site's maximum age (Dickinson and Gehrels, 2008, 2010). The sample was processed by Apatite to Zircon, Inc. in Viola, Idaho. The two youngest zircon U-Pb dates were 130.17 Ma and 131.03 Ma; five additional young zircons, ranging in age from 139.57 to 137.68 Ma, suggest a maximum age of 131 Ma (Milán and others, 2015). Within the study area a low hill on the northern end of Black Mesa overlying the Morrison reference section exposes very well-indurated quartzite preserving the terrestrial *Scoyenia* ichnofacies (Sa1124t) enhanced by desert varnish (figure 28).

CONCLUSIONS

Exposures of the Morrison Formation and its bounding strata on the southwest side of the Blanding basin south of Black Mesa and along Comb Ridge are significant in understanding Upper Jurassic stratigraphic relationships across the Colorado Plateau. Gregory's (1938) Bluff Sandstone, Recapture, Westwater Canyon, and Brushy Basin Members were defined in this region and have been applied across the southernmost outcrops of the Morrison Formation in Arizona and New Mexico. The outcrops extending north along Comb Ridge from the town of Bluff to the west side of the Abajo Mountains expose the transition from the stratigraphic nomenclature of Gregory (1938) to the Tidwell, Salt Wash, and Brushy Basin Member terminology applied to these strata on the central and northern Colorado Plateau (figure 8). The J-5 unconformity at the base of the Bluff Sandstone Member and the interfingering relationship of the Bluff Sandstone into the Tidwell Member at its northern terminus, supports retaining the Bluff as the basal member of the Morrison Formation in its type area. Coarse conglomeratic fluvial beds within the basal bench of the Recapture Member of the Morrison Formation on the west and south sides of Black Mesa are not representative of the Salt Wash Member. This surface may represent a J-6 unconformity at the base of the Salt Wash Member to the west of the study area at Capitol Reef and the Blue Hills area. It is possible that these near basal Recapture conglomerates are a result of local uplift along Comb Ridge. Given either interpretation, the reports of interfingering between the Bluff Sandstone and Recapture Members are incorrect, and that

Figure 28. Burro Canyon trace fossils. (A) Overview of low hill armored by desert varnished quartzite preserving *Scoyenia* ichnofacies at top of the Burro Canyon Formation on northwest side of Black Mesa (Sa1124t). (B to F) Examples of *Scoyenia* ichnofacies preserved in hard quartzite at Sa1124t.

sediment derived from the Bluff Sandstone has been reworked across this surface into the basal Recapture. We note that the Recapture preserves potentially significant vertebrate paleontological sites. We follow O'Sullivan (1999, 2000) in recognizing that the Recapture interfingers into both the upper Tidwell and lower Salt Wash Members as it thins to the north. Likewise, the "main body" of the Westwater Canyon Member grades into the upper Salt Wash Member as it thins to the north. The presence of a smectitic mudstone sequence below the resistant bench-forming No-Mans Island beds complicates the current use of the Salt Wash Member for these uppermost Westwater Canyon beds on the west side of the Abajo Mountains. Whereas a single Salt Wash distributary megafan expanding across the region has been widely accepted (e.g., Owen and others, 2015, 2017), the feldspathic composition of the Recapture and Westwater Canyon Members indicate that a more northward-directed distributary megafan was progressively buried by a more lithic-dominated, northeasterly directed Salt Wash distributary megafan, prior to deposition of the Brushy Basin Member.

Gregory's (1938) type section of the Brushy Basin Member along the Elk Mountain Road clearly extends from the top of the No-Mans Island beds up section to the coarse fluvial sandstones at the base of the main body of the Burro Canyon Formation. It is yet to be determined whether the upper beds of the Westwater Canyon Member pinch-out into a temporally more expansive Brushy Basin Member to the north or are truncated by an unconformity cutting down to the nonsmectitic mudstones beneath the Brushy Basin Member proper, forming a J-7 unconformity at the "clay change". On the southwest side of the Blanding basin, including within Gregory's (1938) Brushy Basin type section, a capping ferruginous interval, herein referred to as the Yellow Cat Member of the Burro Canyon Formation, almost certainly correlates to the lower Yellow Cat Member of the Cretaceous Cedar Mountain Formation of central Utah.

A reference section of the Brushy Basin Member of the Morrison Formation established below the northwest rim of Black Mesa lends support to these stratigraphic hypotheses. Further stratigraphic research of the Morrison along Comb Ridge and farther north along the west side of the Abajo Mountains is needed to more fully substantiate the observations reported here.

We recorded a number of significant paleontological sites in these rocks along the western margin of the Blanding basin. Most of the vertebrate sites represent isolated bones in the Recapture and Brushy Basin Members, although a few sites that may represent bonebeds were also identified, which deserve to be tested for future excavation. Petrified logs and stumps were encountered at a number of sites within the Brushy Basin and Salt Wash Members, as were a few interesting plant debris sites. The overlying Burro Canyon Formation was barely examined and as such its paleontological potential in the region currently cannot be defined.

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APPENDIX A

Morrison Formation and Bounding Strata along Butler Wash up to the top of Northwest side of Black Mesa

Section measured by James I. Kirkland, Sept. 13–17, 2017. Section measured in segments along prominent unnamed drainage extending from near the north end of Black Mesa at approximately S. 30° W. to join Butler Wash (figure A1). Base of measured section (12S 0622143 E 44154963 N) on top of nearly white caprock at the top of eolian sandstone flooring the wash to the southwest that is interpreted as representing the top of the Entrada Sandstone. Measured lower part of section along wall of wash to Butler Wash Dinosaur Tracksite (unit 17), where Butler Wash Road (BLM 262) crosses Butler Wash (12 S 0622294 E 4155019 N). Dip N. 7° E., 2–3° southeast. From east side of BLM 262 section was measured up to the top of thick, largely eolian sequence nearly due east (top unit 21). This surface was followed back to the north to Butler Wash (12 S 0622790 E 4155201 N), where the transition between the San Rafael Group and the overlying Morrison Formation was described from observations on both the north and south sides of Butler Wash. It is noteworthy that the Bluff Sandstone is well-expressed on the north side of the wash, but not on the south side. Lower 33 m (108 ft) of the Recapture Member measured on south side of Butler Wash up through ridge (12 S 0622711 E 4154456 N) capped by laterally extensive channel complex (Salt Wash facies?) that was traced back to Butler Wash to the north (12 S 623180 E 4155315 N), from which the section continued to be measured from bluff to bluff along the north side of Butler Wash up to the top the lower of the two sandstones forming the No-Mans Island beds (12 S 0623807 E 4155992 N). These beds were traced north to a ridge just west of the north end of Black Mesa, where the section was described through the top of the thicker capping sandstone of the Westwater Canyon Member at 12 S 0623873 E 4156394 N. The top of this marker sandstone was traced east into gully (12 S 0624083 E 4156432 N), at base of the steep slope formed by the Brushy Basin Member on the northwest side of Black Mesa. From here the Brushy Basin Member was measured eastward up the side of Black Mesa to where it crosses BLM 233. From here (12S 0624189 E 4156563 N), the upper half of the Brushy Basin Member was measured in a series of segments linked by local marker beds traced to the south along the upslope side of Black Mesa along BLM 233 through the Burro Canyon Formation. The top of section within the Burro Canyon Formation was at east side of cattle guard (12 S 0624497 E 4155947 N), where BLM 233 crosses south onto the top of Black Mesa. Dip N. 12° E., 1–2° southeast. Color identification using the Geological Society of America Rock Color Chart.

