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# Updating the Upper Cretaceous (Campanian) Two Medicine Formation of Montana: Lithostratigraphic revisions, new CA-ID-TIMS U-Pb ages, and a calibrated framework for dinosaur occurrences

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## ABSTRACT

**The Campanian Two Medicine Formation of northwestern Montana, USA, is richly fossiliferous, and discoveries made within the unit over the past century have greatly advanced our appreciation of dinosaur paleobiology and evolution. Previously undifferentiated from a lithostratigraphic perspective, the formation is now subdivided into four new members that include (from base to top) (1) the Rock City Member, (2) the Shields Crossing Member, (3) the Hagans Crossing Member, and (4) the Flag Butte Member. These new formal units and their associated fossil occurrences are also now included in an age model founded on eight high-resolution chemical abrasion–isotope dilution–thermal ionization mass spectrometry (CA-ID-TIMS) U-Pb ages. New age data confirm that the Two Medicine Formation accumulated during much of the Campanian, with deposition spanning ca. 82.4 Ma to 74.4 Ma. New age data further indicate that a major reorganization of depositional systems, marked by a shift from predominantly lacustrine to alluvial facies and accompanied by a dramatic increase in accommodation, transpired near the base of the new Flag Butte Member at ca. 76.3 Ma. This change in depositional regime correlates in age with the Judith River–Belly River discontinuity, which marks the contact between the McClelland Ferry and Coal Ridge Members in the Judith River Formation and coincides with the onset of the Bearpaw transgression in north-central Montana. The new lithostratigraphic and chronostratigraphic framework for the Two Medicine Formation serves to contextualize and calibrate the formation's rich dinosaur fossil record, which can now be interrogated with increased clarity and precision. These results also provide ground truth for numerical models that explore the structure of the fossil record in relation to alluvial architecture and terrestrial sequence stratigraphy.**

## INTRODUCTION

The Two Medicine Formation of northwestern Montana, USA (Fig. 1), hosts a remarkable record of Late Cretaceous dinosaurs and boasts a wealth of spectacular bonebeds and some of the best-preserved dinosaur nests, nesting grounds, embryos, and juvenile specimens known to science (Horner, 1982, 1984a, 1984b, 1997, 1999; Horner and Weishampel, 1988, 1996; among others). Fossils of the Two Medicine Formation are preserved in a suite of terrestrial facies that accumulated over a span of ~8 m.y., during most of the Campanian (Fig. 2), the zenith of dinosaur diversity (Ramezani et al., 2022). Over this multi-million-year span, active tectonism and mountain building in the Cordillera (DeCelles and Currie, 1996; DeCelles, 2004; Miall et al., 2008), regionwide transgressions and regressions of the Western Interior Seaway (Kauffman, 1977), and explosive volcanism (Viele and Harris, 1965; Roberts and Hendrix, 2000) impacted the Two Medicine depocenter. Related short-term environmental perturbations and more protracted episodes of environmental change influenced the Two Medicine terrestrial ecosystem in profound ways and potentially drove the tempo and mode of dinosaur evolution (Horner et al., 1992).

Work in the Two Medicine Formation has focused primarily on the unit's abundant fossils. At least 25 vertebrate species, including dinosaurs, pterosaurs, squamates, mammals, and a bird, have been described and are considered valid (e.g., Gilmore, 1914, 1917, 1930, 1939; Horner and Makela, 1979; Horner and Weishampel, 1988, 1996; Montellano, 1988; Horner, 1992; Horner and Currie, 1994; Padian, et al., 1995; Varricchio and Chiappe, 1995; Burnham et al., 2000; Montellano et al., 2000; Varricchio et al., 2002; Chinnery, 2004; Chinnery and Horner, 2007; Gates et al., 2011; Agnolin and Varricchio, 2012; McGarrity et al., 2013; Penkalski, 2014; Funston et al., 2021), with most based upon very well-preserved material, and, in the case of taxa known from bonebeds, multiple individuals (e.g., Gilmore, 1917, 1939; Varricchio and Horner, 1993; Currie et al., 2005; DeMar et al., 2017; Weaver et al., 2021). Collections of dinosaurs from bonebeds have advanced current understanding of ontogenetic variation and clarified growth histories for select dinosaur taxa (e.g., Horner et al., 2000; Woodward et al., 2015). Studies of Two Medicine Formation nests and nesting sites, embryos, and juveniles have elucidated aspects of dinosaur reproductive biology and provided a window into reproductive behavior and early life history (Horner, 1982, 1984a, 1997, 1999; Horner and Weishampel, 1988, 1996; Varricchio et al., 1997, 1999, 2002;

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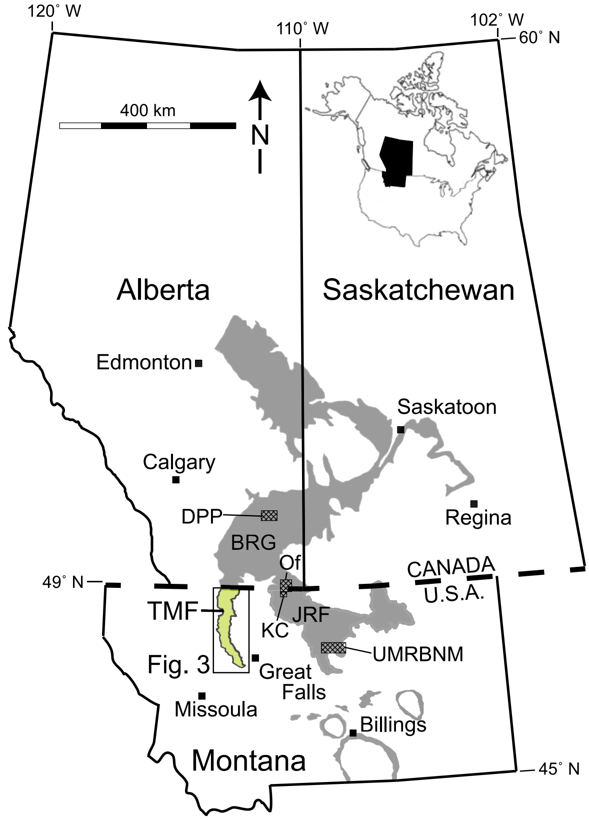


**Figure 1. Generalized outcrop belt of the Two Medicine Formation (TMF; green) in northwestern Montana, USA, the Judith River Formation (JRF) in central Montana, and the Belly River Group (BRG) in the plains of Alberta and Saskatchewan, Canada. Middle and upper portions of the Two Medicine Formation correlate with terrestrial and shallow-marine facies of the Judith River Formation and Belly River Group. Figure is modified from Eberth and Hamblin (1993) and Rogers et al. (2023). KC—Kennedy Coulee, north-central Montana; UMRBNM—Upper Missouri River Breaks National Monument, north-central Montana; Of—Onefour area, southeastern Alberta; DPP—Dinosaur Provincial Park, southeastern Alberta.**

Zelenitsky and Therrien, 2008; Jackson et al., 2015; Prieto-Marquez and Guenther, 2018; among others). Histological, histochemical, and immunological studies of Two Medicine Formation fossils have provided evidence of soft tissue preservation (Bailleul et al., 2012, 2013, 2016, 2020), and studies of botanical records from the formation have yielded insights into the diversity of the paleoflora (Crabtree, 1987a, 1987b) and the paleoclimate (Falcon-Lang, 2003). Investigations of Two Medicine trace fossils (Rogers, 1992; Martin and Varricchio, 2011; Panascí and Varricchio, 2020; Shibata and Varricchio, 2020; Freimuth and Varicchio, 2019) have revealed behaviors for some invertebrates in the unit, and analyses of coprolites have yielded novel insights into dinosaur diets and Late Cretaceous food webs (Chin and Gill, 1996; Chin, 2007; Chin et al., 2009, 2017). Taphonomic studies have explored the fossilization process as it pertains to Two Medicine Formation fossils and revealed aspects of the ancient Two Medicine paleoenvironment that presumably rendered the dinosaur-dominated ecosystem susceptible to recurrent localized mortality events (Rogers, 1990; Varricchio and Horner, 1993; Varricchio, 1995; Rogers and Kidwell, 2000; Rogers and Brady, 2010; Rogers et al., 2010, 2017, 2020; Scherzer and Varricchio, 2010; Schmitt et al., 2014).

Studies of the Two Medicine Formation with a geological focus are decidedly less common. A few reports have summarized the general geology of the unit in the context of the Upper Cretaceous section in northwestern Montana (e.g., Cobban, 1955; Weimer, 1960; Gill and Cobban, 1973; Rice and Cobban, 1977), and brief descriptions of the local geology are often included in paleontologically focused articles (e.g., Scherzer and Varricchio, 2010), but few studies have focused specifically on the sedimentology and stratigraphy of the unit. Notable exceptions include the report of Viele and Harris (1965), which described volcaniclastic facies of the Two Medicine Formation in the southernmost portion of the outcrop belt, and theses by Lorenz (1981) and Gavin (1986), which focused on distinctive facies in the Two Medicine type area and Choteau region, respectively, which were summarized in Lorenz and Gavin (1984). Taking advantage of the numerous bentonite beds in the Two Medicine Formation, Rogers et al. (1993) and Foreman et al. (2008) provided the first $^{40}Ar/^{39}Ar$ geochronology for the unit. Rogers (1994, 1998) further analyzed sedimentologic and stratigraphic datasets, with a focus on throughgoing discontinuities, to subdivide the Two Medicine Formation and place it in a regional stratigraphic framework.

In this report, we revisit the geology of the Two Medicine Formation, with a focus on lithostratigraphy and geochronology. This work is important and timely because, at present, the formation is undifferentiated from a formal lithostratigraphic perspective and thus remains difficult to contextualize and correlate at a level more refined than the formation scale to correlative units in Montana (Judith River Formation, Eagle Formation), Canada (Belly River Group of Alberta and Saskatchewan), and other parts of the Western Interior Basin. Moreover, the six legacy $^{40}Ar/^{39}Ar$ ages reported in Rogers et al. (1993) and Foreman et al. (2008) have limited comparability with modern, high-precision U-Pb geochronology reported from other Campanian units of the Western Interior (e.g., Ramezani et al., 2022). Herein, we propose four new formal members within the Two Medicine Formation, and we report six new U-Pb zircon bentonite ages (Table 1; Fig. 2; Table S1[1]) that complement two U-Pb zircon dates for the formation recently reported by Ramezani et al. (2022). The new chronostratigraphic framework advances regional correlation of the Two Medicine Formation and yields insights into the evolution of the Western Interior Basin, particularly in relation to the response of terrestrial depositional systems to tectonics and changes in accommodation. This study also for the first time places the Two Medicine Formation's rich dinosaur fossil record in a chronostratigraphic framework calibrated with high-precision U-Pb geochronology, and this in turn provides a robust baseline for future studies of dinosaur biogeography and evolution.

## BACKGROUND AND REGIONAL SETTING

Eugene Stebinger (1914), working under the auspices of the U.S. Geological Survey and charged with documenting potential coal and hydrocarbon reserves in the northern Great Plains region, initially described and named exposures of the Two Medicine Formation in the valley of the Two Medicine River on the Blackfeet Indian Reservation (Fig. 3). He delineated distinctive features relative to associated units and included the Two Medicine Formation, along with the underlying Virgelle and overlying Horsethief sandstones, within the Montana Group of Eldridge (1888, 1889). Stebinger (1914, p. 61)

[1]Supplemental Material. Table S1: U-Pb isotopic data for zircon analyses from Campanian bentonites of the Two Medicine Formation, Montana, USA. Table S2: GPS coordinates for measured columns in Two Medicine Formation. Please visit https://doi.org/10.1130/GSAB.S.26015320 to access the supplemental material; contact editing@geosociety.org with any questions.

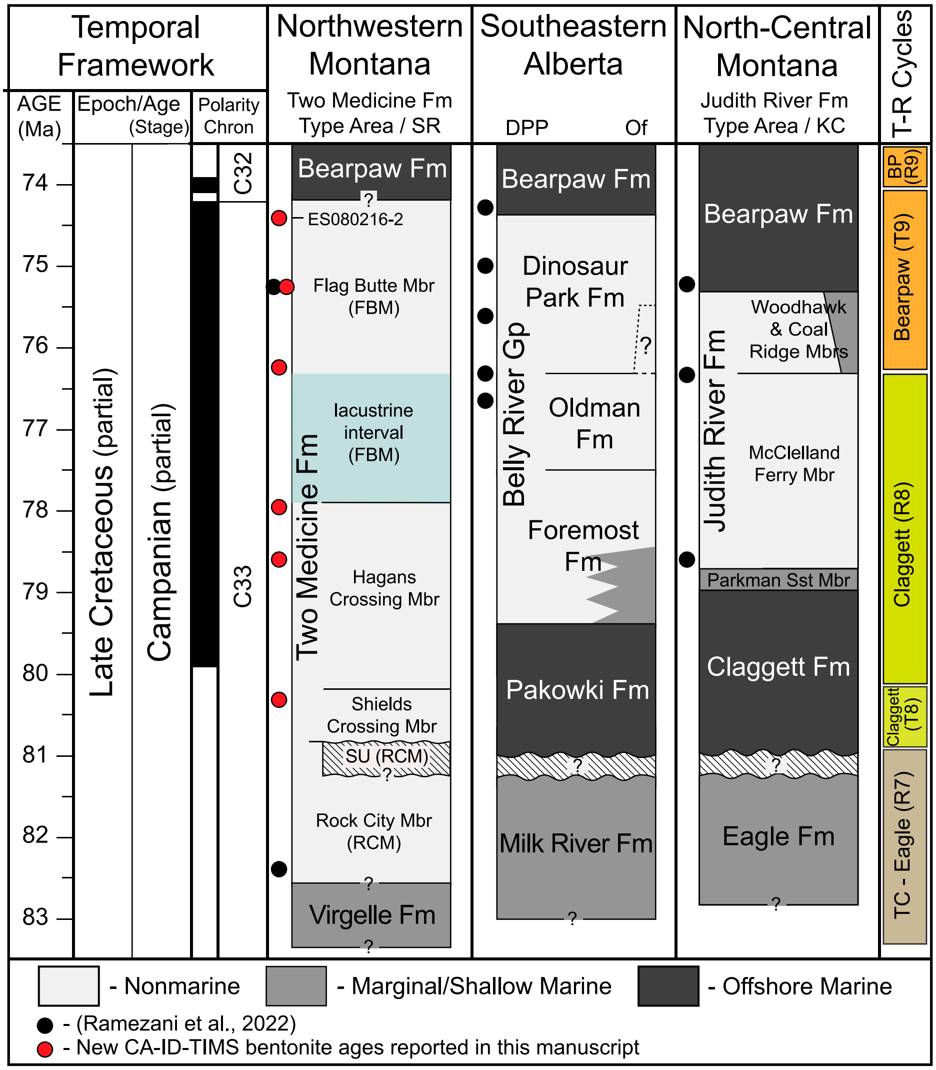


**Figure 2. Chronostratigraphic chart of Campanian strata in northwestern and north-central Montana, USA, and southeastern Alberta, Canada (modified from Ramezani et al., 2022; Rogers et al., 2023). The stratigraphy of recently published U-Pb zircon ages in the Two Medicine Formation, Judith River Formation, Bearpaw Formation, and Belly River Group is indicated in relation to key units with black circles (Ramezani et al., 2022). The stratigraphy of the six new U-Pb zircon ages reported in this study (Table 1) is indicated with red circles. The chronostratigraphy of the Pakowki, Claggett, Milk River, and Eagle Formations and the approximate durations of a hiatus in southeastern Alberta and north-central Montana are based on Payenberg et al. (2002, 2003). DPP—Dinosaur Provincial Park, southeastern Alberta; Of—Onefour area, southeastern Alberta; KC—Kennedy Coulee, north-central Montana; SU—subaerial unconformity; RCM—Rock City Member; FBM—Flag Butte Member; Fm—Formation; Mbr—Member; Gp—Group; Sst—Sandstone; SR—surrounding region, Two Medicine outcrop belt (see Fig. 3); CA-ID-TIMS—chemical abrasion–isotope dilution–thermal ionization mass spectrometry; T-R—transgression-regression.**

noted the excellent nature of the outcrop along the Two Medicine River and proposed that these exposures serve as the "standard for the region." The Two Medicine Formation in the type area was estimated to be ~600 m thick and was characterized as "continental" in nature, consisting mostly of claystone (light gray, greenish gray, variegated red and yellow), with intercalated beds of "nodular and nonpersistent" limestone and sandstone (Stebinger, 1914, p. 63). The abundance of dinosaur fossils was noted (with reference to collections made by C.W. Gilmore in 1913), along with mollusks of both freshwater and brackish affinity and plant remains.

On a more regional scale, Stebinger (1914, his fig. 9) recognized that the Two Medicine Formation represented the updip terrestrial portion of two eastward-thinning clastic tongues that extended across the Sweetgrass arch into central Montana, where both pinch out within marine shale deposits. Deposition of the lower clastic tongue occurred during the Telegraph Creek–Eagle regression and the subsequent transgression of the Claggett sea (R7 and T8 of Kauffman, 1977). The upper clastic tongue accumulated during regression of the Claggett sea and the subsequent transgression of the Bearpaw sea (R8 and T9 of Kauffman, 1977). In northwestern Montana along the Two Medicine River, the lower tongue includes shallow-marine sandstone deposits of the Virgelle Formation and the basal ~100 m of the overlying Two Medicine Formation, and the upper tongue consists of the middle and upper Two Medicine Formation. In north-central Montana along the Missouri River drainage, the lower clastic tongue includes deposits of the shallow-marine/paralic Eagle Formation, and the upper tongue is represented by coastal plain and shallow-marine deposits of the Judith River Formation. Stebinger (1914, p. 67) interpreted the large-scale intertonguing of terrestrial and marine strata of the Montana Group to reflect widespread episodes of "recession" and "advance" of the Cretaceous seaway and linked them to cycles of uplift and subsidence and changing rates of sedimentation in the basin.

