THE LITHOSTRATIGRAPHIC TIDWELL MEMBER OF THE MORRISON OR SUMMERVILLE FORMATIONS (UPPER JURASSIC)—WHO, WHAT, WHERE, WHEN?

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Cover

Tidwell Member of the Morrison Formation (gray bed) between the underlying Summerville Formation and sandstone beds of the Salt Wash Member of the Morrison Formation. Woodside anticline, Emery County, Utah.

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The Lithostratigraphic Tidwell Member of the Morrison or Summerville Formations (Upper Jurassic)—Who, What, Where, When?

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ABSTRACT

The Tidwell Member, a lithostratigraphic unit on the Colorado Plateau, has variously been referred to the Upper Jurassic Morrison Formation or the Upper Jurassic Summerville Formation. Its authorship has been ascribed to U.S. Geological Survey geologists Robert B. O'Sullivan or Fred Peterson. Because Peterson and O'Sullivan have different type sections, a resolution to authorship is needed. Both authors meet the minimum requirements for a new stratigraphic unit as given by the 1983 *North American Stratigraphic Code* under which Peterson and O'Sullivan operated. However, both authors also operated under the more restrictive *Stratigraphic Nomenclature in Reports of the U.S. Geological Survey*, which makes it clear that O'Sullivan used Tidwell Member informally, whereas Peterson made a formal proposal. Thus, Peterson is the rightful author and the type section is at Shadscale Mesa, Emery County, Utah.

To resolve the issue of which formation the Tidwell Member belongs, its strata were examined across the northern Colorado Plateau in context with both the underlying marine Summerville Formation and the overlying terrestrial Salt Wash Member of the Morrison Formation. Meters-thick gypsum beds, one criterion for including the Tidwell Member in the Summerville, was found to be mostly restricted to the west side of the Colorado Plateau. Numerous low-angled anticlines at the top of the Summerville Formation are truncated beneath this gypsum, thus the gypsum beds cannot be part of the Summerville Formation. The unconformity marks the J-5 unconformity. Detailed analysis of the gypsum beds shows a complex origin indicative of smaller playa lakes rather than broad coastal sabkhas. The gypsum beds show an interfingering relationship with the overlying and lateral interbedded thin sandstone-siltstone-mudstone-limestone facies assemblage of the Tidwell Member. This relationship is interpreted as localized gypsum playa lakes that formed at the terminus of prograding fluvial fans from the Elko highlands to the west, with possible lesser contribution from the growing fluvial fan exiting from the Grand Canyon bight near the present-day Arizona-Nevada border. An isopachous map of the Tidwell Member supports this interpretation, and also indicates additional, less significant source areas to the southeast and east of the northern Colorado Plateau. A widespread tabular sandstone at the base of the Tidwell Member lateral to the gypsum facies known as Bed A, is interpreted to have originated mostly as a sand sheet analogous to the Selima Sand Sheet of the eastern Sahara or the sand sheet of the Gran Dieserto in Sonora, Mexico. The source of the sand is from the fluvial fans to the west.

Similarities between the lithofacies of the contemporaneous Tidwell and Ralston Creek Members of the Morrison Formation indicates deposition under similar environmental conditions. This supports the inclusion of the Ralston Creek Member in the Morrison Formation as previously suggested, rather than as a separate formation.

INTRODUCTION

The Upper Jurassic Morrison Formation is widely distributed on the Colorado Plateau and has been divided into several members that are listed in the National Geologic Map Database (Lexicon; https://ngmdb.usgs.gov/Geolex/search; * accepted names by the U.S. Geological Survey [USGS]): *Bluff Sandstone, *Brushy Basin, Casamero, *Chavez, *Fiftymile, *Jackpile Sandstone, *Prewitt Sandstone, *Recapture, *Salt Wash, *Tidwell, and *Westwater Canyon. Off the Plateau, six other members are known: Boise, Cimarron, Kenton, Ralston Creek, *Windy Hill, and *Unkpapa Sandstone (figure 1); those in Oklahoma were recently named by Richmond and others (2020) (figure 1), and their acceptance by the geological community as required by the North American Stratigraphic Code (North American Commission on Stratigraphic Nomenclature [NACSN], 2021, Article 5, Remark (a)) is not yet known. Nor is acceptance yet known for the Ralston Creek Member, which was formerly a formation below the Morrison Formation in eastern Colorado (Carpenter and Lindsey, 2019). However, not all of the members are universally accepted as lithostratigraphic units of the Morrison Formation. The Bluff Sandstone is considered as a formation in the San Rafael Group by some authors (e.g., Anderson and Lucas, 1992, 1995; Lucas, 2014), along with the Recapture and Salt Wash Members (Anderson and Lucas, 1994, p. 312; this position was reversed in Anderson and Lucas, 1995), but these positions were not accepted by others (e.g., Turner and Peterson, 2004; see further discussion on this issue by Kirkland and others, 2020). The Windy Hill is considered as a member of the Morrison Formation by some (e.g., Sprinkel and others, 2019), as a member of the Sundance Formation (e.g., Trujillo and Kowallis, 2015), or as a distinct lithostratigraphic unit (Holland and Wright, 2020).

The most controversial member of the Morrison Formation is the Tidwell because of two contradictory issues: (1) who first named the Tidwell Member and (2) to which formation does it belong. These two controversies about the Tidwell Member are examined below in attempted resolutions.

METHODS

As part of the investigation into the naming of the Tidwell Member of the Morrison Formation, unpublished reports and maps created between 1951 and 1970 were among the documents examined. These particular documents are part of the 2700+ "gray literature" on the geology and occurrences of radioactive ores prepared between 1945 and 1981 by the Grand Junction Office of the U.S. Atomic Energy Commission (AEC), the U.S. Department of Energy (DOE), and Bendix Field Engineering Corporation on behalf of the AEC or DOE (Johnson, 1981; Doelling, 1983; U.S. Geological Survey Open-Files Service Section, 1984). Many of these documents are available online: Mountain Scholar open access repository: https://mountainscholar.org/; National Geologic Map Database: https://ngmdb.usgs.gov/ngmdb/ngmdb_home.html; University of North Texas Digital Library: https://digital.library.unt.edu/; U.S. Department of Energy Office of Scientific and Technical Information: https://www.osti.gov/pages/; U.S. Geological Survey Publications Warehouse: https://pubs.er.usgs.gov/. Some of the gray literature was subsequently published either in part or in whole. For example, Craig and others (1955) is the declassified Craig and others (1951), and Mullens and Freeman (1957) is Mullen and Freeman (1954), which is based on their contribution in the Craig and others (1951) report, but with some differences (e.g., details of the isopachous maps). The accompanying cover letter with Mullens and Freeman (1954) report requested approval for publication in the Bulletin of the Geological Society of America, but security clearance delayed publication until 1957.

Field work for this project was conducted across the northern part of the Colorado Plateau in Utah and Colorado. Outcrops of the Summerville Formation and its lateral equivalent Wanakah Formation, and the Tidwell Member of the Morrison Formation were examined, photographed, measured, and sampled. Hand samples were cut and surfaces polished to reveal lithology and texture. Select samples of gypsum were dissolved with hot hydrochloric acid or a solution of sodium citrate for recovery of detrital minerals (mostly silicate grains).

To gain a better understanding of a natural gypsum depositional environment, the Salt Flat, which straddles the eastern New Mexico and West Texas border was examined and several pits excavated to see the subsurface deposits. Salt Flat covers approximately 9495 km² and
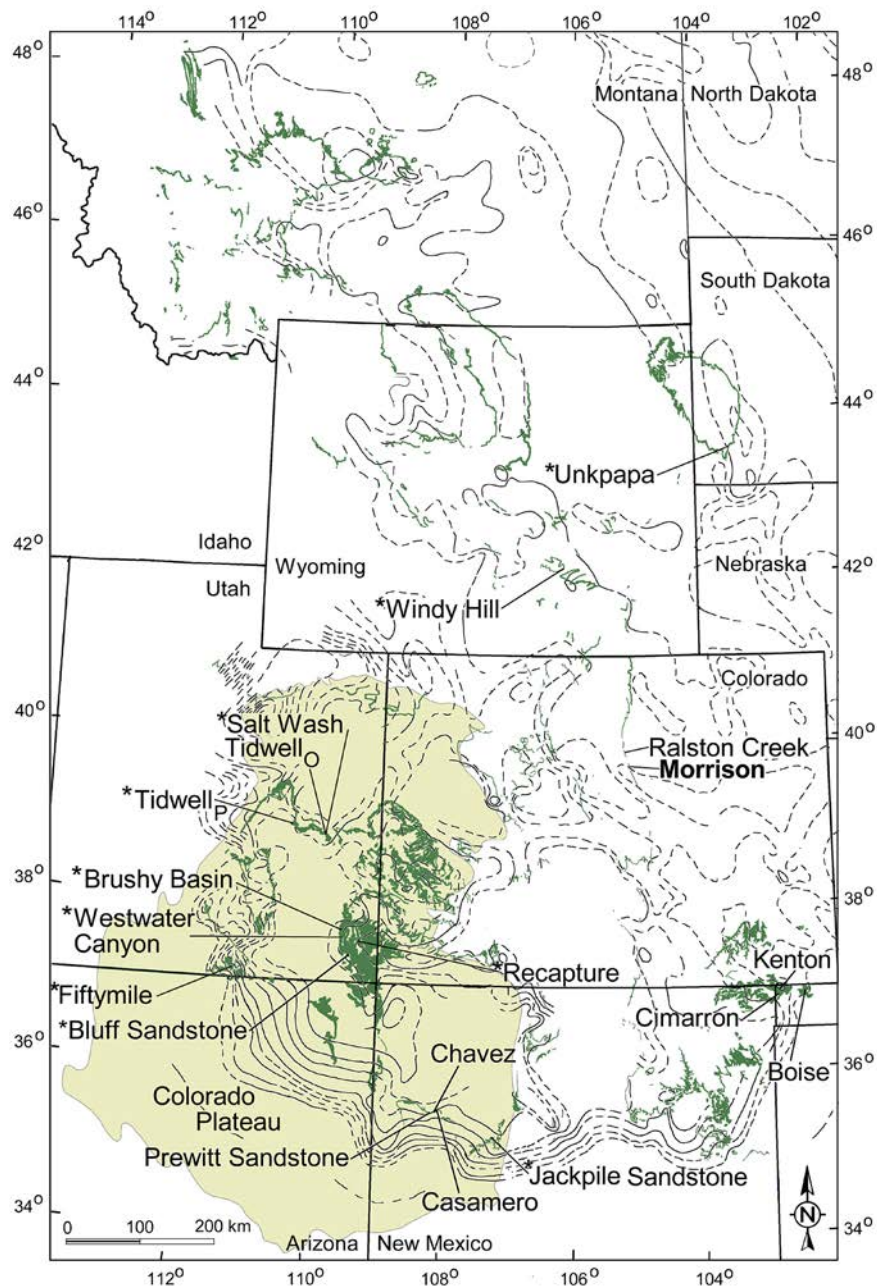
Figure 1. Distribution of the Morrison Formation in the Western United States and location of type localities for the formation (bold text) and members. "Tidwell$_O$" is the location of the type Tidwell of O'Sullivan (1984a); "Tidwell$_P$" is the location of the type Tidwell of Peterson (1988a). Delineation of the Colorado Plateau based on Bayer (1983). Thickness isopach (100-foot contours) from McKee and others (1956); see Peterson (1972) for another interpretation.

is a playa complex containing approximately 40 gypsum-producing playas that have been the subject of several studies (e.g., Boyd, 1982; Chapman, 1984; Hussain, 1986; Boyd and Kreitler, 1987; Hussain and Warren, 1985, 1988, 1989, 1991; Chapman and Kreitler, 1990; Mahan and Kay, 2012).

Abbreviations for fossils: FHPR – Field House Park Record, Utah Field House of Natural History State Park Museum, Vernal, Utah; USNM PAL – United States National Museum, Paleobiology (now the National Museum of Natural History, Smithsonian Institution), Washington DC.

HISTORY OF NOMENCLATURE AND THE AUTHORSHIP CONTROVERSY

Geologists have long noted that there was a strati-

graphic interval of slope-forming, thinly bedded, lenticular siltstone, sandstone, limestone, and mudstone beds between the lowest, white- to gray-colored, thick bedded, typical coarse-grained sandstones of the Salt Wash Member of the Morrison Formation, and the characteristic thin, evenly bedded siltstone beds of the Summerville Formation (figure 2) (e.g., Dake, 1918; Emery, 1918; Gilluly and Reeside, 1928; Gilluly, 1929; Stokes, 1944, 1952; Coleman and others, 1945; Baker and others, 1952; Stokes and Holmes, 1954; Craig and Dickey, 1956; Young and others, 1957, 1960; Holmes, 1960; Craig and Shawe, 1975; Imlay, 1980). These slope-forming strata have been included in the Summerville Formation (e.g., Baker, 1946), the Salt Wash Member (e.g., Gilluly, 1929), partially in both (e.g., Craig and others, 1955), or as a separate stratigraphic unit variously called the "lower member," "lower unit," and "Tidwell unit." The "Peeples Member" was proposed by Holmes (1960) in his dissertation for this same unit, but the name was never formally published (Stokes, 1980), and the North American Stratigraphic Code (NACSN, 2021) does not recognize a dissertation as a valid publication (Article 4, Remarks (a) Inadequate publication). Thompson and Stokes (1970) named the unit the White Point Sandstone Member of the Summerville Formation, with the type section near White Point south of Escalante, Utah. They also noted that the member was probably equivalent to part of the Morrison Formation. Despite having priority as acknowledged by Peterson (1988a, p. 42), the White Point Sandstone Member has not been widely used and is hereby formally abandoned under Article 7(c) of the NACSN, 2021, which states, "Priority in publication is to be respected, but priority alone does not justify displacing a well-established name by one neither well-known nor commonly used; nor should an inadequately established name be preserved merely on the basis of priority…" (see also NACSN, 2021, Article 20). These beds today are called the Tidwell Member of the Morrison Formation (O'Sullivan, 1984a) or the Tidwell Member of the Summerville Formation (Lucas and Anderson, 1997; Anderson and Lucas, 1994, 1995, 1996, 1998; Anderson and others, 1997; previously, Anderson and Lucas, 1992, did not recognize the Tidwell as a valid lithostratigraphic unit).

The earliest use of the term "Tidwell Member" is claimed by Robert Young (1987, p. 17), who referred to an earlier report (Young and others, 1957). This earlier report on the uranium geology of the Green River Min-
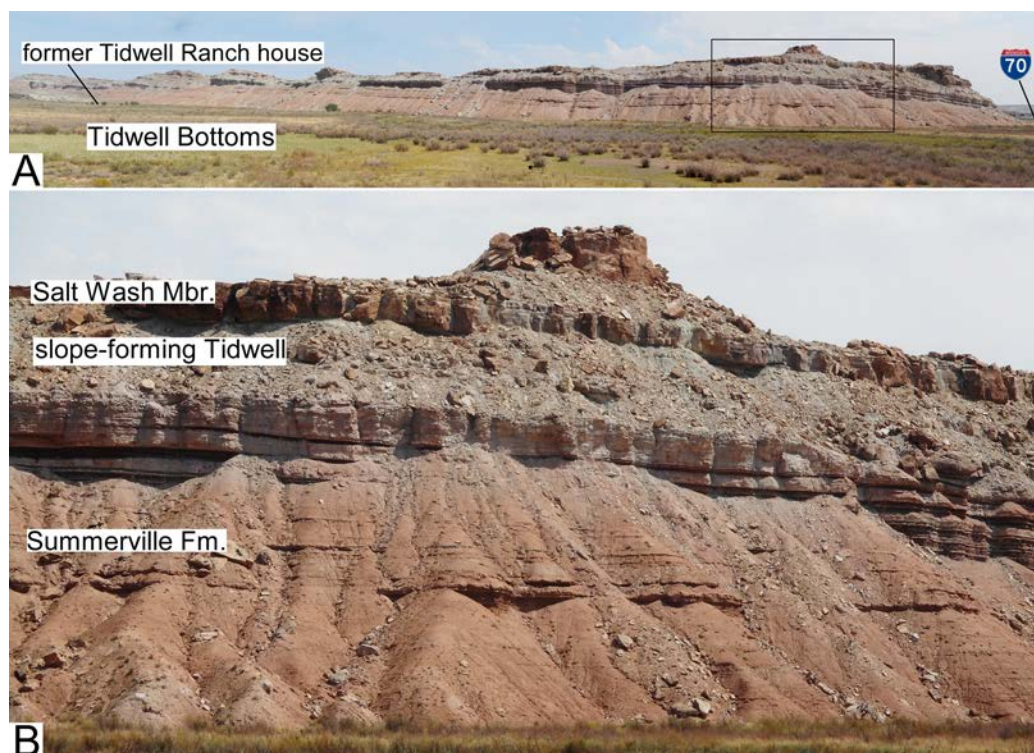

Figure 2. Slope-forming Tidwell Member of the Morrison Formation bracketed by the underlying Summerville Formation and overlying Salt Wash Member of the Morrison Formation. (A) Tidwell Bottoms on the west side of the Tidwell Mineral Belt. (B) Close-up of exposures outlined in A. Butte is at 38.9414°, -110.3938°.

ing District was written while Young was employed by the Grand Junction Office of the AEC (1955–1963, The Daily Sentinel, 2011). Young (1987, p. 17) stated that the earlier usage was an informal designation. The name as used by Young (1987) presumably derived from either Tidwell Bottoms or Tidwell Draw, both of which occur in a small area on the west side of the Green River Mining District (figures 2A and 3A). Young (1978) does not list the Tidwell Member among the four members of the Morrison Formation in his discussion of the uranium deposits of the Colorado Plateau.

A problem arises, however, in crediting Young and others (1957) with the term "Tidwell Member," because that the term does not occur in the 1957 report, nor in their revised report (Young and others, 1960). Instead, they identify the Salt Wash Member of the Morrison

Formation as in unconformable contact with the underlying Summerville Formation. My search of around 150 relevant documents written between 1951 and 1970 for the AEC failed to produce any mention of the "Tidwell Member." Both Young (1987, p. 17) and Peterson (1988a, p. 35) do refer to a discussion between them in 1986 in which "Tidwell Member" was discussed and it is possible that Young conflated "Tidwell Member" and "Tidwell Mineral Belt," because the latter appears for the first time in Young and others (1957); compare Technical Staff (1951), Clark and Million (1956), and Johnson (1956, 1957) with Young and others (1960), Trimble (1976), Mickle and others (1977), Trimble and Doelling (1978), and Bluhm and Rundle (1980). The Tidwell Mineral Belt, also known as Tidwell District, is an area immediately east of Tidwell Bottoms in Emery Coun-
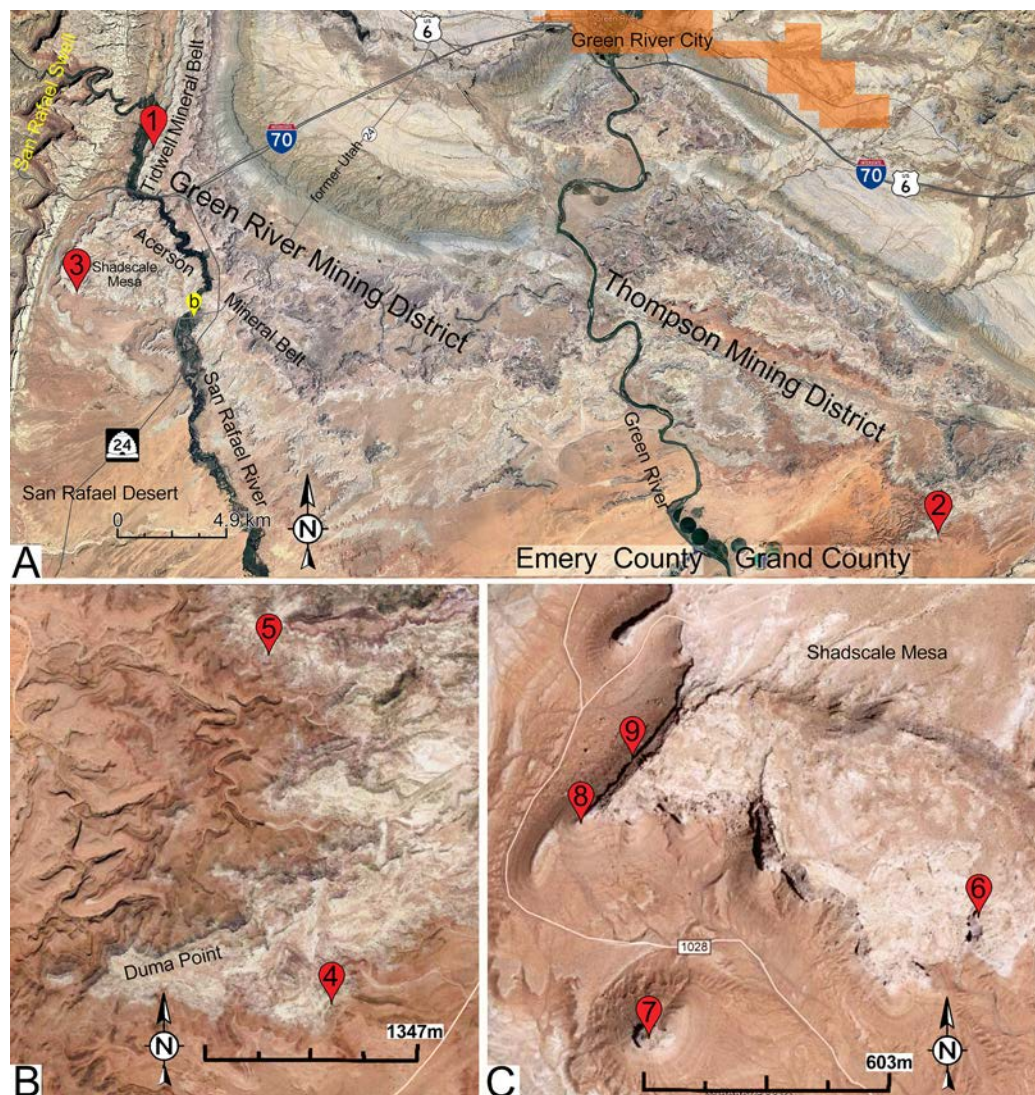
Figure 3. (A) Overview of main study area: 1 – area where Young and others (1957) allegedly introduced the informal term "Tidwell member." 2 – location of Duma Point. 3 – location Shadscale Mesa. Yellow b is the location of the old highway bridge across the San Rafael River. (B) Duma Point area: 4 – location of the stratigraphic section of O'Sullivan (1984a); 5 – stratotype of the Salt Wash Member by Lupton (1914) also shown for reference. (C) Shadscale Mesa area: 6 – location of the stratigraphic section of Peterson (1988a). Other sites include: 7 – butte with Tidwell channel incised into the Summerville, see figure 15C (38.8794°, -110.4436°). 8 – "The Notch," well exposed gypsum, see figure 16 (38.8844°, -110.4456°). 9 – cliff face showing angular unconformity at the top of the Summerville, see figures 7A and 7B (38.8859°, -110.4438°). Satellite imagery and location coordinates here and throughout from Google Earth.

ty, Utah (figures 2 and 3A), which produced uranium and vanadium during the 1950s and 1960s (Young and others, 1960; Trimble, 1976; Mickle and others, 1977; Trimble and Doelling, 1978). The term Tidwell Mineral Belt is still used today (e.g., Gloyn and others, 2003).

The earliest verifiable use of the "Tidwell" name for strata was by Peterson (1980a) for rocks he previously referred to as the "lower member" of the Morrison Formation in the Henry Basin (Peterson, 1974, 1977, 1978). In introducing the term "Tidwell," he referred to the lower member as the "Tidwell unit of the Morrison," but stated that the term was informal (Peterson, 1980a, p. 70). His justification for using "Tidwell" was because "several uranium companies have resurrected the name 'Tidwell member' for this unit because that name appeared on unpublished and unauthored maps thought to have been compiled by R.G. Young in the 1950's [sic] that are in the files of the U.S. Department of Energy (formerly the U.S. Atomic Energy Commission) and are available to the public" (Peterson, 1980a, p. 70). It is unfortunate that Peterson did not reference specific maps because my search failed to find the name on any unpublished geological maps or other documents in the AEC archives (Christine Turner, U.S. Geological Survey, retired, was unable to provide any insights to these files either; written communication, January 19, 2022). These unpublished maps and documents do reference the Salt Wash and Brushy Basin Members, but not the Tidwell Member. Furthermore, these documents state that the Salt Wash Member overlays the Summerville Formation.

O'Sullivan (1980a, 1980b, 1981a, 1981b, 1981c), noted that a reddish, slope-forming stratigraphic interval at the base of the Morrison Formation is exposed through much of the Colorado Plateau and initially called it the "lower beds" of the Salt Wash Member in a series of stratigraphic correlation charts. Later, the beds were referred to as the "Tidwell unit" and acknowledgment was given to Peterson (1980a) for introducing this informal term (O'Sullivan and Pierce, 1983; O'Sullivan and Pipiringos, 1983). Tham and others (1981) used the name "Tidwell unit" for the stratigraphic unit below the Salt Wash and credited Peterson for the name. However, he [Peterson] did not use that name in the three references they cited. The name Tidwell unit was also cred-

ited to Peterson (1980a) by Toth and others (1983) in their unpublished report on the geology of the Dominguez Canyon Wilderness Study Area in western Colorado. Later, Toth and others (1987) referred to the Tidwell Member in their published, much abbreviated geology of the Dominguez Canyon Wilderness Study Area, but no credit for the unit name is given. Tyler (1981) and Tyler and Ethridge (1983a, p. 69) refer to the Tidwell Member as "the earliest fluvial deposit of the Morrison Formation" in the Slick Rock Uranium District. In addition, they show it on a stratigraphic section (also in Tyler and Ethridge, 1983b). They do not state the origin of the name and present it as if it was widely known.

After 1983, the history of the Tidwell Member nomenclature becomes complicated. O'Sullivan (1984a) presented a detailed discussion about the base of the Morrison Formation in east-central Utah, and included a lithological definition of the Tidwell Member at Duma Point, Grand County, Utah (figures 3B and 4). Duma Point is 2.18 km south of Lupton's (1914, p. 126) measured section for the type Salt Wash Member at an unnamed side canyon on White Wash (figure 5; note: Cadigan, 1967, p. 9, erroneously referred to the type locality for the Salt Wash Member as at Duma Point). O'Sullivan considered the angular unconformity between the underlying Summerville Formation and overlying Tidwell Member near the San Rafael Swell as the definitive boundary between the two lithostratigraphic units. O'Sullivan traced this boundary eastwards across the Colorado Plateau as a disconformity that he considered as the J-5 unconformity of Pipiringos and O'Sullivan (1978).

The following year, USGS geologist Brenda Steele (1985) credited O'Sullivan (1984a) for the name Tidwell Member, which has an important ramification regarding authorship as is discussed in the next section. That same year, USGS geologist Cornelius Molenaar (1985) cited "Peterson (in press)" for the name Tidwell Member, but there was no mention of O'Sullivan, 1984a. This citation suggests that a manuscript by Peterson proposing the name was circulating in the USGS offices in Denver, Colorado, at least three years before its publication. O'Sullivan (1986) used the name Tidwell Member in stratigraphic sections between Uravan and Telluride, Colorado, and cited Peterson (1980a, as the "Tidwell
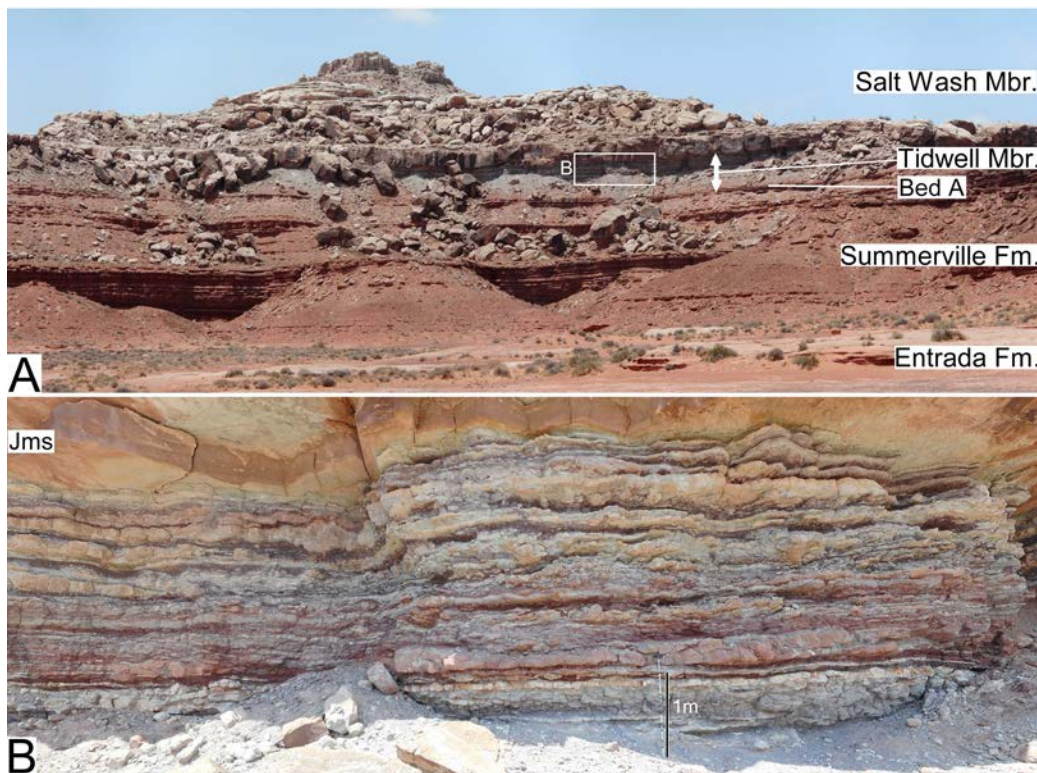
Figure 4. Duma Point location where O'Sullivan (1984a) made his measured section (A). (B) Close-up of the supplemental reference section of the Tidwell Member (38.7818°, -109.9783°); box shown in A.

unit"); however, neither his own work nor Peterson's unpublished manuscript are cited as the source for the name. Doelling (1985) describes the Tidwell Member in and adjacent to Arches National Park citing O'Sullivan (1980a) as the source for the name. Peterson and Tyler (1985) referred to the Tidwell Member, but gave no reference for the name; they did cite Peterson (in press) for the Fiftymile Member in the same article. Peterson (1986) referred to the Tidwell Member without a reference in his discussion of the Jurassic paleotectonics of the central Colorado Plateau implying an accepted name. Finally, in Peterson and Turner-Peterson (1987, p. 4), both O'Sullivan (1984a) and Peterson (in press) are cited for the "newly recognized Tidwell Member…" Here, Peterson and Turner-Peterson seemingly acknowledged O'Sullivan as author, while also acknowledging that the Peterson version was not yet published. Goldhaber and others (1987) refer to the Tidwell Member in the Henry Basin of south-central Utah and noted that the local geology had been described by Peterson (1980b). They replicated his stratigraphic section and changed "Tidwell unit" to "Tidwell Member," but do not give a reason for the change. Baars and Doelling (1987)

cite Doelling (1985) for the Tidwell Member, whereas Kowallis and Heaton (1987) cite a personal communication from Peterson for the name.