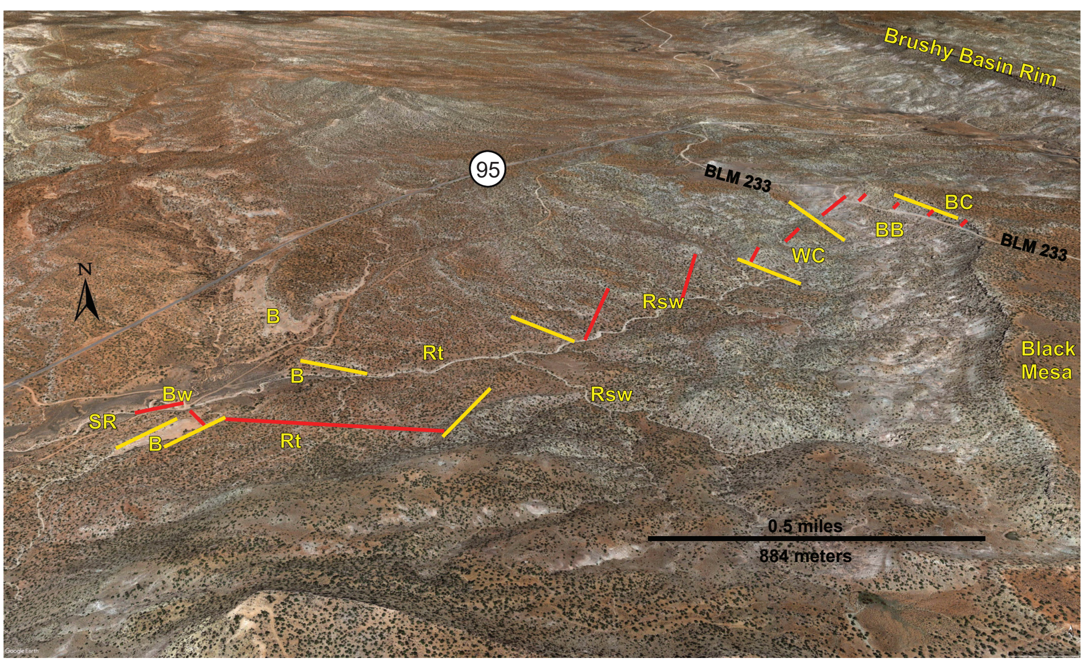

Figure A1. Northeast side of Black Mesa with approximate line of Morrison reference section indicated. Red bars = line of section. Yellow bars indicate stratigraphic divisions. Bottom to top: SR = San Rafael Group, B = Bluff Sandstone, Rt = Recapture Member, Tidwell facies, Rsw = Recapture Member, Salt Wash facies, WC = Westwater Canyon Member, BB= Brushy Basin Member, BC = Burro Canyon Formation. Bw = Butler Wash Dinosaur Tracksite.

UNIT DESCRIPTION	THICKNESS (m) Interval	Total
Burro Canyon Formation		
108. Sandstone, grayish-orange 10YR7/4, medium to very-coarse-grained with conglomeratic lenses, pebbles to 3 cm, large scale trough cross-bedded organized into beds 2 to 3 m thick, very well indurated cliff-former, overlying undescribed sandstone beds are set back from edge of cliff into a series of benches, but laterally, may in part be incorporated into this resistant cliff, defining the margins of Black Mesa, described along road to just above cattle guard (12 S 0624497 E 4155947 N), where road crosses onto top of Black Mesa	8.20	305.79
107. Sandstone, grayish-orange 10YR7/4, medium to coarse grained, divided by sandy partings into two sub-equal beds, rooted and burrowed. Sharp lower contact less than 50 cm of relief visible in roadcut.	0.87	297.59
Total incompletely measured main body of Burro Canyon Formation	**9.07**	
Unconformity sharp with less than 50 cm in relief.		
Yellow Cat Member		
106. Mudstone, grayish red-purple 5RP4/2, top 40 cm bleached light green 10G8/1, below unconformity at base of Burro Canyon Formation	1.66	296.78
105. Sandstone yellowish-gray 5Y8/1, fine grained, poorly bedded, divided into two beds with wavy parting at about 30 cm, rooted with insect burrows	0.72	295.12
104. Mudstone, grayish red-purple 5RP4/2	0.96	294.40
103. Mudstone, moderate green 5G5/6, some ferruginous patches	2.45	293.44
102. Mottled sandy mudstone and muddy very fine to fine-grained sandstone, complexly inter-mottled gray yellow-green 5GY7/2, moderate yellow-brown 10YR5/4, and grayish-red 10R4/2, sideritic nodules, ferruginous paleosol	1.11	291.99
101. Interbedded fine- to medium-grained sandstone in beds about 15 cm thick, grayish yellow-green 5GY7/2, some mottling, rooted with ferruginous nodules	1.01	289.87
100. Mottled sandy mudstone and muddy sandstone, mottled olive gray 5Y4/2 and yellow green 5GY7/2 ferruginous nodules, rooted	0.83	288.86
99. Mudstone, light blue 10B8/1, cherty	0.09	287.97
98. Conglomeratic sandstone, yellow gray 5Y8/1 to nearly white 5Y8.5/1, fine-grained sandstone matrix, light-colored chert pebbles 0.5 to 1.0 cm, trough cross-bedded, marker bed at base of possible "Yellow Cat facies" (Kirkland and others, 2016)" at top of Morrison Formation on western side of Blanding basin. Marker horizon along road cut. Basal unconformable contact sharp and irregular with less than 50 cm of relief along outcrop.	1.64	287.88
Total Yellow Cat Member	**14.14**	
Total incompletely measured Burro Canyon Formation	**23.21**	

Unconformity sharp and irregular between underlying mudstone and overlying conglomerate.