It is now recognized that the Two Medicine Formation was deposited in the Western Interior Basin, a retroarc foreland basin genetically linked to the North American Cordillera and active from the Middle–Late Jurassic to early Cenozoic (Kauffman, 1977; DeCelles and Currie, 1996; DeCelles, 2004; Miall et al., 2008; Fuentes et al., 2009, 2012). Crustal thickening in the North American Cordillera and dynamic loading related to mantle processes drove subsidence and the generation of accommodation in the foreland basin, and this subsidence was asymmetric and focused in proximal reaches of the basin (Beaumont, 1981; Jordan, 1981; Beaumont et al., 1993; Catuneanu, 2004, 2019; DeCelles, 2012). Up to 3 km thicknesses of predominantly terrestrial strata, including the alluvial deposits of the Two Medicine Formation, are preserved in the Western Interior Basin in northwestern Montana, and reconstructions suggest that the strata of the Montana Group (including the Two Medicine Formation) accumulated in the foredeep depozone (Lorenz, 1981; Miall et al., 2008; Fuentes et al., 2012). Exhumed batholiths, thrust sheets carrying Proterozoic and Paleozoic strata, and localized volcanic centers supplied siliciclastic and volcaniclastic detritus to the Two Medicine alluvial plain,

TABLE 1. SUMMARY OF CALCULATED U-Pb AGES AND THEIR UNCERTAINTIES, TWO MEDICINE FORMATION, NORTHWESTERN MONTANA, USA

| Sample | Field area | Latitude* (°N) | Longitude* (°W) | Elevation (m) | $^{206}Pb/^{238}U$ age (Ma) | Uncertainty†† (2σ) | | | MSWD§§ | *N*## | No. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | *X* | *Y* | *Z* | | | |
| 90TMT-590-U60*** | Type area | 48.49722 | −112.60456 | 455† | 75.252 | 0.024 | 0.032 | 0.086 | 0.83 | 5 | 5 |
| LSB-1-14 | Landslide Butte | 48.93715 | −112.65038 | 455§ | 75.243 | 0.023 | 0.030 | 0.086 | 1.1 | 5 | 8 |
| L2R061517-1 | Type area | 48.48619 | −112.54162 | 336† | 76.247 | 0.087 | 0.091 | 0.12 | 0.66 | 4 | 5 |
| Hadro Hill 8-9-93 | Type area | 48.45483 | −112.49770 | 250† | 78.598 | 0.027 | 0.044 | 0.095 | 0.66 | 4 | 5 |
| SC080116-2 | Type area | 48.46858 | −112.36527 | 88† | 80.33 | 0.14 | 0.16 | 0.18 | 1.6 | 4 | 5 |
| CB061417-1*** | Type area | 48.52586 | −112.28953 | 17† | 82.419 | 0.074 | 0.086 | 0.12 | 1.4 | 3 | 7 |
| ES080216-2 | Willow Creek | 47.82694 | −112.49632 | −39# | 74.430 | 0.015 | 0.025 | 0.083 | 0.64 | 6 | 6 |
| EMC080216-1 | Willow Creek | 47.81142 | −112.42026 | −13** | 77.968 | 0.024 | 0.032 | 0.089 | 0.13 | 6 | 6 |

*Note:* Column *X* is referenced throughout this manuscript in relation to 2σ analytical uncertainty.
*Latitude/Longitude relative to World Geodetic System 1984 (WGS84) datum.
†Stratigraphic elevation above the base of the Two Medicine Formation.
§Stratigraphic position based on correlation with 90TMT-590-U60 bentonite.
#Stratigraphic elevation below Horsethief Formation (Bearpaw-Horsethief transition unit), based on personal observation (R. Rogers).
**Stratigraphic elevation below Hagans Crossing Member–Flag Butte Member contact, based on Shelton (2007) and personal observation (R. Rogers).
††*X*—internal (analytical) uncertainty in the absence of all external or systematic errors; *Y*—incorporates the U-Pb tracer calibration error; *Z*—includes *X* and *Y*, as well as the uranium decay constant errors of Jaffey et al. (1971).
§§MSWD—mean square of weighted deviates.
##*N*—number of analyses included in the calculated weighted mean date out of total number of analyses (No.).
***Ramezani et al. (2022).

and this terrestrial setting transitioned downdip to paralic coastal plains (e.g., Judith River Formation) and marginal marine and open-marine environments of the Western Interior Seaway. The large-scale regressions and transgressions of the seaway that Stebinger noted reflect the dynamic interplay among tectonic subsidence, sediment supply, and eustasy (e.g., Kauffman, 1977; Cant and Stockmal, 1989; Leckie and Smith, 1992; Kauffman and Caldwell, 1993; among many others). Previous studies of Two Medicine geochronology (e.g., Rogers et al., 1993; Foreman et al., 2008; Carr et al., 2017; Fowler, 2017) suggest that the unit accumulated during a significant fraction of the Campanian Stage (ca. 83.6–72.1 Ma; Cohen et al., 2013), and the new ages reported herein (see below) and in Ramezani et al. (2022) are consistent with this interpretation (Fig. 2).

## METHODS

More than 45 stratigraphic columns documented by Rogers (1990, 1995, 1998) and Roberts (1999) informed this study. Most were measured in the type area along the Two Medicine River and in nearby exposures on Cut Bank Creek (Figs. 3 and 4), and the new member stratotypes and composite reference section developed herein were compiled from these columns, which were correlated by walking out marker beds, including bentonites, extensive sandstone bodies, and distinctive paleosol horizons. In the few cases where marker beds could not be traced continuously due to limited exposure, the thickness of covered intervals was approximated based on the regional dip of strata and the distance between outcrop belts (Stebinger, 1917; Lorenz, 1981). Stratigraphic columns farther afield (e.g., Milk River drainage near Landslide Butte and Choteau region) were also documented to extend stratigraphic coverage throughout the Two Medicine outcrop belt (Fig. 3). This dataset provided the basis for stratigraphic analysis and afforded a rigorous framework for sampled bentonites and fossils. Field notes and historical records were used to place fossil occurrences as precisely as possible within local stratigraphy. Importantly, it was possible to directly tie most dinosaur occurrences in the Two Medicine Formation to nearby measured columns, and when this was not possible, the placement of fossils in stratigraphic section was carefully approximated using knowledge of the strike and dip of the strata (Stebinger, 1917) and Google Earth.

The bentonite U-Pb geochronology reported herein followed standard methodologies described in Ramezani et al. (2022) and Beveridge et al. (2022). Details of chemical abrasion–isotope dilution–thermal ionization mass spectrometry (CA-ID-TIMS) analytical procedures and age calculation methodologies are described in considerable detail in these two recent articles, which are related outcomes of a collaborative project focusing on the geochronology of Campanian-age dinosaur-bearing strata in the Western Interior Basin (see also Eberth et al., 2023; Rogers et al., 2023; this study). Bentonite ages were derived from weighted mean dates of the youngest zircon analyses (excluding older detrital/xenocrystic zircons), and their uncertainties are reported in the format ± *X*/*Y*/*Z* Ma (Table 1), where *X* is the analytical uncertainty alone, *Y* includes *X* plus the tracer calibration error, and *Z* incorporates the decay constant uncertainties of Jaffey et al. (1971). When comparing U-Pb ID-TIMS data produced using the same isotopic tracer, only *X* needs to be considered. Therefore, only *X* is referenced throughout this paper in relation to 2σ error. The Bayesian age-stratigraphic model for the Two Medicine Formation was developed using the Bchronology R software package (Haslett and Parnell, 2008; Parnell et al., 2008, 2011). The underlying Markov chain Monte Carlo rejection algorithm of the model utilizes the weighted mean dates of all analyzed samples and their relative stratigraphic positions to extrapolate depositional ages and uncertainties for any given stratigraphic horizon of interest (e.g., fossil occurrences, unit contacts, significant surfaces), taking into account possible variations in rock accumulation rate. U-Pb age data were modeled against the ~517-m-thick composite reference section from the Two Medicine Formation type area, which includes five dated bentonite horizons (Table 1; Table S1).

## LITHOSTRATIGRAPHIC UPDATES

### Existing Type Section and Informal Lithofacies

Stebinger (1914, p. 61) identified the type area of the Two Medicine Formation when, in his initial naming of the unit, he referred to the outcrops along the Two Medicine River (Figs. 3 and 4) as "the standard for the region." He did not, however, describe or illustrate a detailed stratigraphic column of the formation that could serve as a suitable stratotype or reference section. This goal was achieved several decades later by Lorenz (1981), who pieced together a composite type section along the Two Medicine River. Lorenz and Gavin (1984) subsequently published a "simplified composite" type section for the Two Medicine Formation based on Lorenz's (1981) initial work. They also provided brief descriptions of three informal lithofacies suites, again first developed in Lorenz (1981), which they employed to subdivide the unit in the type area.

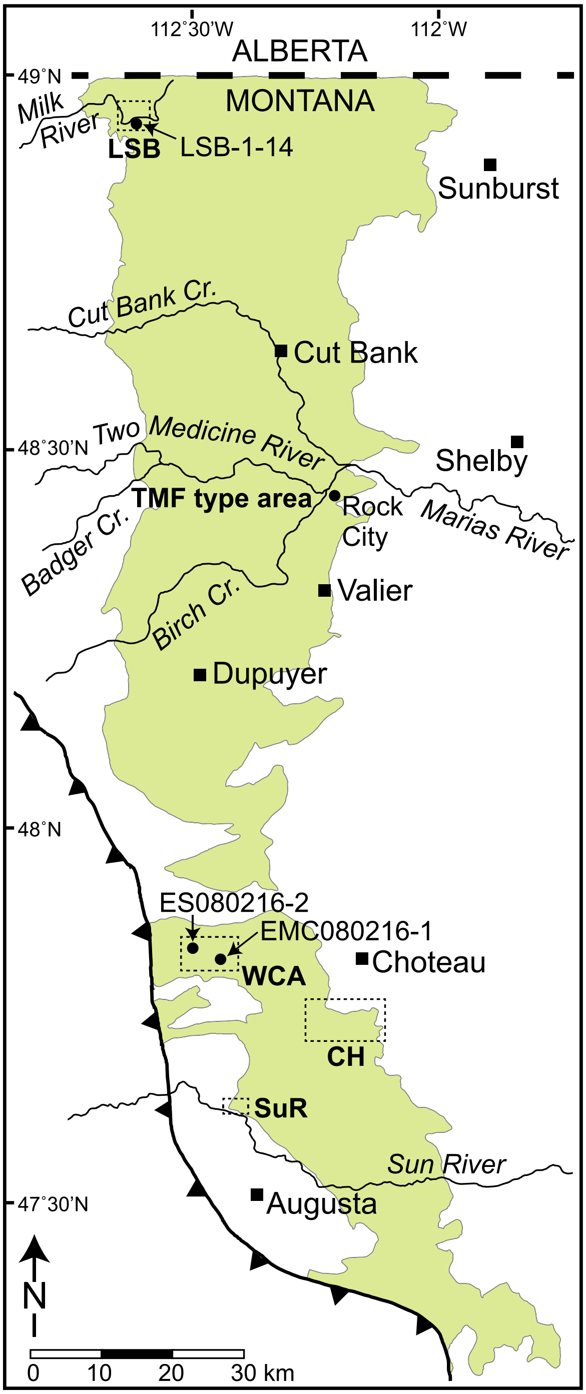


**Figure 3. Two Medicine Formation outcrop belt (modified from Vuke et al., 2007). Focal areas in this report include the formation type area along the Two Medicine River (TMF type area), the Landslide Butte field area (LSB) along the Milk River, the Willow Creek anticline field area (WCA) west of Choteau, the Choteau field area (CH) south of Choteau in the general vicinity of Sevenmile Hill, and the Sun River field area (SuR) along the Sun River in the disturbed belt north of Augusta. Cr.—Creek.**

The "lower lithofacies" of the Two Medicine Formation spans ~100 m within the type area and includes a heterolithic mix of lenticular and sheet sandstones, gray to gray-green beds of mudstone, and scattered vertebrate and invertebrate fossils (Lorenz, 1981; Lorenz and Gavin, 1984). The thick "blanket" sandstone bodies that characterize the lower lithofacies are laterally extensive and can often be traced over several kilometers along the river valley, thus serving as marker beds to correlate stratigraphic columns in this part of the section. The base of the lower lithofacies is typically marked by a thin bed of lignite (although it may be locally truncated by overlying channel deposits), and the top is marked by a laterally extensive 20- to 50-cm-thick mollusk shell bed characterized by a muddy sandstone matrix.

The "middle lithofacies" spans the next ~220 m of the type section (up to ~320 m above base of formation) and is characterized by a "subtly different suite of lithologies" (Lorenz, 1981, p. 25). The basal ~10 m interval of the middle lithofacies is characterized by beds of lignite and dark carbonaceous mudstones. Sandstone bodies of the middle lithofacies were described as less extensive (broadly lenticular), with only minor erosional relief on basal contacts. Intercalated beds of mudstone are typically gray in color and preserve less carbonaceous debris than comparable fine-grained facies in the underlying lithofacies (with the exception of the basal ~10 m). Vertebrate fossils are more common, fossilized wood is rare, and carbonate nodules are abundant, and sometimes coalesced into expansive nodular horizons.

The transition from the "middle lithofacies" to "upper lithofacies" was delineated by the appearance of grayish-purple and reddish-brown mudstones (variegated paleosols) in the Two Medicine section, which, according to Lorenz (1981) and Lorenz and Gavin (1984), first occurs ~320–330 m above the base of the formation. The upper lithofacies is characterized by fewer but thicker and more lenticular sandstone bodies relative to the lower lithofacies, and abundant vertebrate fossils, including articulated dinosaur specimens. Carbonate nodules remain abundant in mudstones, and concentrations of carbonaceous debris are decidedly rare. An "anomalous…lithologic suite" (Lorenz and Gavin, 1984, p. 178) consisting of crudely bedded carbonates, silicified carbonates, and lacustrine siltstones and shales occurs ~20 m above the base of the upper lithofacies (~340 m above contact with Virgelle Formation) and spans the next ~55 m. The entire upper lithofacies was estimated to span ~225 m (Lorenz, 1981, p. 25), which yields a total thickness of ~550 m for the Two Medicine Formation type section, although thickness estimates vary in previous reports, and the upper contact with the Bearpaw Formation is obscured by cover.

## Four New Members of Two Medicine Formation

Starting in the summer of 1988, Rogers (1990, 1994, 1995, 1998) followed the trail blazed by Stebinger (1914) and Lorenz (1981) and worked his way up the Two Medicine River from Rock City (confluence of Two Medicine River and Birch Creek) to the vicinity of Highway 89, documenting the sedimentology and stratigraphy of the Two Medicine Formation and associated units along the way. Following the same general path as Lorenz (1981), Rogers measured 29 stratigraphic columns in and around the type area (including on Badger and Blacktail Creeks). He supplemented this work with additional stratigraphic columns and observations on Cut Bank Creek, Milk River (Landslide Butte), and

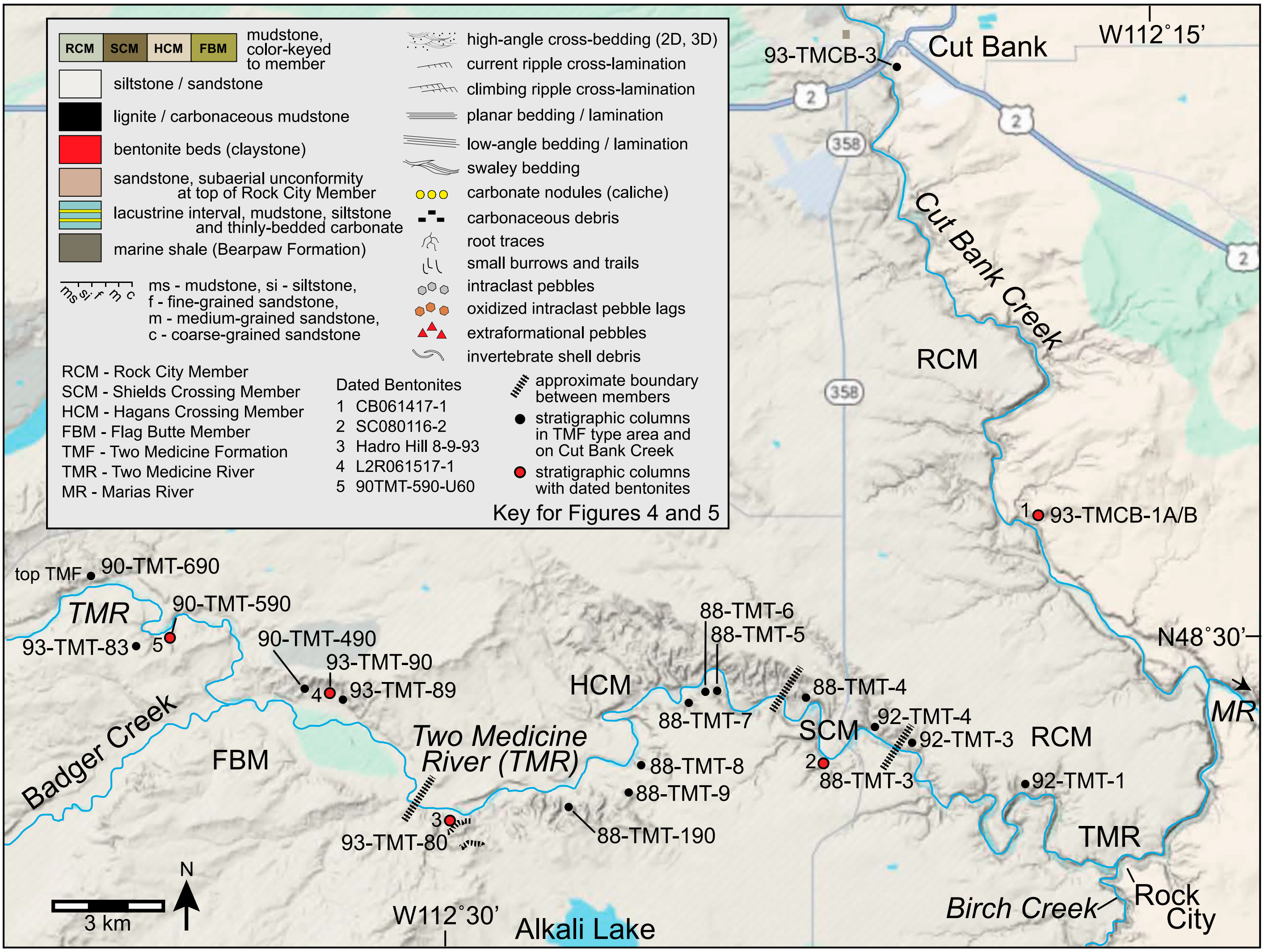


**Figure 4. Google Maps image of Two Medicine Formation (TMF) type area and exposures along Cut Bank Creek extending north to the vicinity of the town of Cut Bank. Inset box includes explanations of symbols and abbreviations used in this figure and in Figure 5. Black and red circles indicate locations of stratigraphic columns used to assemble composite stratotypes and reference sections of four new members in the Two Medicine Formation (see text for details). Red circles indicate columns that include bentonites dated in this report. Black dashed lines approximate boundaries between new members along Two Medicine River (TMR). The short black dashed lines in close proximity to stratigraphic column 93-TMT-80 bracket local exposures of the Flag Butte Member, which is more widely exposed upstream (to the west). See Table S2 (text footnote 1) for GPS coordinates for measured columns in Two Medicine Formation.**

the Choteau area (Willow Creek anticline and Sevenmile Hill). Seven additional stratigraphic columns in the Two Medicine Formation were documented by Roberts (1999) in the outcrop belt south of Choteau (Fig. 3).