In 1988, Peterson's manuscript proposing the name Tidwell Member was finally published. The delay between the circulation of Peterson's draft manuscript and its publication was due to his mandatory involvement in the monumental USGS multidisciplinary analysis of the Morrison Formation in the Grants Uranium District in northwestern New Mexico (Christine Turner, USGS, retired, written communication, September 18, 2020). The volume (Turner-Peterson and others, 1986) was a crucial summary of uranium ore genesis in context of the evolution of a sedimentary basin by the USGS under pressure of the Ronald Reagan Administration (1981–1989). The delay forced Peterson's manuscript to go through the internal USGS review process a second time (Christine Turner, USGS, retired, written communication, September 18, 2020). The published version is mostly a repeat of what Peterson had previously published, although he cites very few of these earlier publications. One important addition was a descriptive stratigraphic section at Shadscale Mesa, which he calls
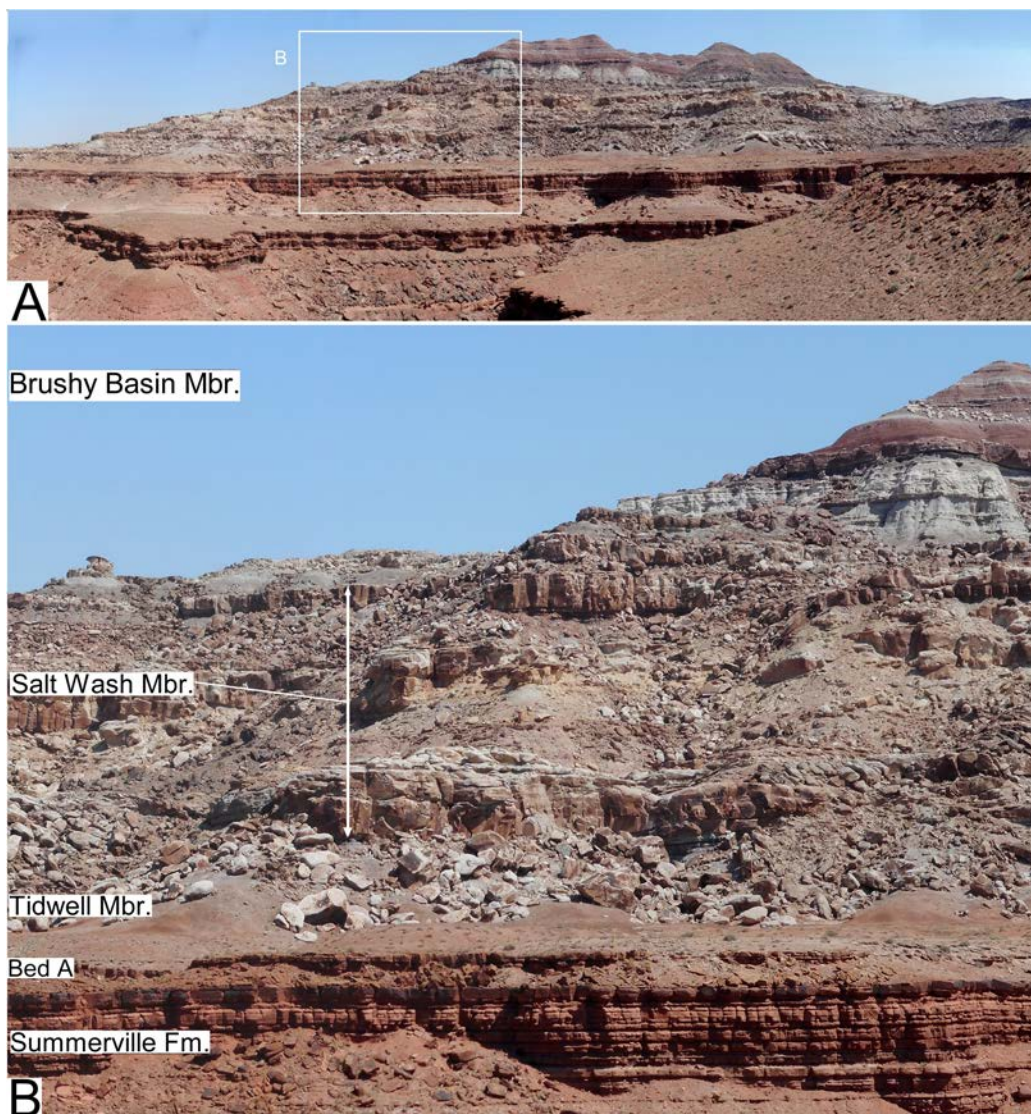
Figure 5. (A) Location of Lupton's (1914) measured section of the Salt Wash Member of the Morrison Formation along an unnamed side canyon of White Wash (38.7982°, -109.9867°). The geographical feature Salt Wash is 3.6 km north in the next drainage. (B) Close-up of the type section; box shown in A. Lupton (1914) included the Tidwell strata with the underlying part of the "McElmo Formation" as it was called.

the type section for the Tidwell Member (figures 3 and 6).

In the years since Peterson (1988a), various researchers have credited Peterson for naming and describing the Tidwell Member (e.g., Lucas, 2018), but others credit O'Sullivan (1984a) (e.g., Kirkland and others, 2020). Because O'Sullivan and Peterson give different localities that could be construed as the type section of the Tidwell Member (Duma Point vs Shadscale Mesa, figure 3), it is important to determine who is the rightful or first author to formally proposed the name Tidwell Member.

The North American Stratigraphic Code (NASC) presents standardized procedures for stratigraphic nomenclature as agreed upon by the geological community (Jordan, 2009). For this reason, the NASC is incorporated into the guidelines for USGS technical reports (Cohee, 1974). Both O'Sullivan (1984a) and Peterson (1988a) operated under the 1983 version of the NASC (NACSN, 1983), which gives the minimum requirements for naming a new geologic unit in Article 3 and which are elaborated upon in Articles 4 through 15. Both O'Sullivan (1984a) and Peterson (1988a) fulfilled the basic requirements for naming the Tidwell Member as summarized in table 1. However, the NASC states that the naming of a new geologic unit is actually a proposal that lacks status until used by others showing that the name served a purpose. In other words, that there was a recognized need by others for the name (NASC, Article 5, Remark(a)). For O'Sullivan, this recognition was fulfilled when USGS geologist Steele (1985) cred-
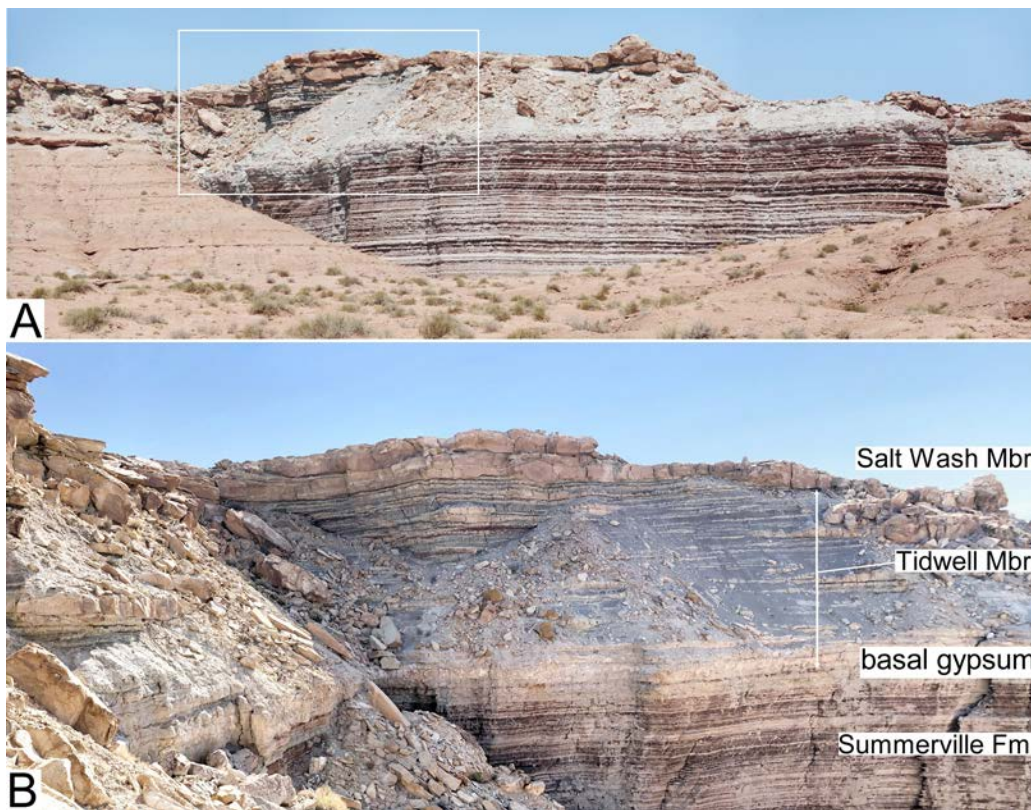
Figure 6. South side of Shadscale Mesa, type section of Peterson (1988a). (A) distant view, (B) closeup. (38.8821°, -110.4341°); box shown in A.

ited O'Sullivan (1984a) for the Tidwell Member. For Peterson (1988a), this recognition came from Northrop and others (1990a).

Despite these recognitions, there is a complication in recognizing O'Sullivan as the author for the Tidwell Member. The internal USGS guidelines, *Stratigraphic Nomenclature in Reports of the U.S. Geological Survey*, requires that the naming of a new stratigraphic name by USGS personnel must include a "1. Statement of intent to introduce a name: This unit is here named ...." (Cohee, 1974, p. 5). O'Sullivan (1984a) makes no such statement and usage of the name as far as the USGS is concerned is assumed to be informal. It is rather unfortunate that the Survey did not enforce the 1983 NASC Article 30, Remark (h) on informal units: "When geographic names are applied to such informal units as … informal members …, the unit term should not be capitalized." Using "Tidwell member" rather than "Tidwell Member" would have been less ambiguous as to O'Sullivan's intent. In contrast, Peterson (1988a, p. 35) wrote, "The Tidwell Member is here named for grayish green mudstone strata at the base of the Morrison Formation…" making an unambiguous statement of his intention for naming a new stratigraphic unit.

I conclude that, although O'Sullivan (1984a) fulfilled the requirements for naming a new stratigraphic unit according to the 1983 NASC, his intent as far as the USGS was concerned, was of an informal usage. Therefore, Peterson (1988a) should be credited with formally naming the Tidwell Member of the Morrison Formation and consequently the type section is at Shadscale Mesa, Emery County, Utah (figure 6). O'Sullivan (1992a) designated a reference section (NASC, Article 8, Remark (e), Reference sections) for the Tidwell Member along a minor drainage of the Gunnison River in Montrose County, Colorado (38.6113°, -107.8449°). In his reference section, he notes a thickness of 50 m, of which gypsiferous beds comprise the lower 24 m. O'Sullivan's (1984a) section at Duma Point (figure 4) may be considered a supplementary reference section (NASC, Article 8, Remark (e)) because it lacks the basal gypsum seen at the type and principal reference sections and is more representative of most of the Tidwell east of the San Rafael Swell and Henry Basin.

The descriptions of the Tidwell Member by Peterson (1988a) and by O'Sullivan (1984a) share similari-

Table 1. North American Stratigraphic Code (1983) requirements for the naming of a lithostratigraphic unit as fulfilled by O'Sullivan (1984a) and Peterson (1988a).

Applicable North American Stratigraphic Code	O'Sullivan, 1984a	Peterson, 1988a
Article 4–Publication permanent, widely available	USGS Bulletin 1561	USGS Bulletin 1633
Article 5–Intent and utility	p. 7–11	p. 35–36
Article 6–Category and rank	p. 5 as "Tidwell Member"	p. 35 as "Tidwell Member"
Article 7–Compound name for a geographic feature	p. 5 "Tidwell Member," but does not give the geographic feature for the name.	p. 35 "Tidwell Member" after Tidwell Bottoms
Article 8–Stratotype	p. 13 (Duma Point)	p. 53 (Shadscale Mesa)
Article 9–Unit description	p. 12, photographic section; p. 13 descriptive section.	p. 38, graphic section; p. 52–53 descriptive section.
Article 10–Boundaries	p. 6, J-5 unconformity to the Salt Wash Member.	p. 38, J-5 unconformity to the Salt Wash Member.
Article 11–Historical background	p. 3–5, 7–11	p. 36
Article 12–Dimensions and regional relations	p. 5, 13, 15	p. 38, 52
Article 13–Age	p. 1 with p. 5, Late Jurassic	Figure B2, Upper Jurassic; p. 20, Late Jurassic
Article 14–Correlation	p. 15	Figure B18
Article 15–Genesis	p. 5, terrestrial, but locally marine or quasi-marine.	p. 42, lacustrine, evaporative, mudflat, minor eolian, fluvial.

ties but also important differences as well, because Peterson's work concentrated on the western side of the Colorado Plateau and O'Sullivan on the central and eastern sides. Where O'Sullivan (1984a) noted that the dominant lithology was red siltstone, Peterson (1988a) noted that it was gray mudstone. Both, however, noted that the Tidwell Member also included interbedded sandstones and limestones, a basal sandstone referred to as Bed A, cherts as small botryoidal masses (welded chert) or larger nodules, and thick basal gypsum beds near the San Rafael Swell. There are also differences in the reported thicknesses of the Tidwell Member. O'Sullivan (1984a) reported that the thickness at Duma Point as 10.8 m, and noted that it ranges from 4.8 to 28.6 m elsewhere in east-central Utah, with an average of 17.2 m. In contrast, Peterson (1988a) reported the thickness of the Tidwell Member at Shadscale Mesa as 29.3 m, of which the basal 5.2 m was gypsiferous. Elsewhere, the Tidwell Member ranges up to 30 m in the San Rafael Swell and from 8 to 21 m in the Henry Basin where the basal gypsiferous beds in the northern end of the basin are up to 14 m thick. O'Sullivan (1984a, p. 15) also not-

ed that towards Blanding, Utah, the Tidwell Member is replaced laterally by the Bluff Sandstone Member of the Morrison Formation and near Glenwood Springs, Colorado, it merges with the undivided Morrison. Peterson (1988a) does not discuss lateral correlation but does show graphically (his figure B18) that the Tidwell Member correlates with the lower parts of both the Bluff Sandstone and Recapture Members.

TIDWELL—A MEMBER OF THE MORRISON FORMATION OR OF THE SUMMERVILLE FORMATION?

Having established that Peterson (1988a) as the geologist who formally named the Tidwell Member and established the type locality at Shadscale Mesa, there remains the question of whether the Tidwell Member is a member at the top of the Summerville Formation or a member at the base of the Morrison Formation. Two issues to resolving this problem is the identification of the J-5 unconformity and the placement of the thick, basal gypsum beds in the San Rafael Swell and Henry

Basin. These two issues were examined in context of the Tidwell and Summerville across the northern half of the Colorado Plateau (figures 7 and 8). In addition, the laterally equivalent Wanakah Formation as defined by O'Sullivan (1992a), was examined as well because there is disagreement as to whether the strata are distinct from the Summerville (see below).

In the following sections, first the basic lithologies of the Summerville Formation and Tidwell Member are described, then detailed descriptions of the gypsum in the Summerville and the controversial, thick gypsum beds at the contact between the Summerville and Tidwell in the San Rafael Swell and Henry Basin, followed by evidence for placement of the J-5 unconformity, and finally comparisons are made with the gypsum of the

Ralston Creek Member which provides indirect support for the placement of the thick gypsum beds.

Summerville Formation

The Summerville Formation conformably overlies the Curtis Formation in central and east-central Utah, and the Curtis and Summerville are correlative with the Stump Formation to the north. The Summerville Formation is considered the regressive phase of a single transgressive-regressive (T-R) sequence represented by with the Curtis-Summerville-Stump Formations (Wilcox and Currie, 2008). Dinoflagellates and ammonites in the basal Curtis and Stump Formations date this T-R sequence to the Early Oxfordian (Wilcox and Currie,
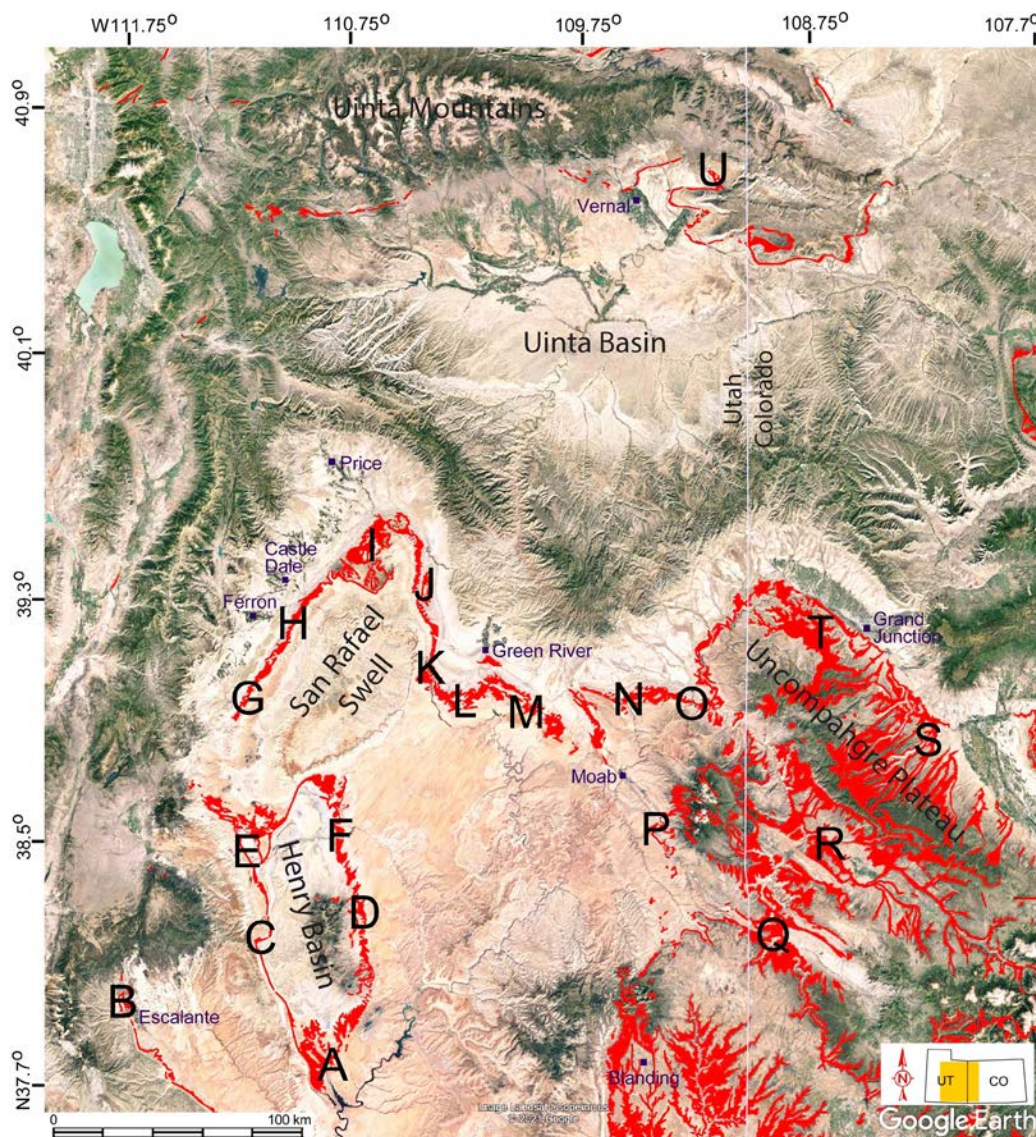

Figure 7. Locations of Summerville and Tidwell strata shown in figure 8. Letters of localities (A, B, C, etc.) correspond to figures 8A, 8B, 8C, etc.
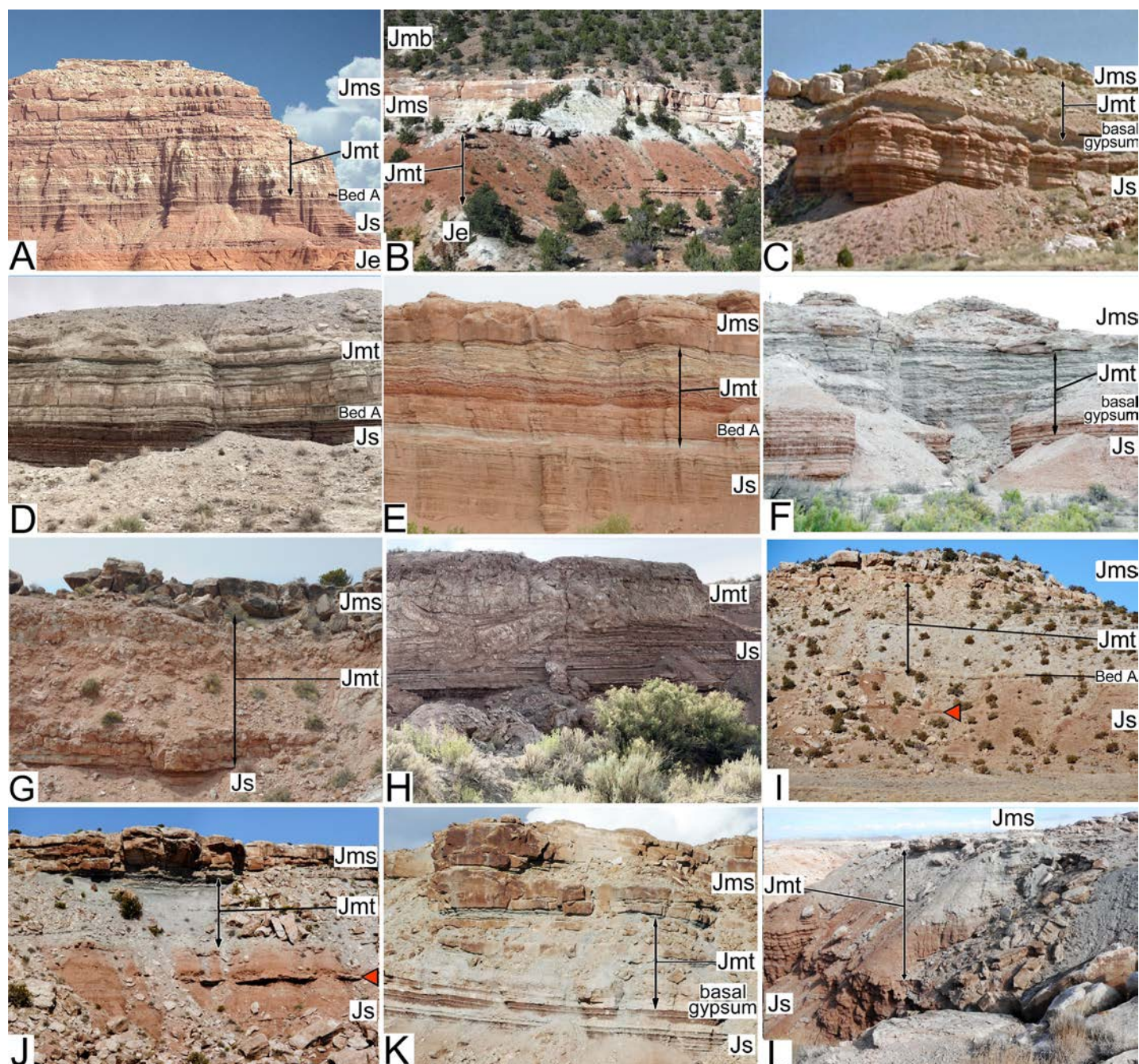
Figure 8A–L. Documenting facies variation of the Tidwell Member (Morrison Formation) and underlying Summerville Formation across the Colorado Plateau. (A) Butte along Bullfrog Creek, Utah (37.6072°, -110.7689°). (B) Escalante Petrified Forest State Park, Utah (37.7876° -111.6294°). (C) Divide Canyon, Capitol Reef National Park, Utah (38.0312°, -111.0637°). (D) Lone Cedar Flat, Utah (38.1081°, -110.6324°; cf., Hunt and others, 1953, figure 17). (E) Notom Junction, Utah (38.2858°, -111.1277°). (F) Fremont River, Utah (38.3727°, -110.7571°). (G) I-70, Mulligan Wash, Utah (38.8318°, -111.1370°). (H) Horn Silver Gulch, Utah (39.0403°, -110.9706°). (I) Lucky Flats, Utah (39.3026°, -110.6377°), arrow indicates a lenticular sandstone in the Summerville Formation. (J) Woodside anticline, Utah (39.1830°, -110.4139°), arrow indicates a lenticular sandstone in the Summerville Formation. (K) Tidwell Bottoms, Utah (38.9244°, -109.4479°). (L) Horse Bench (38.8007°, -110.2181°). Abbreviations: Je – Entrada Formation; Jem – Entrada Formation, Moab Tongue; Jmb – Morrison Formation, Brushy Basin Member; Jms – Morrison Formation, Salt Wash Member; Jmt – Morrison Formation, Tidwell Member; Js – Summerville Formation; Jw – Wanakah Formation. Image C from Google Earth street view.
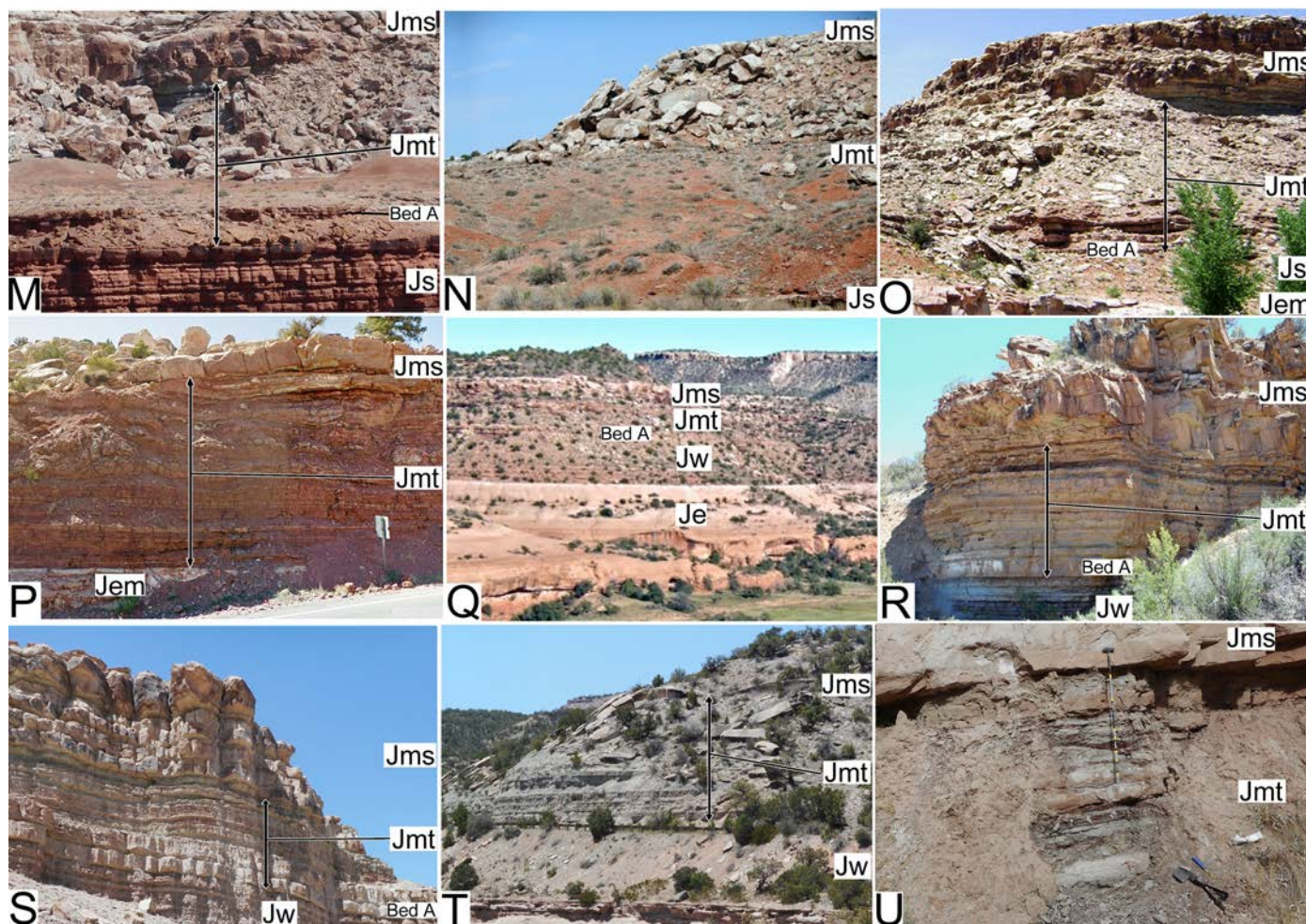
Figure 8M–U. Documenting facies variation of the Tidwell Member (Morrison Formation) and underlying Summerville Formation across the Colorado Plateau, continued. (M) Unnamed side canyon, White Wash, Utah (38.7982°, -109.9867°). (N) Mine Draw, Yellow Cat Mining District, Utah (38.8242°, -109.5468°). (O) Near Dewey Springs, Utah (38.8203°, -109.2845°). (P) US 191 roadcut, Kane Springs Canyon, Utah (38.4061°, -109.4472°). (Q) McIntyre Canyon, Colorado (38.0938°, -108.9401°). (R) San Miguel River, Colorado (38.3474°, -108.7056°). (S) Escalante Canyon, Colorado (38.7116°, -108.2774°). (T) near Artist Point, Colorado National Monument, Colorado (39.0713°, -108.7268°). (U) Rainbow Draw, Utah (40.5489°, -109.1825°). Abbreviations: Je – Entrada Formation; Jem – Entrada Formation, Moab Tongue; Jmb – Morrison Formation, Brushy Basin Member; Jms – Morrison Formation, Salt Wash Member; Jmt – Morrison Formation, Tidwell Member; Js – Summerville Formation; Jw – Wanakah Formation. Image P from Google Earth street view.

