



# GEOLOGY OF THE INTERMOUNTAIN WEST

*an open-access journal of the Utah Geological Association*

ISSN 2380-7601

Volume 6

2019

## REDEFINING THE UPPER JURASSIC MORRISON FORMATION IN THE GARDEN PARK NATIONAL NATURAL LANDMARK AND VICINITY, EASTERN COLORADO

Kenneth Carpenter and Eugene Lindsey



Theme Issue  
An Ecosystem We Thought We Knew—  
The Emerging Complexities of the Morrison Formation  
SOCIETY OF VERTEBRATE PALEONTOLOGY  
*Annual Meeting, October 26 – 29, 2016*  
*Grand America Hotel*  
*Salt Lake City, Utah, USA*



© 2019 Utah Geological Association. All rights reserved.

For permission to copy and distribute, see the following page or visit the UGA website at [www.utahgeology.org](http://www.utahgeology.org) for information.

Email inquiries to [GIW@utahgeology.org](mailto:GIW@utahgeology.org).



# GEOLOGY OF THE INTERMOUNTAIN WEST

*an open-access journal of the Utah Geological Association*

ISSN 2380-7601

Volume 6

2019

## Editors

Douglas A. Sprinkel Utah Geological Survey 801.391.1977 GIW@utahgeology.org	Thomas C. Chidsey, Jr. Utah Geological Survey 801.537.3364 tomchidsey@utah.gov
--	---

Bart J. Kowallis Brigham Young University 801.422.2467 bkowallis@gmail.com	Steven Schamel GeoX Consulting, Inc. 801.583-1146 geox-slc@comcast.net
---	---



## Society of Vertebrate Paleontology

### Editors

Kelli C. Trujillo — University of Wyoming  
John Foster — Utah Field House of Natural History  
State Park Museum  
Cary Woodruff — University of Toronto  
Octavio Mateus — Universidade Nova de Lisboa

## Production

Cover Design and Desktop Publishing  
Douglas A. Sprinkel

Cover

*Jurassic Morrison Formation as exposed at Cope's Nipple lying between the orange Pennsylvanian Fountain Formation and overlying Cretaceous Lytle Formation capping the butte to the left. Photo courtesy of Dan Grenard (retired, Bureau of Land Management, Cañon City, Colorado).*



*This is an open-access article in which the Utah Geological Association permits unrestricted use, distribution, and reproduction of text and figures that are not noted as copyrighted, provided the original author and source are credited.*

## UGA Board

### October 2018 – September 2019

President	Peter Nielsen	peternielsen@utah.gov	801.537.3359
President-Elect	Leslie Heppler	lheppler@utah.gov	801.538.5257
Program Chair	Gregory Schlenker	gcsgeoscience@gmail.com	801.745.0262
Treasurer	Dave Garbrecht	garbrechtd@yahoo.com	801.916.1911
Secretary	George Condrat	gcondrat@loughlinwater.com	435.649.4005
Past President	Paul Inkenbrandt	paulinkenbrandt@utah.gov	801.537.3361

## UGA Committees

Environmental Affairs	Craig Eaton	eaton@ihi-env.com	801.633.9396
Geologic Road Sign	Terry Massoth	twmassoth@hotmail.com	801.541.6258
Historian	Paul Anderson	paul@pbageo.com	801.364.6613
Outreach	Greg Nielson	gnielson@weber.edu	801.626.6394
Membership	Rick Ford	rford@weber.edu	801.626.6942
Public Education	Paul Jewell	pwjewell@mines.utah.edu	801.581.6636
	Matt Affolter	gfl247@yahoo.com	
Publications	Paul Inkenbrandt	paulinkenbrandt@utah.gov	801.537.3361
Publicity	Paul Inkenbrandt	paulinkenbrandt@utah.gov	801.537.3361
Social/Recreation	Roger Bon	rogerbon@xmission.com	801.942.0533

## AAPG House of Delegates

2017–2020 Term	Tom Chidsey	tomchidsey@utah.gov	801.537.3364
----------------	-------------	---------------------	--------------

## State Mapping Advisory Committee

UGA Representative	Jason Blake	blake-j@comcast.net	435.658.3423
--------------------	-------------	---------------------	--------------

## Earthquake Safety Committee

Chair	Grant Willis	gwillis@utah.gov	801.537.3355
-------	--------------	------------------	--------------

## UGA Website

### www.utahgeology.org

Webmasters	Paul Inkenbrandt	paulinkenbrandt@utah.gov	801.537.3361
------------	------------------	--------------------------	--------------

## UGA Newsletter

Newsletter Editor	Bill Lund	uga.newsletter@gmail.com	435.590.1338
-------------------	-----------	--------------------------	--------------

*Become a member of the UGA to help support the work of the Association and receive notices for monthly meetings, annual field conferences, and new publications. Annual membership is \$20 and annual student membership is only \$5. Visit the UGA website at [www.utahgeology.org](http://www.utahgeology.org) for information and membership application.*

*The UGA board is elected annually by a voting process through UGA members. However, the UGA is a volunteer-driven organization, and we welcome your voluntary service. If you would like to participate please contact the current president or committee member corresponding with the area in which you would like to volunteer.*



## **Redefining the Upper Jurassic Morrison Formation in the Garden Park National Natural Landmark and Vicinity, Eastern Colorado**

**Ken Carpenter<sup>1,2</sup> and Eugene Lindsey<sup>3</sup>**

<sup>1</sup>*Prehistoric Museum, Utah State University Eastern, Price, UT 84501; Ken.Carpenter@usu.edu*

<sup>2</sup>*Museum of Natural History, University of Colorado, Boulder, CO 80309*

<sup>3</sup>*Department of Earth Sciences, Denver Museum of Nature and Science, Denver, CO 80205 (deceased)*

### **ABSTRACT**

The Garden Park National Natural Landmark (GPNNL) is north of Cañon City, Colorado, and encompasses all of the major historical dinosaur quarries of the Upper Jurassic Morrison Formation in this area. The formation there can be divided into the lower redefined Ralston Creek Member and an upper unnamed member. The Morrison Formation is bracketed below by the J-5 unconformity and above by the K-1 unconformity.

The Ralston Creek Member is composed of up to 55 m of arkosic conglomerate, sandstone, siltstone, and gypsum conformably underlying the unnamed member. Fossil fishes previously used to infer a Middle Jurassic age are non-diagnostic. A diplodocid skeleton 4 m above the J-5 unconformity from the west-adjacent Shaws Park, and a radiometric date of  $152.99 \pm 0.10$  Ma from the Purgatoire River area demonstrate that the Ralston Creek rightly belongs in the Morrison Formation and correlates with the Tidwell and Salt Wash Members on the Colorado Plateau. The Ralston Creek was deposited in a broad playa complex analogous to those of central Australia and here called the Ralston Creek boinka. Groundwater flux played an important role in gypsum deposition in gypsisols and playa lakes. The overlying unnamed member in the GPNNL can be subdivided on the west side of Fourmile Creek into a lower part composed largely of mudstone with many thin, discontinuous channel sandstone beds, and a thicker upper part containing more persistent tabular sandstone beds; this subdivision does not occur east of Fourmile Creek. Several thin limestone beds occur in the Ralston Creek Member and in the lower part of the unnamed upper member. The limestone contains fresh water ostracods and aquatic mollusks indicating a lacustrine origin. However, these fauna are apparently stunted and the ostracod valves closed indicating periodic hypersaline conditions.

All detrital rocks in the Morrison Formation at Garden Park are composed of varying amounts of quartz, potassic feldspar, and the clay minerals illite, smectite, and kaolinite. Mapping of the clay minerals in the unnamed member reflect various paleosols throughout the mudstone interval, including protosols and argillisols. At the top of the formation, a sandstone previously assigned to the Morrison is reassigned to the overlying Cretaceous Lytle Formation based on similar weathering characteristics, mineral content, and fabric. Thus, the K-1 unconformity between the Morrison and overlying Lytle rests on the uppermost occurrence of the Morrison Formation mudstone-sandstone-limestone complex and beneath the blocky, cliff-forming Lytle Formation.

*Citation for this article.*

*Carpenter, K., and Lindsey, E., 2019, Redefining the Upper Jurassic Morrison Formation in Garden Park National Natural Landmark and vicinity, eastern Colorado: Geology of the Intermountain West, v. 6, p. 1–30.*

© 2019 Utah Geological Association. All rights reserved.

For permission to use, copy, or distribute see the preceding page or the UGA website, [www.utahgeology.org](http://www.utahgeology.org), for information. Email inquiries to [GIW@utahgeology.org](mailto:GIW@utahgeology.org).



## INTRODUCTION

The Garden Park National Natural Landmark (GPNNL)—formerly named the Garden Park Geological Resources Area—is managed by the Bureau of Land Management and encompasses all of the classic dinosaur sites in the Upper Jurassic Morrison Formation north of Cañon City, Colorado (figures 1, 2A, and 2B; Monaco, 1998; Carpenter, 1999; Foster, 2003). The Morrison Formation can be widely traced throughout the western United States (Mook 1916; Craig and others, 1955). It was named by Whitman Cross (1894), with the stratotype given for exposures immediately east of the town of Morrison, Colorado (figure 3A). The formation was defined as “...prevailingly greenish, pinkish or gray shales and marls. Sandstone occurs at the base and is also intercalated at numerous horizons in the upper part of the section with varying development” (Cross, 1894, p. 2). The age was assumed to be Jurassic based on the dinosaurs collected in the vicinity of the type locality. Ethridge (1896, p. 60–62) described the formation in greater detail, but it was Lee (1920) who refined the boundaries of the stratotype and published a measured section.