In this report, we used these stratigraphic columns and accompanying sedimentologic data to designate four new formal members and assemble an updated supplementary reference section for the Two Medicine Formation. These new additions to the lithostratigraphy of the Two Medicine Formation build upon previous observations and interpretations of Stebinger (1914), Lorenz (1981), and Lorenz and Gavin (1984), and they provide new data and some new interpretations that relate to significant surfaces and intervals in the unit (Rogers, 1994, 1998). The new members and composite reference section were calibrated with several new U-Pb zircon ages derived from intercalated bentonite beds (see below). In the following narrative, we describe and illustrate the lithologic characteristics of each new member in the type area, place the dated bentonites in section, and highlight distinctions in relation to the existing Two Medicine type section of Lorenz (1981) and Lorenz and Gavin (1984). We also correlate the new members to outcrop belts beyond the valley of the Two Medicine River (type area).

### *Rock City Member*

The Rock City Member, a new formal member of the Two Medicine Formation, is present in the valley of the Two Medicine River from Rock City (section 16, T31N, R5W) upstream to Shields Crossing (section 10, T31N, R6W), with the most expansive exposures upstream of section 8 in T31N, R5W (U.S. Geological Survey, 2017). On Cut Bank Creek, facies of the new member occur from the vicinity of Cut

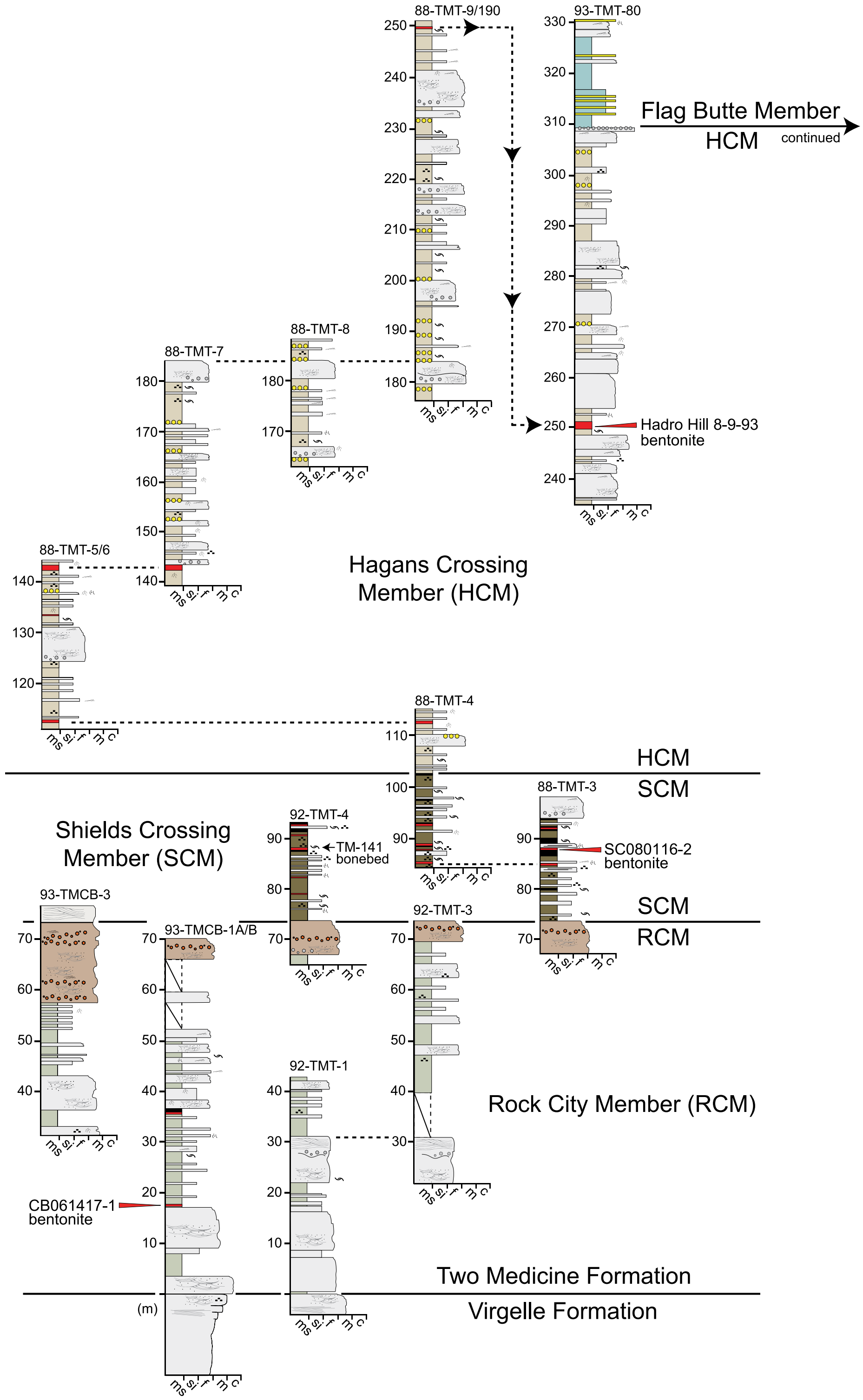


**Figure 5. Suite of stratigraphic columns used to assemble composite type sections and reference sections for the four new members in Two Medicine Formation (Rogers, 1995). See Figure 4 for locations of measured columns and key to lithological and paleontological features illustrated in columns. TM—Museum of the Rockies (MOR) field locality number. (*Continued*)**

Bank town downstream ~14 km to section 20 of T32N, R5W (Fig. 4). The new member spans the basal ~73 m interval of the Two Medicine Formation in outcrop (Figs. 5 and 6), and well logs indicate that the unit thickens to ~95 m to the north and west of the type area. This westward thickening of the Rock City Member, and the Two Medicine Formation in general, is consistent with the wedge geometry of the lower and upper clastic tongues.

The basal contact of the Rock City Member is coincident with the contact between the Two Medicine Formation and the underlying marine Virgelle Formation. At Rock City and elsewhere along the Two Medicine River, the contact is typically marked by a bed of lignite or carbonaceous mudstone resting sharply upon the shallow-marine sandstone deposits of the underlying Virgelle Formation (Fig. 6A). On Cut Bank Creek, the base of the unit is marked by a coarse-grained sandstone in erosional contact with underlying finer-grained sandstones of the Virgelle Formation (Figs. 4, 5 [column 93-TMCB-1A/B], and 6B). The upper contact of the Rock City Member coincides with the top of a distinctive fluvial sandstone body identified by Rogers (1994, 1998). This unit-capping sandstone body is more widespread and generally thicker than other sandstone bodies in the formation (see Figs. 5 [column 93-TMCB-3] and 6C), and it is characterized by pervasive oxidation and a thick and persistent intraclast lag facies associated with meter-scale internal scours (Figs. 5 and 6D). Rogers (1994, 1998) interpreted this distinctive sheet sandstone body as an example of a terrestrial sequence boundary and linked it to an episode of diminished accommodation in the basin. The exact position of the subaerial unconformity within this low-accommodation sandstone body is difficult to ascertain because multiple distinct erosion surfaces are developed in some locations (e.g., column 93-TMCB-3) within the deposit.

Two stratigraphic columns in the Two Medicine River area were correlated to yield the composite stratotype for the Rock City Member (columns 92-TMT-1 and 92-TMT-3), and relevant sedimentologic details are summarized in Figure 5. The composite stratotype is ~73 m thick and consists of a heterolithic succession of gray to tan mudstones, siltstones, and fine- to coarse-grained sandstones of predominantly terrestrial origin (fluvial and floodplain deposits). A brown carbonaceous mudstone with fissile parting marks the basal contact with the Virgelle Formation, and the lower half of the column preserves three relatively thick sheet sandstones (Figs. 5 and 6B), one of which exhibits evidence of marine influence (swaley bedding). A supplementary reference section for the Rock City Member on Cut Bank Creek (Fig. 5, column 93-TMCB-1A/B) exhibits comparable thickness (~70 m) and similar lithologic character and includes a bentonite bed 17 m above the base of the unit (CB061417-1 bentonite) that was dated

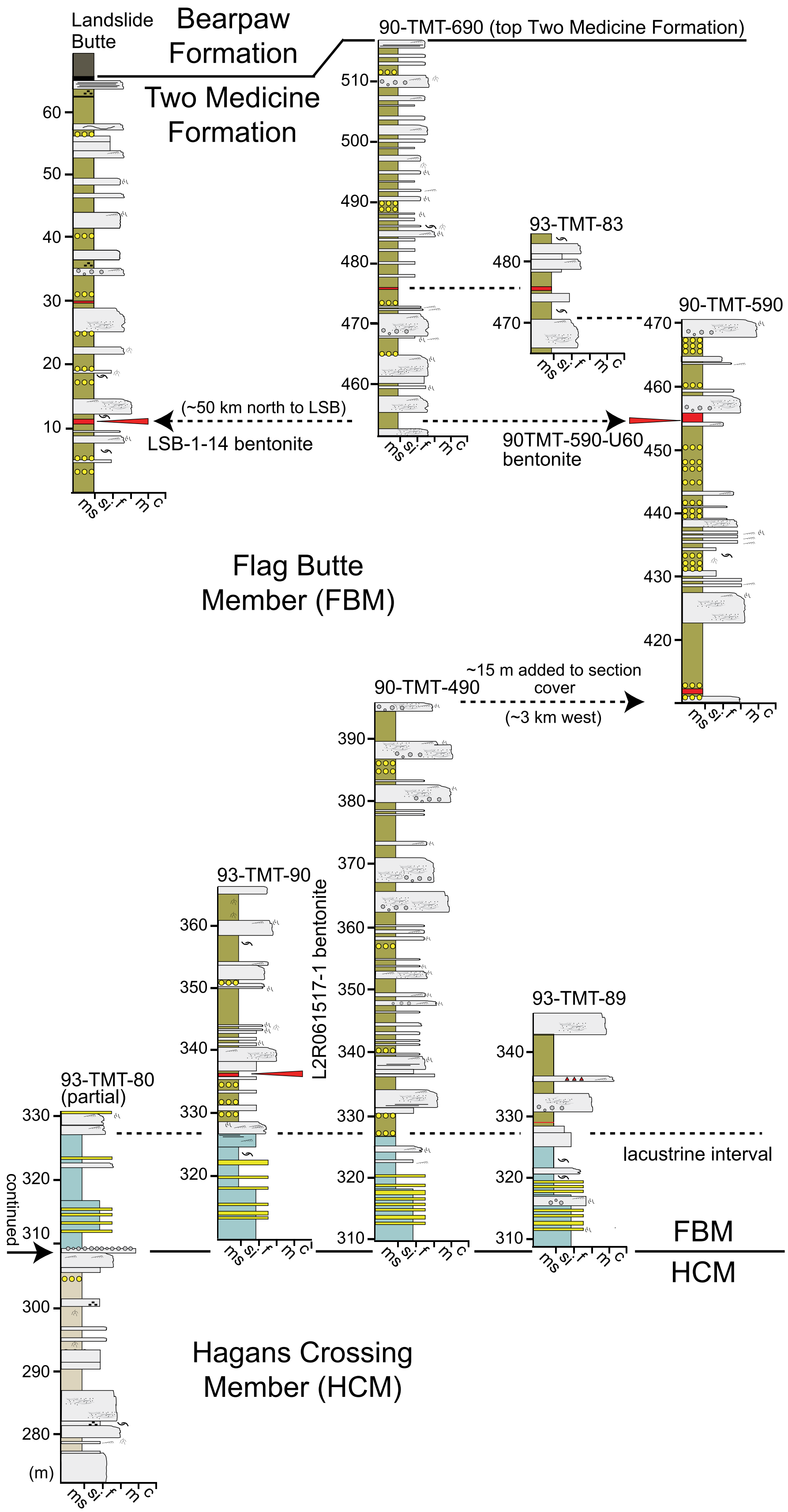


**Figure 5.** (***Continued***)

by Ramezani et al. (2022) to 82.419 ± 0.074 Ma (Table 1).

***Shields Crossing Member***

The Shields Crossing Member of the Two Medicine Formation is exposed along the valley of the Two Medicine River in the immediate vicinity of Shields Crossing on Montana Highway 358 (Figs. 4 and 7), which connects the towns of Valier and Cut Bank. The ~30-m-thick member is mappable for a few kilometers along the river, where its distinctive lithologic character makes it readily distinguishable from surrounding deposits of the other members of the Two Medicine Formation. The base of the Shields Crossing Member rests in sharp contact upon the aforementioned distinctive sandstone body that caps the Rock City Member (Figs. 5, 7A, and 7B), and its top is defined by the highest occurrence of a bed of lignite (or brown carbonaceous mudstone) in the local exposures along the Two Medicine River.

The two stratigraphic columns that establish the composite stratotype for the Shields Crossing Member (Fig. 5, columns 88-TMT-3 and 88-TMT-4) are located just upstream from the Shields Crossing bridge, and a third stratigraphic column, offered as a supplemental reference section (Fig. 5, column 92-TMT-4), is located less than 1 km downstream from the bridge. Sedimentologic details relating to these three columns are summarized in Figure 5. The conspicuously carbonaceous nature of the Shields Crossing Member is its most distinctive lithologic characteristic (Figs. 7B and 7C). Carbonaceous beds of mudstone and siltstone are intercalated with thin tabular beds of carbonaceous fine-grained sandstone, several seams of lignite, and at least six discrete bentonites, one of which (SC080116-2 bentonite) was dated in this report to 80.33 ± 0.14 Ma (Table 1; Fig. 5). Interestingly, all bentonite beds documented in the Shields Crossing Member are tan to yellow in color (Fig. 7D), which contrasts with most bentonites higher in the section, which are typically (but not exclusively) a darker olive-green color. Fragmentary remains of mollusks with brackish affinities are common within the carbonaceous beds of the Shields Crossing Member, and a laterally extensive shell bed that preserves corbulids, corbiculids, oysters, and gastropods in a matrix of brown fine-grained sandstone is intercalated ~20 m above the base of the unit. This massive well-indurated shell bed is ~30 cm thick and is characterized by complete disarticulated valves of bivalves and intact gastropod shells interspersed with densely packed pockets of shell hash and carbonaceous debris (Fig. 7C). Lorenz and Gavin (1984) identified this same shell bed and used it to mark the boundary

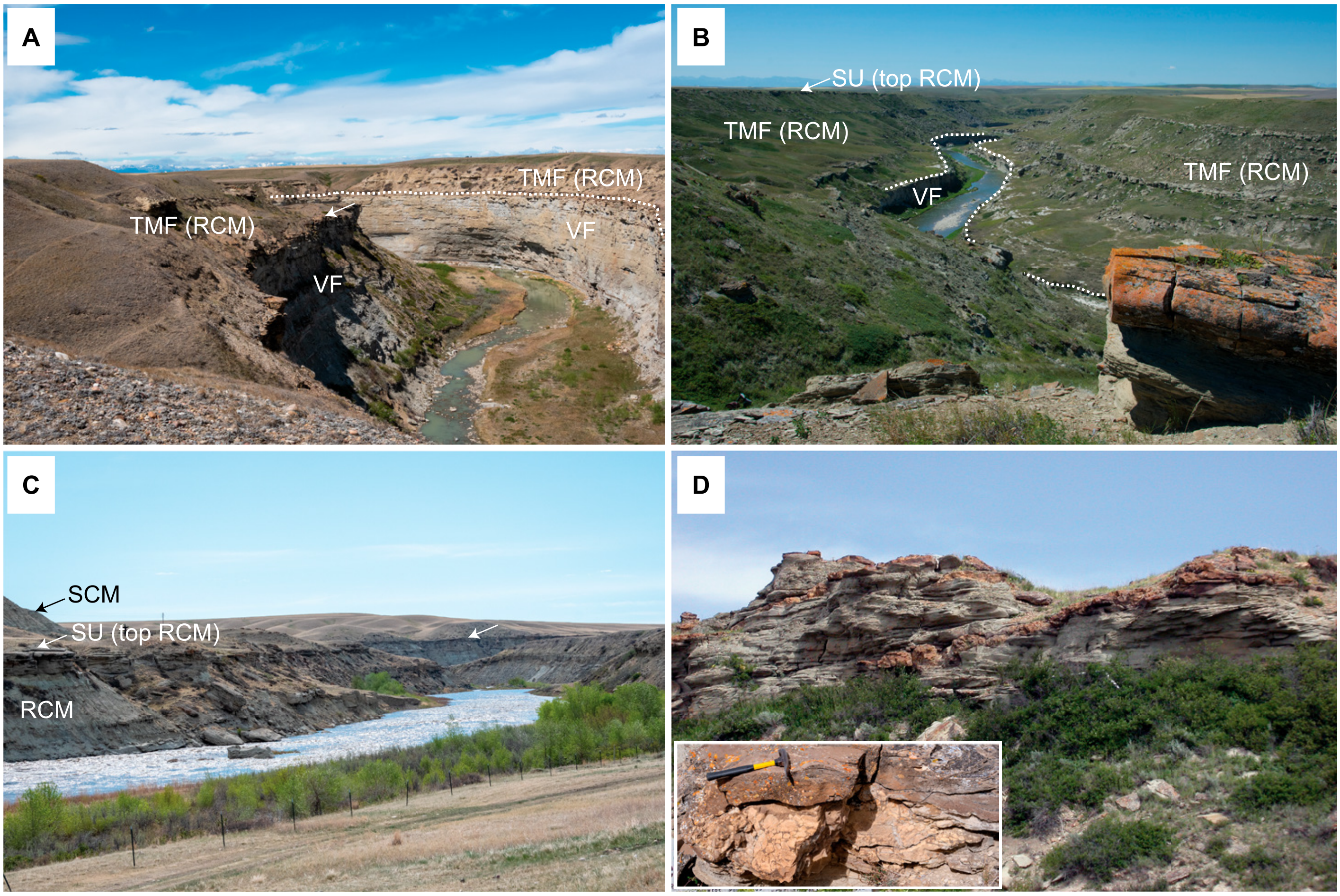


**Figure 6. Outcrop views of the Rock City Member (RCM) of the Two Medicine Formation (TMF). (A) View of contact (white arrow and white dashed line) between Virgelle Formation (VF) and overlying Two Medicine Formation (Rock City Member) on Birch Creek (looking west and upstream) at Rock City above the confluence with the Two Medicine River. Here, the contact between formations is marked by a change in slope. The vertical cliff face of Virgelle Formation is ∼30 m tall. (B) View of contact (white dashed lines) between Virgelle Formation and overlying Two Medicine Formation (Rock City Member) on Cut Bank Creek (looking southwest and downstream). Here, again, a dramatic change in slope marks the contact between formations. A distinctive sandstone body hosting the subaerial unconformity (SU, white arrow) caps the Rock City Member. (C) View of Rock City Member and overlying Shields Crossing Member (SCM) on the Two Medicine River (looking east and downstream). White arrows mark top of sandstone body hosting the subaerial unconformity (SU) at top of Rock City Member. The top of this sandstone body is ∼12 m above river level. (D) View of stacked oxidized intraclast lag facies in the sandstone body hosting the subaerial unconformity along Cut Bank Creek (inset shows close-up of oxidized intraclasts in lag facies). Here, the sandstone body is ∼15 m thick.**

between their "lower lithofacies" and "middle lithofacies." The sedimentology and paleontology of the Shields Crossing Member are consistent with deposition in coastal wetlands and swamps in close proximity to shorelines during the Claggett transgression (T8). Contemporaneous explosive volcanism is indicated by the abundance of bentonites in the unit.