2008; about 163.5 ± 1.0 – 160 Ma, International Commission on Stratigraphy, 2021).

The Summerville Formation was named by Gilluly and Reeside (1928) for Summerville Point in the northeastern San Rafael Swell where is it exposed in its entirety (figures 9A and 9B). However, internal bedding is better seen 4.5 km to the east in the Woodside anticline on the east flank of the San Rafael Swell, Emery County (figure 9C). A better exposure is in a roadcut along Interstate 70 (I-70) on the west side of the San Rafael Swell

(figure 9D). This outcrop has been featured in several studies (e.g., Stanton, 1976; Steiner, 1978; Caputo, 1988; Caputo and Pryor, 1991; Bazard and Butler, 1992; Wilcox, 2007; Wilcox and Currie, 2008). Hunt and others (1953) gave a regional overview of the Summerville in the vicinity of the Henry Mountains, and Caputo (1988) in the vicinity of the San Rafael Swell and eastward.

The Summerville Formation lithology is not uniform across the Colorado Plateau. In the western part of the plateau, the formation consists of thinly bedded,
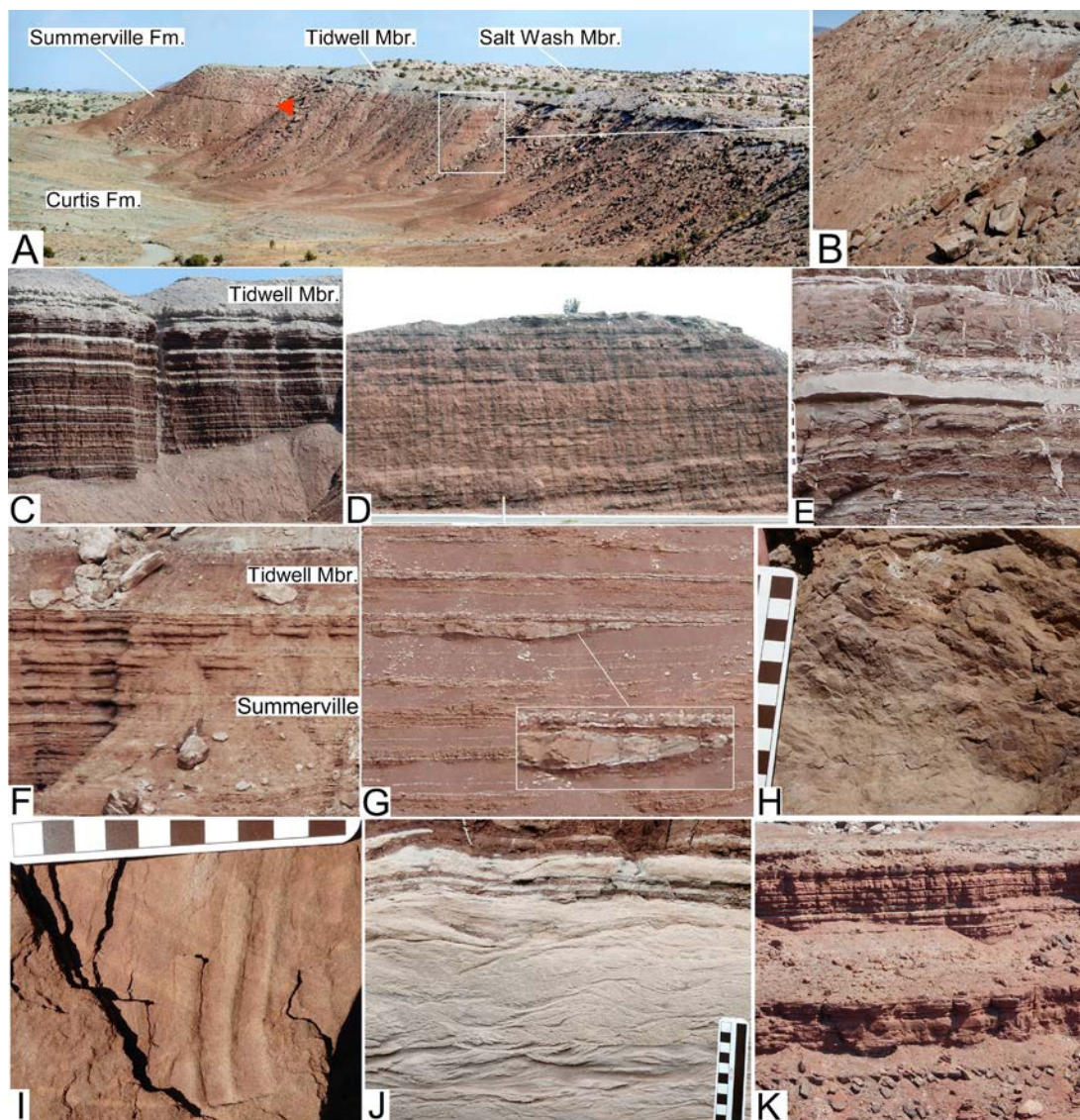
Figure 9. Summerville Formation in Utah. (A) Type locality at Summerville Point (39.1800°, -110.4635°). Red arrow points to a sandstone lens. (B) The only place the type locality where the internal bedding is visible shows thinly bedded siltstone to fine-grained sandstone with little gypsum present. (C) Thinly bedded siltstone, fine- to medium-grained sandstone, and light-colored gypsum, Woodside anticline (39.1826°, -110.4100°). (D) Mostly thinly bedded siltstone, fine-to medium-grained sandstone with little gypsum present, I-70 roadcut, Mulligan Wash (38.8321°, -111.1324°). (E) Characteristic alternating fine-grained sandstone or siltstone and mudstone or shale, roadcut State Highway 24 near Hanksville (38.3710°, -110.7509°). (F) Coarsening and thickening upwards sequence of sandstone beds (lower half to upper half), Horse Bench (38.8032°, -110.2190°). (G) Channel sandstone (note cross-bedding in insert); I-70 roadcut (38.8302°, -111.1385°). (H) Siltstone flakes in fine-grain sandstone, Lucky Flats. (I) Rippled sandstone, Lucky Flats. (J) Climbing ripples, Horn Silver Gulch. (K) More abundant and thicker sandstone beds (up to about 1 m thick) near White Wash, Utah (38.7978°, -109.9876°), about 20 km east of F.

medium-grained, subarkosic and sublitharenitic sandstones or siltstones, alternating with softer, thinly bedded wacke or sandy shale. McKnight (1940) noted muscovite in some sandstone beds east of the Green River. Anhydrite or gypsum occurs as nodules or thin beds,

and thin, gray limestones also occur. White, pink, orange-red, and blue-gray authigenic cherts occur sporadically throughout the formation, either associated with limestone (McKnight, 1940), as small botryoidal masses of welded cherts (e.g., Shadscale Mesa area), or as lenses

up to a meter thick (Stokes and Mobley, 1954). The clay matrix is mostly illite, although kaolinite co-occurs at the Woodside anticline (Weeks, 1953). The upper contact is abrupt (e.g., figure 9E). Where the Summerville is exposed in cliffs or roadcuts, the resistant sandstone and siltstone beds are more resistant to erosion and protrude (e.g., figures 9D and 9F). Colors range from various darker hues of red and orange, with some interbedded lighter sandstone or siltstone beds (figures 8 and 9). The thin-bedded sandstones may be locally lenticular (figures 8J and 9G). Thin, irregular siltstone flakes in fine-grained sandstone (figure 9H) are rip-up clasts or clasts from bank collapse of tidal channels (Stanton, 1976). The thin-bedded sandstone may show fining or coarsening upward successions, ripples (figure 9I), climbing ripples (figure 9J), load casts, cross-laminations, and desiccation cracks (Stanton, 1976; Caputo and Pryor 1991).

The Summerville Formation becomes progressively sandier and thicker bedded eastwards at the expense of siltstones and shales, with some of the sandstone be-coming over a meter thick (compare eastward progressing figures 9D, 9F, and 9K). Gilluly and Reeside (1928) also noted this lithological change and proposed that the Summerville in the eastern part was deposited on a broad, flat continental plain that sloped westward into a restricted, shallow-marine environment. They suggested that the lenticular sandstones in the south and east indicated continental deposition, and the ripple marks, mud cracks, and gypsum in the west indicated marine deposition. Their eastern-most Summerville includes strata that is now the Wanakah Formation (Burbank, 1930), a formation that is a source of controversy (Anderson and Lucas, 1992; Lucas,1993; Anderson and Lucas, 1994; Lucas and others, 2006; vs Condon, 1993). The Summerville Formation thins south and east (figure 10) from a maximum of 129 m in the western San Rafael Swell. East of the Green River, the Summerville is very thin (about 4 m) near Dewey Bridge (figure 8O). West of the San Rafael Swell, well data indicates that the Summerville grades laterally into the upper part of the Twist Gulch Formation near Salina Canyon, Sevier
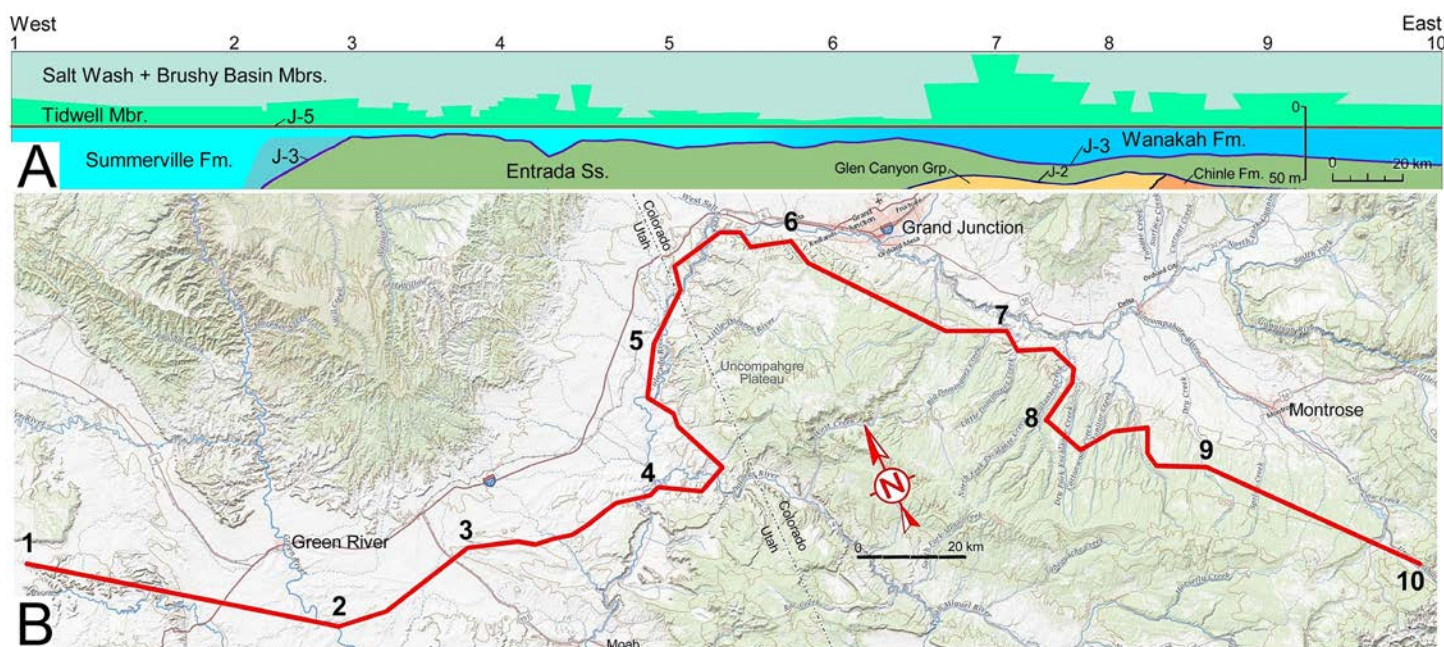
Figure 10. Relative thickness and relationship of the Tidwell Member of the Morrison Formation, and Summerville and Wanakah Formations across the Colorado Plateau. (A) Restored stratigraphic diagram. The boundary between the lithologies of the Summerville and Wanakah is gradational, and the two formations are separated artificially by the Utah-Colorado border. (B) Index map of the stratigraphic diagram (base map from Topozone). Locations for reference: 1, Buckhorn Flat, San Rafael Swell; 2 – Dellenbaugh Butte; 3 – Salt Wash Valley; 4 – Dewey Bridge; 5 – West Water; 6 – Fruita; 7 – Bridgeport; 8 – Escalante Canyon; 9 – Dry Creek Basin; 10 – North Ouray. Data from O'Sullivan (1980a, 1981b, 2004), O'Sullivan and Pierce (1983), and O'Sullivan and Pipiringos (1983).

County, Utah (Perkes, 2010).

Strata of the Summerville-Wanakah Formations can be traced almost continuously from the stratotype of the Summerville Formation at Summerville Point around the north and east sides of the Uncompahgre Plateau to the stratotype of the Wanakah Formation near Ouray, Colorado (figure 10; Holmes, 1960; O'Sullivan and Pipiringos, 1983). Criteria for separating the two units are vague because Holmes (1960) considering the Wanakah Formation as the more calcareous and gypsiferous mudstone facies of the Summerville. O'Sullivan (1980b) noted that the Summerville Formation bevels out in the vicinity of Moab and the La Sal Mountains in eastern Utah, and recommended that the name Wanakah Formation be used instead of Summerville Formation in southwestern Colorado and southeastern-most Utah. The absence of the Summerville Formation can be seen, for example, south of Moab near Kane Springs where the Tidwell Member sits atop the Middle Jurassic Entrada Sandstone (figure 8P; O'Sullivan, 1981a). However, as noted above, the Summerville Formation can be traced around the north end of the Uncompahgre Plateau (Lohman, 1965; Gualtieri, 1988; Willis, 1994; Willis and others, 1996). O'Sullivan and Piperingos (1983)

placed a pair of red and green mudstone beds (figure 11A) along the north side of the Uncompahgre Plateau in the lower part of the Tidwell Member based partly on the assumption that an underlying sandstone was Bed A, which marks the base of the Tidwell. This assumption was challenged by Willis and others (1996), who considered the red and green mudstone beds and the underlying sandstone to be the Summerville Formation based on previous work by Doelling (1993). Later, based on correlations on the east side of the Uncompahgre Plateau, O'Sullivan (2004) agreed with Willis and others (1996), and moved the base of the Tidwell Member to a higher sandstone (formerly called Bed B) and identified the underlying red and green mudstones as belonging to the Wanakah Formation, which he considered to be predominately nonmarine.

Elsewhere on the northeastern Colorado Plateau, the Wanakah Formation is dominated by red mudstone and sandstone beds (figures 11B and 11C; see O'Sullivan, 1992a, for other lithologies and extensive discussion) and resembles the Summerville Formation farther west. These Summerville-like strata are variously known informally as the "marl member" or "beds at Sawpit" (O'Sullivan 1992a; Burbank and Luedke, 2008).
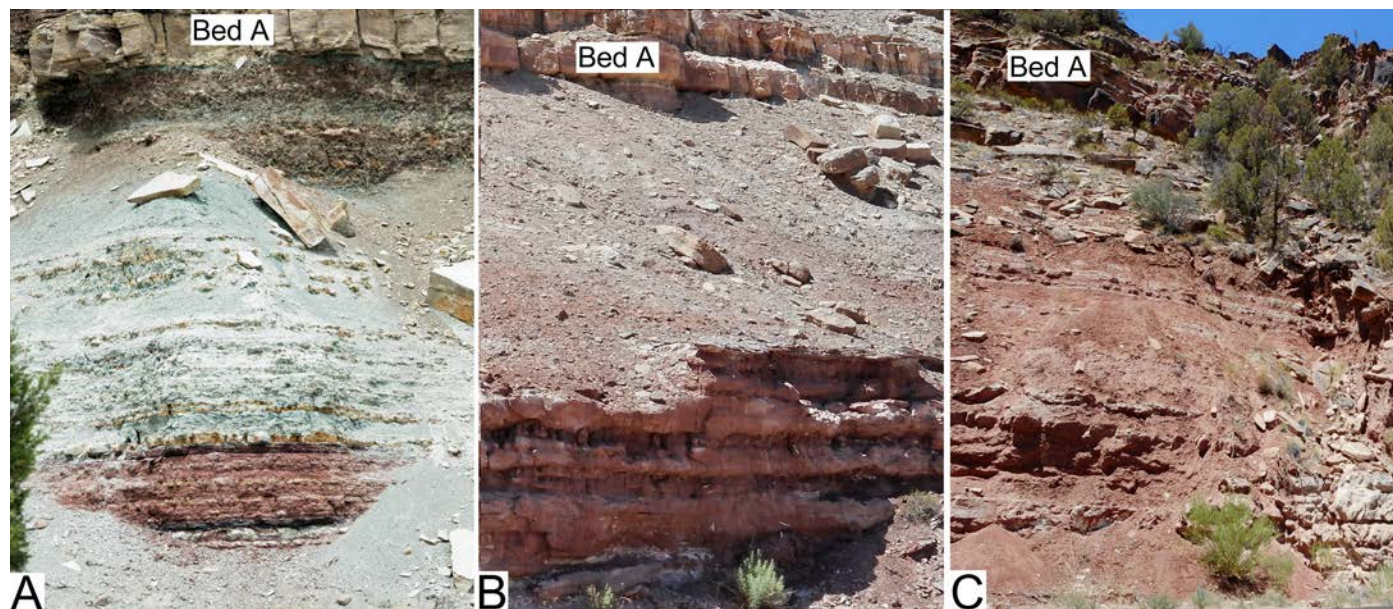
Figure 11. Wanakah Formation, Colorado. (A) Green and red beds at Angle Point, Colorado National Monument; now mostly obscured by talus since this photo was taken in 2007 (39.0727°, -108.7242°). (B) Escalante Canyon (38.7116°, -108.2774°). (C) Roadcut, State Highway 141 south of Uravan (38.3504°. -108.7096°). Base of Wanakah in (B) and (C) at the bushes at the bottom. Image (A) by James St. John from Wikimedia Commons, Creative Commons 2.0.

Currently, the predominately marine Summerville Formation has a state-line boundary separating it in Utah from the predominately nonmarine(?) Wanakah Formation in Colorado (however, see O'Sullivan and others, 2006, for marine fossils). A more thorough analysis of the Wanakah and Summerville Formations is needed because some of the arguments for assigning former Summerville strata to the Wanakah are based on correlation, rather than lithology (e.g., Condon and Huffman, 1986). Such an analysis is beyond the scope of this paper.

Tidwell Member

The Tidwell Member shows considerable lateral variation as noted by the description of the type section at Shadscale Mesa (Peterson, 1988a) and the supplemental reference section at Duma Point (O'Sullivan, 1984a). There is no doubt that the two sections demonstrate a lateral variation of the same stratigraphic unit because the Tidwell Member can be traced along a near continuous cliff between the two sections (figure 3A; see also O'Sullivan, 1980a). Thickness of the Tidwell Member is variable and ranges up to 35+ m thick in its southern occurrences (Robinson, 1994). Much of this variability is due to differences in the interfingering of the Tidwell Member with the overlying Salt Wash Member and with the base of the Salt Wash sandstone channels scoured into the Tidwell Member (figure 8).

As described by Peterson (1988a), the Tidwell Member has two distinct parts: a lower gypsum facies and an upper thin, interbedded sandstone-mudstone-limestone facies assemblage. Because the gypsum facies has been a source of controversy it is described in a separate section. Where the gypsum facies is missing, the base of the base of the Tidwell Member is often a tabular sandstone called Bed A (O'Sullivan, 1980a, 1984a).

Bed A

Over much of the eastern part of the Colorado Plateau where the basal gypsum is absent in the Tidwell Member, O'Sullivan (e.g., 1980a, 1984a) noted a widespread tabular sandstone at or slightly above the contact with the Summerville Formation, which he referred to as Bed A (figures 8 and 12). This sandstone was pre-

viously noted by Holmes (1960) as a persistent datum plane that he used to mark the top of the Summerville Formation. The sandstone ranges from 0.1 m near White Sand Dunes Recreational Area, Grand County, Utah, to 10 m in western Colorado (O'Sullivan, 1992b). It frequently overhangs the softer Summerville (e.g., figure 12C). The sandstone is various hues of brown, red, white to gray, and generally fine- to medium-grained. Bluhm and Randle (1980) described a 0.9 m-thick Bed A on the west side of the San Rafael Swell. It was composed of a very calcareous quartz arenite with about 40% micritic and sparitic carbonate, 45% to 50% fine- to medium-grained, subangular to subrounded, single-crystal and polycrystalline quartz (some of volcanic origin); 5% to 8% fine- to medium-sized, subangular to subrounded, microcrystalline chert; 1% to 2% fine- to coarse-grained, angular to subrounded chalcedony; 1% very fine to fine-sized, subangular to subrounded feldspar (microcline and plagioclase); 1% to 3% very fine to medium-grained, subrounded sedimentary rock fragments (micritic carbonate clasts and mudstone fragments); and trace amounts of detrital gypsum, zircon, garnet, tourmaline, muscovite, biotite, and opaques. Bed A is conglomeratic in places, which include red and green mudstone clasts, or rounded black and gray chert pebbles. Kirkland (Utah Geological Survey, written communication, September 21, 2021) reports a sheetlike conglomerate bed at the base of the Tidwell extending from Notom Junction northward across the northern region of Capitol Reef National Park to at least the south rim of Cathedral Valley in the park. This conglomerate bed is probably the same as that described by Ali-Adeeb (2007) as matrix supported and interpreted as debris flows. Bed A is often thickly bedded or massive, showing no structure, but occasionally showing wavy lamination in possible eolian deposits (figure 12E), as well as cross-bedding, ripple marks, or planar bedding, which occurs in fine-grained sandstone (figures 12F and 12G).

Bed A may not be the same bed everywhere or maybe composed of several closely associated sandstones beds (e.g., figure 12A) that thin and wedge out (e.g., Notom Junction, location E, figure 7). Peterson (1988a) suggested that Bed A correlated with the Windy Hill Sandstone in the northern Utah and Wyoming because
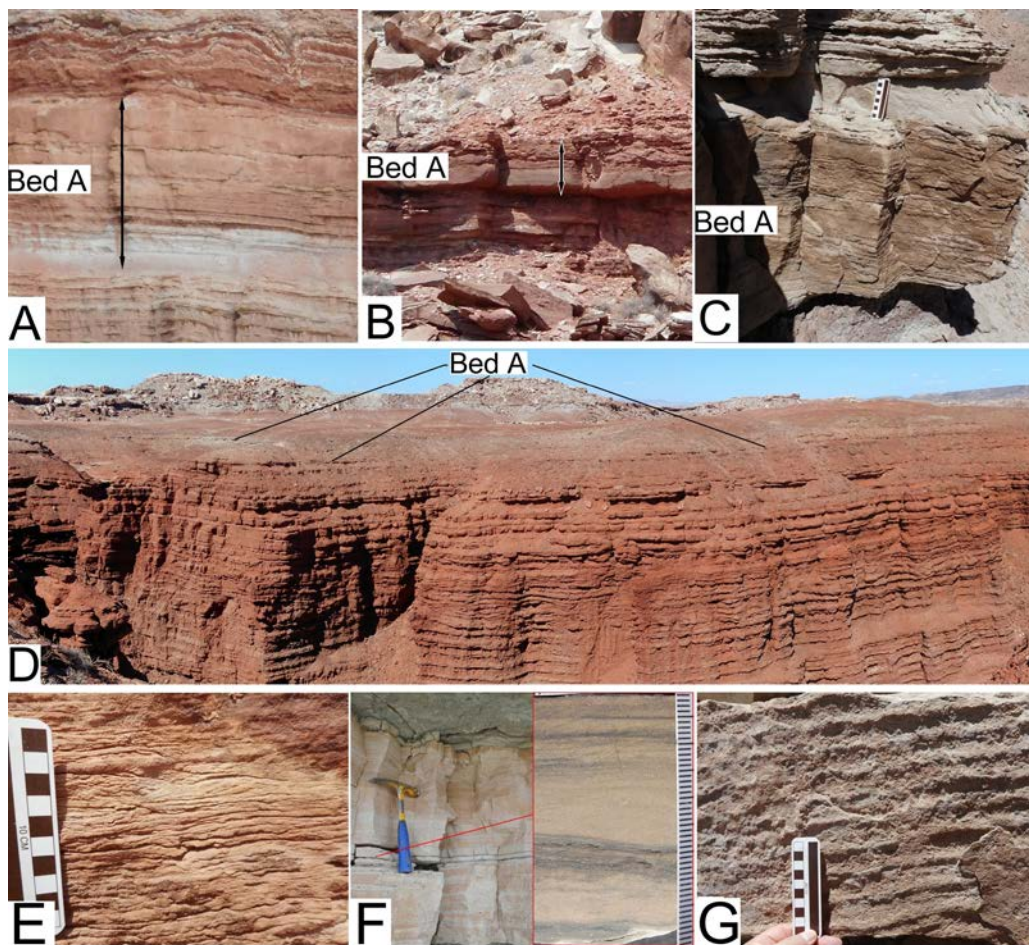
Figure 12. Variations in Bed A. (A) Thin-bedded base below thicker bedded upper part, Notom Junction, Utah. (B) Above thin-bedded Summerville, Duma Point, Utah. (C) Thicker Bed A above the Wanakah, Escalante Canyon, Colorado. (D) Very thin and discontinuous Bed A, Northwestern rim of the White Sand Dunes Recreational Area, Utah (38.8171°, -110.0347°); here the Tidwell and Summerville may be in conformable contact. Structures in Bed A. (E) Wavy lamination in possible fluvially reworked zibar deposit, Duma Point, Utah. (F) Planar laminated, upper flow regime, Lone Cedar Flat, Utah. (G) Ripples with trace fossils, Escalante Canyon, Utah.

both were underlain by the J-5 unconformity of Pieringos and O'Sullivan (1978). In contrast, Holland and Wright (2020) concluded that the base of the Windy Hill is not an unconformity and is a tide-dominated deltaic system that prograded north over the Redwater Shale in Wyoming. Furthermore, the Windy Hill is conformably overlain by the Tidwell in the northern Uinta Basin, eastern Utah (Sprinkel and others, 2019; figure 7, location U, figure 8U). As an important side note, O'Sullivan (2004) corrected previous misidentifications of Bed A, which he had referred to as Bed B located in the middle of the Tidwell, thus moving the contact higher; the stratigraphic significance of this has not always been recognized (e.g., Bernier and Chan, 2006).