More than two decades later, Waldschmidt and LeRoy (1944) designated the West Alameda Parkway roadcut 2.5 km north of Morrison, Colorado, as a new stratotype for the Morrison Formation (figure 3B) and this is still widely followed (e.g., Lockley and others, 2015). Their justification for moving the stratotype was based on the entire Morrison Formation being exposed along the road cut, which had been only completed a few years before, and because the exposure was readily accessible. Such a relocation of the stratotype was not addressed by the stratigraphic code operating at the time (Committee on Stratigraphic Nomenclature, 1933), but the current North American Stratigraphic Code forbids it: “Once a unit or boundary stratotype section is designated, it is never abandoned or changed; however, if a stratotype proves inadequate, it may be supplemented by a principal reference section ...” (North American Commission on Stratigraphic Nomenclature, 2005, Article 8(e)). Therefore, the stratotype for the Morrison Formation remains on the western face of the hogback on the east edge of the town of Morrison as was originally desig-

nated by Cross (1894), and the West Alameda Parkway road cut along the same hogback (now called Dinosaur Ridge) is the principle reference section for the Morrison Formation and is attributed to Waldschmidt and LeRoy (1944).

## Previous Studies in the GPNNL

The Morrison Formation can be traced almost without interruption for about 200 km from its stratotype near the town of Morrison to Garden Park in south-central Colorado. There, it is exposed along the canyon and tributaries of Fourmile Creek. The first, albeit brief, description of the Morrison Formation in Garden Park was by Cross (1894) as part of his description of the geology of the Pikes Peak area. This was followed by a more detailed description by Hatcher (1902), who attempted to place stratigraphically the historic dinosaur quarries of O.C. Marsh (Yale University) and E.D. Cope (Academy of Natural Sciences of Philadelphia). The first stratigraphic section was presented by Mook (1916), who noted a thickness of 97.2 m (originally reported in feet as 319 ft). This contrasted with about 106.7 m (originally reported in feet as 350 ft) given by Cross (1894) and 137.2 m (originally reported in feet as 450 ft) by Hatcher (1902). The disparity in thickness is due to lack of agreement for the upper contact with the Cretaceous beds. Subsequent studies on the Morrison of Garden Park prior to the start of our work were mostly theses or dissertations, with a few exceptions (Giltner, 1953; Schulze, 1954; De Lay, 1955; Saylor, 1955; Frederiksen and others, 1956; Hassinger, 1959; Sackett, 1961; Crammer, 1962; Brady, 1967; Enciso, 1981; Sweet, 1984a; Johnson, 1991).

Beginning in the early 1990s, the Denver Museum of Natural History (now the Denver Museum of Nature and Science) began detailed paleontological and geological studies there. The result of these studies are presented in Ague and others (1995), Harris and Carpenter (1996), Small and Carpenter (1997), Alf (1998), Bray and Hirsch (1998), Carpenter (1998a, 1998b, 2019), Carpenter and Tidwell (1998), Evanoff and Carpenter (1998), Harris (1998), Kirkland and others (1998), McIntosh and Carpenter (1998), Tidwell and Carpenter (1998), Brill and Carpenter (2001), Chure (2001),

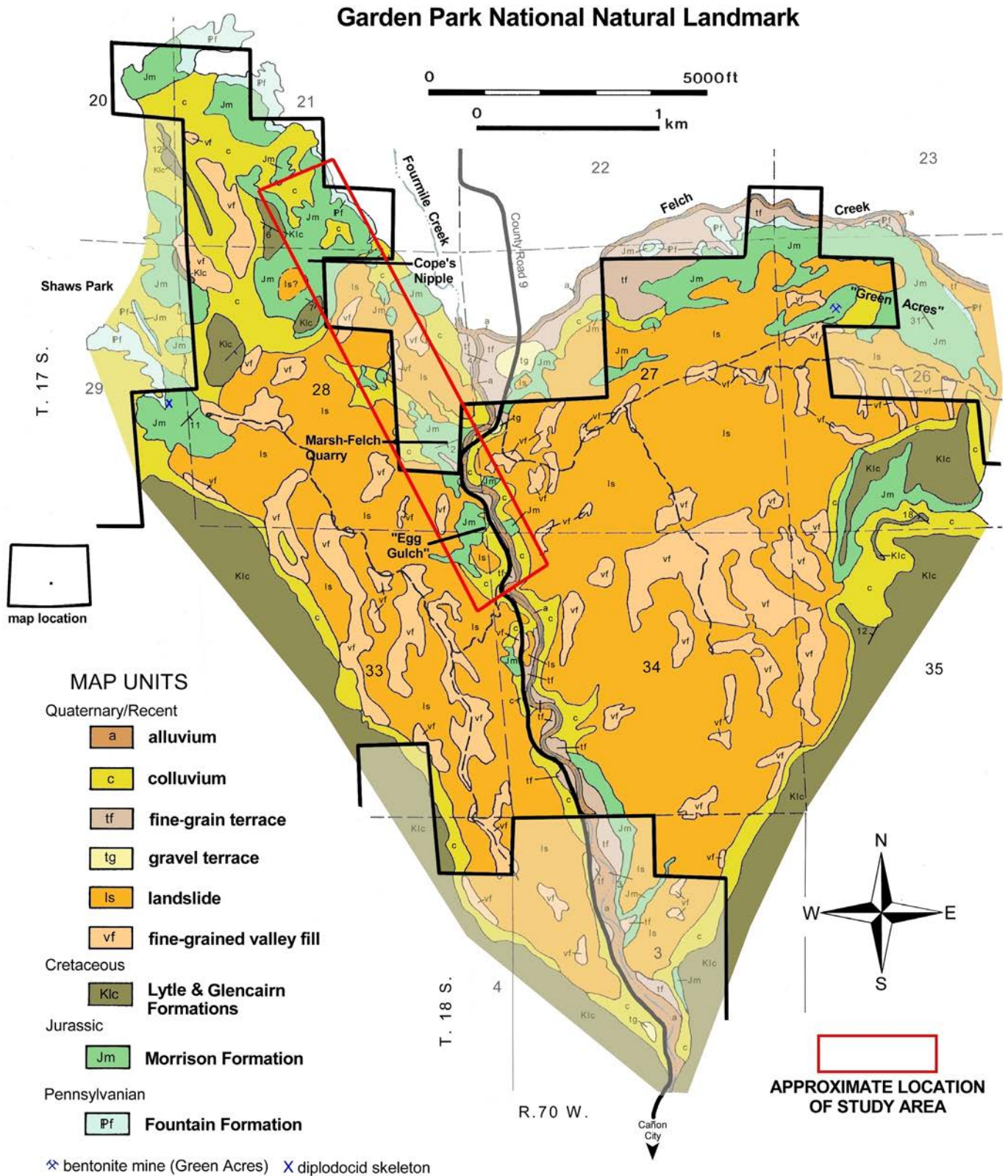


Figure 1. Simplified geological map of the Garden Park National Natural Landmark, which is about 9 km north of Cañon City, Colorado. Map courtesy of E. Evanoff (University of Northern Colorado).



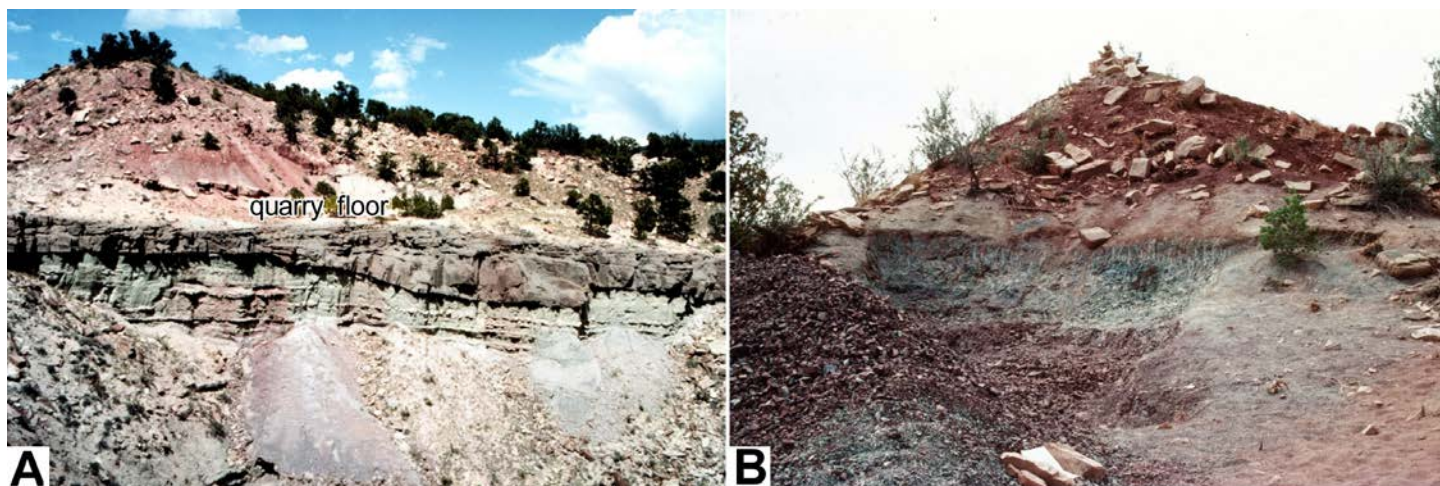


Figure 2. (A) Felch Quarry 1 is in the lower part of the unnamed member of the Morrison Formation. A marked change occurs from the alternating thin beds of greenish-gray mudstone and sandstone underlying the channel sandstone beds, which lie immediately below the quarry floor, to mixed red and gray bentonitic mudstones above. (B) Cope's Nipple Quarry in the upper part of the unnamed member. The illitic mudstone beds are predominately red to maroon with some green lenses. The sandstone beds in this interval are mostly tabular.