Brushy Basin Member, Morrison Formation

97. Mudstone, dark reddish-brown 10R3/4, upper 5 cm bleached light green 10G8/1 .... 1.14 286.24

96. Interbedded sandy mudstone, moderate reddish-brown 10R6/4, and patchy sandstone, yellowish-gray 5Y7/1 and medium red-orange 10YR5/6, rounded sandstone sets about 20 to 30 cm, mudstone and thinner ~5 cm sandstone sets form medial about 50 cm 1.24 285.08

95. Mudstone, dark reddish-brown 10R3/4, moderately smectitic 4.76 283.84

94. Mudstone, pale green 5G7/1, platy, moderately indurated with well indurated 10 cm caprock 1.41 279.08

93. Mudstone, pale olive 10Y6/2, moderately smectitic 0.75 278.33

92. Mudstone, dark dusky-red 5R3/2, marker bed locally, feathering out vanishing into base of unit 93 to south along road 0.72 276.92

91. Mudstone, light greenish-gray 5G8/1, moderately smectitic 1.56 276.20

90. Nodular, sandy mudstone, dark dusky-red 5R3/2, calcareous, well indurated 0.18 274.64

89. Smectitic mudstone, light greenish-gray 5G8/1, fine-grained, calcareous, olive-gray 564/2, sandstone layers about 10 cm thick at about 0.4 m and about 1.0 m above base 1.34 274.46

88. Mudstone, moderate red 5R4/6, rooted 0.30 273.12

87. Smectitic mudstone, yellowish-gray 5YR8/1, popcorn weathering on surface of convex slope 1.69 272.81

86. Sandstone, greenish-gray 5GY6/1, fine-to medium-grained sandstone, platy in set about 5 to 10 cm thick with thin, discontinuous, mudstone partings, moderately well indurated 0.32 271.12

85 Smectitic mudstone, pinkish-gray 5YR8/1, popcorn weathering on surface of convex slope 2.62 270.80

84 Sandstone, greenish-gray 5GY6/1, fine-to medium-grained sandstone, cross-bedded in set about 20 to 30 cm thick with thin, discontinuous, mudstone partings, moderately well indurated, laterally extensive ledge 1.02 268.18

83. Smectitic mudstone, light olive-gray 5Y6/1, popcorn weathering on surface continuing convex slope of unit 82 .... 1.23 267.16

82. Smectitic mudstone, pale red 10R6/2, for basal 3.5 m of unit grading to moderate orange-pink 10R6/6 for approximately next 2 m before gradationally retuning to pale red 10R6/2 at top, slightly sandy in part, popcorn weathering on surface forming convex slope, central orange-pink interval rooted, upper contact gradational over about 10 cm 7.58 265.93

81. Sandstone, light yellow-gray 5GR7/1, in sets about 50 to 70 cm banded pale red-brown 10R5/4 by 20–30 cm interbeds of sandy mudstone 2.87 258.35

80. Smectitic mudstone, moderate reddish-brown 10R4/4, popcorn weathering surface forming

darker convex slope, distinctly darker than unit 79 .... 4.44 255.48

79. Smectitic mudstone, pale reddish-brown 10R5/4, popcorn weathering surface forming darker convex slope, small bone fragments weathered down slope to toe of slope, 5 to 7 cm fine-grained, better indurated sandstone bed at 105 cm above base. 1.83 251.04

78. Muddy sandstone, blackish-red 5R2/2, fine grained, very well indurated, brittle, ferruginous-sideritic cement, rooted 0.22 249.21

77. Mudstone, grayish-yellow 5Y8/4, rooting and insect traces 0.65 248.99

76. Smectitic mudstone, central meter moderate orange-pink 10R6/6 representing a clinoptilolite zone, pale red 10R6/2 for basal and upper about 0.5 m of unit, slightly sandy in part, popcorn weathering on surface forming darker convex slope 2.04 248.34

75. Sandstone, light bluish-gray 10B7/1, very fine grained, well indurated local marker bed, crossed BLM 233 to east on this bed (12S 0624189 E 4156563 N) 0.17 246.30

74. Smectitic mudstone, grayish-red 10R4/2, very smectitic, popcorn weathering surface forming darker convex slope, some thin fine sandstone beds and small calcareous concretions in upper 1 to 2 m 5.51 246.13

73. Interbedded sandstone and slightly smectitic sandy mudstone, fine-grained sandstone, orange-pink 10R8/2, poorly indurated, mudstone pale-brown 10R6/4, forms about 30 to 60 cm bands on straight steep slope below 12 cm hard, rooted calcareous sandstone caprock. 3.33 240.62

72. Finely interbedded slightly smectitic mudstone and sandy mudstone, pale purple-pink 5RP 6/2, forms straight slope, bone fragments noted 1.24 237.29

71. Interbedded sandy mudstone and sandstone, overall pale-brown 5YR5/2, 30 to 50 cm thick mudstone intervals, moderately smectitic with numerous lenticular carbonate concretions, sandstone beds 5 to 20 cm thick, forms steep straight slope 3.60 236.05

70. Muddy sandstone, yellow-gray 5Y7/2, fine to medium grained, poorly indurated forming concave slope, armored in sandstone and concretion fragments from unit 71 .... 2.44 232.45

69. Concretionary limestone bed, medium yellowish-brown 10YR5/4, septarized 0.23 230.01

68. Smectitic claystone to mudstone, moderate orange-pink 5YR8/4, popcorn weathering forming convex slope, scattered small (2 to 3 cm) carbonate nodules........ 0.98 229.78

67. Muddy sandstone to sandstone, yellowish-gray 5Y7/2, fine grained, nearly structureless, poorly indurated, weathers into a concave slope........ 1.15 228.80

66. Claystone to mudstone, very smectitic, moderate orange-pink 5YR8/4, popcorn weathering forming convex slope, represents a clinoptilolite zone, small 3 to 5 cm, irregular carbonate nodules.... 4.24 227.65

65. Sandstone, very light-yellow 5Y8/1, fine grained, moderately indurated, divided into two sub-equal beds ... 0.36 223.41