Interbedded Thin Sandstone-Siltstone-Mudstone-Limestone-Dolomite Facies Assemblage

The Tidwell Member above the thick gypsum or

Bed A is what typically characterizes the member: thickly laminated to thinly bedded, mostly white, very pale-orange, or pale-greenish yellow, fine- to medium-grained sheet sandstone alternating with various shades of lighter reds, and yellowish-gray siltstone, mudstone, and very light to medium-gray limestone and dolomite (figures 13A and 13B). These lithologies are grouped as an interbedded facies assemblage, hereafter abbreviated the SSMLD facies assemblage, which Peterson (1980b, 1982a, 1982b, 1982c) originally described as the informal "Tidwell unit" in the Henry Basin. Weathering and erosion of this facies assemblage is what typically creates the slope-forming interval between the sandstones of the Salt Wash Member and Summerville Formation. Seen from afar, ignoring color, the thin beds of the SSMLD facies assemblage can superficially resemble the Summerville and Wanakah Formations (e.g., figures 6B, 8A, 8E, 8F, 8K, 8R, and 8S), a point raised by Anderson and Lucas (1998) as reason for including the Tidwell Member in the Summer-
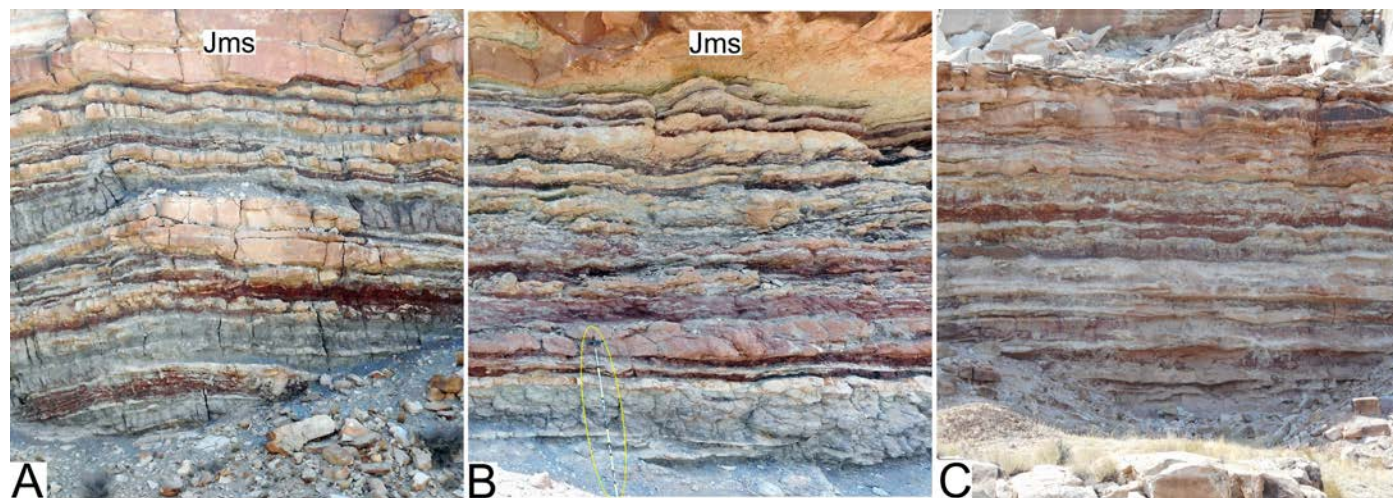
Figure 13. Thin, interbedded sandstone, siltstone, mudstone, limestone, and dolomite facies assemblage of the Tidwell Member: (A) Above the gypsum unit at the type section of the Tidwell Member. (B) At the supplemental reference section of the Tidwell Member at Duma Point. Although these alternating thin bedfacies are considered typical of the Tidwell Member, they in fact also occur within the Salt Wash Member, e.g. (C) Where they are bracketed between two sandstone beds in the Salt Wash Member, Mine Draw, Yellow Cat Mining District (38.8289°, -109.5449°). Jacob staff with alidade holder in B is 125 cm.

ville Formation. However, the SSMLD facies assemblage is not unique to the Tidwell Member, occurring locally between channel sandstones of the Salt Wash Member (figure 13C). In places this facies assemblage in the Salt Wash Member can be traced laterally and become continuous with the SSMLD facies assemblage of the Tidwell Member (see further discussion below in **Contact with the Salt Wash Member of the Morrison Formation** section). These facies assemblages in the Salt Wash Member have been described numerous times, such as by Craig and others (1955), Peterson (1980a), Tyler and Etheridge (1983a, 1983b), Robinson and McCabe (1998) among others.

Details of the interbedded facies assemblage of the Tidwell Member is only visible in fresh exposures or cliff faces (figures 4B, 6B, 8E, 8F, 8P, 8R, 8S, and 8U) because weathering typically creates the characteristic slope that lies between Salt Wash Member and the cliff-forming Summerville Formation (figures 8C, 8I, 8J, 8L, 8N, 8O, and 8Q). In the Henry Basin, the relative proportion of finer-grained strata decrease and thin-bedded sandstones predominate (figures 8A, 8D, and 8E). This presumably reflects a southern source area (Peterson, 1984).

The sheet sandstone component of the SSMLD facies

assemblage are tabular beds, have a thickness measured in decimeters (typically less than 5 dm), and generally composed of fine- to medium-grained sandstones. It is difficult to trace individual beds due to talus, but what can be visually followed along the cliff faces suggests the beds may extend for hundreds of meters and some possibly a kilometer or more. Fisher and others (2007) used a two-dimensional computational fluid dynamics model to show that an unconfined sheet flood can transport sand up to a kilometer across a shallow gradient. Sheet flow is generally not uniform across the surface due to microtopography and vegetation (Abraham and others, 1994), but tends to concentrate as lobes making a bird's foot or bifurcating pattern (Emmett, 1970). A cross section of the lobes would show discontinuous sheet sands on the same surface. Such a morphology is seen in some of the discontinuous thin sandstone beds of the SSMLD facies assemblage (figure 14A). Some of these sheet sandstones can also be traced into small lenticular bodies of sandstone. Sand sheets on opposite sides of a sandstone body were called "wings" by Hirst (1991; Fielding and others 2011; Miall, 2014) and "steer-head channels" by Kjemperud and others (2008). Fielding and others (2011) noted that these wings are distally thinning extensions of the channel margin and
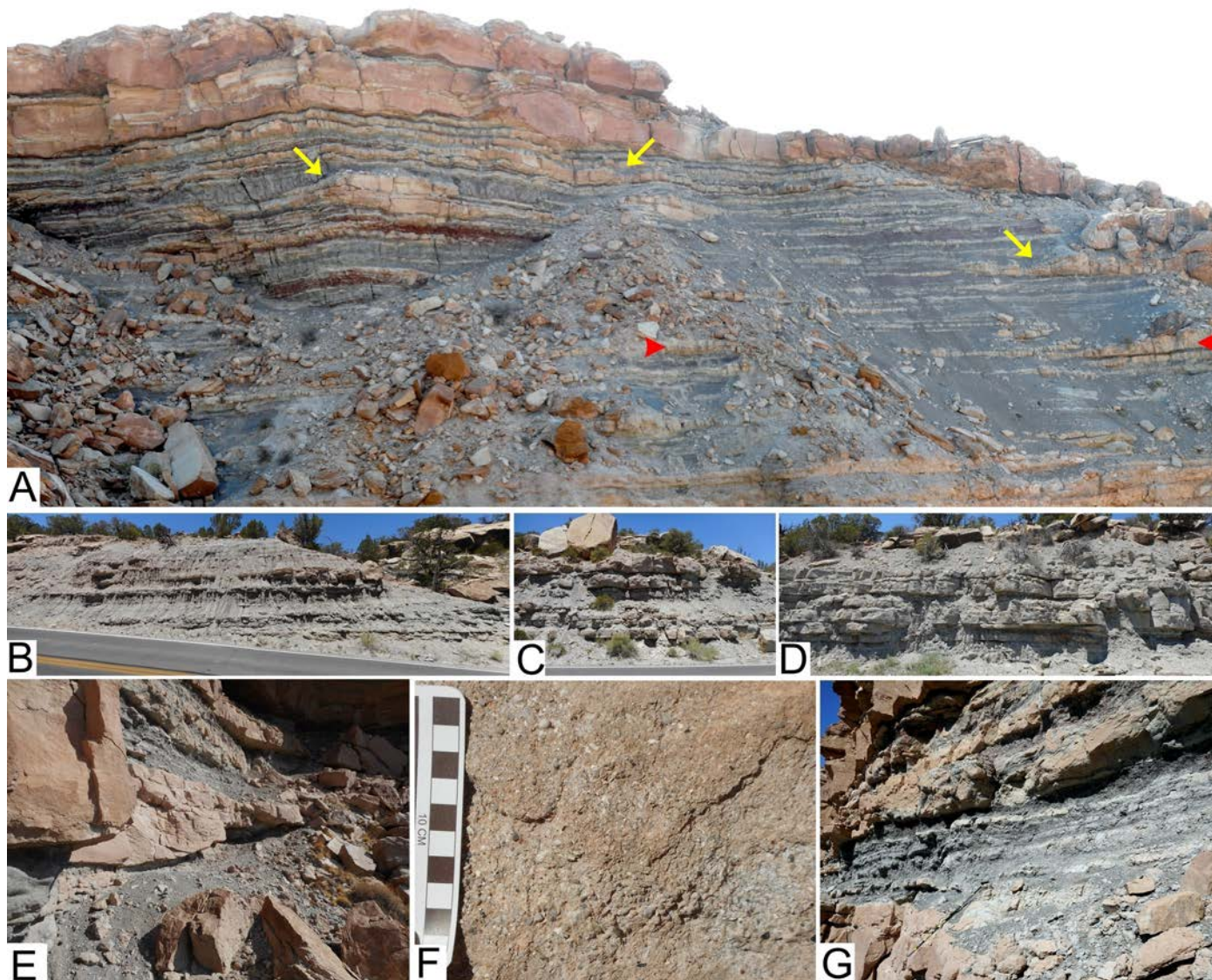
Figure 14. Interbedded sandstone, siltstone, mudstone, limestone, and dolomite facies assemblages. (A) Lenticular sandstone bodies with wings of thin sheet sandstones at their bases (yellow arrows). Also, example of two sandstone bodies (red arrows) connected by the same sandstone sheet at their base. Type locality for the Tidwell Member, Shadscale Mesa (colors enhanced to bring out lithological differences by color, compare with figure 6B). Sequence of roadcuts showing the same coarse-grain overbank deposit (crevasse splay) along Rimrock Drive, Colorado National Monument, Colorado: (B) distal, (C) middle, and (D) proximal (source channel at far right). Sequence is about 160 m long between 39.0700°, -108.7295° and 39.0705°, -108.7282°. (C) and (D) are in adjacent roadcuts, (D) is angled about 30° relative to (C) and (D) because the road curves. (E) Sandstone bed showing sharp upper and lower contacts; sand grains fine distally away from viewer. (F) Predominately white chert pebbles in a coarse-grain sandstone. The sandstone was over 1 m thick and is just to the left off picture of E. (G) Thin beds of limestone interbedded in gray mudstone between orange-weathering sandstone beds.

are characteristic of channel lithosomes of strongly seasonal discharge rivers in dryland environments where the rivers commonly inundate the floodplain with fast flowing water transporting coarse-grained sediments during high-stage flow. Dryland is a collective term for hyper-arid, arid, semiarid, and dry-subhumid environments (Tooth, 2004) and used here because the sedimentary rock record is not always clear as to the climate during sediment deposition. Some of the sandstone bodies with wings appear inverted, with the channel

sandstones convex-upwards and wings extending from their planar bases (figure 14A, yellow arrows). These wings, or sheet sandstone beds may connect multiple convex-upwards channel sandstone bodies (figure 14A, red arrows). Friend (1978) interpreted similar convex-upwards lobes of sand in terminal fan deposits as formed from the loss of flow strength at the margins as the water infiltrated into the adjacent sediment.

Other thin sandstone sheets are crevasse splays. For example, at Colorado National Monument sandstone stacks can be traced laterally into distally thinning and fining sheet sandstones in overbank deposits (figures 14B through 14D). This example is similar to the model of Burns and others (2019) of splays having different breakout times from the same breakout point. These crevasse splays tend to be irregularly spaced in overbank sediments (compare figure 14B with 14A). Other sandstone beds in the SSMLD facies assemblage include lenticular channel sandstone up to 1.3 m thick. These tend to show sharp bottom and top contacts with mudstone (figures 14E and 14G; see Bernier and Chan, 2006, figure 9, for another photographic view). The coarser parts of these beds are composed of angular, coarse-grain quartz matrix, supporting rounded pebbles of mostly light-colored cherts, with some dark cherts and gray limestone, and light-colored carbonate (figure 14F).

Interbedded thin carbonate and non-pedogenetic nodular carbonate beds occur most commonly among gray mudstone and shale intervals (e.g., figures 14G, 15A, and 15B). Some of the limestone beds are wackestones with rounded extraclasts of micrite in a black matrix, a few broken fragments of diplostracan shells, and smell of petroleum when broken (figure 15A). A light etching of the polished surface with dilute hydrochloric acid produced siliciclastic silt-sized grains. Bluhm and Randle (1980) described a sandy limestone from east of Ferron, Emery County, Utah, as composed of 84% sparitic and micritic calcite; 13% very fine to fine-sized, subangular to subrounded, single-grain quartz; 1% or less of chert, opaques, and feldspar (microcline, plagioclase, and perthite); and trace amounts of muscovite, biotite, tourmaline, and zircon. About 4 km farther southeast, three other limestone beds were 51% to 97% sparitic and micritic carbonate, and have up to 20%

fine- to granule-sized, subangular to subrounded, microcrystalline chert, with macro-quartz, remnant carbonate, chalcedony, and opaques; less than 1% to 30% chalcedony as secondary replacement of carbonate or as vug fillings; 2% to 15% silt- to coarse-sized, subangular to subrounded, single and polycrystalline quartz; up to 10% medium- to granule-sized, subrounded carbonate and mudstone clasts; and less than 1% altered potassium feldspar, opaques, and tourmaline.

Micrites often show microtubules presumably of roots and may either be hollow (figure 15B) or filled with calcite. Some of the bedded carbonates that do not react well with hydrochloric acid are presumed to be dolomitic. These beds may be primary in origin because the mineral is an early precipitate in the evaporative mineral precipitate sequence (Warren 2016).

Domed microbialites associated with lacustrine limestones have been reported by Kjemperud and others (2008). They have also been reported from Grand County between the Blue Hills and Duma Point by Kirkland and others (2020), and from the northern Capitol Reef National Park and the Fruita Paleontological Research Natural Area by Kirkland (Utah Geological Survey, written communication, September 23, 2021). Unfortunately, none of these specimens have been described in the detail comparable to that of Neuhauser and others (1987) for specimens from the Morrison Formation of northeastern New Mexico. Thus, it is not known if these are stromatolites or thrombolites (layered or clotted) microbialites (Kennard and James, 1986).

Lacustrine shales also occur in the SSMLD facies assemblage (figure 15D), although these are less abundant than laminated siltstone and fine-grained sandstone beds (figures 15E and 15F). The shale at the Kane Springs roadcut (figure 7, locality P) is composed of dark gray silt-clay couplets, which presumably reflect silt input by individual sheetwash into ponded water followed by mud drapes as the water calmed between events. The yellow mineral stain is probably jarosite, which is indicative of stagnant water after iron depletion is completed (Vepraskas and Vaughan, 2016).

Good (2004) reported the unionid bivalve *Vetulonaia* sp. from lacustrine mudstone in the Tidwell Member. He inferred optimum conditions for growth, including abundant plankton, a constant supply of clean, well-ox-
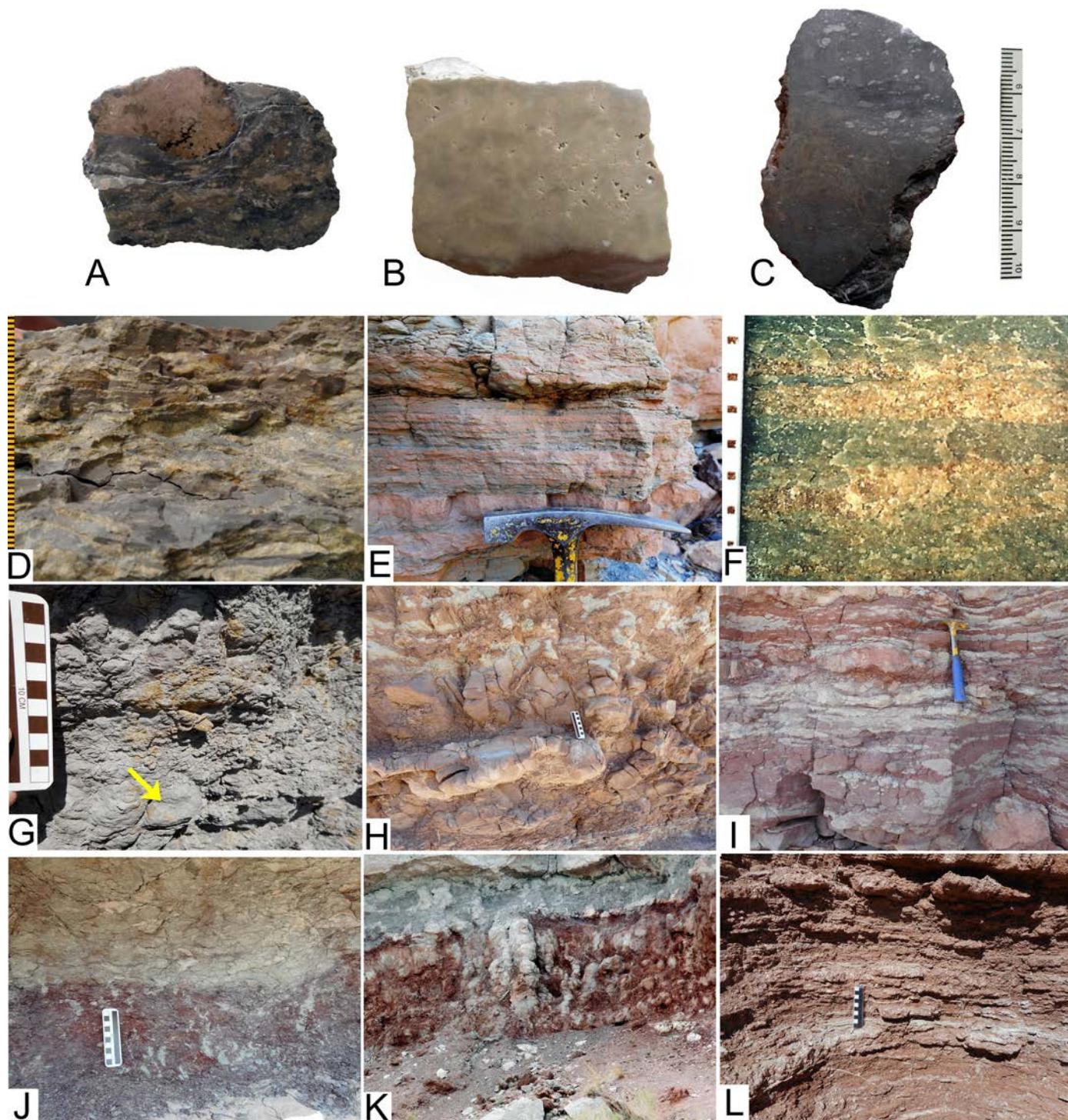
Figure 15. Caption is on the following page.

ygenated, warm, carbonate-rich water having a pH greater than 7, and less than 7 m deep. The absence of growth banding implied continuous growth in a stable, non-seasonal environment, a point cited by Owen and others (2017) as indicating a uniform and stable cli-mate during deposition of the Tidwell sediments. These unionid clams also include those previously reported by Yen (1952; Emmett Evanoff, University of Northern Colorado, written communication, February 6, 2021) as the holotype of *Unio stewardi utahensis* from his locality

Figure 15 (figure is on the previous page). Tidwell carbonates. (A) Extraclasts in a black micritic matrix from lowest limestone in figure 14G, near the type section. (B) Lightly mottled micrite with microtubules from Fremont River, Utah (figure 8F). (C) Carbonate mudstone nodule from paleosol in G; gray specks are small, abraded carbonate grains, and orange tint is part of the diffused iron mass seen in G. Lacustrine or paludal rocks: (D) shale of silt and clay couplets, with sulfide stain (probably jarosite), US 191 roadcut, Kane Springs Canyon, Utah (figure 8P). (E) Laminated siltstone, San Miguel River, Colorado (figure 8R). (F) Detail of laminated siltstone from (E); scale in mm. Paleosols: (G) Gleysol with carbonate cemented nodules and diffuse iron, type Tidwell; arrow is the specimen in A. (H) Stage II carbonate nodules in a Calcisol, upper Tidwell, Escalante Canyon, Colorado (38.7375°, -108.2679°). (I) Calicisols with stage II and III carbonate nodules in siltstone beds near Duma Point, Utah (figure 4). (J) Protosol underlying a channel sandstone. The upper part is a high-chroma, silty, eluviated horizon containing gypsum seams, diffuse iron mass, and irregular carbonate nodules; it is in sharp contact with the mottled red, purple and gray Bk horizon with diffuse and irregular silty carbonates nodules, and pale iron depletion along root channels at the type section of the Tidwell Member. (K) Rhizoconcretions in a Protosol Bk horizon with an upper bleached zone underlying a channel sandstone, I-70 roadcut, Mulligan Wash, Utah. (L) Gypsisol with multiple horizons of gypsum formed in the vadose zone of a playa margin, west of White Sand Dunes Recreational Area, Utah (38.8173°, -110.0605°).

23, southeast of Green River City (figures 16A through 16M). The site was originally discovered in 1943 by Harold Ernest Vokes, who, at the time was the senior geologist for the USGS prospecting for uranium in the Green River Desert (Vokes, 1998). The site was relocated by me using information provided by Yen (1952, p. 31) and was discovered to be in a crevasse splay deposit underlying the basal most Salt Wash sandstone (figure 16P). The sediments fine distally (eastwards) and vertically. Most likely this splay deposit preceded a later avulsion of the channel represented by the overlying sandstone, thus technically the splay deposit belongs with the Salt Wash Member rather than the Tidwell Member. The fossiliferous part of the splay deposit extends 28.5 m (figure 16P, between the yellow arrows) and has been altered by pedogenesis, especially distally where it is mottled red and gray (figures 16Q through 16S). Many fossil clams are in horizontal position, but others are at various angles, including vertical on its lateral edge (figure 16R, #1), hinge-side up (figure 16R, #2), and oblique through the sediments (figure 16S, #1). Shells include single valves and paired closed valves, many of which are collapsed from compaction of the encasing sediments. Single valves are both in current stable and current unstable positions.

Although Good (2004) reported the absence of annual banding in *Vetulonaia* as indicative of continuous growth in a well-oxygenated, warm, stable pond, other specimens (e.g., figure 16N) show annual banding of various widths (figure 16O) indicative of an unstable environment as would be expected in a fluvial system in a seasonal environment (Demko and others, 2004).

Except for a wide growth band indicating a spurt of rapid growth, most bands are narrow to very narrow indicating growth in suboptimal environmental conditions (Mutvei and Westermark, 2001). I did not analyze these shells for seasonal variation of manganese as is known to occur in modern unionids subjected to oxygen depletion and eutrophication (Mutvei and Westermark, 2001). Such an analysis would resolve the issue of water quality for early Morrison time.

Although these fossil unionid clams occur at the base of the Salt Wash Member, their presence in east-central Utah is significant for the Tidwell because they support the sedimentological evidence for seasonality in a dryland environment during early Morrison time. Furthermore, assuming unionids of the Morrison Formation had already evolved a parasitic larval phase (glochidium) on a fish host as is known to occur today (Wächtler and others, 2001; Watters, 2001), then we may assume that freshwater fish were present in the Salt Wash fluvial system as well, despite the absence of fossils. However, a parasitic larval stage at this early time of unionid evolution is far from certain (Watters, 2001).

Paleosols are very prominent in the interbedded mudstone intervals of the SSMLD facies assemblage. Originally many of these strata were referred to as lacustrine deposits (e.g., Peterson, 1978, 1980a), but some were later identified as paleosols by Demko (1998; Demko and others, 2004). Ali-Adeeb (2007) reports Calcisols and silicified Calcisols at the top of the Tidwell east of the town of Moore south to Cathedral Valley, which contain questionable "mammals burrows," carbonate nodules, and rhizoconcretions. Ejembi (2018)
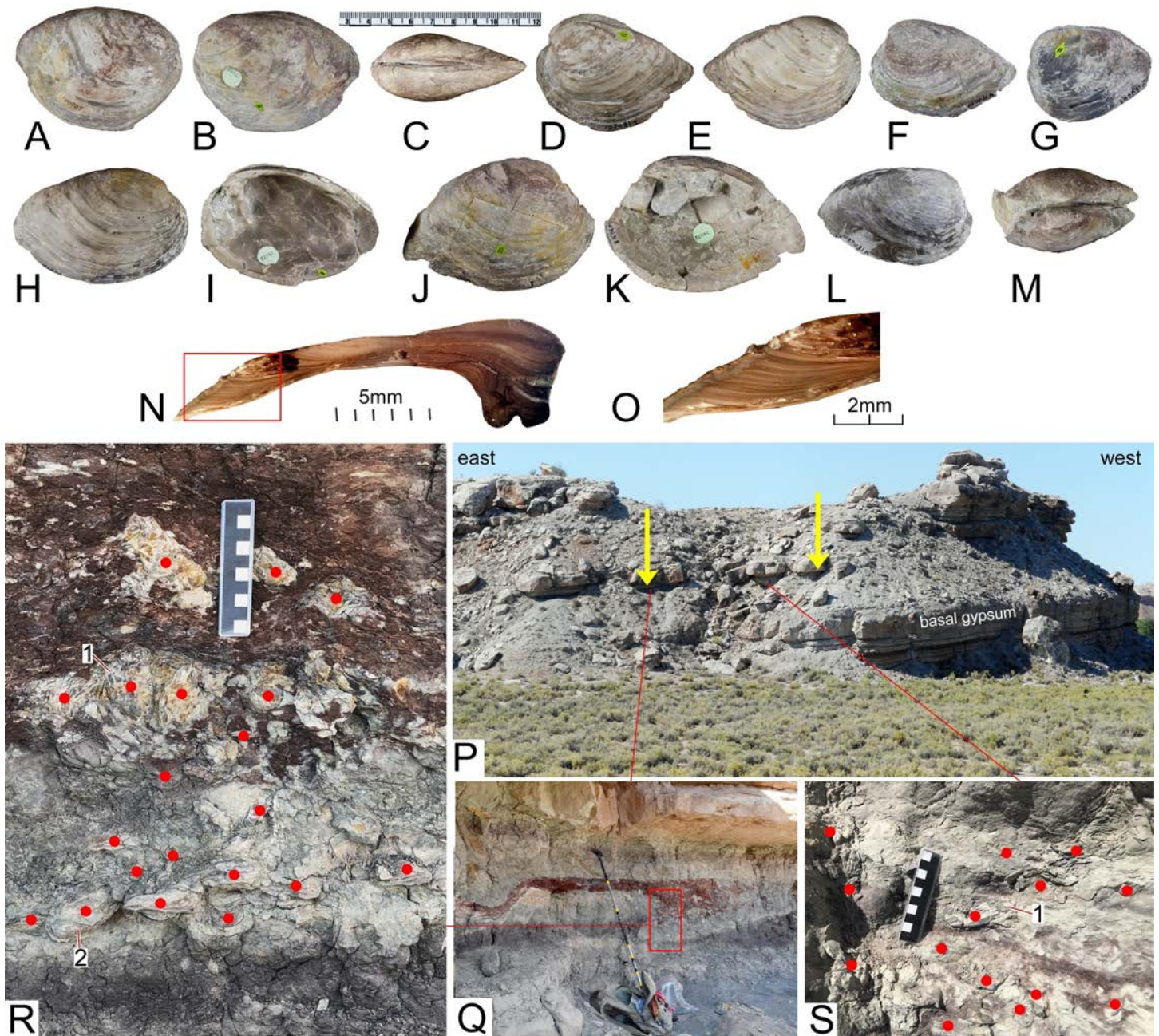
Figure 16. Bivalves supposedly from the Tidwell Member southwest of Green River, Utah. The specimens show a high degree of plasticity in shell morphology that is typical for the unionid clams. *Vetulonaia* sp.: (A–C) USNM PAL 106989 (holotype of *Unio stewardi utahensis* Yen, 1952, probable female shell morphology); (D–E; J–M) USNM PAL 107031 (paratypes of *Unio stewardi utahensis* Yen, 1952), (H–I) USNM PAL 106990 (paratype of *Unio stewardi utahensis* Yen, 1952, probable male shell morphology). (N) Longitudinal cut showing annual banding (FHPR 17808). (O) Close-up of box in (N) showing wide and narrow annual banding. (P) Distant view of the bivalve locality (38.8689°, -110.3685°). Specimens occur beneath the sandstone between the yellow arrows; none occur in deposits at the far left. (Q) View of the crevasse splay beneath the channel sandstone. (R) Pedogenically modified distal crevasse splay. Red dots are bivalves: 1, specimen standing on lateral edge, and 2, specimen hinge up. (S) Pedogenically modified more proximal crevasse splay. Red dots are bivalves: 1, specimen extending oblique through sediments. A–M courtesy of National Museum of Natural History, Smithsonian Institution.

reports Vertisols, Gleysols, Oxisols, and Protosols in the Paradox Basin on the east side of the Colorado Plateau. The paleosols indicate periods of landscape stability between episodes of major sheetfloods. Gleysols (wetland soils) are preserved in many of the mudstone intervals at the type section and typically are very light gray to dark gray, subangular, blocky, coarse granular paleopeds, and contain mudstone carbonate nodules (figures 15C and 15G). The orange iron mass of a redox concentration (figure 15G) is the result of anaerobic soil becoming aerobic again (Vasilas and others, 2010). Gleysols also occur near Hanksville, Utah (figure 8F). More commonly, the paleosols tend towards a higher chroma (figures 15H and 15I) indicative of well-drained soil profiles. These are usually Calcisols (figures 15H and 15I) developed in siltstone intervals. Carbonate nodules are common, although not all react with hydrochloric acid in the field and are assumed to be dolomitic. The reaction of other nodules ranges from weakly calcareous to strongly calcareous as defined by Retallack (2001). Both Stage II and Stage III nodule development (Mack and others, 1993; Tabor and others, 2017) may be present indicating moderately to strongly developed paleosols. Early Stage II nodules have diffuse edges and some may be rhizoliths (figure 15J).

Rhizoconcretions can be extensively developed, especially in underlying channel sandstone beds (figure 15K). These rhizoconcretions, as stacked coalesced nodules (Blodgett, 1988) in the I-70 roadcut near Mulligan Wash, Utah, suggests the presence of extensive vegetation at least in the vicinity of channels prior to their avulsion over the site. Such vegetation explains the presence of large vertebrate herbivores (Bernier and Chan, 2006) in an otherwise inhospitable environment. Excluding the massive gypsum bed to be discussed separately, Gypsisols are especially common in marginal playa strata lateral (distal) to large gypsum beds (discussed separately below). Vertically aligned lenticular crystals grew displacively in the siliciclastic muds near the top of the water saturation zone of the groundwater table where evaporation is highest (Rosen, 1991). These may be seen, for example, in the band above the scale in figure 15L. Gypsum growth can also take place between lamina deposited by sheetwash (Hardie and others, 1978), also shown in figure 15L. Gypsum can also

be deposited in the vadose zone through evaporative pumping (capillary wicking) pulling subsurface brines towards the surface. These gypsums include small spheres or nodules, which may merge into botryoidal layers (figure 15L, lower left).