McWhinney and others (2001), and Rougier and others (2015). Ancillary work on the stratigraphy of Morrison Formation in Garden Park are presented in Peterson and Turner (1998) and Turner and Peterson (1999).

## Methods

As part of our work on the geology of the Morrison Formation in the Garden Park area, one of us (Lindsey) prepared a geological map for a 1.25 km<sup>2</sup> area west of Fourmile Creek where most of the classical dinosaur quarries are located (e.g., figure 2). Thin sections of sandstone samples from the upper unnamed member were examined with a petrographic microscope, and clay minerals in mudstone samples were analyzed with X-ray diffraction. The results of these analyses were used to help reconstruct paleoenvironments at the time of deposition.

## MORRISON FORMATION OF GPNNL

We divide the Morrison Formation throughout GPNNL into two members; the lower Ralston Creek Member (new ranking) and an unnamed upper member (figures 4A and 4B). The Ralston Creek Member unconformably overlies the conglomeratic, brick-red to orange Pennsylvanian Fountain Formation (figure 4A,

4B, and 4D). This unconformity, the J-5, represents a time gap of approximately 159 million years. The unnamed upper member (the “traditional” Morrison of previous usage in eastern Colorado) is overlain by massive sandstone beds of Cretaceous age originally called the Dakota Formation by Cross (1894). Scott and others (1978) and Wobus and others (1985) placed these sandstones in the Lower Cretaceous Purgatoire Formation in their mapping around Cañon City and Garden Park, following the terminology of Finlay (1916) for southern Front Range northeast of Cañon City. They further subdivide the Purgatoire into the basal Lytle Member, a sandstone, and the overlying Glencairn Member, a sandstone and shale unit. Kues and Lucas (1987) and Mateer (1987) proposed abandoning the term Purgatoire Formation and elevating the Lytle and Glencairn to formation status, a proposal accepted by us. Combined, these two Cretaceous formations are about 91 m thick in the Garden Park area.

The placement of the K-1 unconformity between the Morrison and Lytle Formations is controversial. Two massive cliff-forming sandstone beds cap the mesas throughout Garden Park (figures 4A and 5). Peterson (U.S. Geological Survey, verbal communication to Lindsey, 1995; see also Peterson and Turner, 1998, figure 5) described a maroon-colored paleosol marking

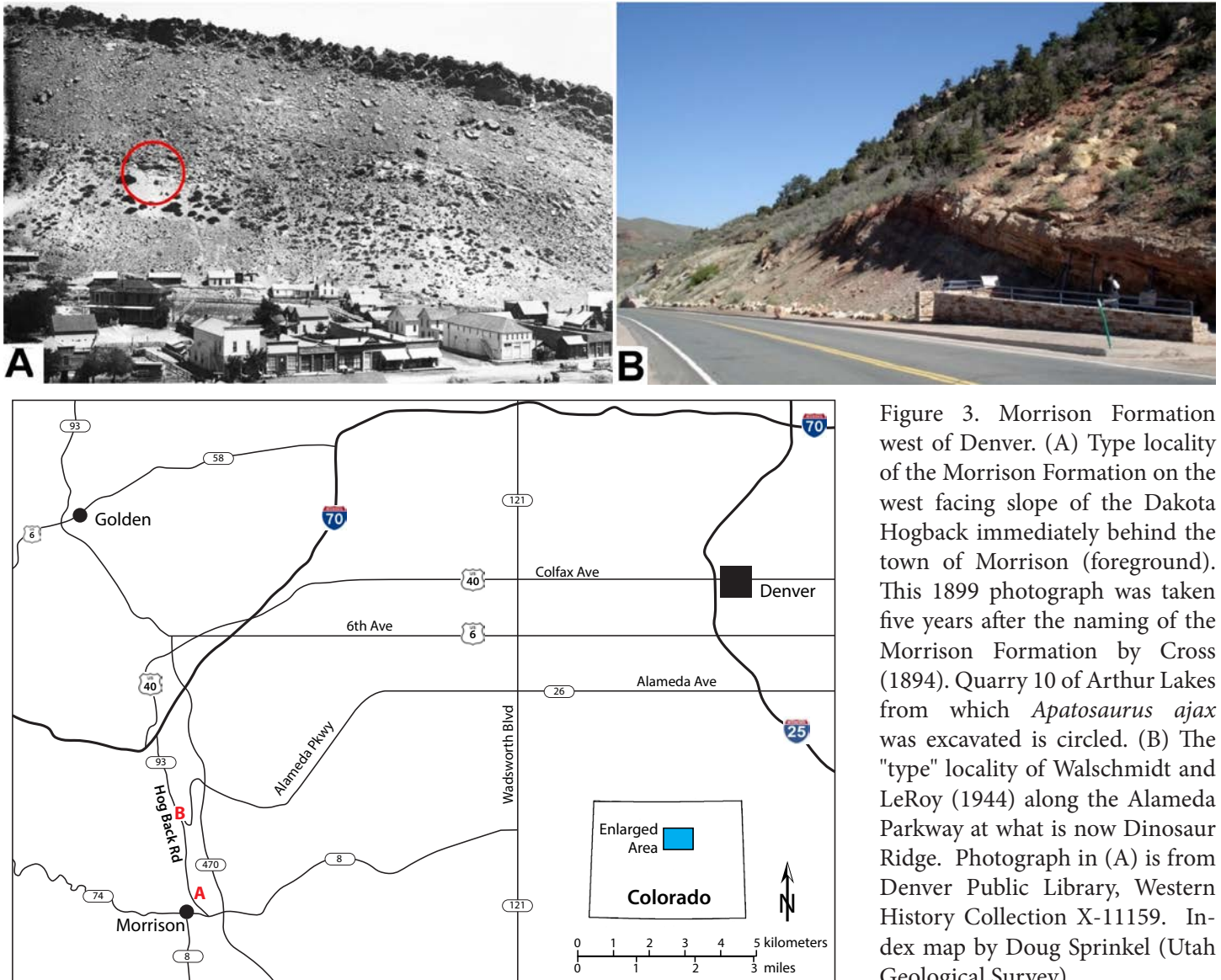


Figure 3. Morrison Formation west of Denver. (A) Type locality of the Morrison Formation on the west facing slope of the Dakota Hogback immediately behind the town of Morrison (foreground). This 1899 photograph was taken five years after the naming of the Morrison Formation by Cross (1894). Quarry 10 of Arthur Lakes from which *Apatosaurus ajax* was excavated is circled. (B) The "type" locality of Walschmidt and LeRoy (1944) along the Alameda Parkway at what is now Dinosaur Ridge. Photograph in (A) is from Denver Public Library, Western History Collection X-11159. Index map by Doug Sprinkel (Utah Geological Survey).

the K-1 unconformity at the top the lower sandstone identified as Morrison. This is seen, for example, on the southeast side of Cottage Rock (figure 5B) and on the unnamed butte immediately west of Cope's Nipple. Both sandstone beds 1 and 2 (figure 5B) are composed of 95% rounded quartz grains, 0.2 to 0.8 mm, and an interstitial mosaic of subangular quartz grains measuring 0.02 to 0.04 mm. Both are cemented with a mixture of clay and iron oxide comprising 5% of the rock. Feldspar and calcite are absent in both. Petrographic examination shows paleosol of Peterson and Turner (1998) to be composed of 75% to 85% subrounded quartz grains measuring 0.2 to 0.5 mm, 10% to 15% potassic feldspar,

with scarce microcline, and 1% to 5% maroon iron oxide. In contrast, sandstones in the unnamed member are heterolithic, coarser grained, have larger quantities of cement that range from calcite to clay and oxide mixtures, and all have potassic feldspars. In light of these observations, we conclude that paleosol of Peterson and Turner (1998) is a local diagenetic feature and we place the K-1 unconformity 15 m lower (figure 5B) at the base of the lower sandstone (no. 1) of the Lytle Formation. We also note that there is a local intra-Lytle erosion surface at the top of lower sandstone (no. 1; figure 5B).