One final distinction of the Shields Crossing Member is the presence of a vertebrate microfossil bonebed ∼14 m above the base of the unit (Fig. 5, column 92-TMT-4). This bonebed (TM-141, "TM-XXX" refers to field localities of the Museum of the Rockies [MOR], Bozeman, Montana, USA) represents the lowest documented concentration of vertebrate fossils in the Two Medicine Formation type area, and it includes teeth of crocodilians and dinosaurs (hadrosaurid, ankylosaurid), along with gar scales and abundant unidentifiable bone fragments. Disarticulated and dissociated vertebrate fossils are found here in association with fragments of eggshell and the remains of freshwater bivalves and gastropods.

### *Hagans Crossing Member*

The Hagans Crossing Member of the Two Medicine Formation extends from section 34 in T32N, R6W (∼2.5 km upstream of the Shields Crossing bridge following the path of river) to the vicinity of Hagans Crossing (section 10, T31N, R7W), representing a straight-line distance of ∼10 km (U.S. Geological Survey, 2014, 2020a). Across this distance, the member crops out in two expansive belts of badland exposures on the north (SW1/4 of T32N, R6W) and south (NE1/4 of T31N, R7W) sides of the Two Medicine River (Fig. 4). The base of the ∼210-m-thick member coincides with the top of the uppermost lignite bed (or brown carbonaceous mudstone) in the underlying Shields Crossing Member, and its top is delimited by a previously recognized discon-

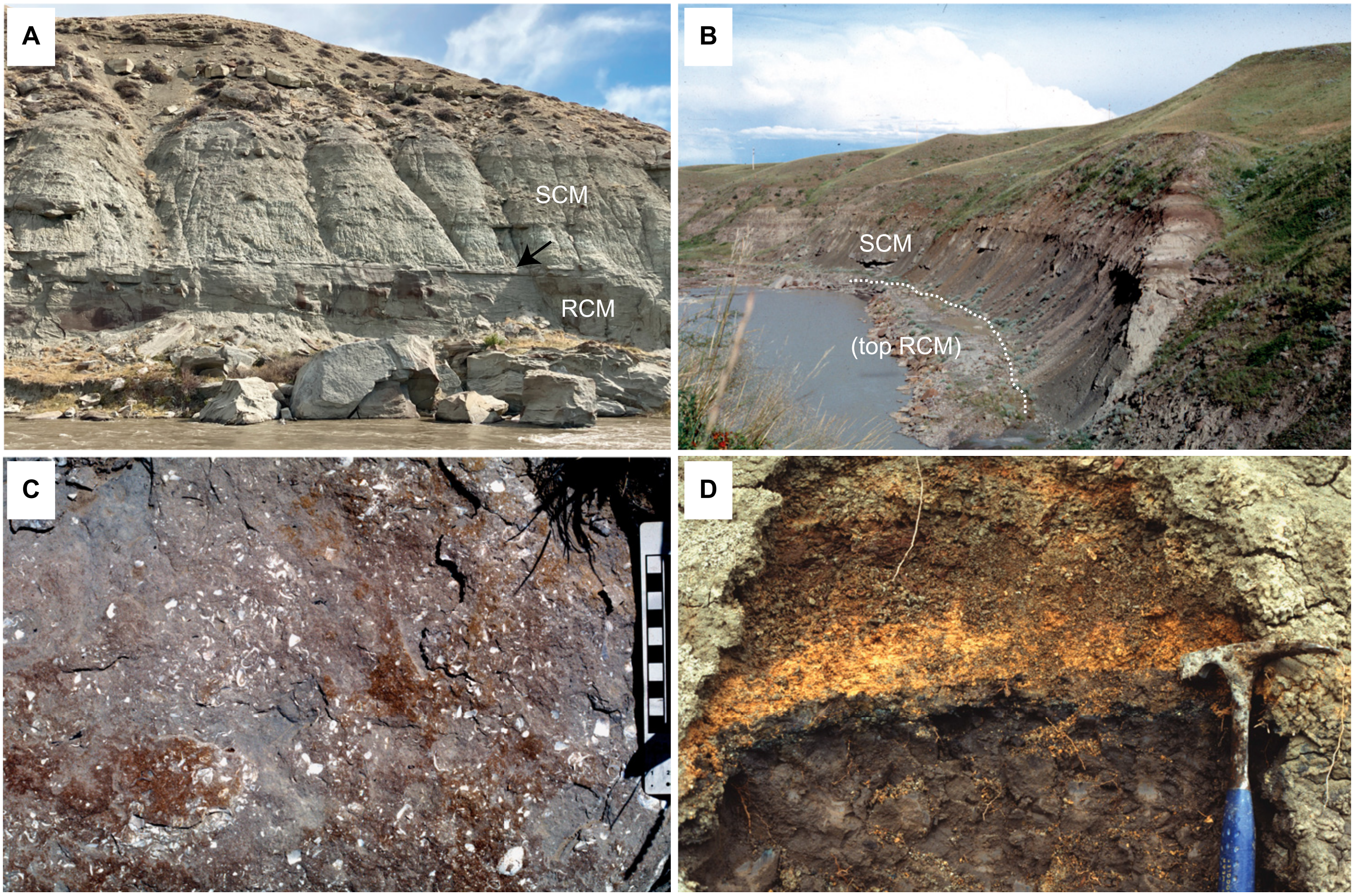


**Figure 7. Outcrop views of the Shields Crossing Member (SCM) of the Two Medicine Formation. (A) View of contact between Rock City Member (RCM) and Shields Crossing Member (SCM) along Two Medicine River just downstream from Shields Crossing. Black arrow marks contact, which is ~8 m above river level. (B) Carbonaceous strata of Shields Crossing Member immediately upstream from Shields Crossing. White dashed line marks contact with underlying Rock City Member. Local exposure spans ~25 m. (C) Fragmentary shells of mollusks with brackish affinities (corbulids, corbiculids, oysters) are common within the carbonaceous beds of the Shields Crossing Member. (D) The numerous bentonites documented in the Shields Crossing Member are tan to yellow in color, in contrast to most bentonites higher in section, which are typically olive green.**

tinuity that marks the base of widespread lacustrine deposits in the Two Medicine Formation (Rogers, 1994, 1998).

Six stratigraphic columns (Fig. 5, columns 88-TMT-4, 88-TMT-5/6, 88-TMT-7, 88-TMT-8, 88-TMT-9/190, 93-TMT-80) were correlated to establish the composite stratotype of the Hagans Crossing Member, which is characterized by beds of gray and gray-green mudstone and siltstone intercalated with narrow sheets and lenses of gray fine- to medium-grained sandstone (Figs. 5 and 8A). The mudstone interbeds are generally massive and tend to exhibit blocky parting and abundant millimeter-scale oxidized root traces. Carbonate nodules (caliche) are common in mudstones and are sometimes coalesced into thin beds that weather as orange-brown indurated horizons. Siltstone interbeds vary from massive to planar-laminated and current ripple cross-laminated and frequently exhibit small root traces. Thicker sandstone bodies are typically characterized by trough and tabular cross-bedding, and they often preserve intraclast lags of carbonate and mudstone pebbles. Paleocurrent data from fluvial sandstones are consistent with a northeast-directed paleoflow. At least four discrete bentonite beds occur in the Hagans Crossing Member. The uppermost bentonite in the type area (Hadro Hill 8-9-93 bentonite) crops out ~140 m above the base of the member (~250 m above the base of the formation) and was dated in this report to 78.598 ± 0.027 Ma (Table 1; Fig. 5). The uppermost ~20 m of the unit preserves the first notable occurrence of variegated red-brown and grayish-purple facies in the Two Medicine section (Fig. 8B). Lorenz and Gavin (1984) used these same variegated beds to delimit the transition from their middle to upper lithofacies.

Shells and shell fragments of freshwater bivalves and gastropods are preserved throughout the fluvial and floodplain facies of the Hagans Crossing Member. Dinosaur fossils are also abundant in the unit, including isolated bones, partial skeletons, and monodominant bonebeds.

### *Flag Butte Member*

The Flag Butte Member of the Two Medicine Formation crops out in the broad valley of the Two Medicine River from Hagans Crossing upstream to the NW1/4 of section 27 in T32N, R8W (Fig. 4; U.S. Geological Survey, 2020b). The member extends for ~10 km along the river valley, starting high in the exposures above Hagans Crossing near Flag Butte (Figs. 4 and 5, top of column 93-TMT-80), and culminating upstream at the top of Two Medicine exposures

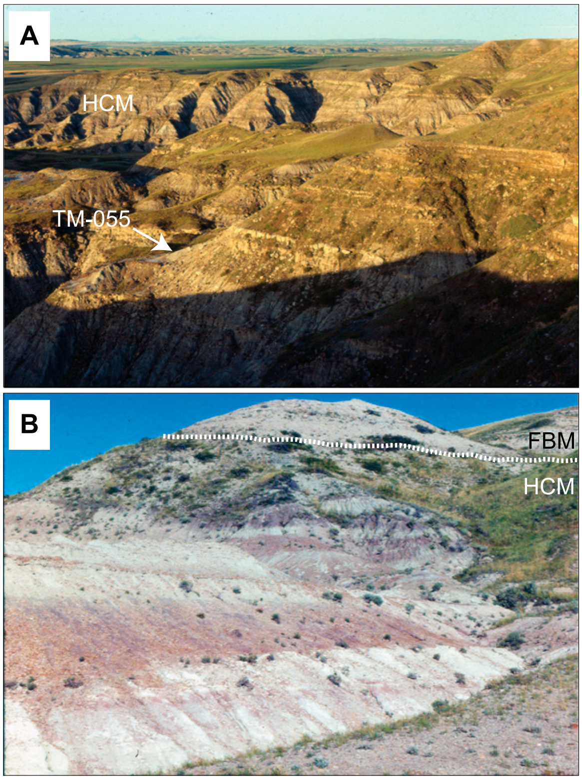


**Figure 8. Outcrop views of the Hagans Crossing Member (HCM) of the Two Medicine Formation. (A) View of Hagans Crossing Member looking northeast across the Two Medicine River (Sweetgrass Hills in far distance). Museum of the Rockies locality TM-055 is a bonebed that yielded disarticulated skeletons of the hadrosaurid *Gryposaurus* sp. (B) The uppermost ~20 m of the Hagans Crossing Member is characterized by variegated red-brown and grayish-purple paleosols. White line marks contact between Hagans Crossing Member and overlying lacustrine facies (gray smooth weathering slope) of the Flag Butte Member (FBM).**

where the topography falls back to the north (Figs. 4 and 5, column 90-TMT-690), reflecting the presence of more easily eroded shales in the marine Bearpaw Formation. The base of the Flag Butte Member is readily discerned in outcrop (see Figs. 8B and 9A) and coincides with the previously described discontinuity marking the upper limit of the underlying Hagans Crossing Member and the base of the widespread lacustrine interval. The top of the Flag Butte Member coincides with the contact between the Two Medicine Formation and the overlying Bearpaw Formation. This contact is covered in the type area, but, based on the break in topography and vegetation patterns evident on Google Earth, it is likely that the upper limit of Two Medicine Formation exposure on the river rises to within a few meters of the formation boundary (Lorenz, 1981).

Six stratigraphic columns were integrated to establish the composite stratotype of the Flag Butte Member, which spans ~205 m (see Fig. 5, top of column 93-TMT-80, 93-TMT-90, 90-TMT-490, 90-TMT-590, 93-TMT-83, 90-TMT-690). The basal lacustrine interval ranges from 15 m to 20 m thick and consists of thin (10–30 cm on average) tabular beds of light gray and tan micritic limestone intercalated with smooth-weathering interbeds of silty gray and gray-green mudstone, siltstone, and fine-grained sandstone (Fig. 9B). The siliciclastic interbeds tend to be thicker (meter scale), and some of the siltstones and sandstones exhibit planar and wavy laminae and current ripple cross-lamination. Bedding planes in the lacustrine interval often exhibit evidence of bioturbation (centimeter-scale horizontal trails and penetrating burrows), and the top of the interval exhibits silicification in the form of thin chert stringers in carbonate beds.

Fluvial and floodplain facies that overlie the lacustrine interval are represented by beds of gray, gray-green, and, to a lesser extent, red-brown and purple mudstone intercalated with thin tabular sheets of siltstone and lenticular sandstones (Fig. 9C). As in the underlying Hagans Crossing Member, the mudstones are generally massive and preserve small root traces, and the thin siltstone interbeds range from massive (bioturbated and penetrated by root traces) to planar-laminated and current ripple cross-laminated. Overall, the alluvial succession positioned above the lacustrine interval is dominated by finer-grained facies (mudstones and siltstones), within which carbonate nodules (caliche) remain relatively common. Most sandstone bodies in the Flag Butte Member are fine to medium grained, and the thicker units generally exhibit trough and tabular cross-bedding. Paleocurrent data are again consistent with a northeast-directed paleoflow. Basal lag deposits typically include claystone and carbonate pebbles along with vertebrate bioclasts (bone pebbles and teeth). An unusually coarse-grained bed of brown sandstone crops out ~28 m above the base of the member (Fig. 5, column 93-TMT-89), and this distinctive bed preserves rounded extraformational pebbles, including quartzite and other metamorphic and igneous clasts, in association with carbonate and mudstone intraclasts and *Unio* shell fragments. The sand-sized fraction of this bed is enriched with abundant volcanic grains. Cobban (1955, p. 116) also noted the occurrence of an "interesting conglomerate" in this part of the section and reported pebbles of quartzite, hornfels, welded tuff, quartz diorite, and quartz monzonite. The occurrence of extraformational pebbles in this part of the Two Medicine section potentially reflects tectonic reorganization of source areas and sediment delivery systems. Lastly, five distinct bentonite beds were documented in the Flag Butte stratotype. The lowest bentonite sampled in the member (L2R061517-1 bentonite), which is ~26 m above the base of the unit, was dated for the first time in this report (76.247 ± 0.087 Ma), and the age of the thick bentonite bed that crops out ~130 m above the base of the unit (90TMT-590-U60 bentonite, 75.252 ± 0.024 Ma) was recently reported by Ramezani et al. (2022; see also Table 1 and Fig. 5).

Shells and shell fragments of freshwater invertebrates are preserved throughout the Flag Butte Member. Ostracods, charophytes, mollusks, and beds of stromatolites have been reported within the basal lacustrine interval, together with trace fossils and the wing of a large pterodactyloid pterosaur (Lorenz and Gavin, 1984; Padian, 1984; Horner, 1987). The lacustrine interval in the Willow Creek anticline field area is remarkable for its preservation of dinosaur egg clutches on nesting horizons; these nests are predominantly referable to the small theropod *Troodon formosus* (Horner, 1982; Varricchio et al., 2002). Body fossils of dinosaurs and other vertebrates remain notably abundant in the overlying fluvial facies of the Flag Butte Member and include isolated bones and teeth, partial skeletons, and both monodominant and multitaxic bonebeds (e.g., Rogers, 1990; Varricchio and Horner, 1993; Varricchio, 1995).

### *Correlation of New Members beyond Type Area*

***Willow Creek anticline field area.*** The Willow Creek anticline field area, located ~17 km to the west of Choteau, Montana (Fig. 3), has yielded a spectacular array of fossils that includes dinosaur eggs (and embryos), nests, nesting horizons, and a remarkably expansive dinosaur bonebed (e.g., Horner and Makela, 1979; Horner, 1982, 1987; Hooker, 1987; Horner et al., 2000; Schmitt et al., 1998, 2014; Woodward et al., 2015). Lorenz (1981) characterized the geology in and

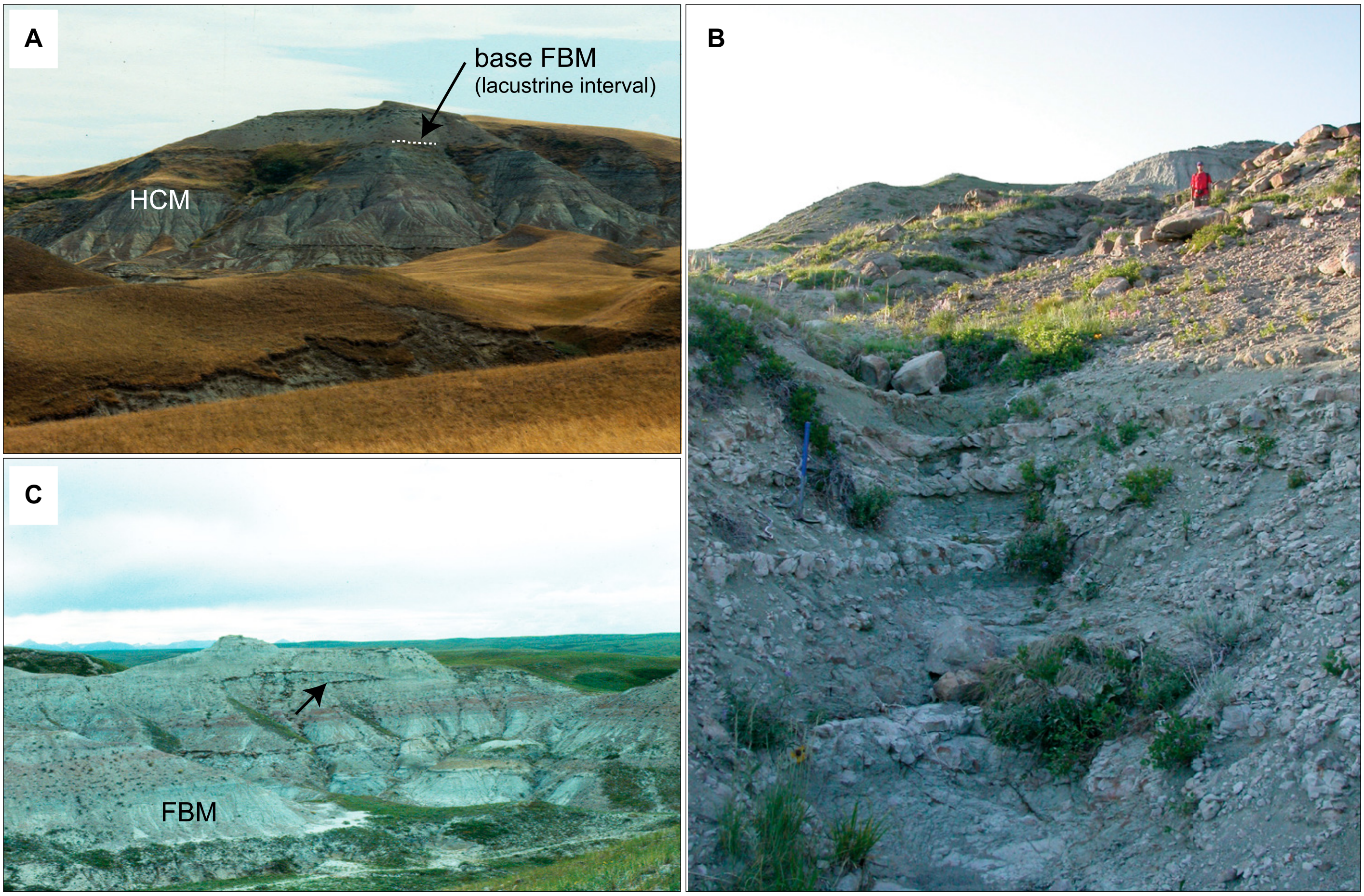


**Figure 9. Outcrop views of the Flag Butte Member (FBM) of the Two Medicine Formation. (A) Upper ~40 m of Hagans Crossing Member (HCM) capped by lacustrine interval (smooth weathering gray slope) at base of Flag Butte Member (column 93-TMT-80 in Figs. 4 and 5). White dashed line delineates contact, which is clearly marked by a change in vegetation. (B) Interbeds of lacustrine carbonate and siltstone at the base of the Flag Butte Member in the vicinity of column 93-TMT-89 (Figs. 4 and 5). (C) Flag Butte Member exposures along Badger Creek in the western portion of the type area (Fig. 4), exhibiting red beds (oxidized paleosols) and a small lenticular fluvial sandstone body (black arrow, ~2.5 m thick).**

around the Willow Creek anticline field area in his broad survey of the Two Medicine Formation and proposed tentative correlations with strata in the type area. Gavin (1986) subsequently studied the rocks of the Willow Creek anticline field area with a paleoenvironmental focus and divided the local section into four "subfacies" that he deemed broadly similar in lithology to Lorenz's (1981) "upper lithofacies" in the Two Medicine Formation type area (Lorenz and Gavin, 1984). Shelton (2007) delved more deeply into the sedimentology of the strata exposed at Willow Creek anticline and placed the local section in a regional sequence stratigraphic framework (e.g., Rogers, 1993, 1998; Roberts, 1999). She compared the Willow Creek anticline section with strata in the Two Medicine Formation type area and proposed that the base of the distinctive lacustrine carbonate interval, which she estimated to be ~14 m thick, correlated with the base of the widespread lacustrine deposits in the formation type area, which are of comparable thickness and lithologic character.