64. Smectitic sandy mudstone, pale pink 5RP8/2, more orange in places, interbedded with very fine sandstones and muddy sandstone intervals, about 10 cm moderately indurated, calcareous, rooted muddy sandstones, pale yellow-green 10GY7/2, overlying 10 to 15 cm carbonate nodule horizons at about 1 and 3 m up, additional 10 cm carbonate nodules toward top of unit........ 3.96 223.05

63. Sandstone, pale yellow-gray 5Y7/2, poorly bedded, moderately indurated with dark greenish-gray 5G4/1 well-indurated caprock about 10 cm thick........ 1.27 219.09

62. Smectitic sandy mudstone, fresh light olive-gray 5Y6/1, weathered surface pale pinkish-purple 5RP7/2, slightly lighter at top, popcorn weathering with distinctly convex slope profile, small carbonate nodules about 2 to 7 cm across first appear at about 1 m up, larger carbonate nodules 10 to 15 cm across in horizon at about 2 m up, about 30 to 40 cm in diameter spar coated carbonate nodule horizon about 80 cm below top 4.22 217.92

61. Sandstone, dark green-gray 5G4/1, very fine grained with few coarse grains, well indurated, fine root traces, erosional base with 10 cm of relief........ 0.18 213.70

60. Smectitic sandy mudstone, fresh dusky yellow-brown 10YR2/2, weathered surface pale pinkish-purple 5RP7/2, popcorn weathering surface with distinctly convex slope profile........ 2.22 213.52

59. Sandy mudstone to muddy sandstone, pinkish-gray 5YR8/1, poorly laminated, poorly indurated, friable, concave slope........ 1.24 211.30

58. Sandstone, gray-green 10GY5/2, very coarse grained, well indurated, includes moderately to well-rounded lithic (mudstone) fragments up to 1 cm across, bed pinches out laterally over about 50 m 0.28 210.06

57. Sandy mudstone, pale yellow-brown 10YR6/2, smectitic, poorly laminated, poorly indurated, first distinct zone with surface characterized by popcorn weathering........ 0.99 209.78

56. Sandstone, very pale yellow 5Y7/2 to grayish-yellow-green 5GY7/2, fine to medium grained, poorly indurated, darker dusky yellow-green 5GY5/2 zones slightly better indurated forming rounded breaks in slope........ 2.95 208.89

Total Brushy Basin Member........775.00

Westwater Canyon Member of Morrison Formation

55. Sandstone, dark yellowish-orange 10YR6/6, medium to coarse grained, planar and trough cross-bedded in sets about 40 cm thick, moderately well indurated at base becoming increasingly well indurated up section to very resistant caprock (12 S 0623873 E 4156394 N), forms top of No-Mans Island beds set back from bench formed by unit 53, traced this surface down slope to east to gully at base of Black Mesa, 12 S 0624083 E 4156432 N........ 3.10 205.14

54. Claystone to mudstone, grayish yellow-green 5GY 7/2, slightly smectitic 1.48 202.84

53. Sandstone, moderate yellow-brown 10YR5/4, fine to coarse grained with conglomeratic lenses, trough cross-bedded, in thick 1.5 to 2 m sets, well indurated caps bench (12 S 0623807 E 4155992 N), traced north to point nearly due west of north end of Black Mesa, lower of two prominent sandstones referred to as No-Mans Island beds........ 4.49 201.36

52. Sandy mudstone, somewhat smectitic, more so toward top, medium olive-gray 10Y6/2 grading upward to greenish-gray 5G6/1, a few sandstone layers in lower half, few scattered dark orange concretions in upper few meters........ 9.56 195.89

51. Sandstone, light-brown 5YR6/4, medium to coarse grained, trough cross-bedded in tabular

sets about 40 cm thick, very well indurated forms laterally extensive marker bed, top of main body of Westwater Canyon Member (12 S 0623598 E 4156052 N) trace to south east to base of slope below ridge capped by unit 53. .... 1.52 186.33

50. Muddy sandstone grading upward into sandy mudstone, drab olive gray 10Y5/2, poorly indurated slope former 4.46 184.71

49. Sandstone, light yellow-gray 5GR7/1, trough cross-bedded in sets of about 50 to 150 cm thick, some pale reddish-brown 10R6/4 mudstone interbeds, but overall nearly pure fine sandstone, mostly only moderately indurated forming slope with harder ledges, some conglomeratic lenses with chert pebbles about 0.5 to 2 cm, basal unit of the main body of the Westwater Canyon Member 24.07 180.25

48. Mudstone, moderate 10R6/6, with scattered thin sandstone beds 5 to 20 cm thick, comparable to typical Recapture floodplain facies, some lenticular sandstone beds up to 50 cm thick, much higher proportion of sand to the north 4.33 156.18

47. Sandstone, light yellow-gray 5GR7/1, medium grained, highly convoluted bedding 0.38 151.85

46. Sandstone, light yellow-gray 5GR7/1, trough cross-bedded in sets of about 40 cm thick, in places moderately well indurated, in places a slope former 2.95 151.47

45. Sandstone, orange-gray 10YR7/4, medium to course grained, cross-bedded in sets 30 to 60 cm thick capped with 25 cm of hard slabby sandstone, well indurated marker bed 2.14 148.52

44. Mudstone, moderate reddish-brown 10R6/4, with scattered thin sandstone beds 5 to 20 cm thick, comparable to typical Recapture floodplain facies 5.09 146.38

43. Sandstone, light yellow-gray 5Y8/1, fine-grained, cross-bedded, in sets 30 to 50 cm thick, separated by medium olive-gray 10Y4/2 mudstone beds 10 to 30 cm thick, thin “chips” of sandstone cover slope 2.88 141.39

42. Hard calcareous sandstones, light yellow-gray 5Y8/1, fine grained, root traces and abundant vertical burrows, 18-cm-thick bed that caps unit 41, and a nearly identical bed 12 cm thick is separated from it by an intervening 33-cm-thick medium olive-gray 10 YR5/1, mudstone 0.63 138.44

41. Sandstone, light yellow-gray 5Y8/1, lower 2 m more gray-orange 10YR7/4, fine grained, trough cross-bedded, sets 40 to 80 cm thick with some mudstone interbeds, moderately to poorly indurated, overall slope former, sandstones feather out to southwest over 100s of meters 5.82 137.81