Overlying the Lytle Formation is the Glencairn Formation. It is the uppermost rock on most of the larger



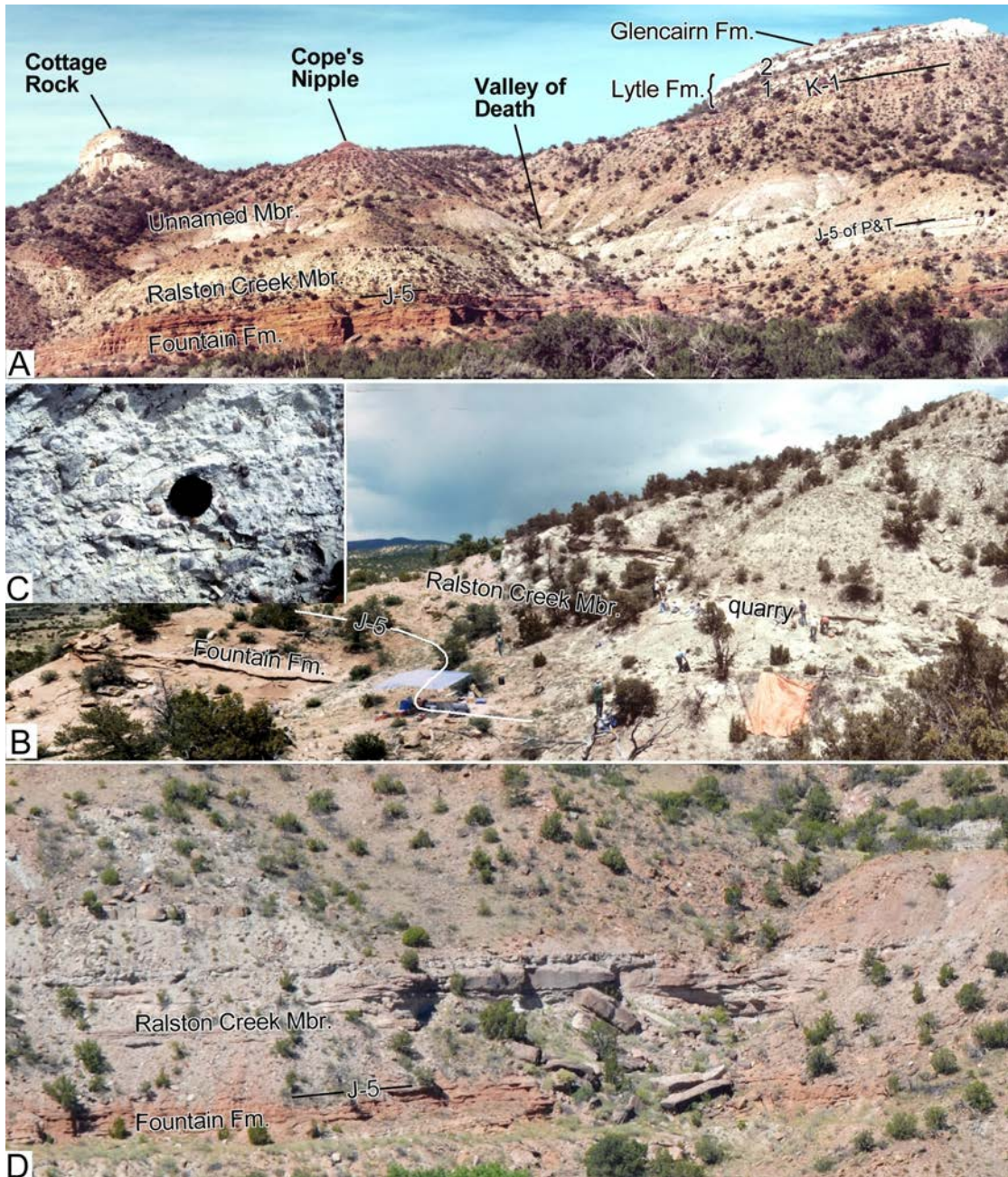


Figure 4. (A) View west across Fourmile Creek from County Road 9 towards Cope’s Nipple and the “Valley of Death” (see figure 1). The J-5 unconformity is visible as the abrupt contact between the Pennsylvanian Fountain Formation and the Ralston Creek Member of the Morrison Formation. This is about 16 m lower than placed by Peterson and Turner (1998) noted on the right side (J-5 of P&T). The lithological and color change marking the lighter colored lower and pinkish upper portions (generally more vegetated reflecting a change in soil clay minerals) of the unnamed member is visible below Cope’s Nipple and in the Valley of Death. The Cretaceous Lytle Formation has a lower (1) and upper (2) sandstone. The K-1 unconformity is at the base of sandstone 1. (B) Ralston Creek Member in Shaws Park, showing the location of the diplodocid quarry 4 m above the Fountain Formation. Downslope wash of weathered Ralston Creek hides most of the abrupt contact of the J-5 unconformity. (C) Angular quartz pebbles of the conglomeratic sandstone in the diplodocid quarry. Camera lens cap ~7.5 cm across. (D) Channel sandstone about 2 m above the J-5 unconformity at the top of the orange-colored Fountain Formation, west side of Fourmile Creek. Photograph in A, courtesy of Dan Grenard (retired, Bureau of Land Management, ) and D. Vicki Garrisi (True West Properties).



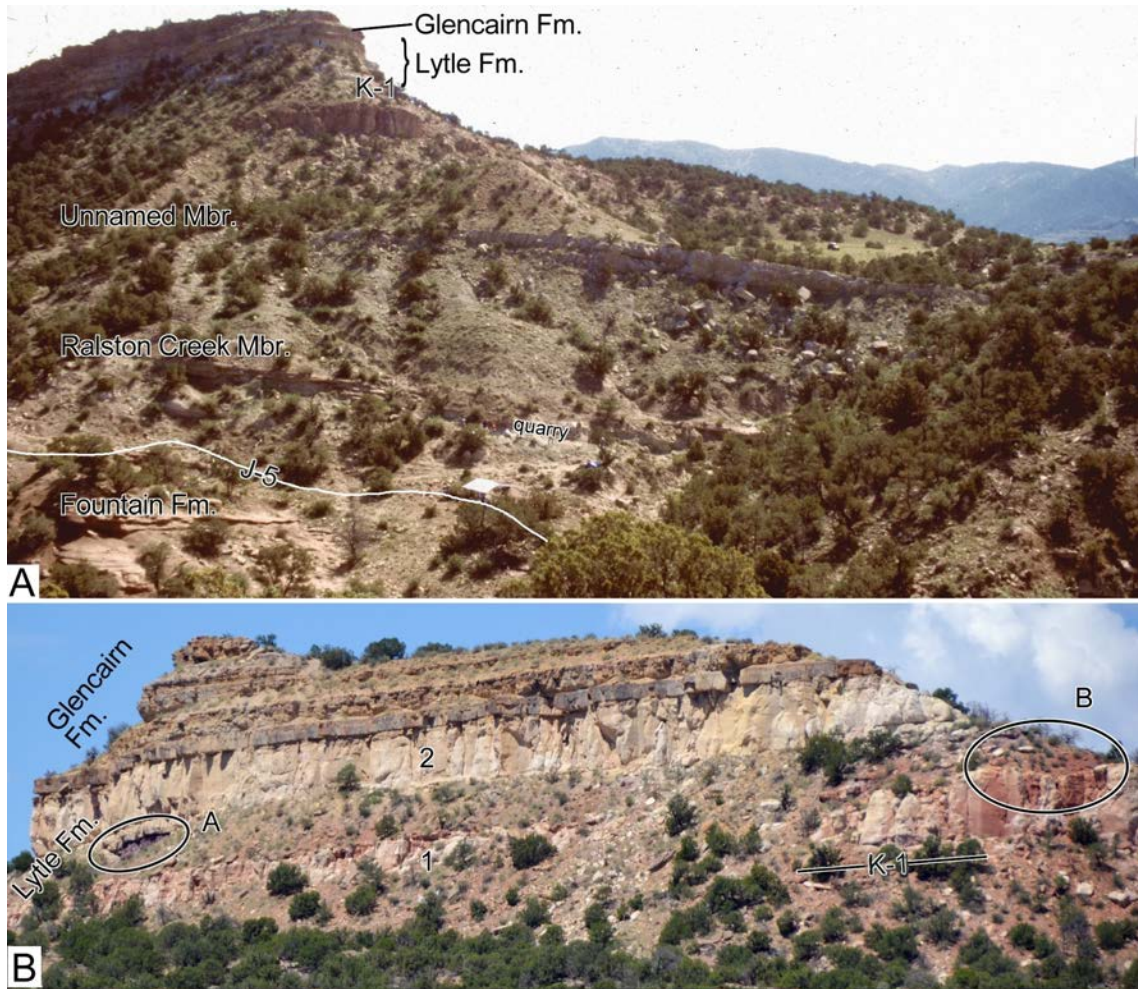


Figure 5. (A) West side of Shaws Park showing the entire Morrison Formation below an unnamed butte. The reddish colors characteristic of the upper part of the formation along Felch Creek are absent here. (B) Cretaceous Lytle Formation sandstone beds 1 and 2 below the capping Glencairn Formation on Cottage Rock. Purple paleosol A and red paleosol B were considered the K-1 unconformity by Peterson and Turner (1998). We place the K-1 below sandstone 1. Photograph courtesy of Vicki Garrisi (True West Properties).

mesas in Garden Park (figures 4A, 5A, and 5B). It is a tan to olive, thin-bedded sandstone with some shale layers. Sand grains range from medium to coarse and are rounded. Calcite is absent. Quartz comprises 85% to 90% of the rock and iron oxide and clay cement is about 5%.

### THE RALSTON CREEK MEMBER

We reassign the strata previously called the Ralston Creek Formation as the lowest member of the Morrison Formation in Garden Park, along the Front Range, and in the Denver Basin. Doing so eliminates lithostratigraphic correlation inconsistencies, conflicting ages,

and contradictory depositional histories.

### Nomenclature History

In the Cañon City embayment (which includes Garden Park at the north), the Morrison Formation rests upon strata that have been called the Ralston Formation (De Lay, 1955; Frederickson and others, 1956; Hassinger, 1959; Sackett, 1961; Cramer, 1962), the Ralston Creek Formation (Brady, 1967, 1969; Enciso, 1981; Sweet, 1984a; Carter, 1984; Gong, 1986; Richardson, 1987; Johnson, 1991; Anderson and Lucas, 1994), the “Ralston Creek Formation” (in quotes, Schultze and Enciso, 1983), the Todilto Formation (De Ford, 1929;

Heaton, 1950), the Wanakah Formation (Schaeffer and Patterson, 1984), and the Bell Ranch Formation (Peterson, 1994; Peterson and Turner, 1998; Turner and Peterson, 1999). Other names that have been applied to the strata in the northern part of the Front Range, which marks the western edge of the Denver Basin, include the Windy Hill Sandstone Member of the Sundance Formation (Pipiringos and O'Sullivan, 1976; Imlay, 1980) and Canyon Springs Member of the Sundance Formation (Pipiringos and O'Sullivan, 1978). The same strata in southeast Colorado have been referred to as the part of the Morrison (Lee, 1902), an unnamed "middle unit of Jurassic age" (Oriol and Mudge, 1956), Bell Ranch (Prince, 1988), and Ralston Creek (Hager, 2015). In Kansas, the gypsum-rich strata are included in the base of the Morrison Formation (Merriam, 1955).