The new lithostratigraphic framework for the Two Medicine Formation developed in the type area readily translates to the Willow Creek anticline section (Figs. 10A and 10B). The strata below the lacustrine interval are comparable from a lithological perspective with the top of the Hagans Crossing Member in the type area (variegated red beds with abundant pedogenic carbonate) and are thus assigned to this unit. An intercalated bentonite bed (EMC080216-1) yielded an age of 79.968 ± 0.024 Ma (Table 1). For similar reasons of lithologic comparability and stratigraphic position, the lacustrine interval and overlying alluvial deposits in the Willow Creek anticline field area are herein assigned to the Flag Butte Member. Strata of the Flag Butte Member persist to the top of Two Medicine exposures in the western portion of the Willow Creek anticline field area near Pine Butte. Here, a bentonite bed (ES080216-2) intercalated ~39 m below the top of the member yielded an age of 74.430 ± 0.015 Ma (Table 1; Fig. 11).

***Choteau field area.*** Two Medicine Formation exposures to the south of the town of Choteau, Montana (Fig. 3), are also notably fossiliferous. Documented fossil occurrences in this general field area include dinosaur eggs and eggshell fragments (Hirsch and Quinn, 1990; Jackson and Varricchio, 2010), along with skeletal remains of hadrosaurs, ceratopsians, and a theropod (Varricchio, 2001; Chinnery and Horner, 2007; Baker et al., 2011; Gates et al., 2011).

Lorenz (1981) and Roberts (1999) studied the Two Medicine Formation in the region south of Choteau. The composite stratigraphic column documented by Roberts (1999) spans ~220 m

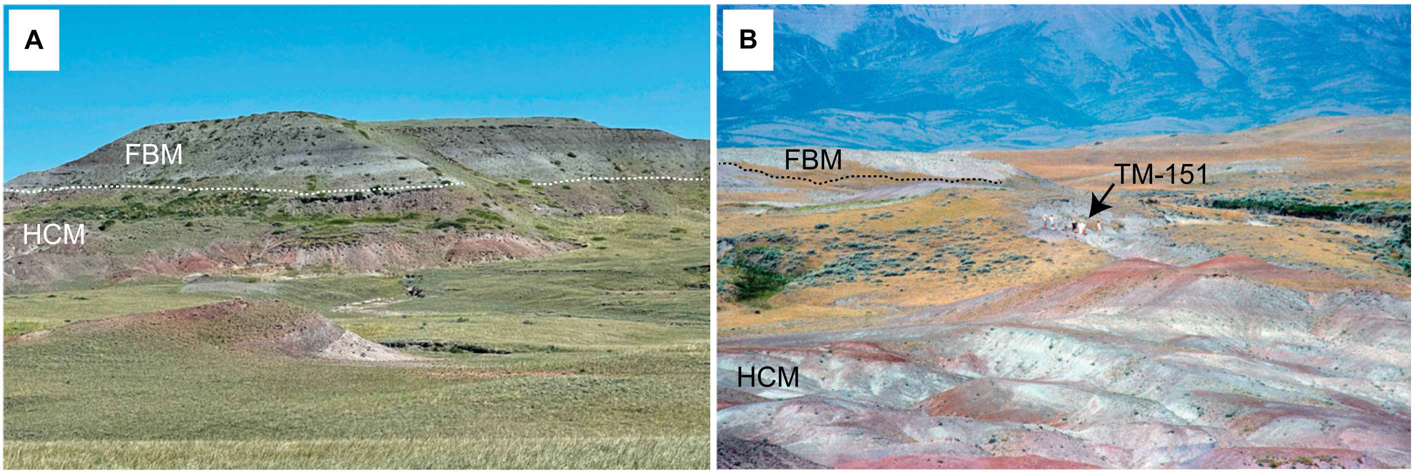


**Figure 10. Outcrop views of Willow Creek anticline field area. (A) View from Egg Mountain locality (Museum of the Rockies locality TM-006) looking north toward exposures of Hagans Crossing Member (HCM) and Flag Butte Member (FBM). The contact between the variegated beds of the Hagans Crossing Member and overlying lacustrine facies of the Flag Butte Member is readily discerned and is marked by white dashed line. (B) View looking west toward Rocky Mountain Front. Again, the contact between the variegated red and gray beds of the Hagans Crossing Member and the overlying Flag Butte Member (basal lacustrine interval) is readily identified (black dashed line). People are gathered at the Brandvold *Maiasaura* bonebed site (Museum of the Rockies locality TM-151).**

and is anchored at its base by the contact with the underlying Virgelle Formation (Fig. 12A). The basal ~75 m interval of the composite column exhibits sedimentologic features comparable to those documented for the Rock City Member in the Two Medicine type area, including laterally continuous sheet sandstones (one of which shows evidence of marine influence, as in the type area), and these strata are thus assigned to this unit. In the Choteau field area, red mudstones and siltstones that display evidence of pedogenesis are developed in the Rock City Member (Fig. 12B), and this is a departure from exposures of the member in the type area, where strata are generally drab gray and gray-green in color. A red lithic crystal tuff and thick overlying bentonite bed cap the top of the Rock City Member (Roberts and Hendrix, 2000), and this distinctive marker couplet occurs throughout the region (Figs. 12A and 12C). The overlying ~35–40 m interval is characterized by numerous discrete bentonite beds (at least six) and associated beds of brown carbonaceous mudstone, although the section is decidedly less carbonaceous than exposures along the Two Medicine River. These generally fine-grained bentonitic strata (including the bentonite–crystal tuff marker) are herein assigned to the Shields Crossing Member, with the upper contact placed at the top of a distinctive and readily traced bed of blue claystone that is rich in mollusk shell debris (Fig. 12A). Strata overlying the Shields Crossing Member in the region south of Choteau consist of interbedded gray and gray-green mudstones and siltstones intercalated with narrow sheets and lenses of gray fine- to medium-grained sandstone. These strata, which preserve dinosaur body fossils, are herein assigned to the Hagans Crossing Member of the Two Medicine Formation (Figs. 12D).

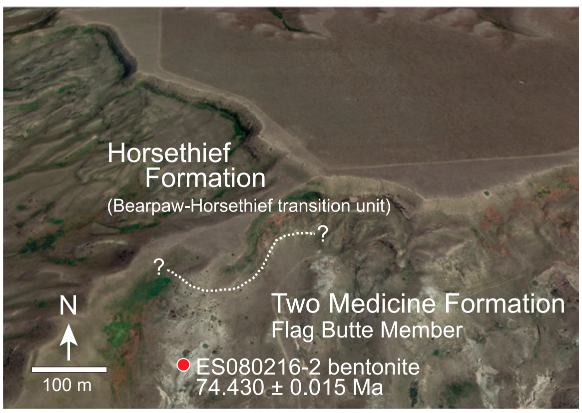


**Figure 11. Google Earth satellite image of Two Medicine Formation exposure that includes the ES080216-2 bentonite (see Fig. 3 for location). The bentonite bed is intercalated ~39 m below the contact between the Two Medicine Formation and the overlying Horsethief Formation (Bearpaw-Horsethief transition unit; dashed white line marks approximate contact). The age of the ES080216-2 bentonite is 74.430 ± 0.015 Ma (Table 1).**

***Landslide Butte field area.*** The Landslide Butte field area is an isolated pocket of badlands along the Milk River in T37N, R8W (U.S. Geological Survey, 2020c), near the international border. Over the past century, this relatively small field area has yielded an incredible abundance of spectacular fossil material, including several dinosaur bonebeds and dinosaur nest sites (e.g., Gilmore, 1917, 1930, 1939; Rogers, 1990; Horner, 1992; Horner and Currie, 1994; Sampson, 1995).

An ~70 m interval of Two Medicine strata is exposed in the Landslide Butte field area, and the local section includes the contact with the overlying Bearpaw Formation (Figs. 5 and 13). The sedimentologic characteristics of the strata, the abundance of dinosaur fossils, and the proximity to the Bearpaw Formation contact all indicate that Two Medicine Formation exposures at Landslide Butte (and nearby exposures at Chalk Butte) represent approximately the upper third of the Flag Butte Member. A new U-Pb zircon age reported herein for a bentonite (LSB-1-14 bentonite, 75.243 ± 0.023 Ma) intercalated ~55 m beneath the Two Medicine–Bearpaw contact is consistent with this interpretation (Table 1). The age of the LSB-1-14 bentonite is statistically indistinguishable from the age of the 90TMT-590-U60 bentonite (75.252 ± 0.024 Ma) in the Two Medicine Formation type area (Table 1; Fig. 5), and it is likely that these two bentonites represent the same eruptive event.

***Sun River dinosaur localities.*** Two notable dinosaur localities occur in exposures of the Two Medicine Formation along the Sun River to the north and west of Augusta, Montana, in a region referred to as the disturbed belt (Mudge,

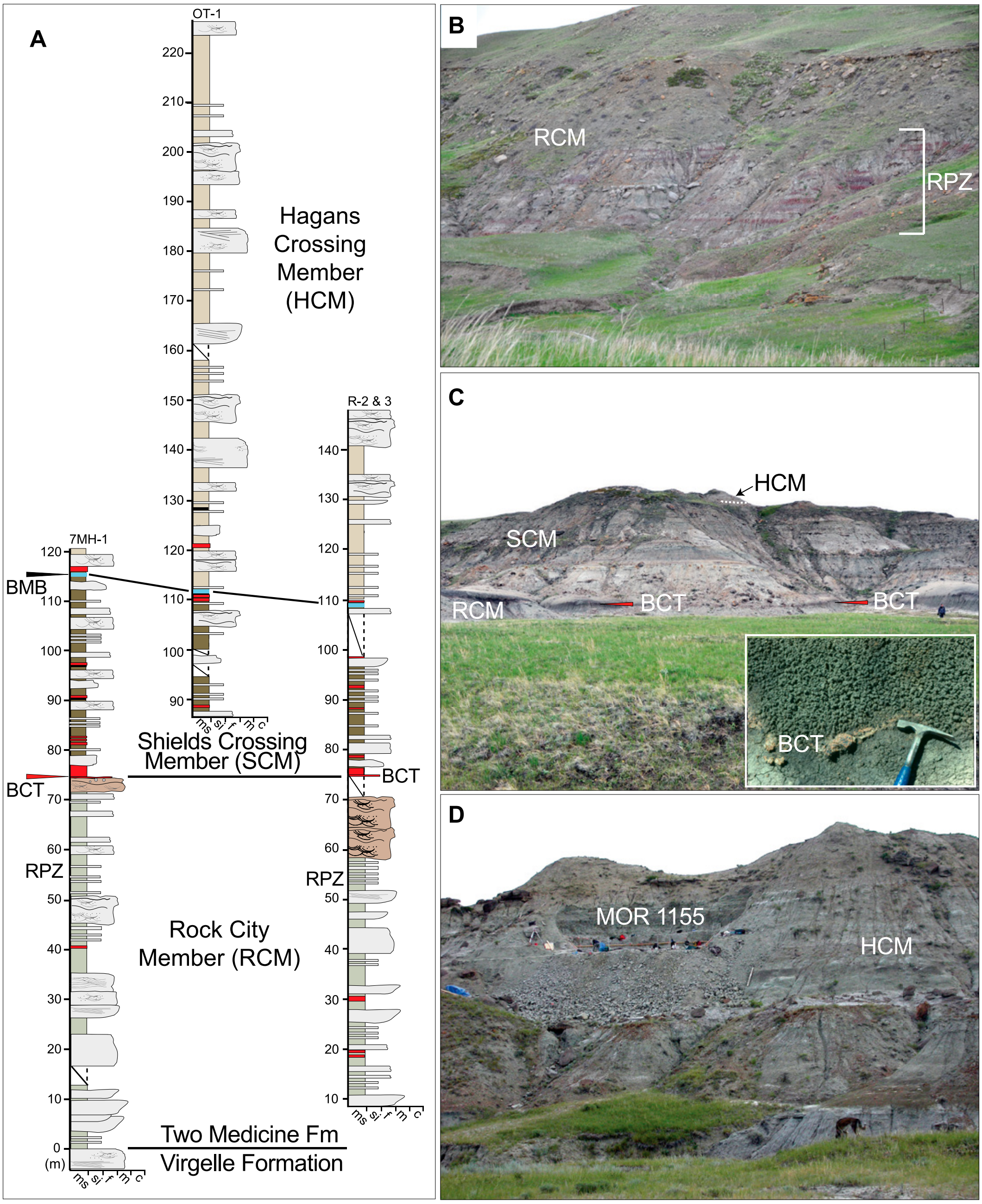


**Figure 12. Two Medicine Formation strata in the region south of Choteau. (A) Schematic stratigraphic columns measured by Roberts (1999) in the Sevenmile Hill region. Stratigraphic columns were correlated using the bentonite–lithic crystal tuff marker (BCT) and a readily traced blue claystone bed rich in molluscan shell debris (BMB). See Figure 4 for key to lithological and paleontological features illustrated in columns. (B) Exposures of upper portions of the Rock City Member, including a distinctive red paleosol zone (RPZ, ∼10 m thick) that is absent in the type area. (C) Exposures of Rock City Member (RCM), Shields Crossing Member (SCM), and Hagans Crossing Member (HCM) at Sevenmile Hill along Highway 287 south of Choteau. The prominent bentonite–crystal tuff marker (BCT) crops out at the base of local exposures (see inset). (D) Fluvial and floodplain facies of the Hagans Crossing Member (HCM) in outcrop belt extending south from Sevenmile Hill. These strata yielded the holotype specimen of the hadrosaurid *Acristavus gagslarsoni* (Museum of the Rockies [MOR] specimen 1155).**

1970). One site yielded a large and well-preserved specimen of the tyrannosaur *Daspletosaurus horneri* (Carr et al., 2017). The second site is a monodominant bonebed of juvenile lambeosaurine hadrosaurs (Sun River bonebed of Scherzer and Varricchio, 2010) preserved in steeply dipping strata ∼6 m above the *Daspletosaurus horneri* site. Faults and folds complicate the stratigraphy in the disturbed belt, rendering the precise stratigraphic placement of these dinosaur localities and other nearby fossil occurrences (e.g., Shibata and Varricchio, 2020) challenging. Their stratigraphy remains difficult to ascertain with certitude, but associated strata exhibit characteristics consistent with assignment to the uppermost Hagans Crossing Member or Flag Butte Member, including variegated paleosols and pedogenic carbonate nodules. A bentonite intercalated ∼6 m below the *Daspletosaurus horneri* site was dated in Carr et al. (2017) and yielded an age of 74.38 ± 1.44 Ma (U-Pb zircon weighted mean age, 2σ error, mean square of weighted deviates [MSWD] = 0.55). This U-Pb age, while lacking precision, nevertheless suggests that the Sun River localities likely occur high in the Two Medicine section, presumably in strata equivalent to the Flag Butte Member.