Geochemical analysis of mudstone beds shows a magnesium spike at the base of the Tidwell Member in the southern Henry Basin (Northrop and others, 1990b). In addition, the mudstones contain sulfur as pyrite, gypsum, and barite (Northrop, 1982; Northrop and others, 1990a); pyrite was also identified in mud clasts that occur as lenses in cross-bedded sandstones in the Tidwell Member. Most of these mud clasts are derived from bank collapse or bank erosion (Karcz, 1969, 1972; Li and others, 2017) despite being commonly called "rip-up clasts," and their greenish color indicate the floodplain source within a reducing environment.

Contact with the Salt Wash Member of the Morrison Formation

Throughout the Colorado Plateau, the Salt Wash Member of the Morrison Formation overlies the SSM-LD facies assemblage of the Tidwell Member. O'Sullivan (1984a) placed the contact between the two units at the base of the lowest channel sandstone that is a part of a continuous zone of channel sandstones. Peterson (1988a) states that the Tidwell and Salt Wash Members interfinger, but the evidence presented is based on interpretated relationships between measured sections (Peterson, 1988a, figures B10, Bl1, B13, and B21). Anderson and Lucas (1998) argue that the evidence for interfingering is non-existent and that the basal sandstones of the Salt Wash Member are in an irregular unconformable contact with the underlying Tidwell strata. This indeed is true for the most part (figures 4B, 6B, 8B, 8C, 8E, 8F, 8J, 8K, 8M, 8O, 8P, 8R, 8S, 8U) and in places the Salt Wash Member is incised deeply into the Tidwell Member. In contrast, Maidment and Muxworthy (2019) separate the Tidwell and lower Salt Wash Members by a sequence boundary. Such a boundary is not supported here as evidenced by the interfingering between the Tidwell and Salt Wash Members, such as seen in a roadcut southwest of Green River, Utah, where thin crevasse splay sandstones can be traced from a Salt Wash sandstone body

into the SSMLD facies assemblage of the Tidwell Member (figure 17A and 17B) or where the uppermost thin-bedded sandstone bed of the Tidwell Member can be traced into the Salt Wash sandstone (figure 17C). Robinson and McCabe (1998) also noted interfingering over a 2-meter interval in the Lost Springs Wash and Bullfrog Creek located in the southern Henry Basin. Gradational contact is inferred for thickening upwards of thin bedded sandstones immediate below Salt Wash sandstone (figure 17D). These examples of interfingering and gradational contact imply a depositional relationship between the Tidwell and the Salt Wash Members (Peterson, 1988a: Kjemperud and others, 2008; Owen and others, 2015b, 2017; Hagen-Kristiansen, 2017).
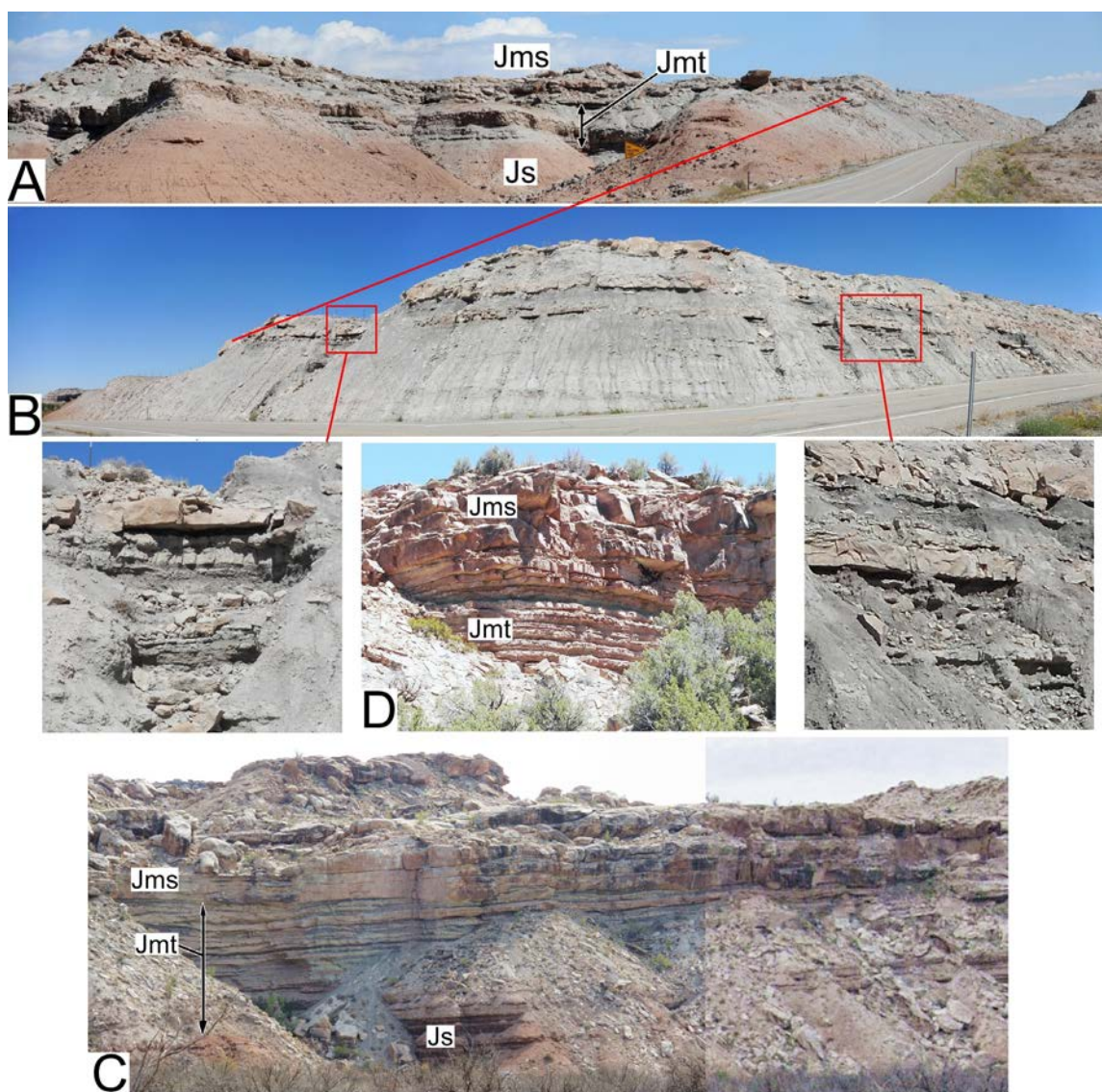

Figure 17. Interfingering between the Tidwell Member and Salt Wash Member east of Shadescale Mesa. (A) Showing the outcrop context of the Summerville Formation, Tidwell Member, and Salt Wash Member. (B) The interfingering, as thin crevasse splay sandstones, is seen in the roadcut along State Highway 24 (38.8636°, -110.3685°). For orientation, a red line connects the same prominent Salt Wash sandstone bed in (A). Red boxes show location of close-ups of the strata. (C) Another example of interfingering on the north side of Shadescale Mesa (38.9196°, -110.4019°). The thin sandstone beds of the Tidwell Member originated as crevasse splays from the Salt Wash Member. (D) Gradual contact between the Tidwell and Salt Wash Members is seen as thickening upwards thin sandstone beds of the Tidwell Member (south of Uravan, Colorado, 38.3595°, -108.7146°). Abbreviations: Jms – Salt Wash Member, Jmt – Tidwell Member, Js – Summerville Formation.

Controversial Gypsum Facies

The gypsum beds of the Summerville Formation and the thick gypsum beds between the Summerville and the SSMLD facies assemblage of the Tidwell Member have not been given the attention they deserve, despite gypsum being a key point for the placement of the boundary between the Summerville and Morrison Formations (Lupton, 1914; Mullens and Freeman, 1957; Trimble, 1976; Trimble and Doelling, 1978; Bluhm and Rundle, 1980; Anderson and Lucas, 1992, 1994, 1998; Lucas and others, 2006; Lucas, 2014). This lack of study seems to be due to the mistaken impression that the gypsum beds are homogenous units deposited in hypersaline environments, which have been interpreted as restrictive marine, sabkhas, or evaporative basins (Imlay, 1980; Peterson, 1986, 1994; Peterson and Turner-Peterson, 1987; O'Sullivan, 1992a; Kirkland and others, 2020). Or, in the case of the gypsum of the Tidwell Member (in the sense of Peterson, 1988a), as a Gypsol created from mobilization of gypsum from the underlying Summerville Formation (Demko and others, 2004). Although gypsum can be altered through dissolution and reprecipitation (e.g., Hussein and Warren, 1989; Warren, 2016), unless deeply buried at some point in their history, the original texture may be retained (Magee 1988; Rosen, 1989, 1991; Schreiber and others, 2007), as well as preserve primary structures (e.g., vertebrate tracks, Bennett and others, 2021). These attributes are important for allowing the interpretation of the gypsum beds and gypsiferous strata of the Summerville Formation and the thick gypsum beds at the Summerville Formation-Tidwell Member boundary on the west side of the Colorado Plateau. These gypsums are described in detail below and show that they formed in different environments.

Gypsum of the Summerville Formation

Gypsum is present locally in the Summerville Formation as beds, seams, and nodules, but it is not ubiquitous and was not used to define the Summerville Formation by Gilluly and Reeside (1927, p. 80: "the even-bedded red and white sandstones and maroon shales of the Summerville formation, so named…"). See also Scott and others (2001). Gypsum in the Summerville is more common on the west side of the Colorado Plateau where the late Middle to early Late Jurassic Elko foredeep developed east of the Elko uplift (Peterson, 1994; Thorman and Peterson, 2003; Thorman, 2011; Thorman and others, 2020).

Elsewhere on the Colorado Plateau, gypsum is less common in the Summerville Formation, but it is locally present in the Wanakah Formation in the eastern part of the Colorado Plateau and adjacent areas (O'Sullivan 1992a; Burbank and Luedke, 2008). These gypsum beds were interpreted as marginal marine based on sulfur isotopes (O'Sullivan, 1992a). This interpretation is supported by the limited fossil evidence indicating a marine incursion (O'Sullivan and others, 2006).

Gypsum nodules may occur along bedding planes and exhibit varying textures. The nodules may be roughly spherical, but are commonly botryoidal (figure 18A). Some of the nodules show displacive growth where clay and silt are crowded towards the margins as gypsum crystals grew diagenetically within the substrate producing what is called "chicken wire" texture (figure 18B). Other nodules are of pure gypsum and have a granular texture of equant, anhedral crystals (figure 18C). Such texture may be the result of rapid precipitation in solutions supersaturated with gypsum under the influence of mutual interference (Jafarzadeh and Burnham, 1992). The anhedral crystals are probably not tertiary evaporite textures created by partial bed dissolution in the near surface weathering zone (Warren, 2016) with the recent uplift of the San Rafael Swell because the texture extends to the core of even the largest nodules. Some gypsum beds also are composed of vertically elongated, tightly packed pelloids that show displacive growth in the substrate (figure 18D), whereas other beds are composed of silt- to fine-sand sized clear gypsum grains (grainstones; figure 18E). Very thin, vertical to diagonal tertiary satin spar gypsum seams are locally common in the near surface weathered zone (figure 18F) and may occur in the absence of other forms of gypsum.

The gypsum of the Summerville Formation is most similar to gypsum of the marine Middle Jurassic Piper Formation in the Bighorn Basin, Wyoming (Imlay, 1980). The similarities include being laterally extensive, and having granular texture (figure 18G) and "chicken wire"
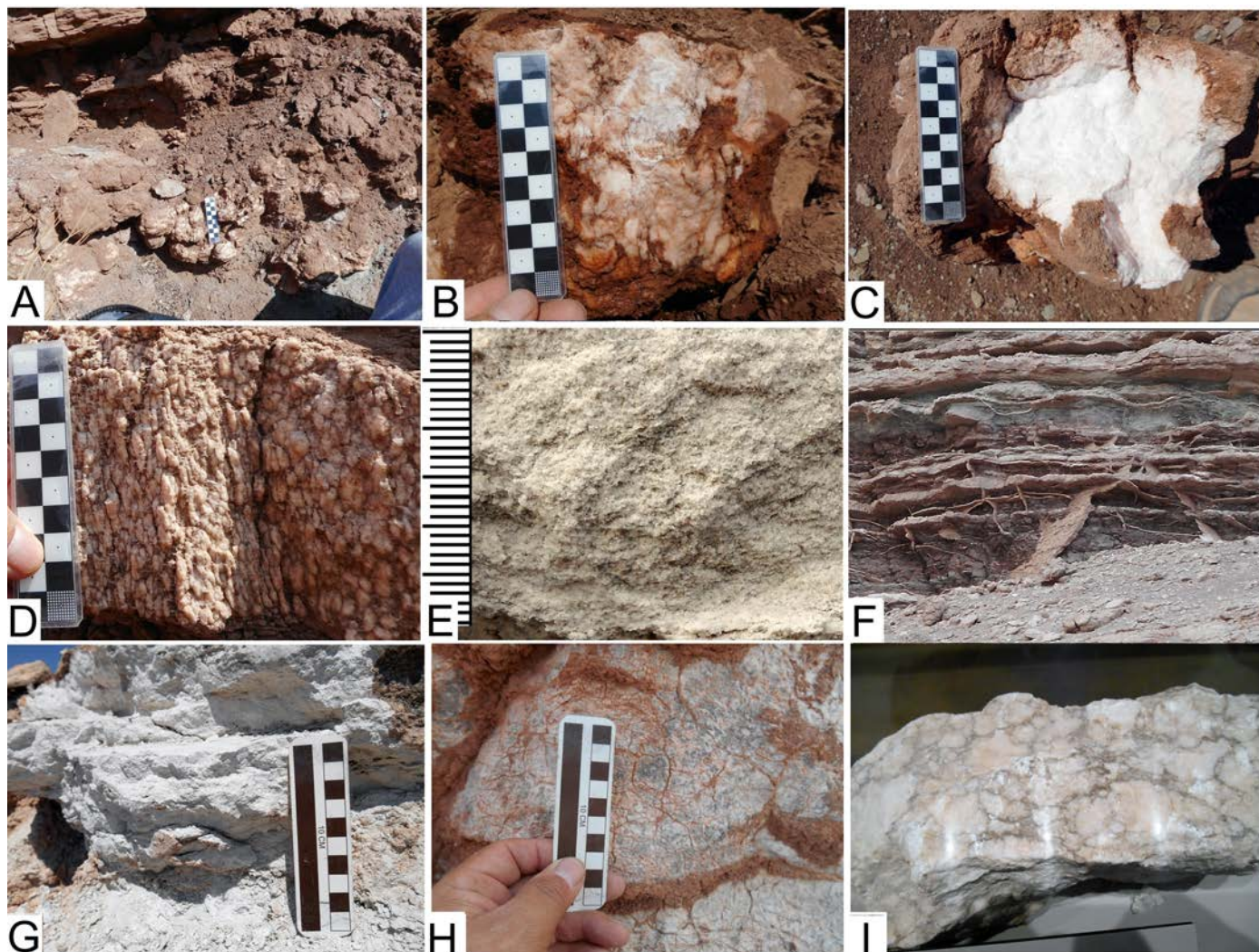
Figure 18. Similarities between the gypsum of the Summerville Formation (A–F) and the gypsum from the marine Piper Formation, Bighorn Basin, Wyoming (G–I). (A) Bed of nodular gypsum, Woodside anticline (39.1831°, -110.4137°). (B) Nodular gypsum showing weakly developed "chicken-wire" texture of displacive growth (sample wetted with water); sample location as A. (C) Nodular gypsum with granular texture, Woodside anticline (39.1927°, -110.3958°). (D) Pelloidal gypsum with displacive growth, middle Summerville, Shadscale Mesa (38.8855°, -110.4464°). (E) Bed of granular gypsum, approximately 24 m above the base, Shadscale Mesa (38.8887°, -110.4437°). (F) Gypsum seams parallel and cross-cutting to bedding, Shadscale Mesa (38.8890°, -110.4435°). (G) Bed of granular gypsum, Piper Formation (45.0199°, -108.4586°). (H) Gypsum showing "chicken-wire" texture of displacive growth, upper Piper Formation (45.0113°, -108.4470°). (I) Cut and polished gypsum showing "chicken-wire" texture of displacive growth (NH.101.11, Draper Museum of Natural History, Cody, Wyoming); bright flares are reflections of display lights. Scales in cm, except E in mm.

texture of displacive growth (figures 18H and 18I). These similarities with the gypsum of the Piper Formation, but in contrast with gypsum of the Tidwell Member described below, suggests that the gypsum of the Summerville Formation had a similar origin as the gypsum in the Piper Formation, i.e., a broad coastal intertidal and supratidal sabkha. In such a depositional setting, renewal of groundwater tidally as well as by seawater infiltration is irregular allowing the underground water to reach the saturation point for gypsum through evaporative pumping at the surface in a warm or hot dryland environment (Al-Youssef, 2014; Warren, 2016). Gypsum may also precipitate beneath algal mats in the intertidal zone within the sabkha (Al-Youssef, 2014).

Gypsum Beds at the Summerville Formation– Tidwell Member Boundary

Thick beds of gypsum occur above the red, thinly bedded Summerville Formation and below the SS-MLD facies assemblage of the Tidwell Member. These gypsum beds are up to 14 m thick and are restricted to the western part of the Colorado Plateau, from the San Rafael Swell to the Henry Basin. Unlike the laterally extensive gypsum beds and gypsiferous facies of the Summerville Formation, these gypsum beds may be laterally discontinuous, show rapid facies change, and have a heterogenous structure, which can be illustrated by three examples.

The first example is gypsum exposed at the southwestern corner of Shadscale Mesa where rock fall created a right-angled notch. This notch is located 1 km west of the type section for the Tidwell Member (location H on figure 3C and figure 19A). This feature, here called "The Notch," formed between 15 August, 1994 and 19 August, 1998 based on dates of aerial photos (see **Acknowledgments**). Unlike most gypsum exposures, which are weathered so that only gross features are visible due to gypsite formation (figures 19B and 19C), the gypsum exposed in The Notch is more pristine. Slight weathering has, however, etched the gypsum bringing out relief and detail showing that the gypsum formation here had a complex depositional history. In contrast, weathering of a roadcut in a similar thick gypsum along I-70 has obliterated much of the internal structure (figure 19C). This roadcut was made between 1964 and 1966 based on aerial photographs (see **Acknowledgments**) and provides an indication of the rate of gypsum weathering.

The base of the gypsum facies at The Notch is in sharp contact with the underlying fine- to medium-grained, moderate-red sandstone of the Summerville Formation. The contact is irregular, with several centimeters of relief (figures 19D and 19E). A thin pale-green bleached zone (about 1 cm thick) is present at the top of the Summerville and similar zones occur throughout that formation. The Summerville Formation is eroded beneath the gypsum, exposing the undersurface of the gypsum facies. This surface preserves traces of a boxwork of thin gypsum that formerly extended down into vertical cracks in the Summerville. In a few places, the undersurface of the gypsum where it is undercut is nodose or lumpy, with nodes a few centimeters in diameter.

The lower part of the gypsum facies consists of stratified gypsarenite, which is best seen on the southeast wall of The Notch (figure 19E). Bedding is well developed and includes laminations (figures 19F and 19K), cross laminations (figure 19I) and crossbedding of aquatic dune migrations (figure 19K). These beds are bracketed by bounding surfaces (e.g., figure 19K arrows). Also sitting on bounding surfaces are oblate gypsum spheres with flattened bottoms (figures 19E and 19H). These gypsum spheres have an aphanitic internal fabric of leiolites (structureless microbialites) and the flattened bottoms indicate that these microbialite domes grew in situ in a shallow (less than 1.5 m) perennial saline lake. There is no evidence that the domes were exposed subaerially for extended periods (De Deckker, 1988; Bąbel, 2004; Riding, 2011; Farías and others, 2014; Rasuk and others, 2014; Warren, 2016; Herrero, 2019). The aphanitic fabric is probably not due to secondary diagenesis because the surrounding gypsarenite shows no loss of texture. Instead, the fabric indicates continuous accretion (Braga and others, 1995; see contrasting interpretation by Riding, 2000). The elongate shapes suggest that the domes grew parallel to the dominate water flow direction as indicated by cross-bedding of the gypsarenite (Bąbel and others, 2011). Gypsarenite supported small, irregular gypsum blocks and spheres (figure 19E), which are probably reworked fragments and possibly small, displaced leiolites (figure 19J). Stratification of the gypsarenite is distorted in places (e.g., figure 19F), especially around leiolites (figures 19E and 19H).

The upper part of the gypsum facies on the wall of The Notch shows a gradual change in the saline lake. There is an abrupt absence of cross-bedding accompanying a change from reddish-colored gypsarenite to gray (figure 19E) that appears to indicate an increase in detrital clay, although this was not confirmed by thin section. At the top of the gray horizon are what appear to be small (about 6 to 10 cm tall), tightly packed, flat-topped columnar thrombolites (figure 19L). The contact between the two layers is irregular and the bases of the thrombolites fade into gray layers at staggered intervals
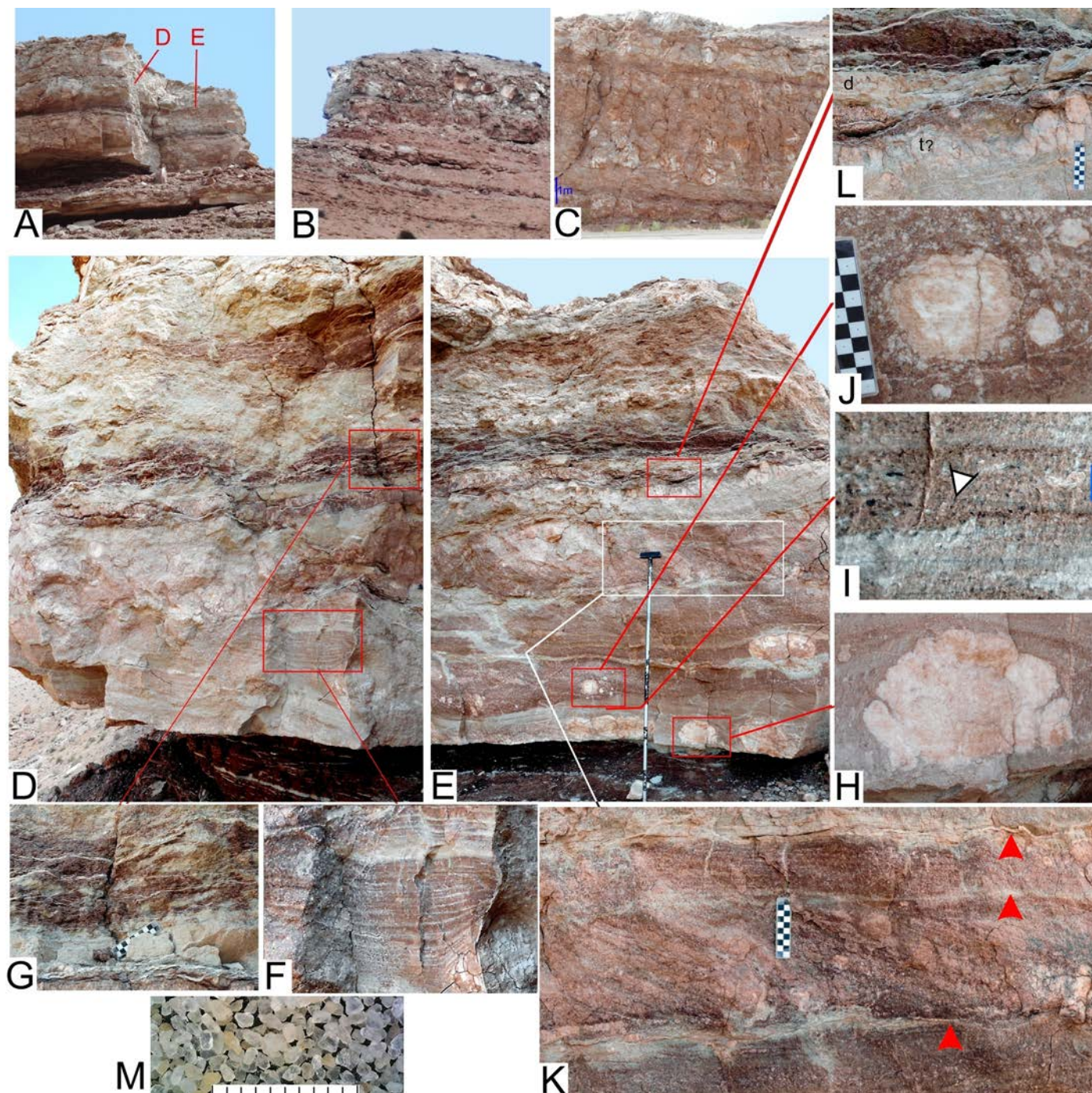
Figure 19. Caption is on the following page.

indicating that the start of their growth was not simultaneous. These possible microbialites were buried by an influx of fine-grain clastic sediment within which vertically aligned gypsum later grew. This type of gypsum shows the characteristic displacive crystallization fabric of tightly packed competitive gypsum formation from

playa groundwater (Rosen and Warren, 1990a, 1990b; Warren, 2016). Alternating light and dark bands of very thinly bedded or thickly laminated gypsum (figure 19F) is reminiscent of similar bands in modern playa environments, such as Salt Flat Playa in West Texas (figures 20A and 20B). The influx of fine-grain clastic sed-

Figure 19 (figure is on the previous page). "The Notch" on Shadescale Mesa, Emery County, Utah (38.8843°, -110.4456°). (A) The Notch, D is the face shown in (D), E is the face shown in (E). (B) South side showing the deeply weathered face of the gypsum. (C) Deeply weathered thick gypsum in a roadcut along I-70; the cut shows the extend of weathering in just over 55 years (vertical white streaks are remnants of drill holes). (D) North face of The Notch, which is more weathered than the east face suggesting that this face formed part of a fissure allowing weathering for many years before the rockfall. (E) East face showing the more pristine gypsum face. (F) Bedded gypsarenite distorted around a leiolite in the lower right corner. (G) Close-up of shale layer on north face (see L). (H) Close-up of an in situ leiolite. (I) Close-up and color-enhanced gypsarenite with dark clay and chert detritus. Arrow indicates cross-bedding. Blue bar = 3 cm. (J) Grain-supported larger fragments of gypsum (including a small leiolite?). (K) Cross-bedding in gypsarenite and bounding surfaces (arrows). (L) Possible thrombolites (t?) at the top of a gray gypsarenite (clay enriched?) and below red and gray mudstones with a thin dolomite layer (d) and gypsum seams. Note patch of vertically aligned gypsum showing displacive growth on far-left side below dolomite. (M) Eolian sand from layer 2; scale in 0.01 mm increments.

iments is seen in several thin beds (figure 19G) and on the weathered face where they separate thicker gypsum beds (figure 19A). The lower clastic influx has a thin layer of dolomite, which becomes thicker on the north wall, indicating a period of standing water. The uppermost part of the east wall is difficult to discern due to weathering, brecciation and possible mobilization and redeposition of gypsum. Dissolution of a small fragment of gypsarenite (using the sodium citrate solution method) from the lower part of the east wall produced a residue of very well sorted, sub-angular to rounded quartz of sand that was windblown into the playa (figure 19M). The changes in in the lake may be related to inflow volume and change in water chemistry. Warren (2016) associated such changes to a change in climate, fluvial supply, and/or tectonics.

The second example is the peripheral playa facies 0.5 km north and across a box canyon (figure 21A). The deposits, nicknamed "The Road," occurs adjacent to a uranium prospecting road built between 13 September, 1952 and 9 October, 1955 (based on dates of aerial photographs) during the peak of uranium prospecting on the Colorado Plateau. The thick gypsum unit can be physically traced around the canyon to The Notch (figure 21B). The peripheral playa facies occur in the lower part of the gypsum cliff (figure 21C) and are overlain by thick gypsum beds that are weathered. The peripheral playa unit consists of lithofacies, which are, in ascending stratigraphic order, (1) a basal muddy interval, (2) thinly bedded interval, (3) a thicker gypsum interval, (4) cross-bedded sandstone interval, and (5) a massive, weathered gypsum interval. The basal muddy, gypsiferous claystone and sandy mudstone interval is

in scoured into the underlying Summerville Formation (figure 21D). The basal bed also contains several lags of small gypsum pebbles (figure 21E) that are similar in size to those produced in a modern playa (figure 20C) and indicate the pebble lag originated from reworking of playa sediments. Several dolomitic boulders occur higher in the interval, including a large one that is about 32 cm in diameter, with the overlying gypsum layer deformed over it from compaction (figure 21F). To move this boulder, water velocity is roughly estimated as 0.7 m/s using the Gauckler-Manning equation (Williams, 1984): $V = R^{0.67} \cdot S^{0.50}/n$, where R is hydraulic radius or mean depth (in m), which here is the boulder height; S is channel slope, which for the Tidwell is assumed to be 0.0011 (based on Trampush, 2013; Trampush and others 2013), and n is the roughness coefficient (Manning's n), which for medium-grained sand is 0.022 (Arcement and Schneider, 1989). The resultant water flow velocity is only meant to be an approximation because there are many unknowns, including the dimensions of the channel, actual bed roughness, obstacles, such as vegetation, etc., that all affect velocity. Regardless, the approximated velocity is reasonable for the size of the boulder in a sand channel. The boulders occur at the same stratigraphic level as the lower cross bedded gypsarenites at The Notch (figure 19A), thus indicating that flowing water rather than blowing wind was the cause for the cross-bedding at The Notch.