The Ralston Formation [sic] was proposed in LeRoy's (1944) dissertation and officially published two years later (LeRoy, 1946). The strata lay between the Lykins and Morrison Formations on the west side of the Dakota Hogback west of Denver, Colorado. Van Horn (1957) amended the name to the Ralston Creek Formation because two other formations were already named Ralston (principle of homonymy, North American Commission on Stratigraphic Nomenclature, 2005, Article 7(b)). LeRoy (1946) designated the stratotype at the southwest end of Ralston Reservoir for 25.3 m (originally reported in feet as 83 ft) of thin beds of predominately gray shale and marlstone, and yellow sandstone and siltstone. The selection of this stratotype is unfortunate because the strata there are not typical of the gypsiferous Ralston Creek that underlies most of the Denver Basin. LeRoy (1946) noted that the gypsiferous facies in the Ralston occurred about 19.5 km south near the town of Morrison. It is unfortunate that LeRoy did not continue to trace the Ralston Creek farther south along the Front Range because the gypsum-free shale-marlstone (i.e., mudstone and calcareous mudstone) facies of the stratotype was atypical. Throughout eastern Colorado, the Ralston Creek mostly consists of variegated mudstone (mostly shades of gray and green with some red) interbedded with gypsum (including some anhydrite) beds, and sandstone (Heaton, 1939; Saylor, 1955; Fredrickson and others, 1956; Johnson, 1962; Prince, 1988; Johnson, 1991; Hager, 2015). In the western part of the

Cañon City embayment and south along the east side of the Wet and Sangre de Cristo Mountains, the Ralston Creek includes arkosic conglomerate, sandstone, and mudstone that probably represent alluvial fans coming off the remnants of the ancestral Rocky Mountains (De Ford, 1929; De Lay, 1955; Fredrickson and others, 1956; Metz, 1959; Hassinger, 1959; Sackett, 1961; Cramer, 1962; Johnson, 1991). Calcite and dolomite are common carbonate minerals in the non-gypsum facies as either cement, limestone, or calcrete (Carter, 1984; Gong, 1986; Richardson, 1987).

### **Ralston Creek Member Contact**

The contact between the Ralston Creek (Member) and Morrison (unnamed member of the Morrison Formation [our usage]) was placed by LeRoy (1946, p. 53) at a disconformity below the "basal sandstone of the Morrison." This criterion assumed that the lowest sandstone cropping out intermittently from the talus, soil, and vegetation was the same all along the Dakota Hogback. Later work demonstrated that this was not the case. Instead, the basal Morrison sandstone was actually lenticular sandstone bodies that were laterally discontinuous and were at slightly different stratigraphic positions relative to one another (Scott, 1963; Johnson, 1991). Elsewhere in eastern Colorado, various conflicting criteria have been used to mark the contact: (1) the combination of loss of gypsum, presence of limestone, welded cherts, and ledge-forming, massive sandstone beds (De Lay, 1955; Saylor, 1955; Frederickson and others, 1956; Carter, 1984), (2) the top of the highest chert bed (Oriol and Craig, 1960), (3) the base of the lowest sandstone (Sackett, 1961), (4) the top of the highest conglomerate and gypsum bed or color change to gray and green mudstones (Cramer, 1962; Brady, 1967), (5) the first laterally extensive limestone bed (Enciso, 1981), (6) at the base of the lowest welded chert (Sweet, 1984a; Peterson and Turner, 1998), (7) the change from sand-sized grains to clay-sized grains and loss of gypsum (Prince, 1988), and (8) at the top of a blue chert bed (Hager, 2015). Giltner (1953), Merriam (1955), Johnson (1959), and Johnson (1991) concluded that no solution was possible and included the lithofacies in the Morrison Formation. In doing so, they reverted back to the



definition of the Morrison Formation given by Cross (1894) and Mook (1916), which included gypsum beds.

The use of the welded chert boundary is strongly advocated by Peterson and Turner (1998) as a nearly isochronous boundary in the lower part of the Morrison Formation. King and Merriam (1969) contend that the source of the silica forming the welded chert is from the devitrification of glassy volcanic ash fall. This hypothesis is supported by the discovery of partially devitrified glass shards in the Morrison of the Front Range by Keller (1962; see also Johnson, 1991). Using the welded chert in the Morrison, however, is at odds with how it was first described by Ogden (1954, p. 914), who identified the welded chert as “near the top of the Ralston formation” and used that to correlate with occurrences in the Sundance Formation of northern Colorado and Wyoming.

In Garden Park, both Hassinger (1959) and Sweet (1984a) noted that welded chert beds occurred in facies identified as the lower Morrison Formation; welded chert is seen, for example, in sandstone beds near the bridge across Fourmile Creek. Prince (1988) on the other hand, noted a change in the stratigraphic position of the welded chert from near the top of the Ralston Creek lithofacies to near the bottom of the Morrison lithofacies along the Purgatoire River. Cramer (1962) noted that the chert is common in a 18.3-m-thick (originally reported in feet as 60 ft) zone of calcareous sediments that span Ralston Creek and Morrison lithofacies. Enciso (1981) concluded that the cherts represented silicified evaporites and discounted the importance of the welded cherts as a reliable marker. Joeckel and others (2007) also noted that chert replaced evaporites in the Morrison of Kansas. At best, we conclude that the welded chert zone is a broad band that straddles the upper Ralston Creek and lower Morrison lithofacies and is not a reliable isochronous surface; it may define a broad zone affected by changing groundwater chemistry during the Late Jurassic (see further below). Whether this holds true for the welded cherts in other formations, such as the Sundance, we cannot say.

### **Ralston Creek Member in Garden Park**

West of Fourmile Creek, the Ralston Creek Mem-

ber is predominately composed of 21 to 24 m of gray, greenish-gray to light-brown sandstone, siltstone, and mudstone, and lesser amounts conglomerate. The conglomerate beds, mostly confined to the lower part, are composed of subrounded- to rounded, pebble- to pea-sized fragments of quartz (figure 4C) and metaintrusives derived from the reddish Pikes Peak Granite of late Mesoproterozoic age (1.1 Ga, Anderson and Cullers, 1999). The sandstone beds consist of subrounded to well-rounded, coarse- to fine-grained sand, and the siltstone beds are composed of quartz and potassic feldspar grains with calcite cement. The quartz:feldspar ratios range between 70:30 and 90:10. Together, quartz and feldspar comprise 40% of the rock at the base of the formation and 75% near the top. Clay content ranges from 50% at the base of the formation to 10% to 15% near the top. East of Fourmile Creek, along the north facing scarp of Felch Creek (figure 6A), the Ralston Creek is composed of sandstone, siltstone, mudstone, and some thin gypsum beds. The gypsum content increases eastwards across the Cañon City embayment (figures 6B and 6C) as noted by De Lay (1955), Frederickson and others (1956), Cramer (1962), and Carter (1984). Poorly preserved fossil fish have been recovered from sandstone beds near the base along Felch Creek (Dunkle, 1942; Schultze and Enciso, 1983; Schaeffer and Patterson, 1984), and are discussed further below.

Composition of the conglomerate and mineral content of the sandstone and siltstone beds suggest that the Ralston Creek Member received sediments from the same source as the underlying Fountain Formation, and/or that the Ralston Creek is derived, at least in part, from reworking the Fountain; this is elaborated further below. A partial diplodocid sauropod skeleton was collected in this conglomeratic facies 4 m above the Fountain Formation near the Shaws Park-Garden Park divide (figures 4B and 5A); it is under study by Virginia Tidwell (volunteer, Denver Museum of Nature and Science).

### **Age of the Ralston Creek Member**

The correlation of the Ralston Creek Member along all or part of the Front Range to the Cañon City embayment has been demonstrated by De Lay (1955), Saylor (1955), Frederickson and others (1956), and especial-