Total Westwater Canyon Member 74.15

Recapture Member of Morrison Formation

40. Mudstone, interbedded with platy, flat-bedded, fine-grained sandstone beds, 2 to 3 cm thick overall, pale-red 10R6/6 on surface with fresh rock dusky-red 5R3/4, units 40 and 38 merge together to south with pinching out of unit 39 .... 4.01 130.99

39. Sandstone, light yellow-gray 5Y8/1, fine to medium grained, trough cross-bedded in sets of

30 to 50 cm thickening to about 1 m to north, unit interfingers with mudstone on unit 38 to south and pinches out over 100s of meters, upper meter ripple cross-bedded with burrows and shaly interbeds in 20-cm-thick sets 2.22 126.98

38. Mudstone, interbedded with platy, flat-bedded, fine-grained sandstone beds, 2 to 3 cm thick overall pale-red 10R6/6 on surface with fresh rock dusky-red 5R3/4 .... 2.93 124.76

37. Interbedded sandstone, light yellow-gray 5Y8/1, planar cross-bedded, with about 50% mudstone, moderate red-brown 10R4/6, in sets about 50 cm thick, increasing thickness of sandstone such that about 2 m up sandstone dominates with lenses of mudstone every 50 cm, induration increases up section as well, capped by 10 cm of softer structureless sandstone 5.48 121.83

36. Sandstone, light yellow-gray 5Y8/1, fine to medium grained, planar cross-bedded in sets of about 30 cm.......... 0.99 116.35

35. Mudstone, interbedded with platy, flat-bedded, fine-grained sandstone beds, 2 to 3 cm thick overall pale-red 10R6/6 on surface with fresh rock dusky-red 5R3/4, at about 1.5 m up is sandstone lens (channel) 50 cm thick by 50 m across, light yellow-gray 5Y8/1, fine to medium grained, flat bedded.......... 3.23 115.36

34. Sandstone, light yellow-gray 5Y8/1, fine to medium grained, trough cross-bedded in sets of 30 to 50 cm 1.23 112.13

33. Mudstone, interbedded with platy, flat to ripple cross-bedded, fine-grained sandstone beds, 2 to 5 cm thick overall pale-red 10R6/6 on surface with fresh rock dusky red 5R3/4, a higher proportion of mudstone to sandstone than in unit 31.......... 3.60 110.90

32. Sandstone, light yellow-gray 5Y8/1, fine to medium grained, flat bedded, thickens to 3.5 m and becomes trough cross-bedded to south in Butler Wash 0.40 107.30

31. Mudstone, interbedded with platy, flat to ripple cross-bedded, fine-grained sandstone beds, 2 to 5 cm thick overall, pale-red 10R6/6 on surface with fresh rock dusky-red 5R3/4, at about 2.0 and 2.5 cm, 30-cm-thick sandstone beds, light yellow-gray 5Y 8/1, cross-bedded splays laterally extended in to channel sandstone lenses.......... 4.40 106.90

30. Sandstones, pale-red 10R 6/6 in beds about 50 cm thick separated by darker red 10R4/6 mudstones beds 5 to 15 cm thick that completely amalgamate into unit 29 to south.......... 3.10 102.50

29. Sandstone, yellowish-gray 58/1, fine to medium grained, wavy and trough cross-bedded in set 30 to 50 cm thick at ridge (12 S 0622711 E 4154456 N) the top of this sand traced northeast to Butler Wash (12 S 623180 E 4155315 N), where the unit is completely trough cross-bedded in sets averaging about 50 cm thick.......... 1.57 99.40

Total Recapture Salt Wash facies..........33.16

Recapture Tidwell facies

28. Mudstone, overall moderate red-orange 10R6/6 on surface with fresh rock dusky-red 5R3/4, with thin friable muddy sandstone layers, thin fine-medium-grained sandstone layers 5 to 10 cm thick, light green-gray 5GY8/1 every 1.0 to 1.5 m forming breaks in slope, much like unit 24, burrows present in sandstones, 50 cm thick sandstone splay 90 cm below top of unit

appears to correlate to multimeter trough cross-bedded sandstone lens to north at Butler Wash 8.62 97.83

27. Sandstone, yellowish-gray 5Y8/1, fine to medium grained, trough cross-bedded, well indurated, upper about 30 cm, reddish, flat to ripple cross-bedded in sets 10 cm thick, pinches out over 200 m laterally 1.24 89.21

26. Mudstone interbedded with platy, flat to ripple cross-bedded, fine-grained sandstones, overall moderate red-orange 10R6/6, light-green to yellow-gray 5GY8/2, fine- to medium-grained sandstone lenses about 50 cm thick and 50 to 100 m across every 1 to 2 m, much like unit 24 but with much more sandstone (50%) 11.13 87.97

25. Sandstone, yellow-gray 5Y8/1, medium grained, lower two-thirds trough cross-bedded in sets 30 to 40 cm thick, upper third with shaly interbeds of set 10 to 20 cm thick, pinches out over 100 m laterally 1.54 76.84

24. Mudstone, overall moderate red-orange 10R6/6 on surface with fresh rock dusky-red 5R3/44, with thin friable muddy sandstone layers, thin, fine- to medium-grained sandstone layers 5 to 10 cm thick, light green-gray 5GY8/1 every 1.0 to 1.5 m forming breaks in slope, thicker about 50 cm thick sandstone lens at about 8.5 m above base 9.04 75.30

23b. Sandstone, yellow-gray 5Y8/1, fine grained although scattered very coarse grains at base, large scale trough cross-beds sets 1 to 2 m thick, to south along outcrop this unit pinches out at 12S 0622624 E 4155098 N and continues to thicken to north, toward south capped by coarser sandstone as in unit 23a. This unit is interpreted to represent reworked sandstone from the underlying Bluff Sandstone 4.27 66.26

23a. Sandstone, pale red-brown 10R5/4 to yellow-gray 5Y8/1, medium to course grained, trough cross-bedded, sets 30 to 40 cm thick, well indurated, burrowed in places. This unit thickens to about 4 m thick south of Butler Wash and appears to directly underlie reddish mudstones typical of the Recapture Member, south of Butler Wash this unit underlies eolian sandstone of the Bluff Sandstone facies (unit 23b), the north-south transition across Butler Wash is complex. South of the wash the lowest set is softer and recessed, preserving intraformational clasts up to 50+ cm in diameter within a finer grained matrix, suggesting that this interval records the J-5 unconformity and that there may have been uplift along Comb Ridge at the end of San Rafael Group deposition. A discontinuous interval of moderate red-brown 10R6/4 mudstone up to a meter thick may separate units 23a and 23b locally 1.39 61.99

T**otal Recapture Tidwell Facies 37.23**

Total Recapture Member..........70.39

Unconformity broadly undulatory over many meters, recognized by large rip-up clasts deposited on the surface.