Overlying the basal muddy interval is an interval of mostly alternating thin- to thinly bedded, greenish-gray and reddish-gray mudstones and gypsum, dolomites, gypsiferous sandstones, and sandstones that is about 1.33 m thick (figures 21C, 21G, and 21H). This interval is
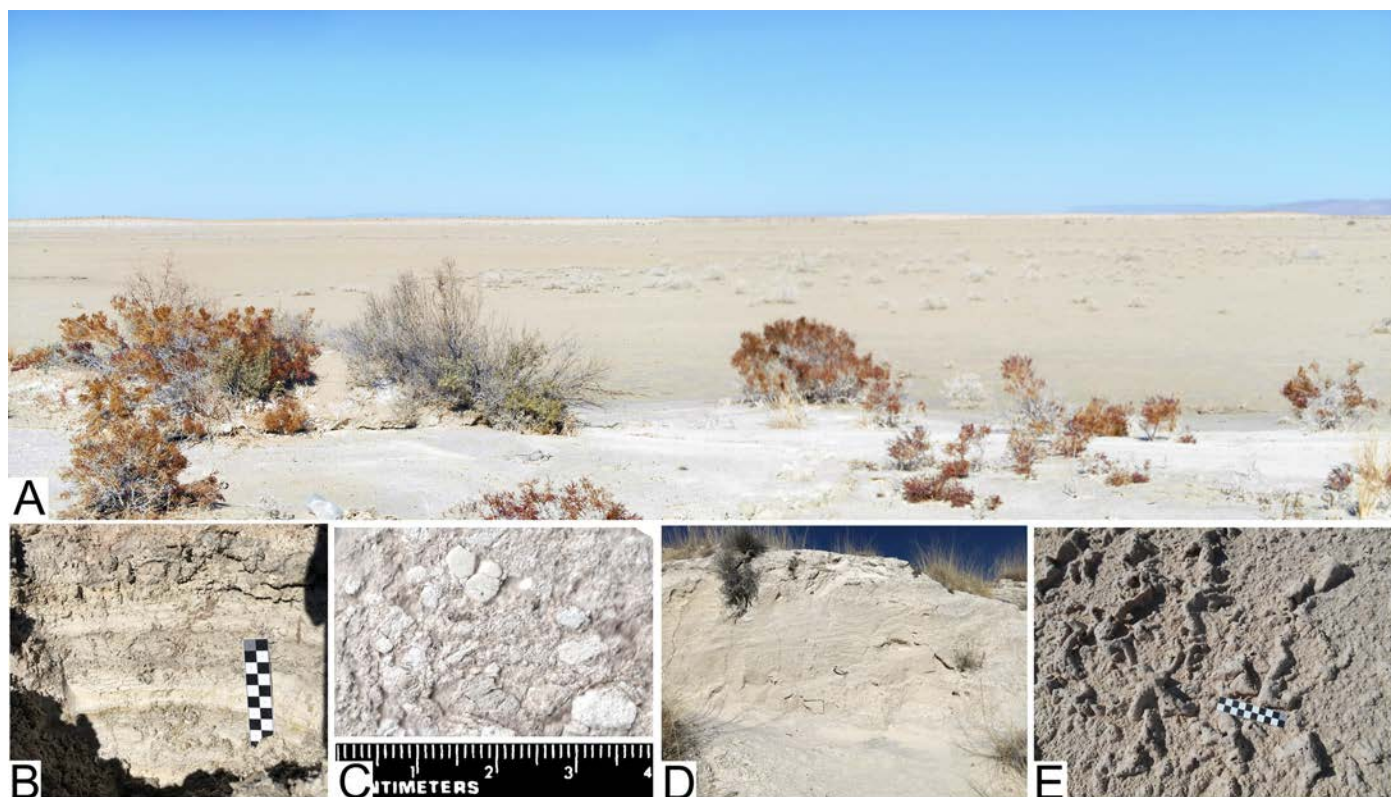
Figure 20. Modern gypsum playa and its deposits. (A) Salt Flat Playa, Hudspeth County, Texas (31.7563°, -104.9860°). View north, with the northern end of the Guadalupe Mountains to the right. White bands on the horizons are gypsum dunes. Dark surface due to high water content and extensive microbialite cover (see D). (B) Alternating light (gypsum) and dark sediment (dolomite and organic carbon-rich) bands in the upper part of the playa. (C) In situ gypsum nodules. (D) Cross section of a gypsum dune on the east side of the playa; wind from the left. (E) Wrinkled sediment encrusted microbialite on playa surface. Scales in cm.

overlain by a 1.3-m-thick bed of gypsum, the upper and lower parts of which are formed by coalesced gypsum nodules. This gypsum bed is overlain by a 1.1-m-thick sequence of red and gray siltstone with gypsum seams (figure 21I), dolomite with rhizoliths (figure 21J), a red and gray mudstone with a meshwork of gypsum (figure 21K). The presence of root-traces in sediments of the playa complex indicates that gypsophylic plants had evolved by the Late Jurassic. Laterally to the gypsum meshwork the gypsum grades into clusters of gypsum blades (i.e., poorly developed desert roses; figure 21L). This red and gray siltstone and mudstone interval is overlain by cross-bedded, medium-grain, gypsiferous sandstone that is 0.9 m thick (figure 21M). The sandstone is overlain by a massive, 5+ m thick, deeply weathered gypsum, which caps the exposure. Where broken, the massive gypsum shows seams of displaced red and gray mudstone (figure 21N) and localized auth-

igenic, red chert (figure 21O). Massive gypsum deposits in nonmarine environments can originate as eolian deposits on the margins of playas, such as seen at Salt Flat Playa in West Texas (figure 20D). Gypsum dunes tend not to have trough or festoon cross-bedding that characterizes sand dunes (Warren, 2016).

The varying lithofacies of these two examples, The Notch and The Road, can be correlated for 0.5 km and records the changes across the playa lake (figure 22A). The siliciclastic layers probably represent floodouts (figure 22B) from the fluvial fan extending from the eastern-most part of the Elko highlands, with sediment input into the playa from heavy precipitation events in the catchment or on the fan (Goudie, 2013). These episodes of freshwater and sediment input at The Road may correlate with some of the bounding surfaces seen at The Notch. The dimensions of the playa lake are unknown due to truncation of the gypsum on the south
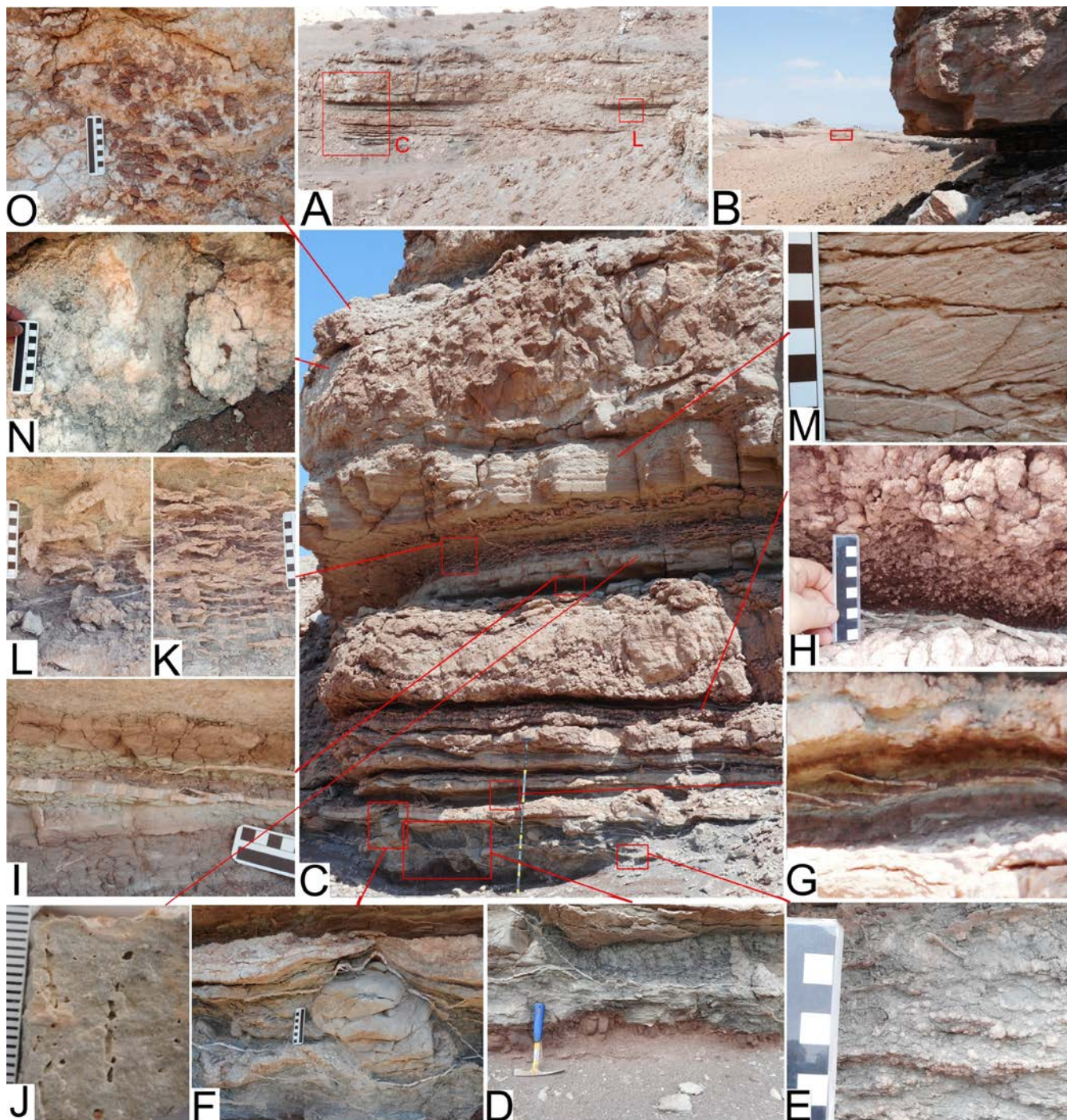
Figure 21. (A) Peripheral playa deposits at The Road locality, Emery County, Utah (38.8890°, -110.4431°). (B) Peripheral playa deposits (red box) can be traced continuously to the gypsum deposits at The Notch (cliff, right side). (C) Close-up showing the peripheral playa deposits and alternating layers of mudstone, and of limestone and gypsum. (D) Basal sandy, gypsiferous mudstone (gray) in erosional contact with the red Summerville. (E) Lags of gypsum pebbles. (F) Reworked dolomite boulder. (G) Example of a red and gray mottled mudstone, (H) Detail of coalesced gypsum nodules. Incipient nodules seen in the red mudstone, grading upwards into coalesced nodules. (I) Pale-red and green siltstone beds bisected by a tan, fine-grain sandstone. (J) Rhizoliths in a dolomite. (K) Mesh of gypsum blades. (L) Clusters of gypsum blades (desert roses). (M) Cross-bedded medium grain sandstone. (N) Massive gypsum with seams of displaced clay. (O) Authigenic red chert in gypsum.
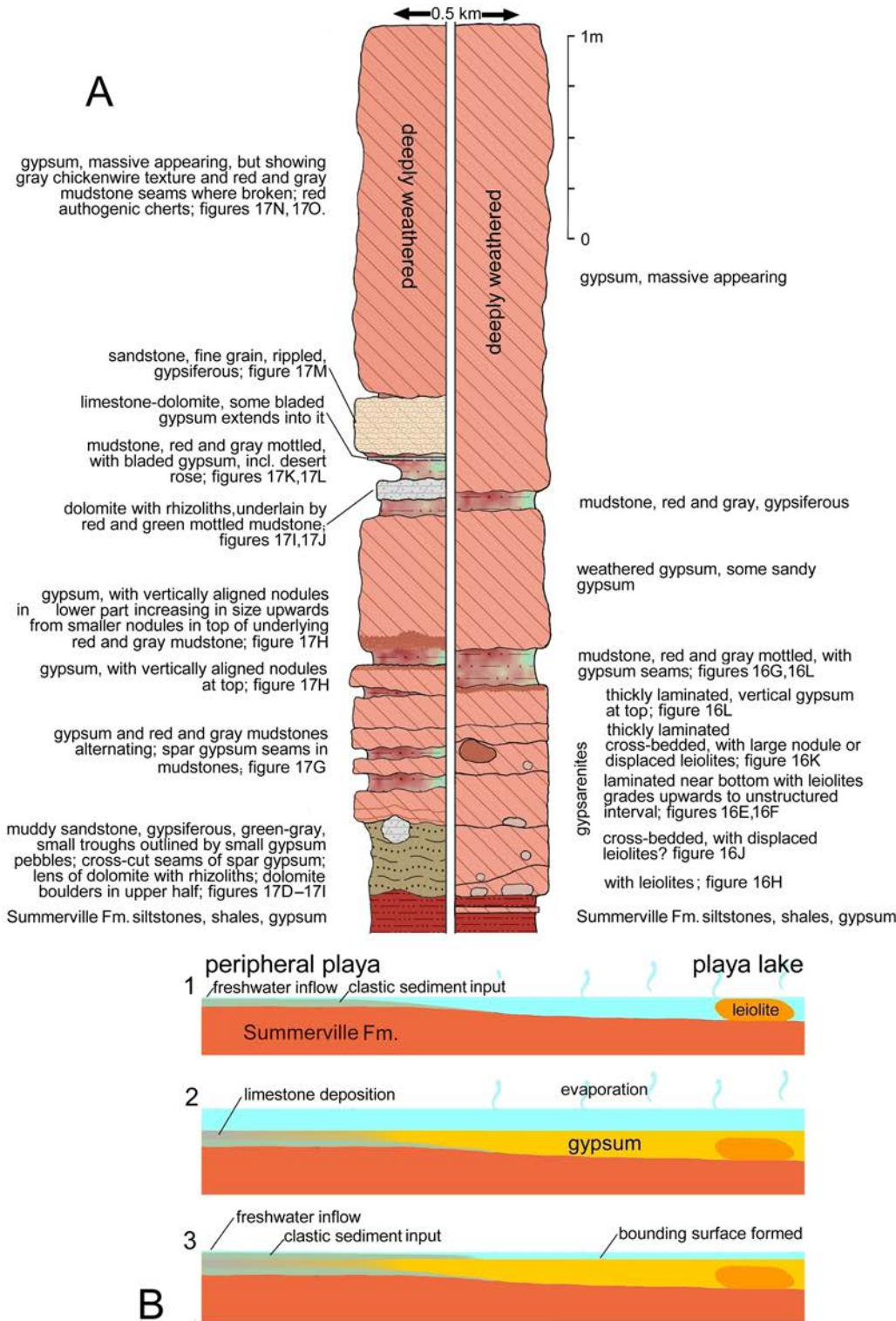
Figure 22. (A) Correlation of the peripheral deposits at The Road with the gypsum deposit at The Notch. (B) Reconstructed sequence interpretation for sediment deposition of the periphery playa lake deposits (left side) and main playa lake (right). Not to scale.

and west sides of Shadscale Mesa, but the gypsum bed can be continuously traced 7.53 km eastwards along the southern face of the mesa to where it grades rapidly into gypsiferous siltstone beds within a few hundred meters. This rapid lateral change is common in the thick gyp-

sum beds (figure 23A). Gypsum thickness data on the east side of the San Rafael Swell from Trimble (1976) shows that the saline lake at Shadscale Mesa was the southern-most of three centers of thickest gypsum deposition (figures 23B and 23C). These lakes are in-

formally named the Shadscale Mesa, Tidwell Bottoms, and Cottonwood Wash playa lakes. The absence or near absence of gypsum at locations 4 and 5 of figures 23B and 23C suggests that little or no gypsum was deposited there and represent interplaya mudflats (this absence was not independently verified owing to inaccessibility on the now heavy eroded old uranium prospecting access road).

The third example of a thick gypsum bed is exposed in the cut bank of Horn Silver Gulch (location H on figure 7) and shows that gypsum beds also occur as infilling of paleochannels. Gypsum along Horn Silver Gulch was briefly described by Gilluly (1929, p. 114) and by Lupton (1913), who noted a sample was 97.3% pure gypsum, the rest being "impurities" including nodules of variegated chert. A sample that I dissolved produced eolian quartz grains and red clay among the residue.

The gypsum bed at Horn Silver Gulch is deposited into a broad channel cut 4.3 m into the underlying Summerville Formation (figure 24A, red arrows). This channel was infilled by over 4.8 m of gypsum beds sepa-

rated by thin mudstone layers. The texture and fabric of these gypsum layers share some similarities with those on Shadescale Mesa, but with some important differences as well. The fabric of the gypsum at Horn Silver Gulch includes closely packed vertical pelloidal gypsum surrounded by displacive clay matrix (figure 24B), and vertical lenticular blades that are also surrounded by displacive matrix (figure 24C). The displaced sediments show that these two fabrics formed within the sediments of playas rather than on the sediments of a playa bottom or be transported into the channel by wind or water. The absence of microbialite domes (stromatolites, dendrolites, thrombolites, leiolites [Warren, 2016]), suggests that standing water was too irregular for microbialites to grow. This does not exclude the possibility that biolaminates (cyanobacterial mats) may have been present because these are common on modern playa surfaces (e.g., figure 20E; also, Dupraz and others, 2011). Gypsarenite is absent but because the exposed surfaces are more weathered than at The Notch (example 1), I cannot rule out that this absence is due to weathering
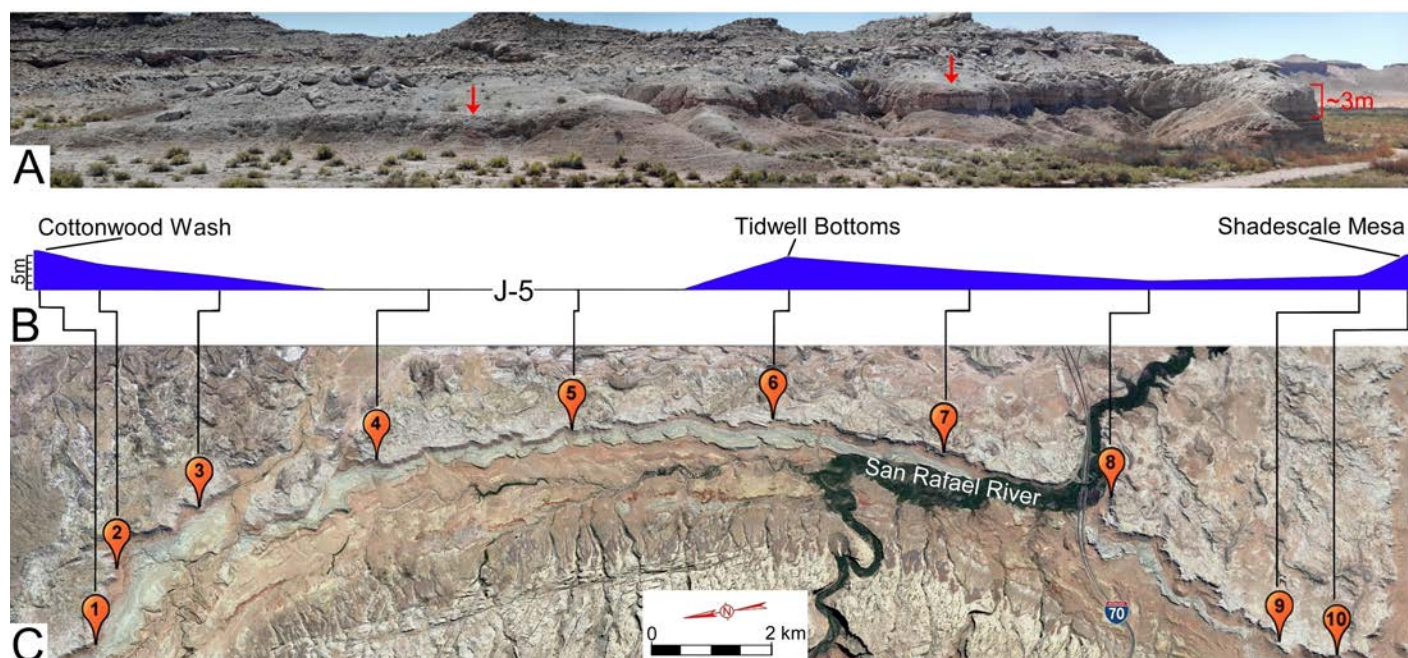

Figure 23. (A) Rapid lateral change in the basal gypsum from a maximum of approximately 3 m to a thinner gypsiferous siltstone. Red arrows denote the gypsiferous bed, east of San Rafael River, Utah (38.8548°, -110.3672°). (B) Gypsum thickness at the base of the Tidwell Member relative to the J-5 unconformity along a section of the eastside of the San Rafael Swell. Three major depositional centers as peaks are indicated. (C) Map showing the location of the ten measured sections given by Trimble (1978) used to infer the basal gypsum thickness. Image from Google Earth.
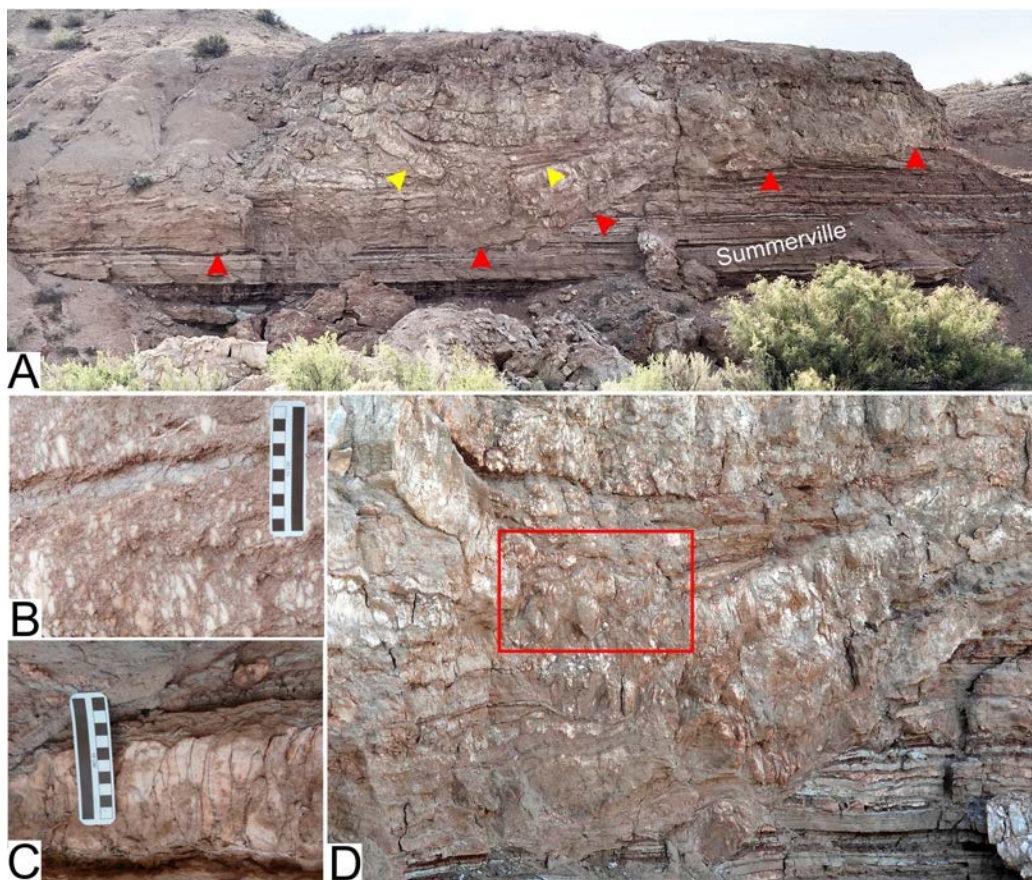
Figure 24. (A) Thick gypsum bed at Horn Silver Gulch, Emery County, Utah (39.0402°, -110.9722°). Red darts indicate the unconformable contact with the Summerville Formation; yellow darts indicate a channel cut into the gypsum and filled with gypsum. Two major gypsum morphs: (B) Closely packed vertically oriented pelloids; note clay layer separating beds. Near the base of the gypsum. (C) Tightly packed lenticular gypsum blades higher than the pelloid gypsum layer. (D) Close-up of the fluvial channel cut and collapsed bank gypsum debris (red box).

and a surface coating of gypsite. Examination of a core through the deposit might resolve this. The individual gypsum beds range in thickness from a few centimeters to almost 0.75 m, and many are separated by thin red or gray claystone or mudstone seams. Not all of the seams are continuous across the outcrop and adjacent gypsum beds may merge.

Superimposed on the gypsum beds is a U-shaped fluvial channel, a paleo-gully (figure 24A, yellow arrows; figure 24D) that is approximately 11.5 m wide and 3 m deep. The channel does not extend into the underlying Summerville Formation. Below the lowest part of the channel, the gypsum is extensively brecciated. On the north (left) side, gypsum blocks show a chaotic arrangement of a paleo-gully bank collapse (figure 24D, red box). Above the channel bed, is an interval of thinly bedded red and gray mudstone and this in turn, is overlain by two gypsum beds separated by a thin mudstone.

Three explanations may account for the channel and infilling. One is incision of a channel between two smaller playa lakes due to a drop in water level of a larger playa lake leaving the smaller lakes isolated, such as seen at the south end of Lake Kurdyma, a large playa lake among many playas in the steppes of southeastern Aktobe Oblast, Kazakhstan (48.0192°, 63.0278°). The second explanation is the incision of a gully into peripheral playa deposits due to intense, heavy rains as is common in dryland environments (Blair and McPherson, 2009; Goudie, 2013). Possibly there had been a drop in the base level of the playa lake from a period of little rain fall. After the channel was cut, downward seepage into the channel bed by fluvial water, which was undersaturated with respect to gypsum, dissolved the underlying gypsum causing it to collapse and brecciate. Siliciclastic sediment, represented by the red and gray mudstone, brought by the fluvial water, is found intermingled with the breccia and eventually sealed the bed thereby halting further dissolution. A rise in the playa lake or localized ponding of gypsiferous water and subsequent evaporation created the overlying gypsum beds. The

third explanation is that the channel is a karst feature and the mudstone layers are siliciclastic grains liberated from the dissolution of a gypsum bed. This hypothesis seems less likely because of the uniform cross section of the channel, and its smooth edges appear water worn. In addition, a single sinkhole would be unusual because no others were seen in the area. The significance of the example from Horn Silver Gulch is that the channel that was cut into the gypsum about midway during the history of gypsum deposition. Such a deep cut in a marine or coastal sabkha seems unlikely given the widespread uniformity of the depositional environment. Rather, the very localized erosion and infilling by siliciclastic sediments is more in keeping with fluvial erosion and deposition.

Excluding interbedded mudstones, the thick gypsum deposits around the San Rafael Swell contain a small percentage of windblown detrital grains. Bluhm and Randle (1980) report that detrital grains comprised less than 10% by volume of the gypsum. The grains are subangular to subrounded, very fine to fine-sand sized grains consisting of ferric oxide-stained clay, single crystal detrital quartz, sparitic carbonate cement, little altered to fresh plagioclase and microcline feldspars, disseminated detrital opaques, detrital chert, and detrital chalcedony. Weeks (1953) reported the presence of the water-soluble anhydrous sodium sulfate mineral thenardite. The specimen was reported to be from the Summerville Formation, but is more likely to have come from the Tidwell Member because this mineral forms in playas and is among the last minerals to precipitate out (Warren, 2016).

Contact between the gypsum facies and the overlying interbedded thin sandstone, mudstone, and limestone facies assemblage is very poorly exposed because of talus or weathering. Seen from a distance, there appears to be an abrupt change in lithology, which Trimble and Doelling (1978) and Anderson and Lucas (1998) construed as an unconformity. Peterson (1988a), however, interpreted the change as due to local dissolution of the gypsum. The contact is well exposed opposite the type section and this shows, at least here, that the transition is gradational, with interfingering with the base of the SSMLD facies assemblage (figure 25).
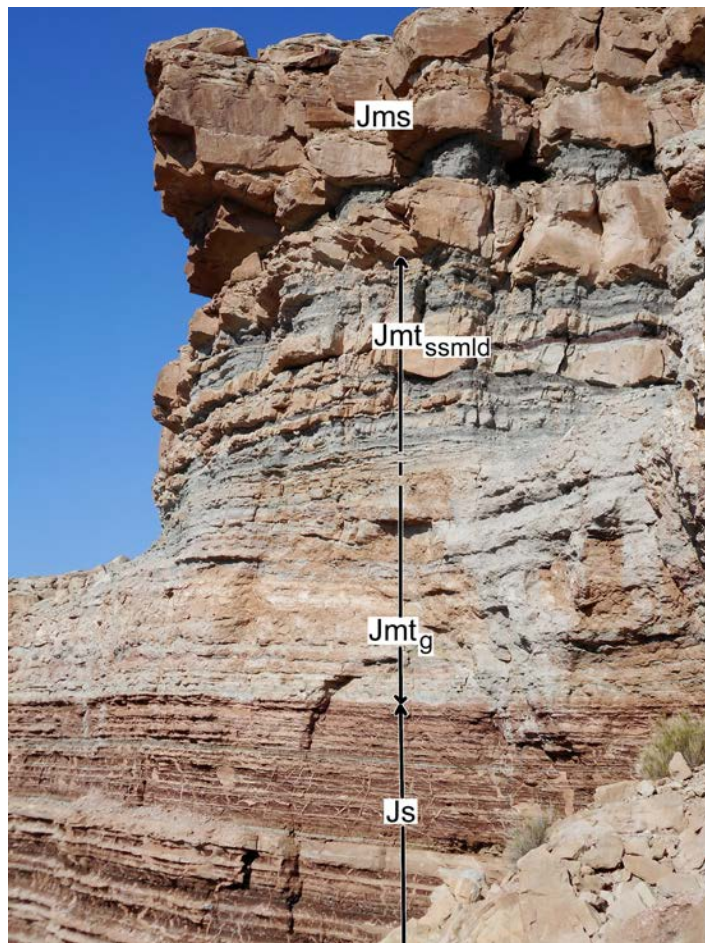

Figure 25. Interfingering between the top of the thick gypsum and the SSMLD facies assemblage opposite Peterson's stratotype at Shadscale Mesa. Abbreviations: Jms – Salt Wash Member, Morrison Formation; Jmt_g – Tidwell Member, Morrison Formation, gypsum bed; Jmt_{ssmld} – Tidwell Member, Morrison Formation, thin bedded sandstone, siltstone, mudstone, limestone and dolomite facies assemblage; Js – Summerville Formation.