## CA-ID-TIMS U-Pb GEOCHRONOLOGY AND BAYESIAN MODEL RESULTS

The suite of eight new U-Pb CA-ID-TIMS ages derived from bentonite beds in the Two Medicine Formation, including the two ages recently reported in Ramezani et al. (2022), is presented in Table 1. Ages range from 82.419 ± 0.074 Ma (CB061417-1 bentonite, type area) to 74.430 ± 0.015 Ma (ES080216-2 bentonite, Willow Creek anticline field area). Ranked age plots for all new dates are presented in Figure 14. The five ages from the Two Medicine type area were integrated with


**Figure 13. Two Medicine Formation (TMF) exposures at Landslide Butte field area (Fig. 3). Here, upper reaches of the Flag Butte Member (FBM) are exposed along the drainage of the Milk River. The Bearpaw Formation caps the flat buttes on the right side of the image.**

associated stratigraphic data to produce a Bayesian age-stratigraphic model, which is developed in Figure 15. Modeled ages for well-documented fossil occurrences, formation and member contacts, and other significant surfaces within the type area and surrounding region (e.g., Badger Creek and Blacktail Creek) are reported in Table 2. Unfortunately, the base and top of the Two Medicine Formation are not bracketed by datable bentonites, and thus, the age model places highly imprecise constraints on the formation boundaries. Accordingly, modeled ages for formation contacts are reported in light gray text in Figure 15 (and italic in Table 2) to distinguish them from more reliable age interpretations. For the same reason, the six dinosaur occurrences above the 90TMT-590-U60 bentonite,

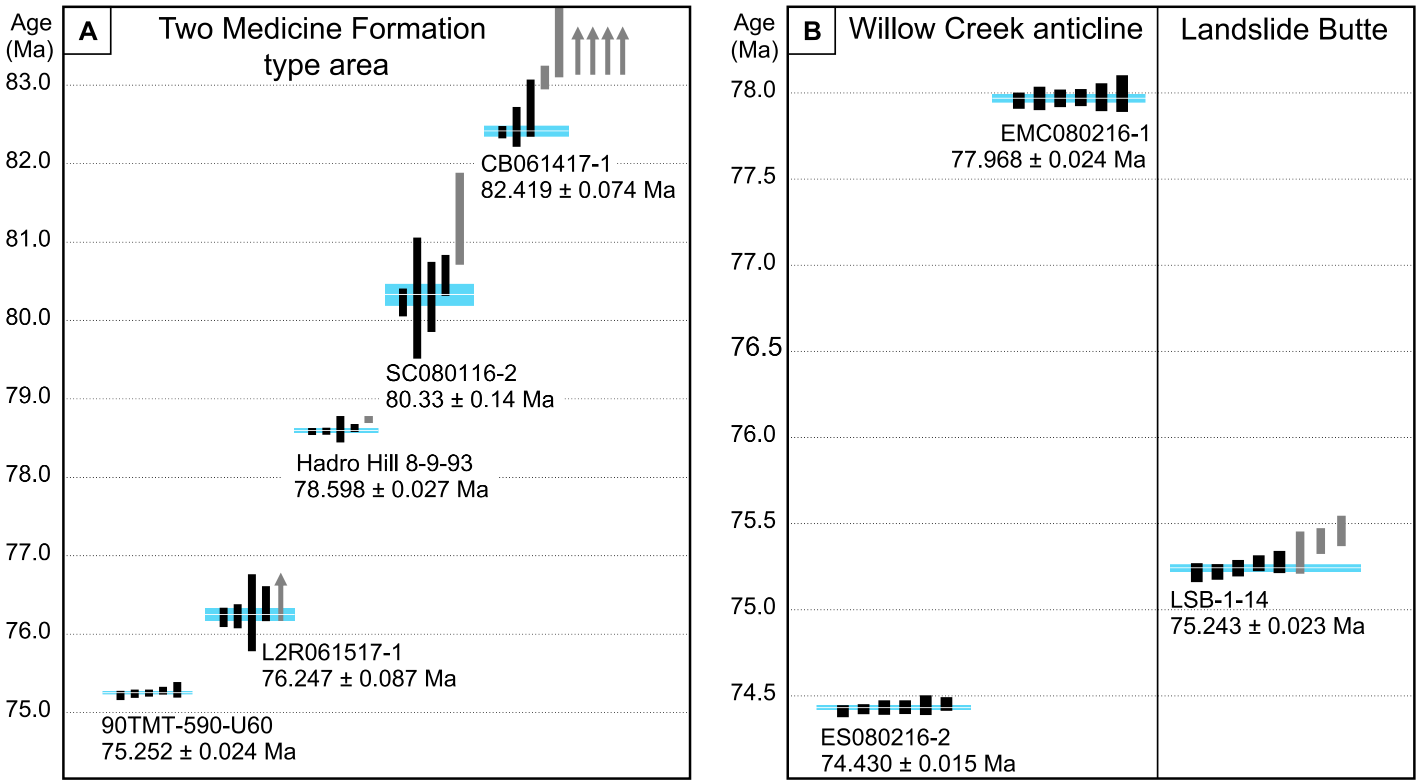


**Figure 14. Ranked age plots of analyzed zircons from bentonites in the Two Medicine Formation. (A) Two Medicine Formation type area. (B) Willow Creek anticline and Landslide Butte field areas. Vertical bars are individual zircon analyses with their 2σ analytical uncertainty; black bars represent analyses used in age calculation. Arrows represent the analyses that plot outside the diagram. Blue band signifies the weighted mean age with its 95% confidence level (2σ) internal uncertainty. See Table 1 for bentonite and age information, and see Table S1 (text footnote 1) for complete U-Pb isotopic data.**

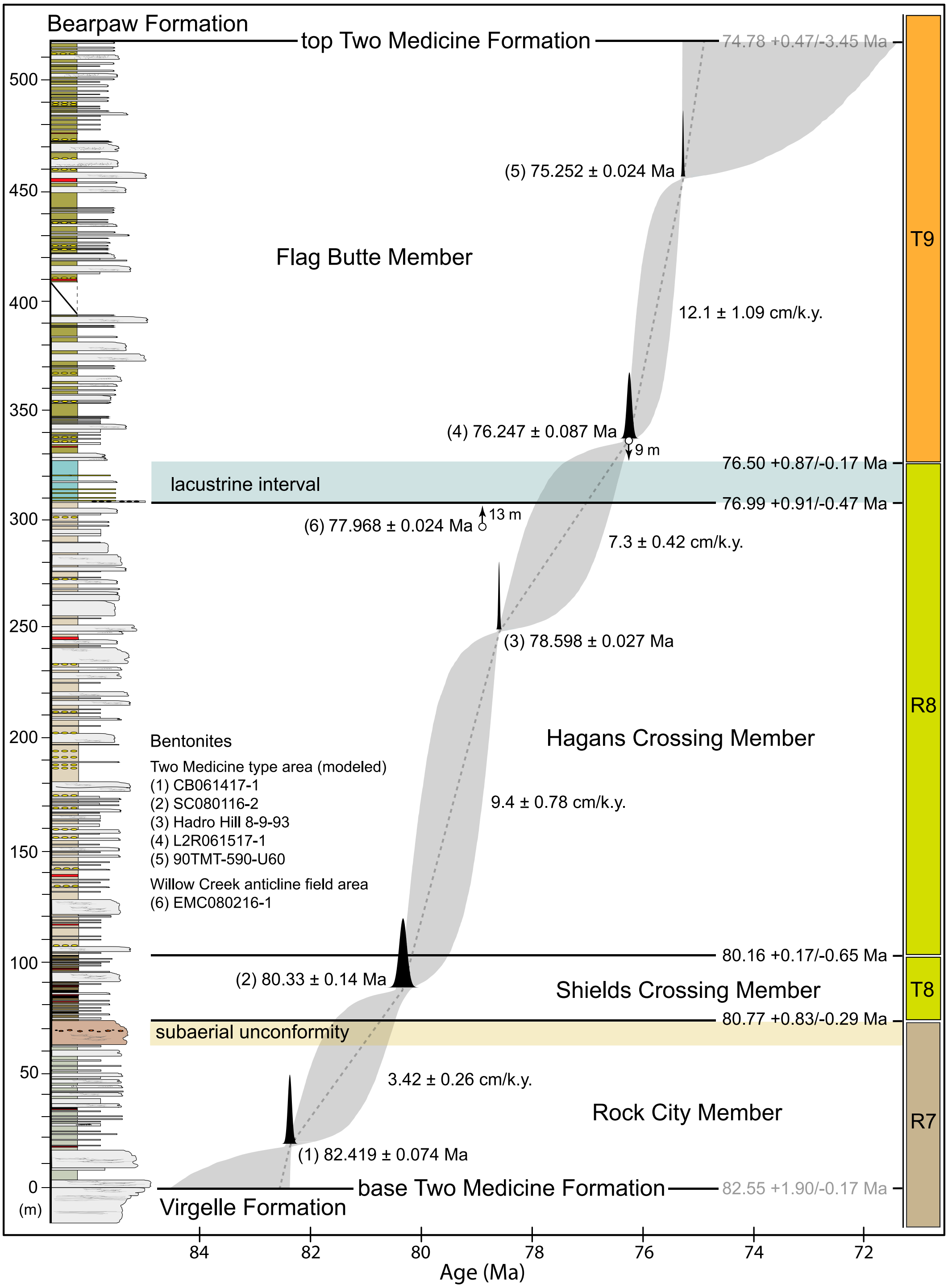


**Figure 15. New lithostratigraphy, U-Pb geochronology, and Bayesian age-stratigraphic model for the Two Medicine Formation in its type area in relation to major regressive and transgressive cycles of the Western Interior Seaway (R7, T8, R8, T9). One U-Pb age from the Willow Creek anticline field area (EMC080216-1 bentonite, 77.968 ± 0.024 Ma) is included on the graphic to inform age interpretation relating to the base of the Flag Butte Member (see text for explanation). Dashed line indicates the median of the model ages, and gray shading incorporates their 95% confidence interval uncertainties. Rock accumulation rates based on model outcomes are also reported. Modeled ages for the basal and top contacts of Two Medicine Formation have large errors and are reported in light gray text to distinguish them from more reliable age interpretations. See Figure 4 for key to colors and patterns in stratigraphic column. R7—Telegraph Creek–Eagle regression; T8—Claggett transgression; R8—Claggett regression; T9—Bearpaw transgression.**

which are shown in their relative stratigraphic positions in Table 2, are not linked to modeled ages due to the imprecise nature of the model results. That said, all dinosaur occurrences in the Two Medicine Formation type area above the 90TMT-590-U60 bentonite are definitively younger than 75.252 ± 0.024 Ma and, by correlation, demonstrably older than 74.430 ± 0.015 Ma based on the age of the ES080216-2 bentonite in the uppermost Flag Butte Member in the Willow Creek anticline field area (Fig. 11).

Another complication arises where the age model spans the subaerial unconformity associated with the thick sandstone body at the top of the Rock City Member (previously referred to as the "80 Ma sequence boundary") and the widespread lacustrine interval at the base of the Flag Butte Member (Rogers, 1994, 1998). The lithologic boundaries of these two key intervals are not bracketed closely by dated bentonites, and thus, the model yields broad drops in average rock accumulation rates that span beyond the two intervals (see Fig. 15, 17–88 m and 296–336 m). Therefore, we employed alternative age interpretations for these stratigraphically significant features consistent with their

TABLE 2. STRATIGRAPHY AND MODELED AGES OF SELECT FOSSIL OCCURRENCES, UNIT CONTACTS, SIGNIFICANT SURFACES, AND DATED BENTONITES (IN GRAY SHADING) IN THE TWO MEDICINE FORMATION TYPE AREA AND SURROUNDING REGION (BADGER AND BLACKTAIL CREEKS), NORTHWESTERN MONTANA, USA

| Fossil occurrence, contact, bentonite | Member | Height in section above base (m) | Modeled age ($\pm 2\sigma$) (Ma) |
|---|---|---|---|
| ES080216-1 bentonite (Willow Creek anticline field area) | FBM | ~39 m below top | 74.430 ± 0.015 |
| Bearpaw Fm/Two Medicine Fm contact, type area | — | 517 | *74.83 +0.43/−2.92* |
| MOR 591, *Achelosaurus horneri* skeleton | FBM | 500 | NR |
| TM-066, *Hypacrosaurus* nesting horizon | FBM | 500 | NR |
| MOR 600, *Hypacrosaurus* bonebed | FBM | 500 | NR |
| MOR 563, *Troodon* skeleton | FBM | 500 | NR |
| MOR 691, holotype *Montanazhdarcho minor* (pterosaur) | FBM | 470 | NR |
| TM-018, *Daspletosaurus* sp. | FBM | 470 | NR |
| 90TMT-590-U60 bentonite | FBM | 455 | 75.252 ± 0.024 |
| MOR 553S-7.30.91.274, *Bambiraptor feinbergi* (JBS) | FBM | 440 | 75.38 +0.40/−0.09 |
| MOR 553, *Troodon formosus* (JBS) | FBM | 440 | 75.38 +0.40/−0.09 |
| MOR 459, holotype *Hypacrosaurus stebingeri* | FBM | 440 | 75.38 +0.40/−0.09 |
| MOR 590, holotype *Daspletosaurus horneri* | FBM | 425 | 75.50 +0.42/−0.17 |
| TM-088/MOR 660, theropod eggs, dromaeosaurid indet. #2 | FBM | 370 | 75.96 +0.20/−0.41 |
| L2R061517-1 bentonite | FBM | 336 | 76.247 ± 0.087 |
| Top lacustrine interval | FBM | 327 | 76.50 +0.87/−0.17 |
| Lacustrine interval | FBM | | |
| Base lacustrine interval/member contact | — | 309 | 76.99 +0.91/−0.47 |
| MOR 721, dromaeosaurid indet. #1 | HCM | 290 | 77.51 +0.68/−0.76 |
| MOR 457, *Maiasaura peeblesorum* bonebed | HCM | 282 | 77.72 +0.56/−0.87 |
| MOR 550, pachycephalosaurid indet. #1 | HCM | 250 | 78.60 +0.03/−0.03 |
| ROMVP44770, *Maiasaura peeblesorum* | HCM | 250 | 78.60 +0.03/−0.03 |
| Hadro Hill 8-9-93 bentonite | HCM | 250 | 78.598 ± 0.027 |
| MOR 478, *Gryposaurus* sp. bonebed | HCM | 215 | 78.97 +0.74/−0.26 |
| MOR 3087, hadrosaur skull | HCM | 180 | 79.35 +0.62/−0.50 |
| AMNH 5465, holotype *Gryposaurus latidens* | HCM | 160 | 79.56 +0.52/−0.61 |
| Member contact | — | 103 | 80.16 +0.18/−0.67 |
| SC080116-2 bentonite | SCM | 88 | 80.33 ± 0.14 |
| TM-141, vertebrate microfossil bonebed | SCM | 88 | 80.33 +0.14/−0.14 |
| Member contact/top sandstone body hosting SU | — | 73 | 80.78 +0.83/−0.30 |
| CB061417-1 bentonite | RCM | 17 | 82.419 ± 0.074 |
| Two Medicine Fm/Virgelle Fm contact, type area | — | 0 | *82.55 +1.90/−0.17* |

*Note*: Fm—Formation; MOR—Museum of the Rockies specimen numbers; TM—Museum of the Rockies locality numbers; JBS—Jack's birthday site bonebed (TM-068); ROMVP—Royal Ontario Museum specimen; AMNH—American Museum of Natural History specimen; FBM—Flag Butte Member; HCM—Hagans Crossing Member; SCM—Shields Crossing Member; RCM—Rock City Member; SU—subaerial unconformity. Modeled results for base and top of the Two Medicine Formation (italic) and fossil occurrences above the 90TMT-590-U60 bentonite have large errors and are deemed too imprecise for reliable age assignment. Modeled ages for the fossil occurrences above the 90TMT-590-U60 bentonite are not reported (NR).

more limited physical stratigraphic ranges (see Discussion section).

Moving beyond the Two Medicine type area, the LSB-1-14 bentonite (75.243 ± 0.023 Ma) from the Landslide Butte field area and the 90TMT-590-U60 bentonite (75.252 ± 0.024 Ma) from the type area are statistically indistinguishable in age (Table 1; Fig. 14) and thus potentially represent the same ash-fall event on the Two Medicine alluvial plain. Given this correlation, we can provisionally extend the Bayesian age-stratigraphic model to some of the dinosaur fossil occurrences in the Flag Butte Member within the Landslide Butte field area (Table 3), ~50 km to the north of the type area. As in the type area, the stratigraphic ages of dinosaur fossil occurrences above the LSB-1-14 bentonite at Landslide Butte cannot be modeled without

TABLE 3. STRATIGRAPHY AND MODELED AGES OF SELECT FOSSIL OCCURRENCES IN THE TWO MEDICINE FORMATION, LANDSLIDE BUTTE FIELD AREA, NORTHWESTERN MONTANA, USA

| Fossil occurrence, contact, bentonite | Member | Height in section above base (m) | Modeled age ($\pm 2\sigma$) (Ma) |
|---|---|---|---|
| ES080216-1 bentonite (Willow Creek anticline field area) | FBM | ~39 m below top | 74.430 ± 0.015 |
| Bearpaw Fm/Two Medicine Fm contact, Landslide Butte | — | 510 | *74.88 +0.38/−2.76* |
| MOR 485, holotype *Achelosaurus horneri* | FBM | 490 | NR |
| MOR 477, lambeosaurine egg clutch | FBM | 485 | NR |
| MOR 479, pachycephalosaurid dome | FBM | 485 | NR |
| MOR 468, *Daspletosaurus* sp. skeleton | FBM | 485 | NR |
| TM-052, hadrosaurid egg horizon | FBM | 475 | NR |
| TM-031, ankylosaurid tail | FBM | 475 | NR |
| TM-023, *Einiosaurus procurvicornis* bonebed | FBM | 470 | NR |
| MOR 456, holotype *Einiosaurus procurvicornis* | FBM | 470 | NR |
| TM-046, *Einiosaurus procurvicornis* bonebed | FBM | 470 | NR |
| TM-041, holotype *Prosaurolophus blackfeetensis* bonebed | FBM | 465 | NR |
| TM-020, vertebrate microfossil bonebed | FBM | 465 | NR |
| TM-051, lambeosaurid egg horizon | FBM | 460 | 75.22 +0.05/−0.89 |
| TM-035, lambeosaurid egg horizon | FBM | 456 | 75.24 +0.03/−0.28 |
| LSB-1-14 bentonite (correlated with 90TMT-590-U60 bentonite) | FBM | 455 | 75.243 ± 0.023 |
| TM-053, vertebrate microfossil bonebed | FBM | 445 | 75.34 +0.36/−0.06 |
| MOR 433, holotype *Oohkotokia horneri* | FBM | 445 | 75.34 +0.36/−0.06 |
| USNM 7951, holotype *Brachyceratops montanensis* | FBM | 445 | 75.34 +0.36/−0.06 |
| MOR 492, holotype *Stellasaurus ancellae* | FBM | 445 | 75.34 +0.36/−0.06 |
| MOR 455, *Hypacrosaurus* skull | FBM | 445 | 75.34 +0.36/−0.06 |
| TM-019, *Hypacrosaurus* bonebed | FBM | 445 | 75.34 +0.36/−0.06 |

*Note*: Dated bentonites are in gray shading. Fm—formation; MOR—Museum of the Rockies specimen numbers; TM—Museum of the Rockies locality numbers; USNM—U.S. National Museum specimen number; FBM—Flag Butte Member. Modeled ages are based on Bayesian model developed for Two Medicine type area. Result for Two Medicine–Bearpaw contact (italic) and fossil occurrences above the LSB-1-14 bentonite that have large errors are deemed too imprecise for reliable age assignment. Modeled ages for fossil occurrences more than 5 m above the LSB-1-14 bentonite are not reported (NR).