Bluff Sandstone

22. Sandstone, moderate red-brown 10R4/6, faintly, medium scale cross-bedded, nearly structureless, forming more vertical cliff than unit 21, includes mudstone lenses, red-brown 10 R6/6, 0.4 to 1.0 m thick by 10s of m wide, scoured surface representing the J-5 unconformity locally, this surface with overlying unit 23 was traced north to where bed crossed Butler Wash 4.33 60.60

21. Sandstone, moderate pink 5R7/4 grading upward to moderate orange-pink 10R 7/4, fine

grained, well indurated, large scale trough cross-bedded with sets about 1.5 to 4.0 m thick, sets broadly rounded in surface expression, at 4.4 m shaly parting seeping water, at 5.8 m above base hard silica cemented wavy layer, 1 cm thick, forms local marker bed. Main body of the beds of Bluff Sandstone (O'Sullivan, 1980)........ 22.50 56.27

Total Bluff Sandstone 32.49

TOTAL MORRISON FORMATION........254.53

Unconformity present not recognizable beyond sharp basal contact.

SAN RAFAEL GROUP

SUMMERVILLE -WANAKAH FORMATION

20. Interbedded fine-grained sandstone and sandy mudstone, grading from moderate red-brown 10R5/6 to pale red-brown 10YR4/4 up section, laterally variable, overall interbedded at 20 to 30 cm in lower 1 to 1.5 m, sandstone beds thicken to 0.8 to 1.5 m up section with about 40 cm sandy mudstone lenses 10s of m across separating sandstone sets with no internal bedding observed, but many burrows and root traces, disconformity at top of San Rafael Group? 4.34 33.77

19. Sandstone, light brown 5YR5/6, fine grained, sweeping trough cross-beds in sets 20 to 50 cm thick in lower and upper meter, medial sets 1 to 1.5 m........ 8.39 29.43

18. Mudstone, moderate red-brown 10YR6/6, includes a few fine- to medium-grained sandstone layers less than 0.5 cm thick. 0.38 20.94

17. Sandstone, light-brown 5YR5/6, fine grained, bedded in sets of 5 to 10 cm thick, internal bedding obscure weakly ripple bedded in part, dinosaur tracks at top of basal set about 10 cm above base, about 140 cm above base, and at top of well indurated 11-cm-thick caprock, main Butler Wash Dinosaur Tracksite level, cross BLM 262 to east on this surface; units 17 to 19 interpreted as representing the Black Steer Knoll beds as used by O'Sullivan (1980) and Lucas (2014)... 2.85 20.56

16. Sandstone, light-brown 5YR5/6, fine grained, bedding obscure in sets 20 to 40 cm thick, weakly expressed cross-bedding and some ripple bedding, some dinosaur tracks at top 2.38 17.71

15. Sandstone, moderate red-brown 10R6/6, fine grained, massive, cross-bedded, weakly expressed convolute bedding toward top 2.24 15.33

14. Sandstone, moderate light-brown to salmon 5YR5/6, fine to medium grained, coarsening upward with increasing induration, wavy bedded, sets in lower 22 cm about 1 to 3 cm, overlying beds thicken to 20 to 30 cm 0.88 13.09

13. Mudstone, moderate red-brown 10R3/6 .... 0.57 12.21

12. Sandstone light-brown to salmon 5YR5/6, fine to medium grained, flat bedded in sets 25 to 40 cm thick, with unit 11 forms straight cliff in sides of wash, top 10 cm thick set forms more resistant caprock. 0.95 11.64

11.	Sandstone light-brown with salmon streaks along bedding 5YR5/6, medium-grained, large scale tough cross-bedding, more indurate sandstone columnar structures in lower 30 cm, small sandstone nodules 0.2 to 30 cm in upper 20 cm, units 12 to 11 interpreted as representing the Butler Wash beds as used by O'Sullivan (1980, 2010a) and Lucas (2014)	0.89	10.69
10.	Sandstone, yellow-gray 5Y8/1 at base darkening to light-brown 10R6/6, very fine grained, flat bedded, like unit 9 except better indurated and for yellow-gray clay parting in lower portion	0.25	9.40
9.	Sandstone, red-brown 10R6/6, very fine grained, flat bedded to low angle cross-bedded, vague ripple cross-bedded	0.45	9.15
8.	Mudstone, moderate red-brown 10R6/6, about 10-cm-thick sandy mudstone marker bed with light yellow-gray 10 YR 8/2 sandstone nodules 3 to 5 cm thick by 10 cm wide at 8.4 m	0.68	8.70
7.	Interbedded muddy sandstone and mudstone, pale red-brown 10R4/4, coarsening upward in 10 to 20 cm sets, moderately indurated, poorly bedded, light yellow-gray sandstone nodules toward top 5 cm thick by 10 to 20 cm wide, in about upper 15 cm	0.86	8.02
6.	Sandstone, medium red-orange 10R6/6, lighter mottles, fine grained, in two sets about 10 cm thick, separated by sandy mudstone with sandstone lenses	0.32	7.16
5.	Mudstone, red-brown 10R4/6	0.16	6.84
4.	Sandstone, yellow gray 5Y8/1, fine to medium grained, slabby, little clear bedding, sets 5 to 10 cm	0.42	6.68
3.	Shaly mudstone, partially covered, pale red-brown, 10R4/4, with scattered mm thick sand layers, like unit 1	3.87	6.26
2.	Sandstone, moderate pink 5R7/4, fine-medium grained, platy, planar cross-bedded grading upward into ripple cross-bedded, in set 3 to 10 cm thick with shaly partings, ripple crests N. 70° W. to N. 30° W.	0.60	2.39
1.	Shaly mudstone, pale red-brown, 10R4/4, with scattered mm thick sand layers, one about 10 cm fine, slabby, sandstone starting at about 1.2 m	1.79	1.79

Total Summerville-Wanakah Formation 33.77

Entrada Sandstone(?)