PLACEMENT OF THE J-5 UNCONFORMITY

The contact between the Summerville Formation and the base of the Morrison Formation was originally considered to be an erosional unconformity by Emery (1918), Dake (1919), and Gilluly and Reeside (1927). In contrast, Mullens and Freeman (1954, 1957) considered the Morrison-Summerville Formations to be in conformable contact over most of the Colorado Plateau and that the change in lithologies was due to a change from marine to terrestrial depositional environments as a result of withdrawal of the Sundance sea

from this region. This position was supported by Mobley and Santos (1956), who considered the Summerville Formation to interfinger with the basal sandstone beds of the Salt Wash Member of the Morrison Formation. Craig and Shawe (1975) were equivocal, noting that the Morrison Formation appeared to be conformable with the Summerville Formation, but they did not rule out that the contact might be a disconformity because of the temporal gap between what was then considered the Callovian aged Summerville and Kimmeridgian aged Morrison. Peterson (1980b), however, concluded that the conformable interpretations of the contact were in error because Tidwell strata were placed in the top of the Summerville.

The prominent, thick gypsum beds in the Green River Mining District were placed at the base of the Salt Wash Member of the Morrison Formation by some authors (e.g., Gilluly and Reeside, 1927; Gilluly, 1929; McKnight, 1940; Young and others, 1957, 1960). Whereas other authors place the beds in the Summerville Formation (e.g., Lupton, 1914; Clark and Million, 1956; Mullens and Freeman, 1957; Trimble, 1976; Bluhm and Rundle, 1980; Anderson and Lucas, 1994, 1998; Lucas and others, 2006; Lucas, 2014), and some have done so despite acknowledging an angular unconformity below the gypsum (e.g., Trimble, 1976; Trimble and Doelling, 1978). Given that this part of the Colorado Plateau is not underlain by Pennsylvanian salt deposits (Hallgarth, 1962; Peterson, 1983), halokinesis cannot be the cause for the angular unconformity. Peterson (1984, 1988a) linked the cause of the angular unconformity to the Emery uplift without elaboration.

The angular unconformity between the Summerville sandstones and siltstones and the thick gypsum beds is one of many unconformities that truncate low-amplitude anticlinal folds at the top of the Summerville Formation (figures 26A through 26E) around Shadscale Mesa (Trimble, 1976; Trimble and Doelling, 1978) and in the Henry Basin (figures 26F through 26H). The anticlines occur as far east as the Green River. The amplitude of the anticlines based on the amount of truncation is between 30.5 and 61 m (Trimble, 1976; Trimble and Doelling, 1978). The distance from crest to trough varies considerable from 200 to 800+ m (Trimble, 1976; Trimble and Doelling, 1978).

Despite their wide distribution, the anticlines have largely gone unnoticed or unremarked (e.g., Hunt, 1953; Witkind, 2004; Bernier and Chan, 2006). It is also probable that the Gilbert-style delta reported by Kirkland and others (2020, their figures 4B through 4D) at the top of the Summerville is the southern limb of an anticline, with the northern limb hidden by talus from the overlying Morrison Formation. Otherwise, the delta is prograding south in opposition to the northeastward regression of the Sundance sea.

Because most anticlines in the Summerville are visible as cross sections in cliffs, the azimuth for most of the fold axes can seldom be determined and the orientation of the anticlines relative to the Sundance sea or Elko highlands are unknown. However, it is possible to extrapolate the fold axis azimuth for one anticline at the southwest corner of Shadscale Mesa. The Summerville Formation here forms an angular unconformity with the overlying thick gypsum. A thin, distinctive gypsum bed near the top of the Summerville Formation is truncated by the angular unconformity on both sides of a ridge or spur (figures 26A and 26B). A plane parallel to the gypsum bed intercepts the unconformity on both sides of the ridge (figure 26C, line connecting points A and B, which correspond to figures 26A and 26B) with an azimuth of N. 21° E. and a dip direction of 290° W. indicating that the Summerville Formation here is the west limb of an anticline (dip angle was not calculated). The east limb of the anticline is visible in cross section along the south face of Shadscale Mesa (figure 26D, corresponds to point D in figure 26C), and the fold axis is seen in a shallow box canyon (figure 13C, green line). The axis is N. 21° E., parallel to the plane intercept of the west limb with the angular unconformity. The azimuth confirms the observation by Trimble (1976) that the almost two dozen paleo-folds, as he called them, trend north to northeast (he does not explain how these were determined). These orientations are roughly parallel to the Elko uplift and may reflect movement of the Elko forebulge.

Peterson (1980b) mentioned the presence of anticlines in the Summerville Formation in the Henry Basin, but nothing is said about their orientation. He does note that paleo-anticlines in the lower part of the Morrison Formation in the Henry Basin trend mostly

northwest-southeast, which would be perpendicular to the southern part of the Elko highland front as shown by Thorman (2011). These paleo-anticlines were inferred from variations in bed thickness and recurring facies over the inferred anticlines and synclines (Peterson, 1980a, 1984, 1986). Re-examination of these anticlines is needed to determine if they were formed post-Summerville deposition.

The significance of the truncated Summerville anticlines is that they demonstrate a passage of time between the withdrawal of the Sundance sea and deposition of the thick gypsum beds (figure 27). The Summerville is therefore a diachronous surface from south to north as the sea regressed northwards. The truncating of the anticlines may have also coincided with the erosion of the top of the Summerville east between the Green and Colorado Rivers reported by O'Sullivan (1980a). The amount of time represented by the erosional surface is unknown, but was long enough for the anticlines to develop and be truncated. Anticline uplift rates of 2.1+ mm/yr have been reported (Li and others, 2020; Kleber and others, 2021) and based on the estimated amplitudes of 30.5 to 61 m (Trimble, 1976; Trimble and Doelling, 1978), those in the Summerville may have formed in as little as 14,500 to 29,000 years. Considering how rapidly the Summerville Formation erodes today (Howard, 2009), assuming the erosion rate equaled uplift rate, the anticlines formed and were eroded in as little as 29,000 to 58,000 years. However, given that rates of erosion may have been significantly less in the Jurassic arid environment, a reduction of erosion to 25% of uplift rate, the anticlines could have formed and been eroded in 58,000 to 232,000 years. The actual time would very much depend on the rate of anticline formation, and even if halved, the results suggest that the J-5 unconformity was less than a half-million years as also estimated by Peterson (1994).

This weathered and eroded surface across the top of the Summerville Formation has been identified as the J-5 unconformity (Pipiringos and O'Sullivan, 1978; O'Sullivan, 1984a; Peterson, 1988a). As a result, this places the thick gypsum beds in the San Rafael Swell and Henry Basin at the base of the Tidwell Member of the Morrison Formation as originally stated by Peterson (1988a). O'Sullivan (1984a) and Peterson (1980a)

believed that the J-5 unconformity can be traced almost continuously over most of the Colorado Plateau as a disconformity, an idea previously suggested by McKnight (1940, p. 108). The disconformity can be difficult to determine if exposures are weathered and the most commonly used criterion introduced by O'Sullivan (1980a) has been the presence of the Bed A sandstone (figures 8 and 12A through 12D). A similar criterion is used to separate the thinly bedded Windy Hill Member of the Morrison in northeastern Utah from the overlying Tidwell Member (Sprinkel and others, 2019). However, in places the lower Tidwell can be thin bedded (figure 12A) giving the impression that the contact is gradational. Placing the boundary in the vicinity of White Sand Dunes Recreational Area west of Duma Point, is problematic because the sandstone that could be construed as Bed A is thin and discontinuous (figure 14D). Here, at least, I cannot rule out that the Tidwell is conformable with the Summerville. McKnight (1940) made a similar observation in the area and used the color change from red or reddish-brown of the Summerville and lavender of the Morrison as the contact. Potter-McIntyre and others (2016) and Ejembi and others (2021) concluded that the Wanakah and Tidwell in western Colorado were conformable based on similar Cambrian detrital zircon dates sourced from recycled older deposits. At most, the similar zircon dates indicate continued erosion of the same source and do not by themselves rule out a disconformity.

Channel cuts into the top of the Summerville Formation occur (figure 28), some containing black cherts (figures 28A and 28B; Peterson, 1988a, figure B23) and others containing Paleozoic fossils derived from the Elko highlands (Peterson, 1987; 1994). Significantly, no lithic fragments of the Summerville have been found in the base of the Tidwell Member suggesting that the sediments had not undergone significant lithification prior to erosion. Hunt and others (1953) report channels up to 15 m deep cut into the Summerville Formation. The incision of these channels may be due to the fall of regional base level that marked the withdrawal of the Curtis-Summerville sea and the development of the J-5 unconformity (Caputo and Pryor, 1991; Peterson, 1994).
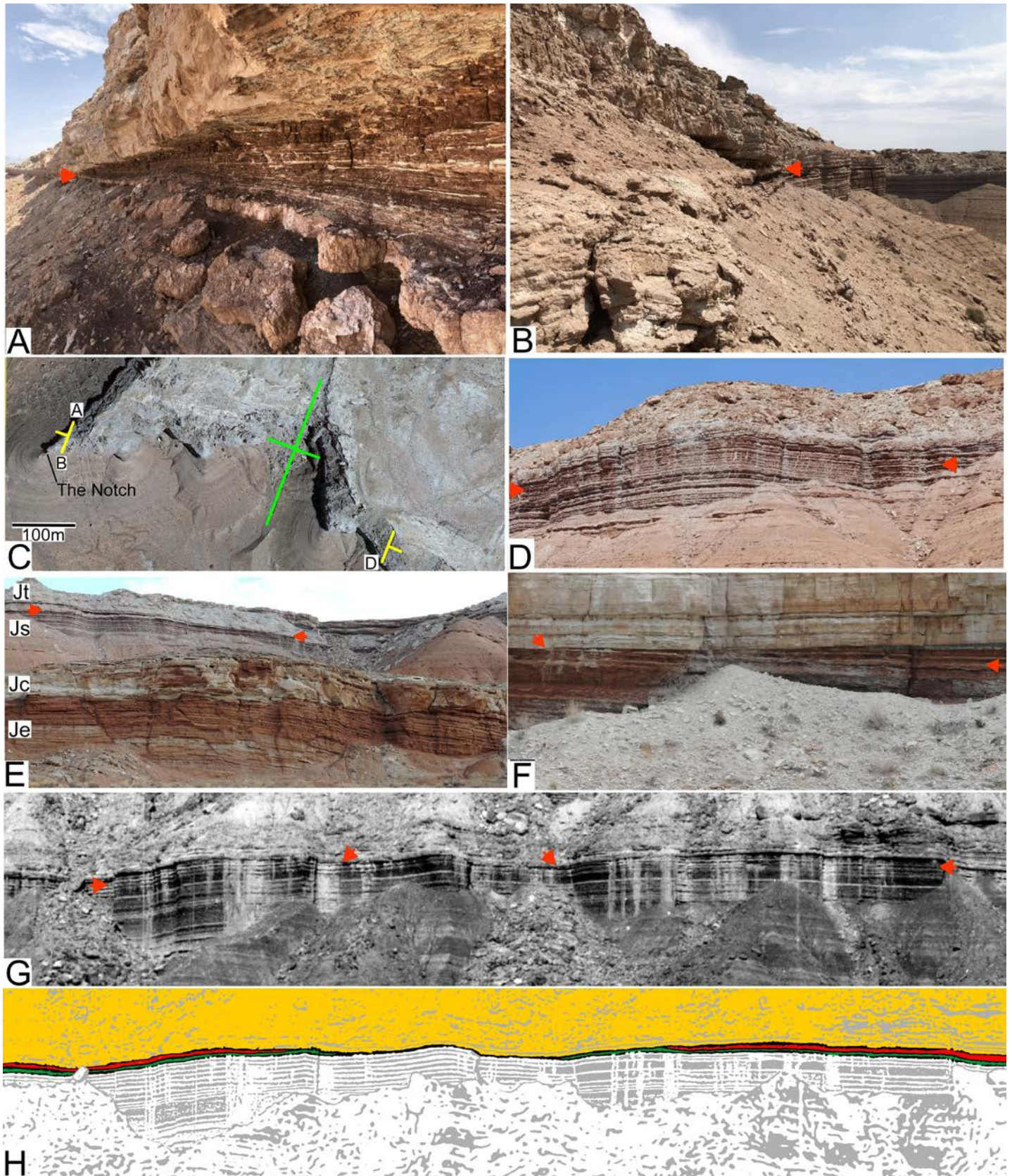
Figure 26. Caption is on the following page.

Figure 27. Summary illustration for the formation of the basal gypsum of the Tidwell Member. Approximately west to east: (A) regression of the Sundance sea with gypsum formation in the sabkha environments of the coastal, tidal and supratidal zones; (B) syncline and anticline phase; (C) erosional truncation of the anticlines and development of playa complex; (D) progradation of the megafan over the former playa complex. These sediments are of the SSMLD assemblage facies.

and Warwick, 2007; Shroder, 2013; Bowman, 2019) and rejected by some sedimentologists (e.g., Fielding and others, 2012). The concept of the Salt Wash alluvial fan, was first discussed by Craig and others (1951, 1955) based on lithofacies and isopachous maps of the Salt Wash Member. They concluded that there was a single source apex in south-central Utah near the present-day confluence of the Colorado and San Juan Rivers. Although a map of paleocurrent azimuths also was given, these were not used to identify the location of the fan apex, but rather were cited as supporting evidence for the location of the fan apex. Emphasis on paleocurrent data to locate the Salt Wash fan apex was done by Owen and others (2017) using statistical analysis to place the apex about 150 km farther west and south in the vicinity of the Kaibab Plateau north of the Grand Canyon, Arizona. This plateau, superimposed on the Colorado Plateau, formed by Laramide reactivation of basement faults (Davis and Bump, 2009), but otherwise this region of the Colorado Plateau lacks evidence for a Jurassic orogeny as the Owen and others (2015a, p. 150) model requires. This lack of evidence for an orogeny also holds true for the location of the fan apex of Craig and others (1951, 1955) and Mullens and Freeman (1954, 1957). The Mogollon highlands, the northern rift shoulder to the Bisbee Basin, were over 150 km farther south from

the fan apex of Owen and others (2015a, 2017) based on evidence presented by Bilodeau (1986), Dickinson and Lawton (2001), and Turner and Peterson (2004).

In contrast to the problematic single source model, others have concluded that the strata of the Tidwell and Salt Wash Members had multiple sources mostly from the south and west of the Colorado Plateau (Cadigan, 1967; Peterson, 1980, 1986, 1987, 1988b, 1994; Peterson and Turner-Peterson, 1987; Robinson and McCabe, 1998; Turner and Peterson, 2004; Dickinson and Gehrels, 2008, 2010; Maidment and Muxworthy, 2019), and also from the southeast (Potter-McIntyre and others, 2016; Ejembi, 2018). Peterson and Turner-Peterson (1987) and Peterson (1988b) argued that the localized thickness of the Salt Wash presented by Craig and others (1951, 1955) was due to basin subsidence during deposition, rather than proximity to source. In addition, the presence of 1-m-diameter boulders in the Henry Basin and San Rafael Swell indicated a western source. Different source areas for sandstone are supported by detrital zircons. Dickson and Gehrels (2008, 2010) determined that sandstone from near Notom, Utah (near location E, figure 7), in the west-central part of the Colorado Plateau originated from recycling of older Jurassic eolianites from the Elko and Mogollon highlands, and particularly from a drainage system
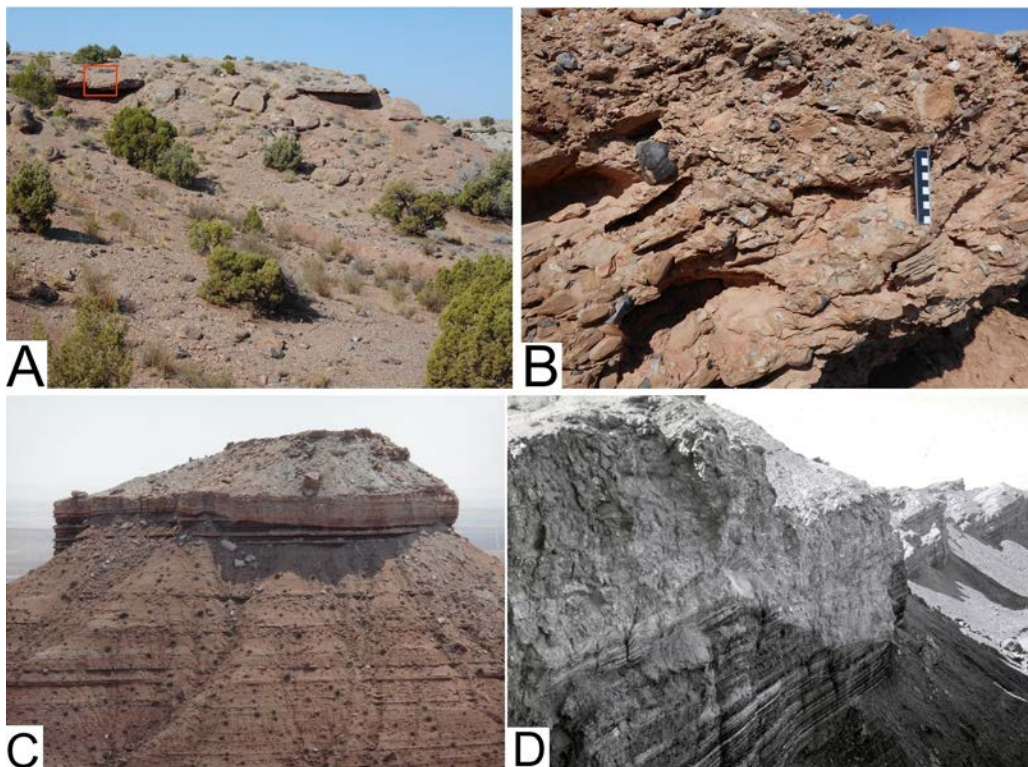
Figure 28. Channels and fills cut into the Summerville Formation. (A) Conglomeratic channel fill near Summerville Point (39.1691°, -110.4574°); red box shown in B. (B) Close-up of fill showing abundant black cherts. Scale in cm. (C) Deep channel cut filled with gypsum, near Shadscale Mesa (38.8794°, -110.4436°). (D) Gypsum filled 15 m channel cut 1 km northeast of Muddy River, west side of Little Wild Horse Mesa (38.5408°, -110.9187°), USGS photo hcb00360.

emerging from their syntaxis in what is now the Grand Canyon area (Stokes and Heylmun, 1963, named this syntaxis the "Grand Canyon bight"). Peterson (1987, 1994) used Pennsylvanian and Early Permian invertebrates in pebbles to identify two narrow source zones in the eastern Elko highlands, and an additional source of red and green cherts from Ordovician and Silurian strata in the western Elko highlands in central Nevada. Yingling (1987) and Yingling and Heller (1992) located three possible sources for Paleozoic cherts in the eastern Basin and Range, of which the southern two coincide with those identified by Peterson (1994). Potter-McIntyre and others (2016) concluded that detrital zircons in the northeastern part of the Colorado Plateau indicate a source from the Wet Mountains in the southern ancestral Rocky Mountains of south-central Colorado, as did Ejembi (2018) and Ejembi and others (2021), who also suggested additional sources in in the Amarillo-Wichita Mountains of southwestern Oklahoma. The multiple sources may reflect the time of transition from streams originating from Pangaean terranes and the North American craton of the Early and Middle Jurassic to the Cordilleran terranes of the Late Jurassic and Cretaceous (Blakey, 2019). Precambrian quartzites in Triassic and Jurassic conglomerates along the Arizona and New Mexico border suggests that the eastern Mogollon highland was an active sediment source during the Mesozoic (Dodge, 1973). An eastern Mogollon locality for some Paleozoic cherts was also noted by Yingling (1987).

An isopachous map of the Tidwell Member supports multiple source areas to the west, southwest, south, and east (figure 30), whereas paleocurrent data for sandstones in the SSMLD facies assemblage presented by Bernier and Chan (2006) suggests primarily a west-southwest source (figure 31A). Assuming that the sediments of the Tidwell Member are the distal facies of Salt Wash fluvial fans (Peterson, 1977, 1980a, 1984, 1994; Condon and Peterson, 1986), then the paleocurrent data for the Salt Wash Member should also reflect the paleocurrents of the Tidwell Member. These paleocurrents for the Salt Wash are presented in figure 31B. Based on a larger data pool than those originally given by Craig and others (1951, 1955), these paleocurrents suggest multiple sources to the west and southwest (figures 31C and 31D). The southwestern source does coincide with the Grand Canyon bight, and is approximately 150 km farther west than the location of the fan apex for the Salt Wash distributive fluvial system given by Owen and others (2015a). The source lies in the direction of the "Las Vegas cluster" of intersecting back
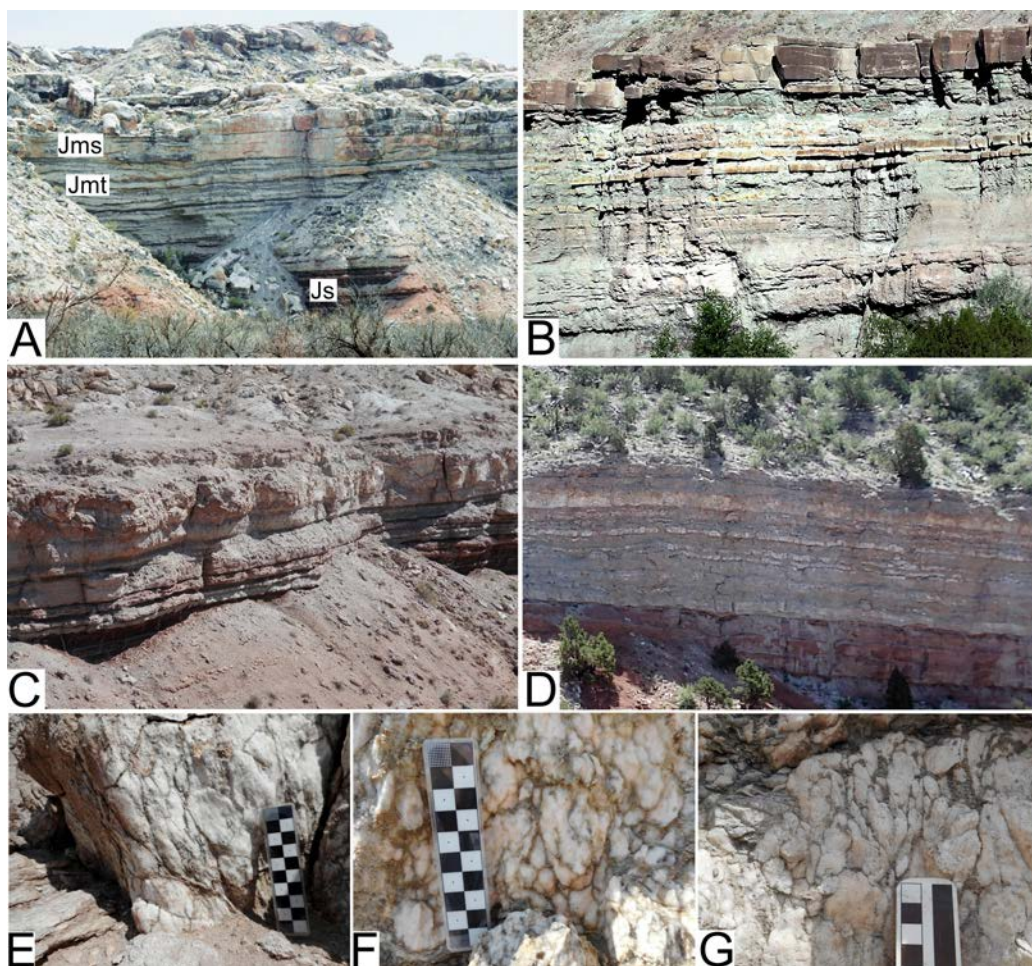
Figure 29. Similarities of the Tidwell and Ralston Creek Members. Alternating thin bedded sandstones and siltstones or mudstones: (A) upper Tidwell on the north side of Shadscale Mesa (38.9196°, -110.3978°), (B) Ralston Creek along Nine Mile Creek (38.5375°, -105.2216°); thick bed of gypsum (C) Tidwell at Shadscale Mesa (38.8887°, -110.4426°), (D) Ralston Creek at Eight Mile Park (38.4959°, -105.0806°); characteristic marginal playa lenticular gypsum in the Tidwell at (E) Shadscale Mesa (38.8885°, 38.8885°) and (F) Tidwell on the Woodside anticline (39.1828°, 39.1828°); (G) Tidwell in Ralston Creek (38.5446°, -104.9582°).

traces of paleocurrents given by Owen (2014), which lies near Lake Mead along the Nevada-Arizona border.

The average paleocurrents should reflect the ground slope in the direction of the retreating Sundance sea, hence the surface upon which the Tidwell was deposited. Webber (1946) had previously suggested that the flat topography left by the regression of the Sundance sea in a dryland environment greatly influenced the deposition of the Salt Wash Member, and by extension the underlying Tidwell Member. The paleogradient for the flat landscape was estimated to be 1.1×10^{-3} (i.e., 1.1 m/km, or 0.06°) and was consistent throughout the deposition of the Morrison Formation (Trampush, 2013; Trampush and others, 2013). However, these paleocurrents show a strong eastward azimuth (figure 31) and less of a northeastward component, which is surprising given that the Sundance sea is thought to have regressed towards the Utah-Colorado-Wyoming borders (Peterson, 1994; Holland and Wright, 2020). A possible explana-

tion is an eastward deflection of the fluvial system from the Grand Canyon bight by fluvial fans from the Elko highlands to the west. These results do not support the distributive fluvial system model for the Salt Wash advocated by Weissmann and others (2013), Owen (2014), and Owen and others (2015b, 2017).

As for the gypsum facies of the Tidwell Member in the San Rafael Swell and Henry Basin, brine evolution models (e.g., Hardie and others, 1978; Warren, 2016) predict the evaporite sequence based on available ions. The predominance of gypsum in the lower Tidwell on the westside of the Colorado Plateau indicates a continuous renewal of both calcium and sulfur from a source area, which was most likely itself a gypsum. It is probably no coincidence that the Tidwell playa complex, containing an estimated 24 km³ of gypsum (assuming an average thickness for the gypsum of 3 m), is east of the Elko highland, where evaporites of the Summit Springs Member of the Pequop Formation were exposed by the
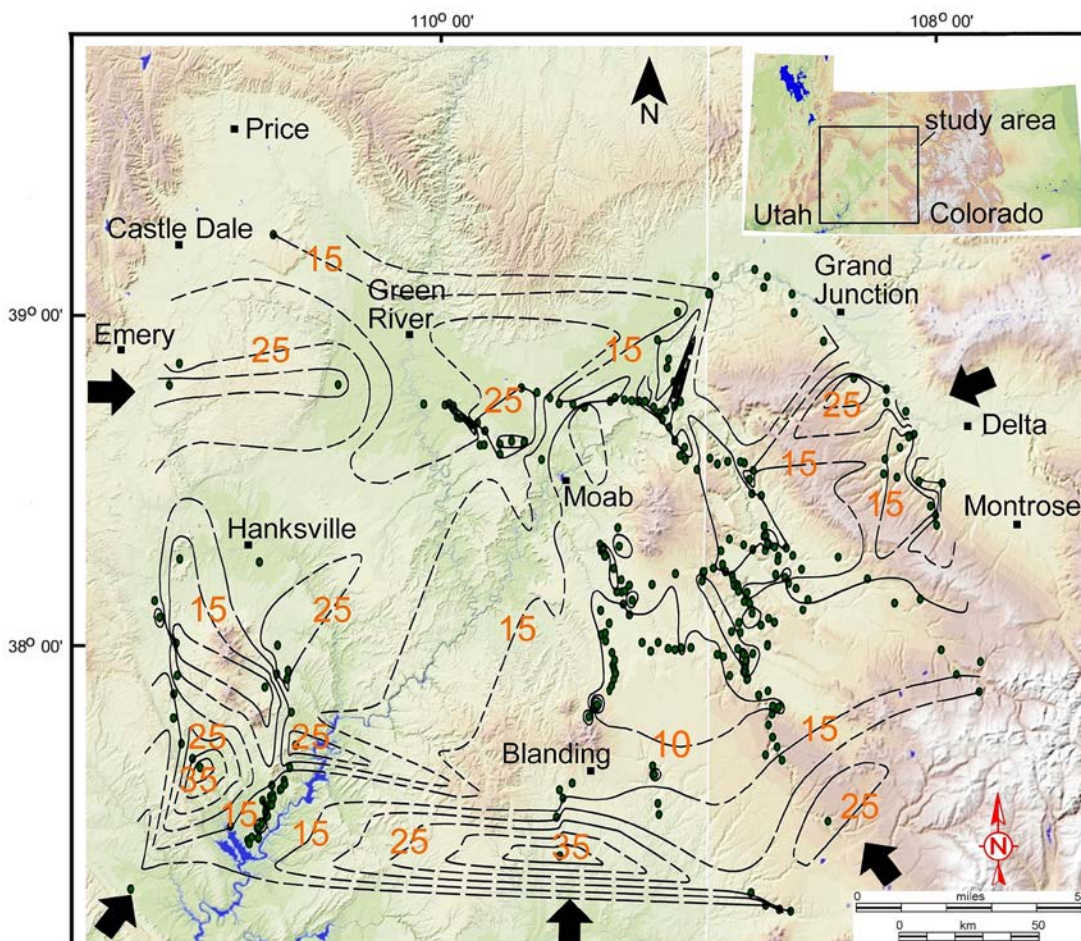
Figure 30. Isopach of Tidwell thickness, contours in m. Several depositional sites are present around the peripheries, the most important of which are towards the west and southwest. Data from Peterson (1978, 1980a, 1980b, 1982c, 1988a), O'Sullivan (1980a, 1980b, 1981a, 1981b, 1984a, 1984b, 1986, 1989, 1991, 1992b, 1995a, 1995b, 1996, 1998, 2000, 2004), O'Sullivan and Pipiringos (1983), Kowallis and Heaton (1987), Robinson (1994), Kjemperud and others (2008), Doelling and Kuehne (2013), Swan (2018), Kirkland and others (2020).

late Middle to early Late Jurassic (Thorman, 2011; Thorman and others, 2020). Such recycling of older gypsum is known to be a major source for later gypsum deposits (Warren, 2016). An analogous situation occurs with the gypsum playa complex of Salt Flat, New Mexico and Texas, in which the gypsum is sourced from erosion of the Permian evaporites and carbonates of the nearby Guadalupe Mountains (Chapman, 1984; Hussain, 1986; Chapman and Kreitler 1990; Hussain and Warren, 1991).