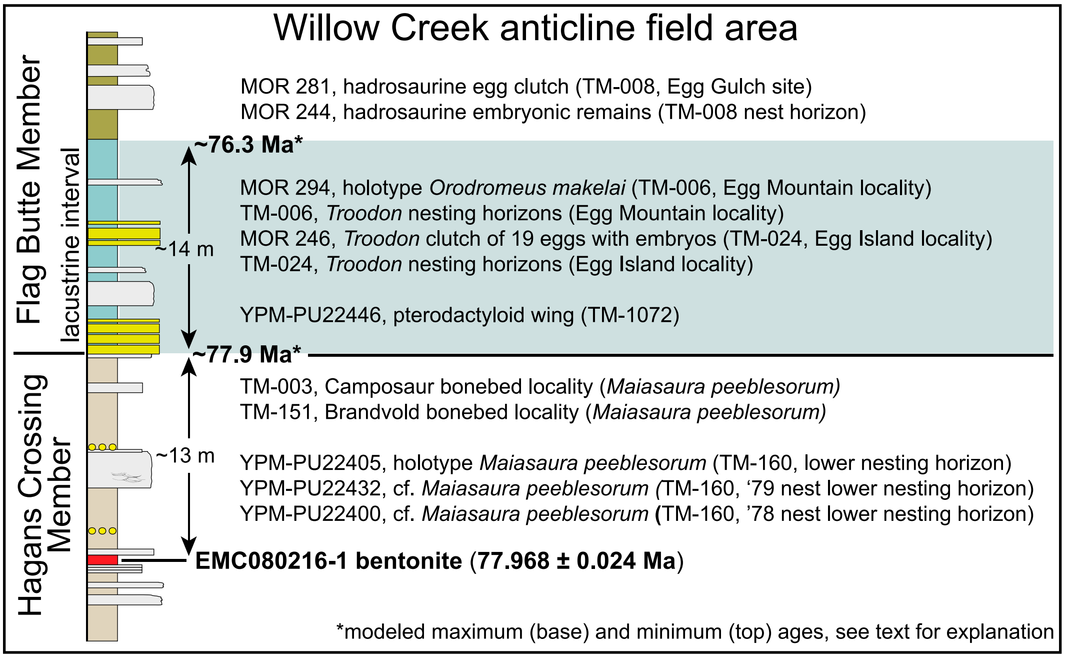


**Figure 16. Stratigraphy of dinosaur occurrences in the Willow Creek anticline field area. In this field area, the dinosaur occurrences are all clustered either within or in close proximity to the lacustrine interval at the base of the Flag Butte Member. See Figure 4 for key to colors and patterns in stratigraphic column. MOR—Museum of the Rockies specimen numbers, Montana State University, Bozeman, Montana, USA; TM—Museum of the Rockies field locality numbers; YPM-PU—Yale Peabody Museum (New Haven, Connecticut, USA), Princeton University (Princeton, New Jersey, USA) specimen numbers.**

any upper bentonite age constraint, but they can all be confidently assumed to be younger than 75.243 ± 0.023 Ma (LSB-1-14 bentonite) and, by correlation, older than 74.430 ± 0.015 Ma (ES080216-2 bentonite).

Fossil occurrences in the structurally complex Willow Creek anticline field area do not directly correlate into the type area chronostratigraphy but can now be placed in relation to the EMC080216-1 bentonite and the overlying lacustrine interval (Fig. 16). The nesting horizons of the hadrosaurid *Maiasaura*, the *Maiasaura peeblesorum* holotype, and the expansive *Maiasaura* bonebed are intercalated between the EMC080216-1 bentonite (77.968 ± 0.024 Ma) and the base of the lacustrine interval, which is positioned 13 m above the bentonite. The well-known Egg Mountain locality (TM-006, Museum of the Rockies field locality) is situated within the lacustrine interval, which is bracketed by modeled ages of ca. 77.9 Ma (maximum modeled age for base of lacustrine interval) and ca. 76.3 Ma (minimum modeled age for top lacustrine interval), as explained in the Discussion section below. The few remaining occurrences in the Willow Creek anticline field area above the lake interval, which include an egg clutch and embryonic remains of an unidentified hadrosaurine, are interpreted to be slightly younger than 76.3 Ma (Fig. 16).

Assessment of the ages of fossil occurrences in the Choteau field area is a more speculative endeavor because the localities from this patchy outcrop belt cannot be as precisely placed in the overall section relative to dated bentonites. Nevertheless, updated approximations of the ages of key fossil occurrences are possible based on our new member boundary age constraints. Dinosaur eggs and eggshell occurrences (Hirsch and Quinn, 1990; Jackson and Varricchio, 2010) are localized at the base of the Shields Crossing Member (just above the prominent bentonite–lithic crystal tuff marker), in strata that are presumably close in age to 80.78 +0.83/−0.30 Ma based on the age model. The few documented occurrences of dinosaur skeletal remains in the local outcrop belt, including the hadrosaurid *Acristavus gagslarsoni* and ceratopsid *Cerasinops hodgskissi* (Chinnery and Horner, 2007; Baker et al., 2011; Gates et al., 2011), are intercalated in the basal ~25 m of the Hagans Crossing Member, in strata that are presumed to be slightly younger than 80.16 +0.18/−0.67 Ma (Fig. 17). Along with the hadrosaurid *Gryposaurus latidens* from the formation type area, fossils of *Acristavus gagslarsoni*, *Cerasinops hodgskissi*, and an as-yet-undescribed *Daspletosaurus* (Theropoda) from the Choteau field area represent the oldest dinosaur skeletal occurrences in the Two Medicine Formation, aside from isolated teeth in the Shields Crossing Member.

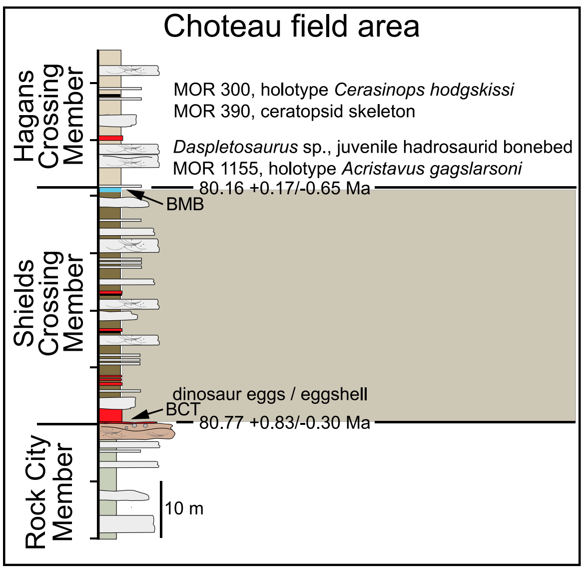


**Figure 17. Stratigraphy of dinosaur occurrences in the Choteau field area in relation to units and modeled ages (Fig. 15). In this field area, dinosaur occurrences, with the exception of eggs and eggshell collected in close proximity to the bentonite–crystal tuff marker, all occur within the basal ~25 m of the Hagans Crossing Member, in strata that are presumably slightly younger than ca. 80.2 Ma. See Figure 4 for key to colors and patterns in stratigraphic column. BCT—bentonite–crystal tuff marker; BMB—blue mollusk bed marker; MOR—Museum of the Rockies specimen numbers, Montana State University, Bozeman, Montana, USA.**

## DISCUSSION

### Regional Correlation and Regressive-Transgressive Cycles

The four new members of the Two Medicine Formation are objectively defined based on lithologic distinctions readily observed in outcrop. They are mappable along the Two Medicine River in the formation type area, and they correlate beyond the type area into outlying regions with paleontological significance, including the Willow Creek anticline, Choteau, and Landslide Butte field areas (Fig. 3). Establishment of the four new members facilitates communication as it relates to Two Medicine fossil occurrences, and advances understanding of the unit in relation to regional geological history. Importantly, while based as they should be on lithologic criteria, the new members also have implications for reconstructions of regional geological history because they closely track regressive-transgressive cycles of the Cretaceous Western Interior Seaway: This reflects links between the new lithostratigraphy and underlying stratigraphic processes that operated at the basin scale (e.g., variations in rates of accommodation and sedimentation). Existing reconstructions that contextualize the Two Medicine Formation and its dinosaurs in relation to major marine cycles (Gill and Cobban, 1973; Rogers, 1998; Horner et al., 1992, 2001) can now be reevaluated in the context of the four new members and calibrated with several new U-Pb CA-ID-TIMS ages (Fig. 18).

Physical stratigraphic relationships on the regional scale and new geochronologic data indicate that the Rock City Member accumulated during the final stages of the Telegraph Creek–Eagle regression (R7), between ca. 82.4 Ma (CB061417-1 bentonite, 17 m above base of member and formation) and 80.77 +0.83/−0.29 Ma (model age, top of member). The Rock City Member correlates to the east with shallow-marine sandstones of the Eagle Formation on the eastern flank of the Sweetgrass arch. The distinctive fluvial sandstone body that caps the Rock City Member hosts a well-documented subaerial unconformity that Rogers (1994, 1998) interpreted as a terrestrial sequence boundary (see also Miall and Arush, 2001), and the top of this sandstone body presumably correlates with the "Eagle shoulder," a regional marker horizon readily identified in geophysical well logs (most readily in resistivity logs) that coincides with the contact between the Eagle Formation and overlying Claggett Formation in marine strata (Fig. 18). This widespread stratigraphic datum is referred to as the Milk River shoulder in the plains of southern Alberta and Saskatchewan (e.g., Payenberg et al., 2002, 2003; Glombick and Mumpy, 2014; Mumpy and Catuneanu, 2019; Rogers et al., 2023).

Given the correlation with the Eagle/Milk River shoulder, there is considerable potential for a hiatus associated with the subaerial unconformity at the top of the Rock City Member. Estimates from the marine realm based on biostratigraphic and magnetostratigraphic evidence suggest that the unconformity coincident with the Eagle/Milk River shoulder could express up to 2.5 m.y. of hiatus (Payenberg et al., 2002; Mumpy and Catuneanu, 2109), although estimates vary across southern Alberta, Saskatchewan, and north-central Montana. Comparable data that would inform estimates of the potential duration of this hiatus are lacking in the terrestrial Two Medicine Formation record, but the nature of the sandstone body hosting the subaerial unconformity and our new U-Pb geochronology do afford some insights. Physical evidence of an appreciable hiatus is notably developed in the multistory sandstone body in question, including unusual diagenesis (widespread oxidation and indication of early cementation) and widespread internal scouring and erosion (Rogers, 1994, 1998; Howes and Rogers, 2014). Where the sandstone body is at its thickest (~15 m) in the vicinity of the town of Cut Bank (Fig. 6D), model ages for the base (81.21 +0.72/−0.54 Ma) and top (80.77 +0.83/−0.29 Ma) suggest a potential hiatus of ~0.4 m.y.

The overlying Shields Crossing Member accumulated on the Two Medicine coastal plain in paralic settings during transgression of the Claggett sea (T8), and it ranges in age from 80.77 +0.83/−0.29 Ma (modeled age, base of member) to 80.16 +0.17/−0.65 Ma (modeled age, top of member). The Shields Crossing Member presumably correlates with the basal portion of the marine Claggett Formation, which hosts the widespread Ardmore bentonite beds (Spivey, 1940; Gill and Cobban, 1966). The succession of closely spaced bentonite beds in the Shields Crossing Member presumably represents the terrestrial expression of the Ardmore bentonite beds (Rogers, 1993, 1998; Dyman et al., 1994; Roberts and Hendrix, 2000; Bertog et al., 2007). The contact that separates the Shields Crossing Member from the underlying Rock City Member (and the sandstone body hosting the subaerial unconformity) correlates basinward with the Eagle shoulder. This contact between the Eagle and Claggett Formations marks the first major incursion of the Claggett sea into northwestern Montana (Figs. 7 and 18) and corresponds to the maximum regressive surface (transgressive surface).

The transition from the Shields Crossing Member to the overlying Hagans Crossing Member is marked by a shift from organic-rich paralic facies to more typical (and better drained) fluvial and floodplain facies of the Two Medicine Formation. This shift in lithofacies is herein interpreted to coincide with a change in shoreline trajectories, with the Hagans Crossing Member accumulating in more inland settings as shorelines prograded eastward over time with regression of the Claggett sea. The Bayesian age model suggests that the regression of the Claggett sea began ca. 80.16 +0.17/−0.65 Ma in northwestern Montana, coincident with the contact between the Shields Crossing and Hagans Crossing Members.

The top of the Hagans Crossing Member is delineated by the base of the distinctive lacustrine interval, which is readily identified in both the Two Medicine type area and in the Willow Creek anticline field area (see above). The Bayesian age model places the base of the lacustrine interval (contact between the Hagans Crossing and Flag Butte Members) at 76.99 +0.91/−0.47 Ma and its top at 76.50 +0.87/−0.17 Ma (Fig. 15). However, in the absence of proximal bentonite ages, the model fails to properly relate the apparent decrease in rock accumulation rate in this part of the section to the distinctive facies of the lacustrine interval. We, therefore, consider the maximum of the model age for the base and the minimum of the model age for the top of the lacustrine interval to provide more meaningful age constraints, which allows us to interpret an age of ca. 77.9 Ma for the base and ca. 76.3 Ma for the top of the lacustrine interval in the type area. This reconstruction in turn allows a maximum time span of ~1.6 m.y. for deposition of the ~18-m-thick lacustrine interval, yielding a rock accumulation rate of ~1.13 cm/k.y. Importantly, in the Willow Creek anticline field area, the EMC080216-1 bentonite with an age of 77.968 ± 0.024 Ma crops out ~13 m below the base of the lacustrine interval (Fig. 16). It is, therefore, likely that the shift to lacustrine sedimentation at ca. 77.9 Ma was synchronous, or nearly so, across the region.

Deposits of the Flag Butte Member above the lacustrine interval accumulated during the transgression of the Bearpaw sea (T9 of Kauffman, 1977), which commenced ca. 76.3 Ma in north-central Montana (Rogers et al., 2016, 2023). Sedimentologic data indicate that back-stepping marine shorelines stacked in north-central Montana until ca. 75.2 Ma (as evidenced by the Woodhawk Member of Judith River Formation; Rogers et al., 2016, 2023), at which time the transgression pushed shorelines westward across the Sweetgrass arch (Fig. 18). The ES080216-2 bentonite (Table 1; Fig. 11) in the Willow Creek anticline field area (Fig. 3) yielded the youngest age in our suite of dated Two Medicine bentonites, and its age indicates that the Bearpaw transgression was still advancing westward at 74.430 ± 0.015 Ma. Deposits

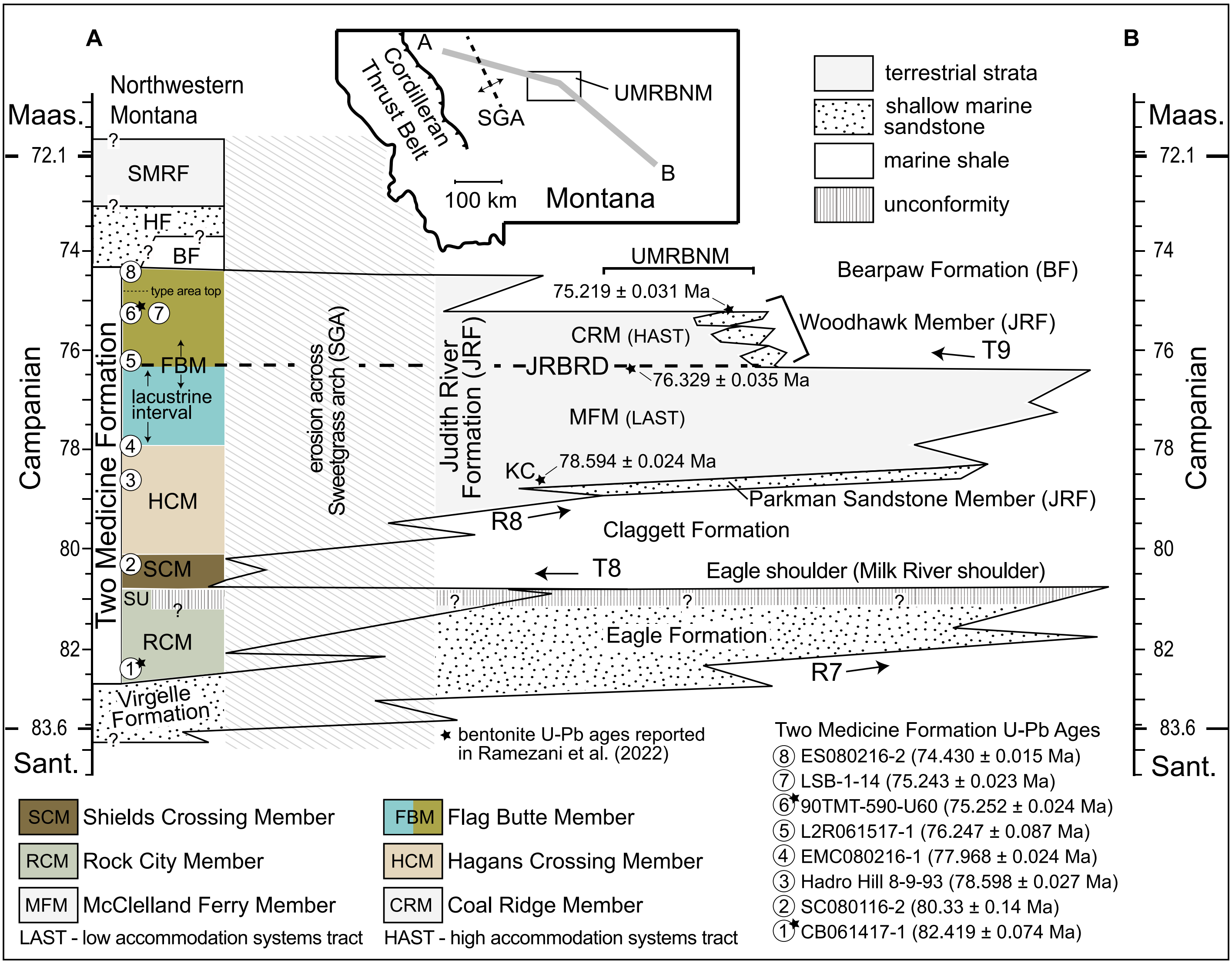


**Figure 18. Schematic cross section detailing chronostratigraphic relations among Upper Cretaceous (Campanian) units in Montana, USA (modified from Gill and Cobban, 1973; Rogers et al., 2016), calibrated with U-Pb bentonite ages reported in this article and in Ramezani et al. (2022). Significant surfaces and intervals within the Two Medicine Formation include the subaerial unconformity (SU) at the top of the Rock City Member, which correlates basinward with the Eagle shoulder, and the condensed lacustrine interval at the base of the Flag Butte Member. The approximate top of the lacustrine interval correlates downdip with the Judith River–Belly River discontinuity (JRBRD) in the Judith River Formation. Regional regressive (R7, R8) and transgressive (T8, T9) phases of deposition are from Kauffman (1977). Ages of stage boundaries are based on Cohen et al. (2013); Sant.—Santonian; Maas.—Maastrichtian. SMRF—Saint Mary River Formation; HF—Horsethief Formation; BF—Bearpaw Formation; JRF—Judith River Formation; FBM—Flag Butte Member; HCM—Hagans Crossing Member; SCM—Shields Crossing Member; RCM—Rock City Member; CRM—Coal Ridge Member; MFM—McClelland Ferry Member; JRBRD—Judith River–Belly River discontinuity; KC—Kennedy Coulee, north-central Montana; SU—subaerial unconformity; UMRBNM—Upper Missouri River Breaks National Monument; LAST—low accommodation systems tract; HAST—high accommodation systems tract.**

of the Horsethief Formation (Bearpaw-Horsethief transition unit) occur ~39 m above the ES080216-2 bentonite (Fig. 11; Berg, 2008), which suggests that this new age is close to the culmination of transgression and the turnaround to regression of the Bearpaw sea (R9 of Kauffman, 1977). These new age data indicate that the Bearpaw transgression spanned ~2 m.y. within Montana, transpiring from ca. 76.3 Ma to slightly younger than ca. 74.4 Ma during the late Campanian (Fig. 18).