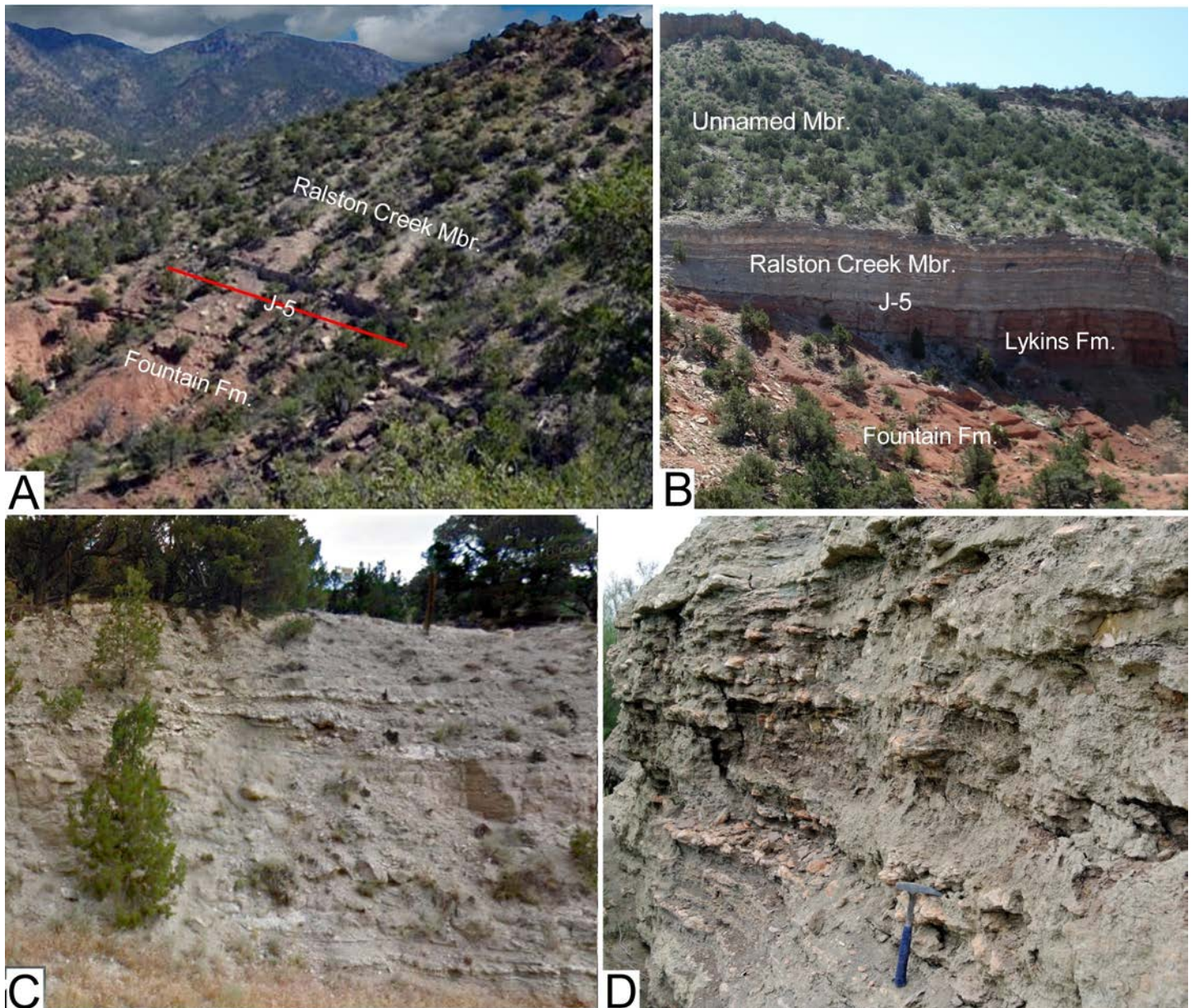


Figure 6. Lateral changes in the Ralston Creek Member. (A) Exposure along Felch Creek, east of Fourmile Creek with prominent sandstone lenses in the lower part and thinner calcic sandstone, siltstone, and mudstone beds in the upper; some gypsisol horizons also occur in this upper part. (B) Alternating petrogypsic horizons, mudstone and sandstone at Cramer’s (1962) measured section 12 in Eightmile Park. This site is about 12.2 km southeast of (A). (C) Repetitious alternating gray-weathering gypsisols, and gypsiferous fine-grain sandstone and grayish-green mudstone of a playa margin facies in a road cut of Colorado State Highway 115, 21.5 km east of (A). (D) Alternating thin, laterally discontinuous gypsum beds, reddish- to greenish-gray mudstone with nodular gypsum along the Purgatoire River, PRC site of Hager (2015); 173.75 km southeast of (A). Rock hammer for scale. Photograph (D) courtesy of Paul Myrow (Colorado College).

ly Johnson (1991). Their results contrast with Peterson and Turner (1998) who are of the opinion that the strata in Garden Park cannot be assigned to the Ralston Creek because “some of these beds are Middle Jurassic in age

and therefore older than the type Ralston Creek west of Denver” (Peterson and Turner, 1998, p. 26). The Middle Jurassic age was inferred from the fish taxa *Huletia americana* and *Todiltia schoewei* that were reported



from near the base of the strata along Felch Creek (Enciso, 1981; Schultze and Enciso, 1983; Schaeffer and Patterson, 1984). These taxa are also present in the Todilto Formation of New Mexico and in the Hulett Sandstone Member of the Sundance Formation in the Big Horn Basin, Wyoming (Schultze and Enciso, 1983; Schaeffer and Patterson, 1984). Lucas and others (1985) using regional correlation concluded that the Todilto Formation of New Mexico is middle Callovian, and Imlay (1982) concluded the Hulett Sandstone of Wyoming is lower Callovian.

Two crucial, but overlooked, comments regarding the specimens from Garden Park are that the specimens are poorly preserved (Dunkle, 1942) and are of juveniles in which the diagnostic characteristic features of the adults are not yet developed (Schultz and Enciso, 1983). The descriptions of *Todiltia* by Schultz and Enciso (1983) are not of the Garden Park specimens, but on the better-preserved specimens from the Todilto Formation of New Mexico. Furthermore, Kirkland (1998) described a second species of *Hulettia*—*H. hawesi*—from the Morrison Formation suggesting that, at least at the generic level, Jurassic freshwater fishes may be long lived. However, Schultz (retired, University of Kansas, verbal communications to Carpenter, 2017) is not convinced that *H. hawesi* is diagnostic because the crucial skull is unknown. At best, the specimens from the Ralston Creek strata indicate the presence of primitive actinopterygians. Finally, if as we show below, the Ralston Creek is nonmarine, then the fish from Garden Park were probably freshwater and are doubtfully the same taxa as from the marine Sundance and Todilto Formations. We therefore contend that the Middle Jurassic age for the Ralston Creek Member has not been established based on the fossil fishes.

There is now evidence for a Kimmeridgian age for the Ralston Creek strata making it 10 Ma younger than previously considered. This evidence includes the diplodocid skeleton collected 4 m above the Pennsylvanian-age Fountain Formation in strata previously identified as Ralston Creek (De Lay, 1955; Fredrickson and others, 1956; Enciso, 1981; Schultze and Enciso, 1983; Gong, 1986; Richardson, 1987), and a zircon  $^{206}\text{Pb}/^{238}\text{U}$  weighted mean date of  $152.99 \pm 0.10$  Ma reported by Hager (2015, appendix C) from near the top

of the Ralston Creek along the Purgatoire River (figure 6D). Schumacher (reported in Hager, 2015) obtained a U-Pb date of  $151.46 \pm 3.1$  Ma in the same general area from an ash just above the upper-most gypsum bed in traditional Morrison lithofacies. These dates straddle the Kimmeridgian-Tithonian boundary at  $152.1 \pm 0.9$  Ma (Cohen and others, 2013) and show that the Ralston Creek strata are coeval with the Salt Wash Member of the Morrison Formation of the Colorado Plateau (Trujillo and Kowallis, 2015) and possibly the Tidwell Member as well.

The younger age (Late Jurassic) for the Ralston Creek strata does much to resolve the alleged 10 Ma-old disconformity that is supposed to separate the Ralston Creek and Morrison (unnamed member of our usage) Formations (Schultze and Enciso, 1983; Schaeffer and Patterson 1984; de Albuquerque, 1988; Anderson and Lucas, 1994, and others). We agree with De Ford (1929, p. 78), Schulze (1954), Fredrickson and others (1956), Hassinger (1959), Brady (1967, 1969), Enciso (1981), Schultze and Enciso (1983), Sweet (1984a), Richardson (1987), and Johnson (1991) that the contact is conformable, except locally beneath the lowest sandstone of the typical Morrison (unnamed member of our usage). Peterson and Turner (1998, p. 27) acknowledged the difficulty in identifying an unconformity (contrary to their figure 5); “the upper contact of a ‘Ralston Creek Formation’ would have to be determined by the presence of a thick or moderately thick sandstone bed at the base of a restricted Morrison Formation. But where a reasonably thick sandstone bed is absent, the similarity of limestone-bearing red and green mudstone in both formations would make it difficult if not impossible to establish a contact between the two formations.”

In addition, it seems inconceivable for there not to be paleosol development in the mudstone marking the alleged 10 Ma disconformity or unconformity such as that seen separating the Upper Jurassic Morrison Formation from the Lower Cretaceous Cedar Mountain Formation in eastern Utah (e.g., Kirkland and Madsen, 2007; Kirkland and others, 2016). Schulze (1954) and Hassinger (1959) made a similar observation, noting that the gypsum at the top of the Ralston Creek does not show erosion or weathering that would be expected for long subareal exposure.

Finally, excluding the dubious identification of the fishes, other fossil evidence suggests a greater affinity of the Ralston Creek with the Morrison Formation as acknowledged by LeRoy (1946) and by Curtis (1963). Cramer (1962) reported palynomorphs from low in the Ralston Creek strata in Garden Park, including the cheirolepidiacean conifer *Classopollis minor* (abundant), the araucariacean *Callialasporites dampieri* (as *Zonalapollenites dampieri*, common), *Monosulcites* sp. (common), and the caytoniacean seed ferns *Caytonipollenites* sp. and *Vitreisporites* sp. (rare). Baghai-Riding and others (2014) and Dangles and others (2014) report a small assemblage of palynomorphs from near Colorado Springs, which Paul Myrow (Colorado College, verbal communications to Carpenter, 2017) states is high in the Ralston Creek. Taxa include the ferns *Ischyosporites marburgensis* (abundant) and *Cyathidites minor* (abundant), the cheirolepidiacean conifer *Classopollis* (abundant), araucariacean conifer *Araucariacites* spp. (rare), possible taxodiacean conifer *Exesipollenites tumulus* (rare), and bisaccates (pine, voltziales, or podocarp – rare), as well as the probable freshwater dinoflagellates *Spiniferites* and cf. *Odontochitina* (rare).