Despite the great thickness of some of the gypsum beds, the time involved may not have been great. Schreiber and Hsü (1980) report that the depositional rate for gypsum is 1 to 2 m/kyr, whereas Allen and others (2009) reported an accumulation rate of 0.5 m/kyr based on C^{14} dates of organic material in the Pleistocene Lake Otero basin in New Mexico. These rates can be applied to the basal gypsum of the Tidwell Member to estimate possible duration of gypsum accumulation.

The retention of texture and minimal bed distortion indicates that the gypsum did not undergo deep burial and significant compaction (Warren 2016). Therefore, the thickest gypsum bed (14 m) reported by Peterson (1988a) required only between 7000 to 28,000 years to precipitate.

DISCUSSION

Summerville Depositional Environment

McKnight (1940) interpreted the Summerville Formation on the western Colorado Plateau as a delta that emptied into a lagoon that underwent cyclic evaporation causing the precipitation of gypsum. McKnight (1940) interpreted the Summerville Formation in the eastern Colorado Plateau as continental deposition because of the sequence of lenticular sandstone beds. Baker (1946) also considered the thin, regularly bedded sandstone and siltstone and the bedded gypsum as in-
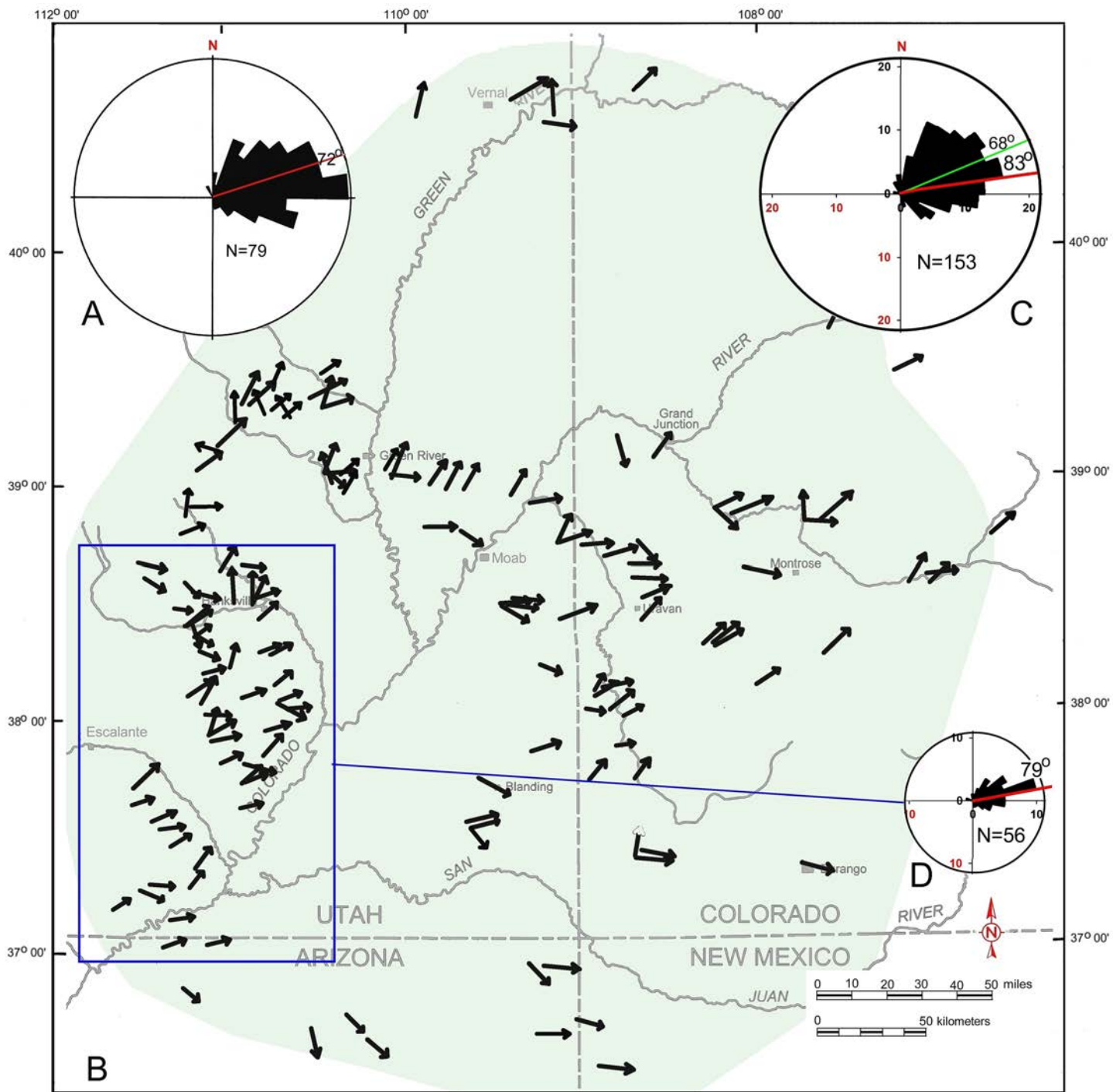
Figure 31. Paleocurrent summaries. (A) Rose diagram summary for the ripple sandstone facies of the Tidwell Member. (B) Compilation of paleocurrent arrows plotted on map of the Salt Wash Member (green area). (C) Rose diagram of paleocurrent arrows shown in B excluding outliers (e.g., around Vernal, Utah). Average azimuth is 83° and the median is 68°, close to the average azimuth for A. (D) Rose diagram of the southwestern most paleocurrents which suggest multiple sources. (A) Modified from Bernier and Chan (2006), figure 6. (B) Base map modified from Craig and others (1955). Data for paleocurrents from Stokes (1954), Stokes and Mobley (1954), Craig and others (1955), Dawson (1970), Derr (1974), Mickle and others (1977), Tyler (1981), Peterson and Royce (1982), Peterson (1984), Yingling (1987), Owen (2014), and Chesley and Leier (2018).

dicative of deposition in large shallow lagoons. Webber (1946) suggested that the Summerville was deposited in a large playa because of the gypsum. In the first detailed study of the Summerville Formation, Stanton (1976) interpreted the depositional environment of the Summerville Formation as a broad tidal flat crisscrossed with tidal channels. The tidal range was assumed to be up to a meter in height based on channel sandstone thickness. Subsequent depositional environment interpretations have been variations of this tidal-flat model, including as a supratidal flat (e.g., Kocurek and Dott, 1983; Wilcox and Currie, 2008; Zuchuat and others, 2018, 2019). Caputo (1988) and Caputo and Pryor (1991) interpret the Summerville deposition as a supratidal sabkha because of the gypsum. They suggested inundation by spring tides, storm surges, and wadi flooding in a restricted evaporative basin with hypersaline conditions. Given that the Summerville Formation extends almost the entire north-south length of Utah (about 390 km), only a narrow band shoreward of the northeastward regressing Sundance sea could have been an active tidal flat (= intertidal zone between normal low and high tide). The narrowness of the tidal flat is due to the limitations imposed by slope and tidal ranges. Assuming that the paleoslope 5.09×10^{-4} to 1.53×10^{-3} estimated for the Morrison Formation is inherited from the Curtis-Summerville depositional sequence (Trampush, 2013; Trampush and others, 2013), and the tidal range is estimated to be 2.6 m (mesotidal range) for the Curtis seaway (Zuchuat and others, 2020), then the active zone of the tidal flat would be 1.7 to 4.4 km wide, which is reasonable based on modern tidal flats (Gao, 2019, table 10.1). The implication for the overlying Tidwell Member is that much of the Summerville sediments were exposed to weathering prior to the deposition of the Tidwell sediments and therefore the surface of the Summerville was a diachronous surface from south to north as the Sundance sea regressed.

Tidwell Depositional Environment

Possibly coincidental with the withdrawal of the Sundance sea was the formation of the low-amplitude anticlines and synclines, and the subsequent erosional truncation of the anticlines (figure 27). The absence of coarse lag erosion remnants at the top of the Summerville Formation may be due to the limited size range (silt and fine sand grains) composing the Summerville sediments.

The folds in the Summerville Formation suggest renewed tectonic activity of the Elko orogeny before deposition of the thick gypsum beds in the Tidwell Member. Although it might seem logical that the synclines would provide the low-relief areas in which individual playas developed, that does not appear to be the case. Gypsum over the synclines do not appear to be thicker, nor does gypsum over the anticlines appear to be thinner. In many places, such as along the south face of Shadescale Mesa and in the Henry Basin, the gypsum appears to occupy very broad, very shallow topographic lows that were eroded into the top the Summerville Formation across both anticlines and synclines (summarized in figure 27). Although water erosion is usually assumed to be the mechanism in such cases, deflation by wind may have also played a role and might be the source for the eolianites of the Bluff Sandstone Member located downwind. Aeolation (wind erosion) is a major cause of erosion of landforms in some dryland environments (Shao, 2008; Goudie, 2004b, 2013).

The geographic area covered by the thick gypsum deposits extends from north of the Woodside anticline to approximately 25 km south of Hanksville (north of Butler Wash), and from the west side of the San Rafael Swell to within about 1.5 km of the White Sand Dunes Recreation Area (see figures 7 and 8 for location information). This large area of approximately 6800 km² indicates the existence of a huge playa complex composed of playa lakes as indicated by the local thicker gypsum bodies (e.g., figures 23B and 23C). The sulfur isotope of this gypsum and carbon isotope of associated limestone indicates a nonmarine source of brines in a closed basin (Northrop, 1982). Thus, these saline bodies of water are not coastal sabkhas. What is not certain is whether all of these gypsum-depositing playa lakes were active at the same time, or whether they record a sporadic shift eastward with the prograding Elko highland fluvial fans. The presence of a non-pedogenic limestone bed at the base of the gypsum near the Yen (1952) clam site suggests a localized lacustrine setting prior to salinization and gypsum deposition. As noted previously, the gyp-

sum probably originated from weathering and erosion of the evaporites of the Lower Permian Summit Springs Member of the Pequop Formation in the Elko highlands (Steele, 1960; Kellogg, 1963). The north-south arrangement of the thick gypsum beds along the west side of the Colorado Plateau supports this interpretation. The gypsum playas probably formed at the distal end or terminus of fluvial fans as they do in modern situations (Shaw and Bryant, 2011; Goudie, 2013).

Where the basal gypsum is absent, Bed A is present at the base of the Tidwell Member. However, this stratigraphic unit is rather problematical in that it is a relatively thin, tabular sandstone that is wide spread across the central and eastern side of the northern Colorado Plateau. Bernier and Chan (2006) considered the origin of Bed A in terms of traditional fluvial deposition as overbank sheetflood in part because of ripple structures (e.g., figure 12G). Not resolved, however, is the originating channels for the overbank flows. Demko and others (2005) suggested instead that Bed A in the Henry Mountains was deposited in part as zibars, but unfortunately gave no reason for this conclusion. Zibars are a low-relief (less than 10 m) eolian bedform composed of coarse sands or granules (0.3 to 0.65 mm) and lacking well-developed slip faces (Biswas and others, 2014). Zibars are typically spaced 50 to 100 m and are preserved as sand sheets that are usually structureless, but may retain low-angled, flat-rippled laminae, and interbedded coarser-grained sand interzibar deposits (Biswas, 2005). Zibars occur on the upwind margin of dune fields as the winnowed residues because the grains are too heavy for wind mobilization into dunes (Nielson and Kocurek, 1986; Lancaster, 2009). Zibar deposits would be expected on the paleo-upwind side adjacent the sand dune deposits represented by the Bluff Sandstone Member of the Morrison Formation. A possible fluvially reworked zibar deposit (based on the uniform coarse grain size) in the Tidwell Member is present at Duma Point (figure 12E).

Sand sheets like Bed A also can form in dryland environments where conditions limit mobility of sand into dunes. These limiting conditions include a high water table (capillary water tension), periodic or seasonal flooding (wetting of the surface), microbial surface binding (by cyanophytes and fungi) or cementation (duricrusts and rain-splash crust), coarse-grained sand (including surface armoring), and the stabilizing effect of vegetation (Kocurek and Nielson, 1986). These same features also promote sand accumulation as sheets where otherwise sand transport without deposition would occur. Perhaps the best analogous modern sand sheet to part or most of Bed A is the Selima Sand Sheet on the border between Sudan and Egypt (centered at 22º N., 28º E.). Occupying 120,000 km^2 (Maxwell and Haynes, 2001), the enormous size is due to the absence of topographic barriers allowing long distance wind transport (Breed and others, 1987). Sand sheet microstrata are composed of bimodal combination of fine to medium sand laminae separated by granules or coarse sand. These laminae are nearly horizontal because the stoss and lee slopes are < 5º. The recent sand sheet rests disconformably on an older, more consolidated, massive sand sheet that lacks the distinctive coarse-fine laminae (Breed and others, 1987). The source for the sand is the underlying Cretaceous Nubia Formation. The sand is moved across the Selima Sand Sheet in giant ripples up to 10 m thick. Because the ripples are low profiled and very wide, they give the ground a gently undulating surface making them difficult to discern on the ground; they are best seen on satellite images (Breed and others, 1987). The ripples have no slip faces and lack grainflow stratification, so are not classified as dunes (Breed and others, 1987).

Bed A is estimated to have originally covered over 32,000 km^2, but much of this was lost with erosion of the Monument uplift. Nevertheless, the area is a quarter of the Selima Sand Sheet, so Bed A as a large sand sheet is well within the realm of possibility. The main sources for the sand may be deflation of the Summerville surface and unchannelized flow or floodouts at the distal end of fluvial fans or distributive fluvial systems. Floodouts occur in a variety of environments today, but are especially common in dryland settings (Tooth, 1999, 2004, 2013; North and Davidson, 2012), such as shown in figure 32.

The sand sheet and floodout origin for Bed A calls into question the stratigraphic occurrence of unionid bivalve escape structures reported by Hasiotis (2004) from the base of Bed A at Hatt Ranch located just east of the type section of the Tidwell Member. Bed A by defi-
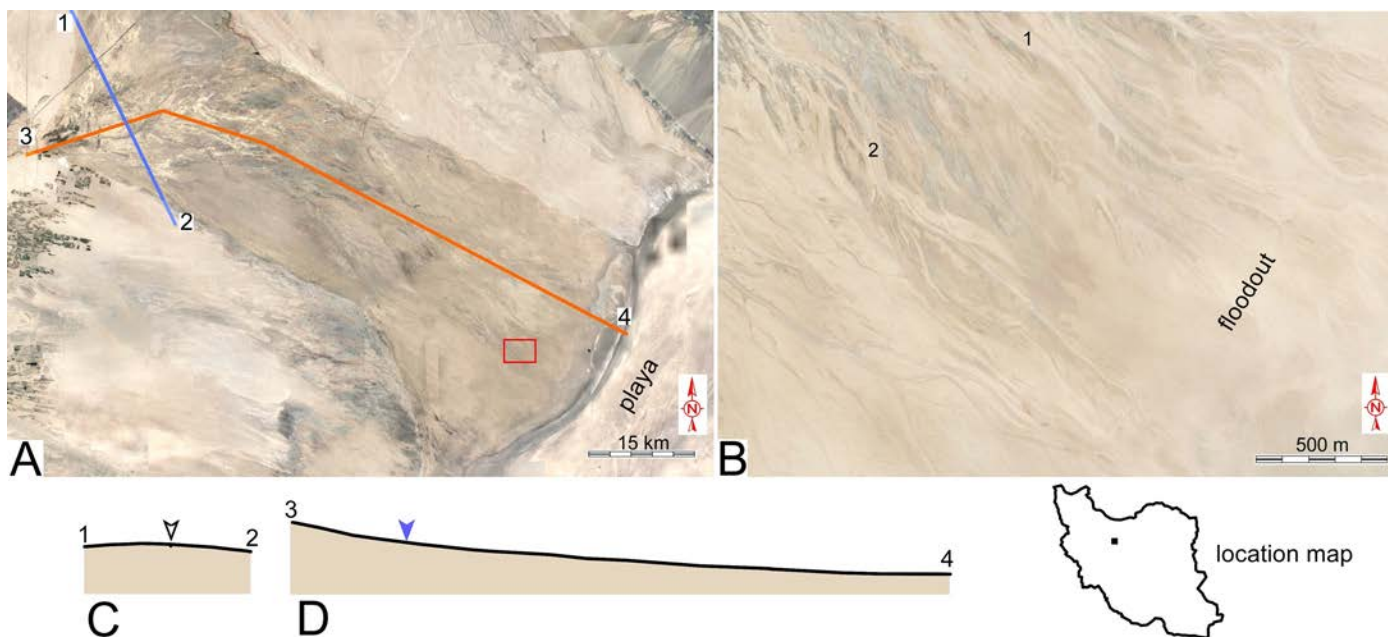
Figure 32. Example of a floodout at the distal end of a fluvial fan near Darya-ye Namak ("Sea of Salt"), northern Iran. (A) The fluvial fan from space (digitally enhanced to show channels). (B) Close-up of red box in (A) showing floodouts distal to two channels (1, 2) (34.6412°, 51.6609°). Note the smaller distributive channels extending from channels 1 and 2, which are themselves distributive channels of a larger network. (C) Concave-up cross section of the proximal fan at line 1–2 of (A). Dart shows location of the active channel, which is on the right flank of the fan. (D) Concave-up longitudinal profile of the fluvial fan; dart is location of cross section of (C). Length is approximately 68 km between points 3 and 4 of A. Point 3 is approximately 47 m higher than point 4. Gradient at the floodout example is 0.29°. Images from Google Earth; profiles redrawn from Google Earth.

nition occurs at the base of the Tidwell Member (O'Sullivan, 1984a), but at Hatt Ranch, the base of the Tidwell is represented by the thick gypsum facies. It seems more likely that the fossils came from a sandstone higher in the Tidwell Member or more likely, a sandstone in the Salt Wash Member.

The continued progradation of the fluvial fans across the Colorado Plateau resulted in the interfingering of the gypsum facies and the overlying SSMLD facies assemblage (figure 25), which Kjemperud and others (2008) considered as indicative of an increasing accommodation/sediment supply (A/S) regime. This interfingering of gypsum and SSMLD shows that cessation of gypsum deposition was not abrupt, but rather clastic influx was discontinuous as would be expected in a dryland environment (Blair and McPherson, 2009; Goudie, 2013). Wide spread of overbank sheet sand from channelized streams are common in the SSMLD assemblage facies as seen by the "wings" extending from channel sandstones (e.g., figures 14A through 14E), which are

common in dryland floodplains (Fielding and others, 2011). Other sheet sandstones may represent floodout deposits. North and Davidson (2012) note that the rate of flow deceleration would be low for an unconfined flow across the planar surface of the playa, thus allowing for wider dispersal of floodout deposits.

Peterson (1978, 1980a) and Demko and others (2005) note that lacustrine facies dominate the SSMLD facies assemblage. However, it is difficult to account for the large volume of water that is implied in a dryland environment with ephemeral fluvial sources (Demko and others, 2004, 2005). Rainfall was probably both strongly seasonal and erratic from year to year (Parrish and others, 2004), as it is in modern drylands (Goudie, 2013). A further complication is the absence of prograding deltaic sandstone facies associated with the supposed lacustrine facies. In addition, there is an apparent absence of seasonal salinization of the lakes as would be expected under such climatic conditions (Eugster and Hardie 1978; Warren 2016). Nevertheless,

the presence of the lacustrine algae, *Botryococcus*, and charophytes in some of the dark mudstones do indicate the presence of ponds or lakes (Peterson, 1984). These may have formed from occasional overbank flow and ponding on the floodplain. However, not all of the dark mudstones are lacustrine. Some are paleosols with a high organic content as discussed previously. Given the importance of organic material, especially plant debris, in promoting redoximorphic conditions (Vepraskas, 2015; Vepraska and Vaughan, 2016), the presence of redox reduction features in some of the dark mudstone is an indirect indication for the presence of vegetation. This explains how large herbivorous sauropod dinosaurs could exist in the Tidwell environment (Gillette, 1996; Bernier and Chan, 2006).

The Tidwell Member in northeastern Utah has been interpreted as marginal marine, tidal flat or lagoon complex because of symmetrical ripples in sandstone interpreted as due to oscillatory waves (Currie, 1998). Such oscillation ripples can also form in lacustrine environments, so that alone is insufficient for conclude a marine setting. Turner and Peterson (2004) also considered the Tidwell Member in northeastern Utah as having brief marine transgressive beds based on the presence of glauconitic sandstone (Peterson, 1994). However, glauconite can also form in nonmarine alkaline environments (Furquim and others, 2010; Roelofse, 2010). Finally, a previous report of marine dinoflagellates in the Tidwell Member near Dinosaur National Monument (Turner and Peterson, 1999), is now known to be in error. The specimens came from the Redwater Member of the Stump Formation (Litwin and others, 1998, p. 302). Currently, there is no compelling evidence for a marine influence in the Tidwell Member in northeastern Utah.

A visual summary of depositional environment for the Tidwell Member is presented in figure 33. Placement of the Elko orogeny is based on Thorman (2011) and the three ranges that were sources for the Morrison Formation are based on Yingling (1987). The Windy Hill Formation as a coastal depositional environment is based on Holland and Wright (2020). The Laurentian fluvial system is based on the conclusions of Ejembi and others (2021). The Mogollon uplift as the northern rift shoulder with associated slope is based on Bilodeau

(1986). Two interesting discoveries in the compellation of the image was the position of the playa complex and two of the sources of Yingling (figure 33, number 5 with numbers 4a and 4b), and the relative position of the southernmost source for the fluvial fan that may have deflected eastward the Salt Wash fluvial fan (figure 33, number 4c with number 8). These discoveries are preliminary and need confirmation.

CONCLUSIONS

The Tidwell Member belongs as a member of the Morrison Formation, not the underlying Summerville Formation. The member is here considered to have been formally named by Peterson (1988a). Although O'Sullivan (1984a) earlier met all the requirements of NASC, he did not meet the requirements of the USGS. The Tidwell Member is restricted to the Colorado Plateau where it crops out between the underlying Summerville or Wanaka Formations and the overlying Salt Wash Member of the Morrison Formation. In the northwestern part of the Colorado Plateau (San Rafael Swell-Henry Basin), the Tidwell is composed of a lower gypsum facies and an overlying interbedded thin sandstone-siltstone-mudstone-limestone-dolomite (SSMLD) facies assemblage. Elsewhere across the Plateau, the Tidwell Member consists only of the SSMLD facies assemblage overlying a basal sandstone, Bed A. This assemblage in the southern part of Utah differs from the type and supplemental reference sections in being dominated by sandstones, and in the northern part of the Plateau (Uinta Basin) in having proportionally more mudstone. Identifying these outliers as the Tidwell Member is based more on stratigraphic correlation with the type and reference sections than lithology.

The lower gypsum facies is separated from the Summerville Formation by the less than 500,000 year gap of the J-5 unconformity, which in places are angular conformities from truncated low amplitude anticlines. These anticlines and associated synclines may be the last gasp of the Elko foreland basin, which was more active as a depositional center during the Middle Jurassic (Thorman, 2011). Gypsum deposition preceded the arrival of the distal clastic sediments of the fluvial fans of the Salt Wash Member. The arrival of these clastic sediments ef-
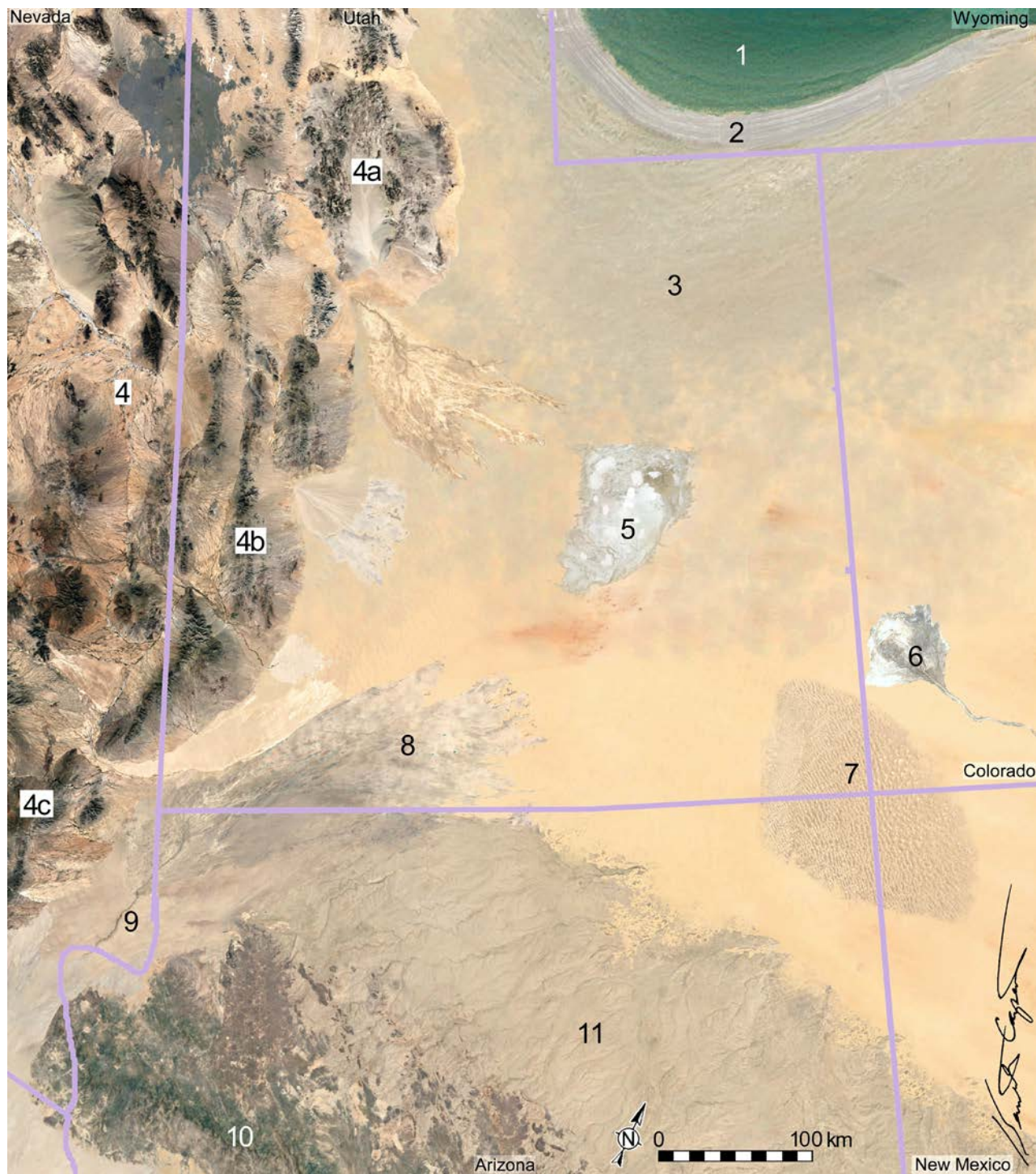
Figure 33. Reconstruction of the region of the Colorado Plateau during Tidwell deposition. (1) Regressing Sundance seaway. (2) Coastal deposition of the Windy Hill Formation. (3) Exposed surface of the Summerville Formation. (4) Remnants of the Elko orogeny, with a volcanic region in the north; placement of ranges 4a, 4b, and 4c based on Yingling (1987; see also Peterson, 1994). (5) Playa complex with playa lakes. (6) Relict fluvial system from Laurentia. (7) Eolian dunes of the Bluff Sandstone Member with zibars along the west side. (8) Early phase of what will become the Salt Wash fluvial system. (9) Region of the Grand Canyon bight. (10) Mogollon highlands. (11) Mongollon slope. Although the landscape may look barren, it was probably covered with xeric and gypsophilic plants except in active playa lakes and dune field. Composed from Google Earth images.

fectively smothered the playa complex, and spread over the exposed Summerville surface on the eastern part of the Colorado Plateau.

ACKNOWLEDGMENTS

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