Sandstone, light gray N2, fine to medium grained, only upper surface exposed and examined, appears to have been heavily tracked by dinosaurs to the point of obscuring individual tracks (dinoturbated), may represent the top of the Entrada Sandstone .... not measured

TOTAL SAN RAFAEL GROUP .... not measured

APPENDIX B

Processing, Analysis, and Maximum Depositional age for Sa1115v

by

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While examining a vertebrate locality Sa1115v in the lower Recapture Member above the lower Recapture bench south of Black Mesa, thin smectitic clay layers a few mm thick were identified interspersed with thin layers of mudstone and sandy shale. This interval was sampled for detrital zircons resulting in a mixing of these thin clastic layers.

Detrital zircons were separated from the Sa1115v sample at the University of Iowa (figure B1). Samples were crushed using a jaw crusher and disc mill, followed by processing through an ultrasonic clay separator (e.g., Hoke and others, 2014), sieving to <350 µm, and cycling through free fall and barrier Frantz magnetic separators to eliminate grains with high magnetic susceptibilities. The final nonmagnetic fraction was separated

Figure B1. Representative transmitted light microscope image of zircon crystals from sample Sa1115v.

using methylene iodide (ρ = 3.32 g/cm^3) where lighter minerals float and heavier minerals (including zircon) sink. All zircon grains were hand picked from the heavy liquid sinks, mounted with standards in a 1-in puck with epoxy, and polished down to a depth of about 20 µm to expose grain interiors prior to analysis.

Detrital zircons were analyzed by laser ablation inductively coupled plasma mass spectrometry (LA-ICPMS) at the University of Arizona's LaserChron Center using a Thermo Element2 single-collector ICPMS (Gehrels and others, 2008). Standards used include Duluth Gabbro (FC) zircon (~1099 Ma), Sri Lanka (SL) zircon (~563.5 Ma), and R33 (~420 Ma). Fractionation corrections were made using ^{207}Pb/^{206}Pb and ^{206}Pb/^{238}U ratios as well as a correction for ^{204}Pb (Stacey and Kramers, 1975) using the E2AgeCalc Excel spreadsheet at the Arizona LaserChron Center. Best ages were determined using the filter of ^{206}Pb/^{238}U ages for grains younger than 900 Ma and ^{206}Pb/^{207}Pb ages for grains older than 900 Ma. Analyses with discordance greater than 20% for ages >700 Ma or uncertainty greater than 10% for all ages are not reported. Calculating discordance using the difference between the ^{206}Pb/^{238}U and ^{206}Pb/^{207}Pb ages for young grains is difficult using a LA-ICPMS approach because the ^{206}Pb/^{207}Pb system relatively insensitive for young systems and measuring small ^{207}Pb signals in young zircon grains is challenging.

In order to interpret the maximum depositional age (MDA) of this sample, and for the type of dataset presented here (n = about 100 with a small-moderate number of near-depositional age grains), using the youngest single grain (YSG) to approximate the true depositional age of the sample has been shown to be the most successful method in most cases, although Pb-loss and reproducibility are potential issues (Coutts and others, 2019; Dickinson & Gehrels, 2009). The youngest single grain in the dataset is 145.9 ± 1.6 Ma, but the youngest single grain for which discordance is <20% is 150.2 ± 2.1 Ma. The next two youngest grains that pass the discordance filter are 153.7 ± 2.1 Ma and 153.8 ± 2.2 Ma (see attached table B1).

Another technique that has been demonstrated to approximate the true depositional age in this type of dataset is the youngest detrital zircon (YDZ) method (Dickinson and Gehrels, 2009; Coutts and others, 2019).

This method applies an algorithm in Isoplot (Ludwig, 2012) that uses ~10,000 iterations in a Monte Carlo approach to perturb each date randomly by its assigned error, selects the youngest ages from each iteration, and then calculates the mode using all the youngest dates as the best estimate of the youngest age, with the upper and lower limits defining the uncertainties at 95% confidence. The MDA based on this technique is 144.38 +2.7 -4.7 Ma. A third technique that has been used to assess MDA is the weighted average of the group of youngest grains whose ages overlap within their 1σ error. The MDA calculated from this approach is 151.4 ± 1.8 Ma with n = 18 and an MSWD of 2.9. Both of these techniques use all of the young grains in the dataset, even those who do not pass the discordance filter.

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APPENDIX C

Final Report on U-Pb Dating of Morrison Ash Sample Sa1114vp, Southern Black Mesa, Utah

by

Kevin Chamberlain, Research Professor, University of Wyoming, April 24, 2017

INTRODUCTION

Zircons were isolated from the ash sample using a multistage ultrasonic separation technique to deflocculate clays and release all crystalline grains. Heavy liquid density and magnetic separations purified the zircons further. The sample contained abundant elongate zircons with longitudinal bubble tracks and cavities that are characteristic of ash-fall volcanic origins (figure C1). Sub-populations of these 'ash-fall' zircons along with euhedral grains were selected for single grain U-Pb dating. A minor population of rounded, detrital zircons also exists but was not dated.

Selected zircons were annealed at 850°C for 50 hours, then dissolved in two steps in a chemical abrasion, thermal ionization mass spectrometric U-Pb dating method (CATIMS) modified from Mattinson (2005). The first dissolution step was in hydrofluoric acid (HF) and nitric acid (HNO_3) at 180°C for 12 hours. This removed the most metamict zircon domains in the annealed crystals (figure C2). Individual grains were then spiked with a mixed ^{205}Pb-^{233}U-^{235}U tracer (ET535), completely dissolved in HF and HNO_3 at 240°C for 30 hours, and then converted to chlorides. The dissolutions were loaded onto rhenium filaments with phosphoric acid and silica gel without any further chemical processing. Pb and UO_2 isotopic compositions were determined in single Daly photomultiplier mode on a Micromass Sector 54 mass spectrometer. Data were reduced, and ages calculated using PbMacDat and ISOPLOT/EX after Ludwig (1988, 1991, 1998). Measured procedural blanks and total common Pb varied from 2.0 to 0.3 picograms, except for one analysis (see attached table C1). All common Pb was assigned to blank.

Figure C1. Examples of recovered elongate (left) and euhedral, short to equant (right) zircons from Morrison ash JK16-10. A minor population of rounded, detrital zircons also exists, but was not imaged. Longitudinal bubble tracks and transverse channels displayed in the elongate zircons are characteristic of ash-fall zircons. Single grains of both morphologies were dated and yielded similar results.