Other plants reported from the Ralston Creek include leaves of the cupressacean *Elatides williamsoni* and the cone *Palissya* sp. (this identity is doubtful because *Palissya* is Rhaetian–Lower Jurassic, Pattenmore and others, 2014), and the Kimmeridgian charophytes *Aclistochara* sp. and *Echinochara spinosa* (LeRoy, 1946; Van Horn, 1957; Peck, 1957; Scott, 1962, 1963). Microbialites (mats, stromatolites, biolaminates) also have been reported (Cramer, 1962; Enciso, 1981; de Albuquerque, 1988). Invertebrates include freshwater gastropods *Lymnaea morrisonensis* and *Gyraulus veternus*, the unionid cf. *Vetulonaia faberi*, and ostracods indent. (LeRoy, 1946; Van Horn, 1957; Scott, 1962, 1963). Yen (1952) noted that *G. veternus* is widely distributed in the Morrison Formation.

Vertebrate fossils include the diplodocid skeleton in Shaws Park mentioned above, unidentified dinosaur bones (Richardson, 1987), and large ornithopod tracks reported by Prince (1988). Another dinosaur skeleton was reported in a letter by William Utterback from the Carnegie Museum who was digging at Cope’s Nipple (see Carpenter, 2019); “Have portions of a small skel-

eton found in the Jurassic near the Trias or red beds. It shows several vert. and what looks to be the sacrum” (letter to John Hatcher, December 1, 1901, Carnegie Museum archives). Unfortunately, the skeleton cannot be found in the Carnegie Museum collections. The “red beds” were assume by Hatcher (1902) to be Triassic but are now known as the Pennsylvanian Fountain Formation.

## Ralston Creek as a Member

Our proposal to include the Ralston Creek strata in the Morrison Formation is not without precedence as other authors have included Ralston Creek in the Morrison along the Front Range (Heaton, 1950; Im-lay, 1952; Boos and Boos, 1957; Grose, 1960; Pipirinos and O’Sullivan, 1976, in part; and Johnson, 1991). O’Sullivan (1992) even recommended designation of the Ralston Creek as a member; “The gypsum-bearing beds in the Front Range embayment probably should be assigned to the Morrison Formation as a lower member,” a conclusion we had independently reached as well. We therefore formally reassign (North American Commission on Stratigraphic Nomenclature, 2005, Article 19(b)) the Ralston Creek as a basal member of the Morrison Formation, with the stratotype at Ralston Reservoir as originally designated by LeRoy (1946) for the “Ralston Formation” (North American Commission on Stratigraphic Nomenclature, 2005, Article 8(e)).

The Ralston Creek has four lithofacies as first noted by Frederickson and others (1956) that grade into one another west-to-east: (1) a conglomerate facies (figure 4b and 4C), (2) a sandstone facies (figure 4D), (3) a gypsum-mudstone facies (figure 6B and 6C), and (4) a sandstone-mudstone-gypsum facies (figure 6D). Owing to the contentious nature of the upper contact in the gypsum-mudstone facies (see above), we place the contact with the overlying unnamed member at the highest readily traceable gypsum or gypsiferous bed (North American Commission on Stratigraphic Nomenclature, 2005, Article 23(a)). So defined, the contact is not isochronous, nor does it need to be (North American Commission on Stratigraphic Nomenclature, 2005, Article 22 (e)). The bottom contact is the J-5 unconformity, which is well expressed where: (1) the con-



glomerate beds of the Ralston Creek Member lap onto Precambrian granites west of Cañon City, (2) it overlies the Pennsylvanian Fountain Formation in the GPNNL, (3) it overlies the Triassic-age Lykins Formation east of Cañon City (figure 6B), and (4) it laps onto older rocks subsurface in eastern Colorado and western Kansas (De Ford, 1929; Heaton, 1939; De Lay, 1955; Merriam, 1955; Saylor, 1955; Fredrickson and others, 1956; Oriel and Mudge, 1956; Hassinger, 1959; Sackett, 1961; Cramer, 1962; Schultz and Enciso, 1986; Richardson, 1987; de Albuquerque, 1988; Prince, 1988; Johnson, 1991; Hager, 2015).

### **Gypsum of the Ralston Creek Member**

The gypsum facies of the Ralston Creek Member have greatly influenced previous interpretations of the depositional environment. These hypotheses range from marine, including hypersaline embayment, lagoon, or tidal flat (Heaton, 1939, 1950; De Lay, 1955; Frederickson and others, 1956; Hassinger, 1959; Cramer, 1962; Curtis, 1963; Scott, 1963; Martin, 1965; Schaeffer and Patterson, 1984; de Albuquerque, 1988; Anderson and Lucas, 1994; Peterson and Turner, 1998), sabkha (Carter, 1984; Gong, 1986; see Al-Youssef, 2014 for discussion of gypsum production in a classic sabkha), fluvial (Johnson, 1991), lacustrine (LeRoy, 1946; Sackett, 1961; Hager, 2015), or playa (Giltner, 1953; Merriam, 1955; Oriel and Mudge, 1956; Sweet, 1984b; Richardson, 1987; Prince, 1988; Peterson and Turner, 1998).

A marine influence is seemingly strengthened by the report of glauconite in sandstones in the Ralston Creek along the southern margin of the Cañon City embayment (de Albuquerque, 1988). Keller (1958, 1962), however, reported glauconite in the Brushy Basin Member elsewhere in Colorado. The presence of glauconite in sediments associated with alkaline-saline lakes has been reported by Furquim and others (2010), which supports the hypothesis of Keller (1958) that playa lakes might have been responsible. Furquim and others (2010) note that transformation of smectites into nonmarine glauconite requires groundwater high in dissolved potassium but low in silica, a moderately alkaline pH, seasonal wet-dry cycles, a high availability of ferric oxide, and a reducing redox potential. Presum-

ably, these conditions were present at the time of glauconite production in the Ralston Creek Member, with a potassium source from the weathering of potassium feldspars in the Precambrian Pikes Peak granite. Finally, J. Ridgely (in Prince, 1988) noted that the geochemical signature of the Ralston Creek gypsum is nonmarine in origin, which we look at next.

Groundwater, not subaquatic precipitation, is the major source for nonmarine evaporites because groundwater leaches minerals from the surrounding sediments and bedrock, and then precipitates evaporite minerals in arid and semiarid climates (Rosen, 1994; Warren, 2016). Rosen and Warren (1990a, 1990b) present five criteria to distinguish between groundwater-formed gypsum and subaquatic-formed (playa lake and marine evaporite basin) gypsum, which we apply to the Ralston Creek gypsum: (1) individual gypsum layers are typically <30 cm thick (figure 6A and 6B), versus meters thick beds of subaqueous settings (figure 7D). (2) Crystals grow displacively below the ground surface (figure 7A), versus subaqueous crystals that are deposited on or grow upwards from a nucleation surface, i.e., the sediment-water interface, thus have a distinct bedding plane (figure 7D; see Warren, 2016, figure 1.28). (3) Crystals are typically lenticular due to elevated ground temperature and the presence of terrestrial humic compounds (Cody and Cody, 1988), and the crystals are arranged vertically, with matrix seen as inclusions following the crystal twin planes and surrounding the crystals (figures 7A to 7C), versus subaqueous crystals that are usually prismatic, forming irregular “chicken-wire” texture in laminated beds, and nucleated on a common bedding plane (figures 7D to 7F). (4) Crystals form in a zone parallel to the playa lake strandline and rarely co-occurs with halite, versus subaqueous crystals formed in the basin center or inland of the coastline and interlayered with subaqueous halite facies. (5) Hydrology is dominated by capillary evaporation (evaporative pumping) from groundwater versus hydrology of evaporite brines formed in a playa lake. However, Al-Youssef (2014) notes that ground surface evaporation causes recharge of the groundwater from the adjacent Arabian Gulf in the coastal Umm Said Sabkha, eastern Qatar. Separating thick gypsum beds formed subaqueously in large playa lakes or marine evaporite basins is difficult (Chi-