With regard to the correlation of the Two Medicine Formation with the Judith River Formation in north-central Montana, previous reports (Rogers, 1994, 1998; Rogers et al., 2016) postulated that the distinctive lacustrine interval at the base of the Flag Butte Member correlated in a broad sense with the ca. 76.3 Ma "mid-Judith discontinuity" of Rogers et al. (2016, see their fig. 2), which is now referred to as the "Judith River–Belly River discontinuity" (Rogers et al., 2023). This throughgoing discontinuity is intercalated approximately midunit within the Judith River Formation, marking the contact between the McClelland Ferry Member and overlying Coal Ridge Member, and it is traceable from north-central Montana to Dinosaur Provincial Park in southeastern Alberta, where it marks the contact between the Oldman Formation and overlying Dinosaur Park Formation. New age data presented in this report are consistent with this cross-unit correlation, with the top of the lacustrine interval assigned a minimum modeled age of ca. 76.3 Ma (see reasoning above). Additional age constraint is provided by the L2R061517-1 bentonite, which has an age of 76.247 ± 0.087 Ma (Table 1), and which is intercalated in alluvial facies 9 m above the top of the lacustrine interval. Given these age constraints, the approximate top of the Two Medicine lacustrine interval in the type area is herein correlated with the Judith River–Belly River discontinuity (Fig. 18).

Focusing on changes in accommodation, sedimentation rates, and terrestrial sequence stratigraphy, the Hagans Crossing Member and basal lacustrine interval of the Flag Butte Member correlate downdip with the McClelland Ferry Member of the Judith River Formation, which was interpreted by Rogers et al. (2023) to represent a low accommodation systems tract (LAST). Facies of the Flag Butte Member above the lacustrine interval correlate downdip with the Coal Ridge Member of the Judith River Formation, which was interpreted to represent a high accommodation systems tract (HAST). The intervening Judith River–Belly River discontinuity was interpreted by Rogers et al. (2016, 2023) to represent an expansion surface (sensu Martinsen et al., 1999) linked to a pulse of accommodation and the onset of the Bearpaw transgression (Fig. 18). This reconstruction of accommodation history is consistent with the dramatic increase in rock accumulation rate at the top of the lacustrine interval in the Two Medicine Formation, where rates increased from ~1.13 cm/k.y. within the condensed lacustrine interval to 12.1 ± 1.09 cm/k.y. in overlying alluvial facies (Fig. 15).

The stratigraphic architecture that typically serves to distinguish low and high accommodation systems tracts in alluvial records (for a comprehensive review, see Holland and Loughney, 2021) is notably more evident within the Judith River Formation. For example, the McClelland Ferry Member LAST is a sandstone-dominated alluvial succession characterized by thick amalgamated sandstone sheets. The overlying Coal Ridge Member HAST is a mudstone-dominated succession characterized by thinner and more lenticular sandstone bodies (Rogers et al., 2016). These distinctions in alluvial architecture are readily observed in both surface exposures and subsurface datasets (Rogers et al., 2023). Distinctions in the alluvial architecture of the Hagans Crossing Member (LAST) and Flag Butte Member (HAST) are far less pronounced, and this more limited expression of accommodation-related stratigraphy is presumably a reflection of the more proximal setting of the Two Medicine Formation within the foreland basin. Strata of the Hagans Crossing Member and Flag Butte Member (excluding the condensed lacustrine interval) collectively accumulated under high rock accumulation rates (~9.4–12.1 cm/k.y.; see Fig. 15) relative to those reported for the Judith River Formation (~2.4–8.6 cm/k.y.; Rogers et al., 2023), and the change in accommodation between alluvial records of the LAST and HAST was certainly less pronounced in the proximal Two Medicine portion of the basin.

## Two Medicine Dinosaur Record in Chronostratigraphic Context

The stratigraphy of well-documented dinosaur occurrences (including skeletons, bonebeds, and nesting horizons) in the Two Medicine Formation in relation to the new U-Pb geochronology, new formal members, and major regressive-transgressive cycles of the Western Interior Seaway is illustrated in Figure 19. Most occurrences are single individuals or groups of individuals collected from a single bonebed, and thus, most taxa are not characterized by well-defined stratigraphic ranges. Accordingly, only best approximations of first occurrences are illustrated in relation to the composite reference section. The three dinosaur occurrences that lack detailed locality data (the ceratopsids *Prenoceratops pieganensis* and *Styracosaurus ovatus*, the ankylosaurid *Palaeoscincus rugosidens*) are indicated by light gray shading, and their stratigraphic positions are approximated. All other taxa are arguably placed in close proximity to their stratigraphic first occurrence in the composite Two Medicine Formation section.

Key insights that inform previous reconstructions emerge from our compilation of Two Medicine dinosaur occurrences. For example, as previously proposed by Horner (1984b) and Horner et al. (2001), stratigraphically discrete dinosaur assemblages are preserved in the Two Medicine Formation. Specifically, the Hagans Crossing Member and overlying Flag Butte Member yield distinct assemblages of dinosaurs with seemingly little, if any, overlap at the genus level (Tables 2 and 3; Fig. 19). Horner (1984b) ascribed this pattern to the evolution of distinct paleofaunas in response to shifts in habitable area on the Two Medicine–Judith River alluvial/coastal plain during regional cycles of regression and transgression. In this model, transgression of the Bearpaw sea led to habitat bottlenecks in the terrestrial realm, and this in turn led to a pulse of extinction and diversification among dinosaurs. While our new dataset neither confirms nor refutes this macroevolutionary model, the data do indicate that the terrestrial record that accumulated during the Bearpaw transgression (= Flag Butte Member above lacustrine interval, ca. 76.3 Ma and younger) is distinct with regard to species membership and more speciose than underlying regressive phase deposits (= Hagans Crossing Member + Flag Butte lacustrine interval). This pattern is not an artifact of variable unit thickness, uneven outcrop accessibility, or facies distinctions, because both units are of comparable thickness, both have roughly comparable outcrop areas based on Google Earth surveys, and both units are represented by generally comparable alluvial facies. Moreover, the Hagans Crossing and Flag Butte Members are characterized by similar taphonomic modes of preservation, with both units typified by bonebeds and occurrences of isolated skeletons and nests (Rogers, 1990; Varricchio and Horner, 1993; Varricchio, 1995).

Another insight relating to the recognition of distinct dinosaur assemblages in the Two Medicine record relates to the newly calibrated duration of the intervening lacustrine interval. We now know that the lacustrine interval intercalated at the base of the Flag Butte Member potentially accumulated over a span of up to 1.6 m.y., from ca. 77.9 Ma to ca. 76.3 Ma. With the exception of the theropod *Troodon formosus* and the ornithopod *Orodromeus makelai*, which are the only well-documented dinosaurs recovered from within the lacustrine interval itself (Willow Creek anticline field area, Egg Mountain locality), all other documented dinosaur occurrences occur in alluvial facies either below (Hagans Crossing assemblage) or above (Flag Butte assemblage) the lacustrine interval. The stratigraphically distinct dinosaur assemblages of the Two Medicine Formation described above are now known to be separated by a sizeable condensed interval (up to 1.6 m.y.) represented by a unique paleoenvironment (widespread carbonate and siliciclastic lakes). This would presumably allow for substantial taxonomic turnover. Moreover, with a new regional chronostratigraphic model in place for the Campanian of Montana, dinosaur occurrences in both the Two Medicine Formation and correlative Judith River Formation can now be considered in relation to predicted ecological gradients (e.g., elevation and distance from the coast; Holland, 2022) during major transgressions and regressions of the Western Interior Seaway.

Horner et al. (1992) also proposed that some of the dinosaurs of the Two Medicine Formation evolved via anagenesis during the transgression of the Bearpaw sea. This model of dinosaur evolution hinges upon the sequential and non-overlapping occurrence of what are deemed to be transitional (intermediate) taxa. Again, while our new dataset neither confirms nor refutes the proposed evolutionary model, the new calibrated occurrences of dinosaurs from the Two Medicine Formation are consistent with the temporal distribution of taxa outlined in the original report and model (see Horner et al., 1992; Wilson et al., 2020). For example, the known occurrences of the ceratopsian dinosaurs *Stellasaurus ancellae*, *Einiosaurus procurvicornis*, and *Achelousaurus horneri*, a presumed anagenetic lineage of centrosaurines, still occur in stratigraphic succession over a span of a few hundred thousand years (Tables 2 and 3; Fig. 19). Moving forward, rigorous testing of the anagenesis hypothesis hinges upon the discovery of additional specimens within the Hagans Crossing and Flag Butte Members so that taxon ranges can be more rigorously defined and compared.

## CONCLUSIONS

To advance understanding and appreciation of Two Medicine Formation stratigraphy and fossils, we formalized four new members, including (1) the Rock City Member, (2) the Shields Crossing Member, (3) the Hagans Crossing Member, and (4) the Flag Butte Member. We incorporated these new members and their included fossils in an age model founded on eight new high-resolution CA-ID-TIMS U-Pb ages (see also Ramezani et al., 2022). The establishment of a new calibrated stratigraphic framework for the Two Medicine Formation and its remarkably rich fossil record affords an opportunity to assess potential controls on the distribution of fossils from proximal to distal portions of a terrestrial foreland basin setting. Indeed, the stratigraphic distribution and taphonomic quality of Two Medicine fossils (vertebrate, invertebrate, plant) can now be evaluated in relation to changes in accommodation and stratigraphic architecture (punctuated by a subaerial unconformity and condensed interval) and compared with regional patterns of transgression and regression. These results provide important ground truth for numerical models that explore the structure of the fossil record in relation to terrestrial sequence stratigraphy and alluvial architecture (e.g., Holland, 2022, 2023).

Finally, the new chronostratigraphic framework established in this report confirms previous reconstructions that claim the dinosaurs of the Two Medicine Formation exhibit discrete patterns of occurrence that coincide with the paleogeographic evolution of the basin (e.g., Horner, 1984; Horner et al., 2001). Dinosaurs of the Hagans Crossing Member inhabited the Two Medicine alluvial plain during the regression of the Claggett sea. Dinosaurs of the overlying Flag Butte Member (occurrences above the lacustrine interval) inhabited the Two Medicine alluvial plain during the subsequent transgression of the Bearpaw sea (Figs. 18 and 19). Again, this interpretation is not new, but the realization that the intervening condensed lacustrine interval at the base of the Flag Butte Member potentially spans up to 1.6 m.y. is new, and this significant time span is certainly relevant to models that attempt to explain the distinct nature of the dinosaur assemblages in the Two Medicine Formation. With the stratigraphy and

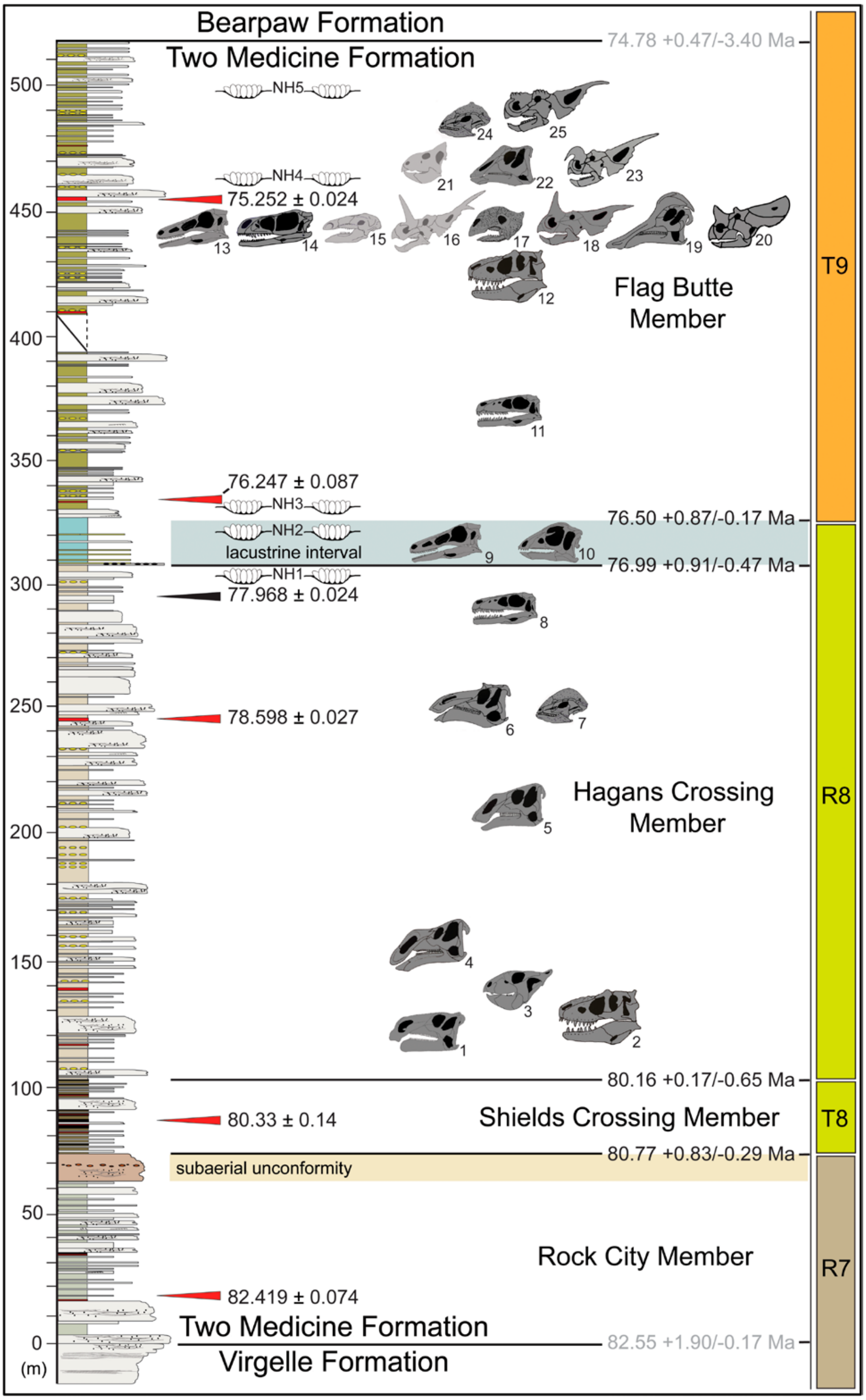

**Figure 19. Stratigraphy of dinosaur occurrences, including nesting horizons (N1–N5) in the Two Medicine Formation (all major field areas, composite reference section from type area), in relation to new U-Pb geochronology, new formal members, and major regressive-transgressive cycles of the Western Interior Seaway. The five bentonite ages marked in red are from the Two Medicine Formation type area, and these ages were incorporated in the age model. The bentonite age marked in black (EMC080216-1) is from the Willow Creek anticline field area (see Table 1). Modeled ages for basal and top contacts of the Two Medicine Formation have large errors and are reported in light gray text to distinguish them from more reliable age interpretations. Best approximations of first occurrences are indicated for 25 dinosaur taxa. Occurrences that lack detailed locality data are indicated by light gray shading (occurrences 15, 16, and 21), and their stratigraphic placement is more speculative. Dinosaur taxa figured (skulls not to scale) include (1) *Acristavus gagslarsoni* (holotype); (2) *Daspletosaurus* sp.; (3) *Cerasinops hodgskissi* (holotype); (4) *Gryposaurus latidens* (holotype); (5) *Gryposaurus* sp.; (6) *Maiasaura peeblesorum*; (7) pachycephalosaurid indet. #1; (8) dromaeosaurid indet. #1; (9) troodontid indet.; (10) *Orodromeus makelai* (holotype); (11) dromaeosaurid indet. #2; (12) *Daspletosaurus horneri* (holotype); (13) *Troodon formosus*; (14) *Bambiraptor feinbergi*; (15) *Palaeoscincus rugosidens* (holotype, potential junior synonym of *Edmontonia rugosidens*, Russell, 1940); (16) *Styracosaurus ovatus* (holotype); (17) *Oohkotokia horneri* (holotype, potential junior synonym of *Euoplocephalus tutus*, Arbour and Currie, 2013); (18) *Stellasaurus ancellae* (holotype); (19) *Hypacrosaurus stebingeri* (holotype); (20) *Brachyceratops montanensis* (holotype); (21) *Prenoceratops pieganensis* (holotype); (22) *Prosaurolophus blackfeetensis* (holotype, potential junior synonym of *Prosaurolophus maximus*, McGarrity et al., 2013); (23) *Einiosaurus procurvicornis* (holotype); (24) pachycephalosaurid indet. #2; (25) *Achelousaurus horneri* (holotype). Nesting horizons include (NH1) TM-160, lower nesting horizon, cf. *Maiasaura peeblesorum* (Willow Creek anticline field area); (NH2) TM-006, troodontid nesting horizons (Willow Creek anticline field area); (NH3) TM-008, hadrosaurine nesting horizon (Willow Creek anticline field area); (NH4) TM-035, TM-037, lambeosaurid nesting horizon (Landslide Butte field area); and (NH5) TM-066, *Hypacrosaurus* nesting horizon (Blacktail Creek site, close proximity to Two Medicine type area). See Figure 4 for key to colors and patterns in stratigraphic column. TM—Museum of the Rockies field locality numbers, Montana State University, Bozeman, Montana, USA; R7—Telegraph Creek–Eagle regression; T8—Claggett transgression; R8—Claggett regression; T9—Bearpaw transgression.**

fossil record of the Two Medicine Formation now understood within a high-resolution age model, future advances in our understanding of dinosaur evolution and dinosaur paleogeography within this formation and in the broader region will depend upon new analyses of specimens residing in museum collections and future discoveries of new fossils that better define stratigraphic and paleogeographic ranges. Fortunately, the Hagans Crossing and Flag Butte Members of the Two Medicine Formation are remarkably fossiliferous and thus will likely rise to meet this challenge.

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# Erratum

**ERRATUM: Updating the Upper Cretaceous (Campanian) Two Medicine Formation of Montana: Lithostratigraphic revisions, new CA-ID-TIMS U-Pb ages, and a calibrated framework for dinosaur occurrences**

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The age of bentonite L2R061517-1 was reported incorrectly as $76.252 \pm 0.087$ Ma in Table 2 and Figure 19. The correct age of this bentonite is $76.247 \pm 0.087$ Ma. In addition, the label for the Hadro Hill 8-9-93 bentonite was reported incorrectly as Hadro Hill 8-9-92 in Table 2. The correct Table 2 and Figure 19 now appear in the final published version of the paper to which this erratum is appended.