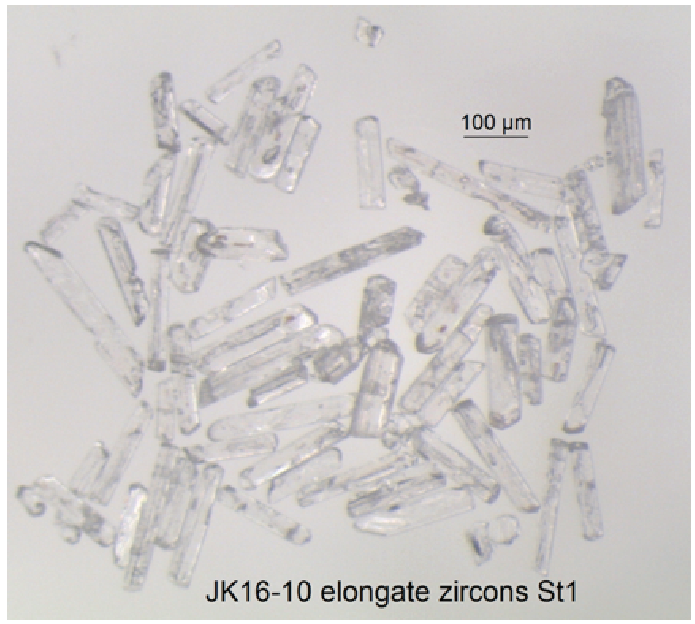

Figure C2. Close-up image of elongate, ash-type zircons from JK16-10, upper Morrison ash, after the first partial dissolution step of chemical abrasion (CA). Gray domains have been partially dissolved. Individual grains were selected for subsequent, complete dissolution and isotope dilution thermal ionization mass spectrometric dating (ID-TIMS).

RESULTS

Five single grain analyses from JK16-10 produced concordant data that overlap within error (figure C3; see attached table C1). The concordia age (Ludwig, 1998) from these data, which incorporates both the $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ data, is 150.67 ± 0.32 Ma (95% confidence

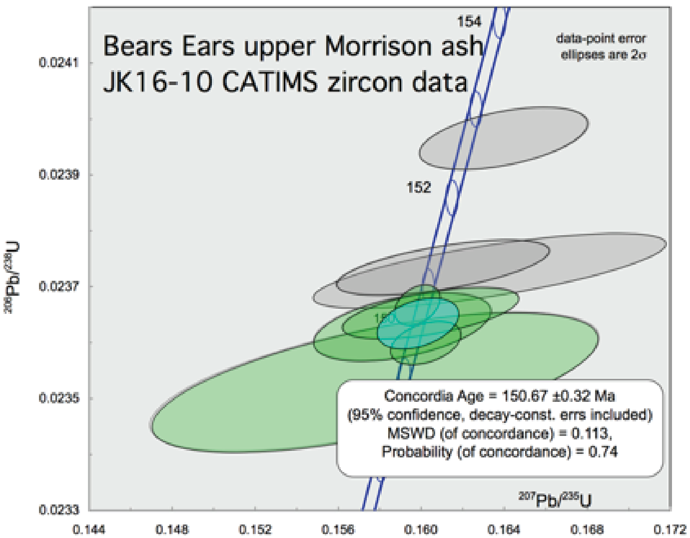

Figure C3. Concordia plot of eight single zircon CATIMS analyses from volcanic ash sample JK16-10, upper Morrison. Data from the five youngest zircons (green ellipses) overlap each other and Concordia and are interpreted to reflect the eruptive age. The Concordia Age (aqua ellipse; Ludwig, 1998) includes both $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ data and propagates the decay constant errors in this case. It can be directly compared to dates from other methods as long as those dates include all external sources of error. The older zircons (gray ellipses) are interpreted as pre-eruptive, antecrystic zircons from the magma chamber, or slightly older, volcanic zircons entrained during ash-fall deposition. Their data were excluded from the Concordia Age calculation. Concordia is plotted as a swath reflecting the errors in decay constants.

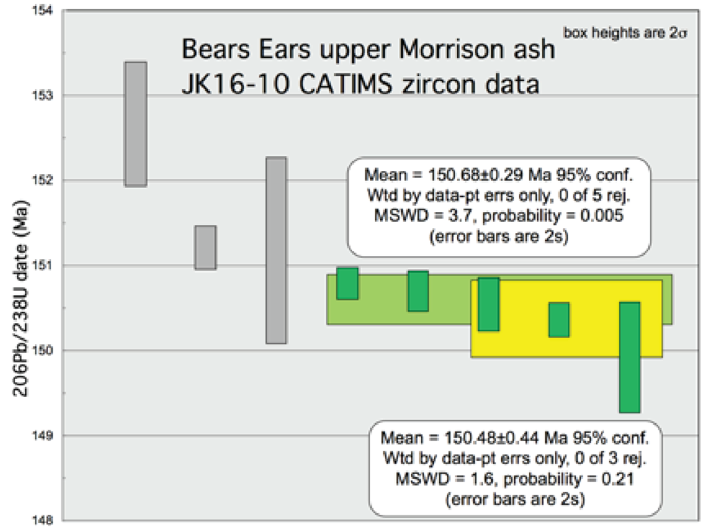

Figure C4. Plot of thorium-disequilibrium corrected $^{206}Pb/^{238}U$ dates of the eight zircon analyses from JK16-10, and weighted mean calculations of the five (green box) and three (yellow box) single grain, youngest analyses (green bars). Weighted mean dates overlap the Concordia Age calculation from these same zircons.

limits, MSWD 0.11; figure 3) including uncertainties in the two U decay constants, and with correction for ^{230}Th disequilibrium (after Schärer, 1984) assuming a magma Th/U of 2.2. The weighted mean $^{206}Pb/^{238}U$ date from these same five analyses is 150.68 ± 0.29 Ma (figure C4; 95% confidence, MSWD 3.7), Th-corrected. Weighted mean $^{206}Pb/^{238}U$ date from the youngest three analyses is 150.48 ± 0.44 Ma (figure 4; 95% confidence, MSWD 1.6). The ^{230}Th correction increased the dates by about 80 Ka. The concordia age of 150.67 ± 0.32 Ma is interpreted as the best estimate of the eruption age for this sample.

This date includes all external sources of U-Pb errors and can be directly compared to $^{40}Ar/^{39}Ar$ dates as long as the $^{40}Ar/^{39}Ar$ dates have similarly included all external errors and have been recalculated to reflect the new age for the Fish Canyon $^{40}Ar/^{39}Ar$ standard (e.g., Kuiper and others, 2008; Smith and others, 2010).

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