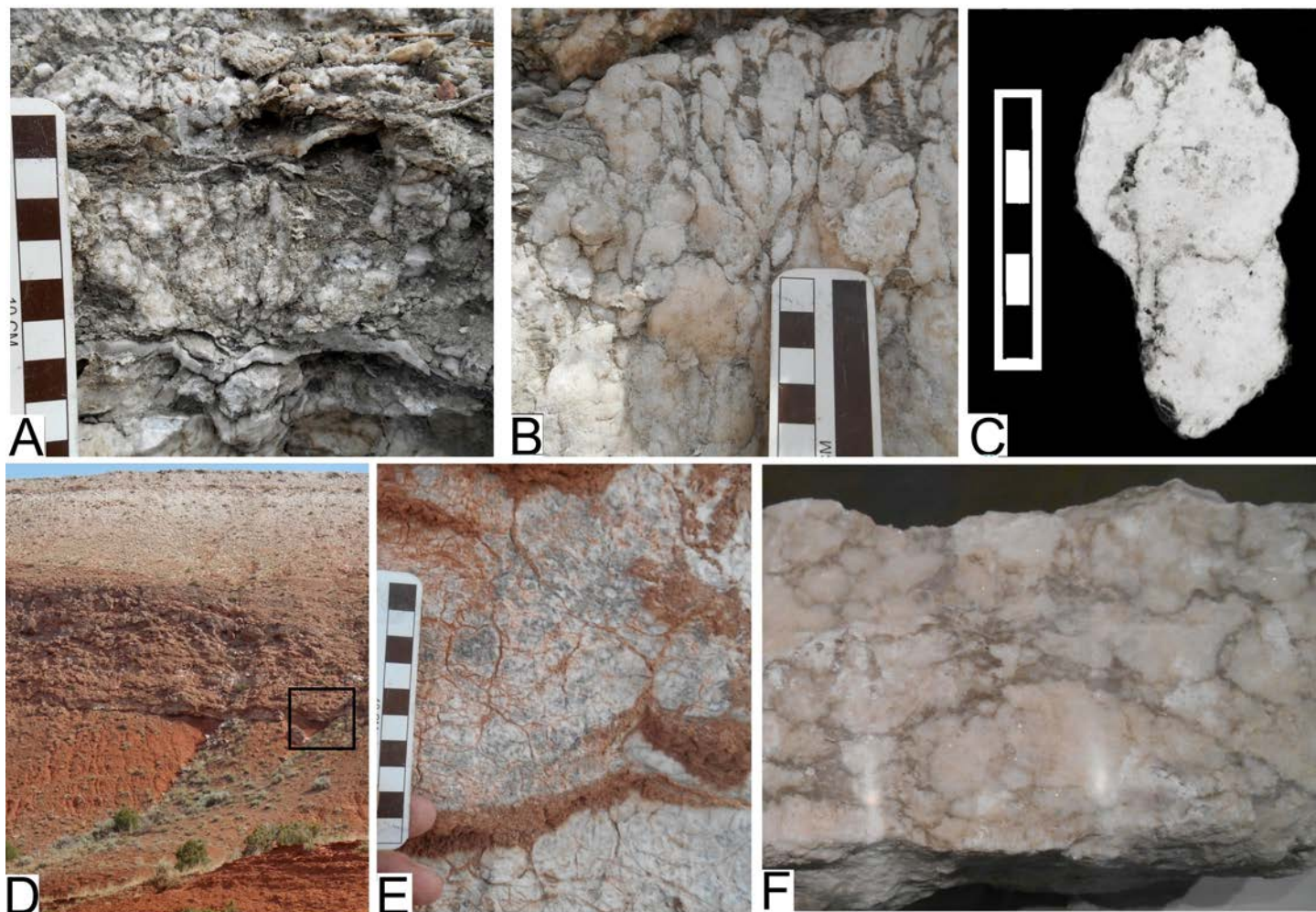


Figure 7. Comparison of playa and marine gypsum. (A) Playa gypsum has vertically oriented crystals that formed within soils of the playa margin. (B) These crystals grow by displacing the substrate silt and clay, which is crowded to edges, thus outlining the crystals. (C) Slabbed section showing the internal crystal fabric and displaced substrate outlining the crystals. Dark speckles in the center are tiny gypsum or selenite crystals; sample taken from just right of (B). Images (A) and (B) from road cut in figure 6C. (D) Bed of weathered marine gypsum (center band) at the base of the Piper Formation (equivalent to Sundance Formation) south of Big Pryor Mountain, Montana. (E) Marine gypsum is not dominated by vertically oriented crystals as seen in a close-up of the weathered gypsum (black box in D). Displaced substrate outlines the crystals, which are better seen in (F), a polished slabbed section (sample NH.101.11) on display at the Draper Museum of Natural History in Cody, Wyoming (bright flares are reflections of display lights). This sample shows the characteristic “chicken wire” texture of marine gypsum. Scales in cm.

vas, 2007; Warren, 2016), although context helps (e.g., marine invertebrates in associated shale or limestone). On a regional scale, playa lake gypsum beds are interspersed with gypsiferous paleosols (e.g., figures 6C and 6D) that formed in a zone marginal to the strandline.

For clarification, we use “playa” in the restricted sense of Rosen (1994) and Briere (2000) with one slight modification; a playa is a discharging intracontinental basin with a negative water balance, remaining

dry most of the year. Rosen (1994) and Briere (2000) set an annual minimum for being dry at 50% and 75%, respectively. In the geological record, we can only make assumptions about how long a playa is dry annually. We assume from studies of modern playas that those in the geologic past were dry for a significant part of the year, thus our vague qualifier “most of the year.” A playa complex is an intracontinental depositional basin that features multiple playas (see Jacobson and Jankowski,



1989, figure 13; Warren, 2016, figure 2.22) and is the concept we envision for the depositional environment of the Ralston Creek.

## Geologic Setting and Depositional Environment of the Ralston Creek Member

The Ralston Creek was deposited in a broad, 575-km-wide basin that was bounded on the west by the low remnants of the ancestral Rocky Mountains and on the east by the Cambridge arch-central Kansas uplift (Merriam, 1955) (figure 8). The basin was also bounded on the south by the Sierra Grande (Apishpa) and Cimarron arches (Prince, 1988), but was mostly open to the north towards the Sundance sea, which was located at this time in central or northern Wyoming. The base of the Ralston was deposited on an irregular terrain with up to 33 m of relief (De Lay, 1955; Merriam, 1955; Frederickson and others, 1956; Richardson, 1987). The ancestral Rockies at this time were very low, and probably measured in tens to hundreds of meters, not thousands of meters, because they were eroded and buried in the short time represented by Ralston Creek Member. If start of Ralston Creek deposition was about the same time as the start of the gypsiferous Tidwell Member on the Colorado Plateau, then deposition of the Ralston Creek Member took about 4 million years (see Trujillo and Kowallis, 2015). The inferred low profile of the

ancestral Rockies was insufficient to produce an effective rain shadow in the manner analogous to the Basin and Range-created playas today (Rosen, 1994). Because groundwater apparently could flow northwards down the potentiometric gradient towards the Sundance sea, the Ralston Creek depositional basin is a through-flow or open playa complex as defined by Rosen (1994) and Chivas (2007). This through-flow groundwater system with local surface discharge (playa lakes) being surrounded by topographically low relief is similar to a system called a boinka in Australia (Macumber, 1991; Rosen, 1994).

The formation of gypsisols (as defined by Mack and others, 1993) is a “bottom up” phenomenon due to evaporative pumping at the surface, whereas most soils form from the top down. The predominance of gypsum over other evaporites in the Ralston Creek Member is probably due to two equally important phenomena. The first phenomenon is the attainment of a steady state flux ratio, whereby groundwater outflow (evaporation, through-flow, etc.) to inflow is such that only one or two evaporite minerals precipitate rather than a spectrum (Wood and Sanford, 1990, in contrast to the brine evolution concept of Eugster and Hardie, 1978). As a result, more soluble minerals such as halite, may never form. Or if they do form when the flux ratio changes due to increase groundwater outflow (e.g., during drought), they will quickly dissolve when the system returns to

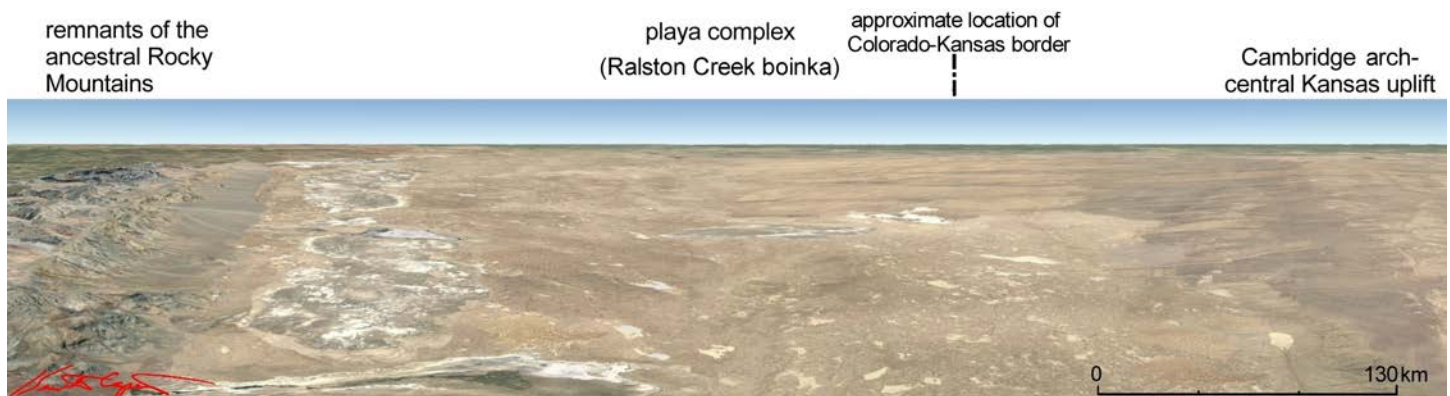


Figure 8. Reconstruction of the Ralston Creek boinka, a huge complex of playa lakes and gypsisols. View towards the north from what is now southeastern Colorado. The basin is bounded to the west by low remnants of the ancestral Rocky Mountains, to the east by the Cambridge arch-central Kansas uplift, and along the south by the Sierra Grande (Apishpa) and Cimarron arches. The open northern end of the basin is marked by vegetation. Thick beds of gypsum east of the present Front Range suggests long-lived playa lakes were present near the ancestral Rocky Mountains. Although the landscape may look barren, it was probably covered with gypsophilic and other xeric plants (see discussion by Czaja and others, 2014).

the steady state position with seasonal rain. Richardson (1987) reported salt pseudomorphs at the top of limestone beds in the Ralston Creek near Cañon City, and Hager (2015) reported salt casts in the Ralston Creek along the Purgatoire River. Presumably these are halite pseudomorphs or casts. The second phenomenon was that inflow groundwater along the basin margins was already saturated with dissolved gypsum from older, gypsum-rich bedrock present along the margins of the basin (e.g., Triassic Lykins Formation along the west side, and Permian Flower-Pot, Blaine, and Dog Creek Formations along the east side). A strong correlation between gypsic soils and underlying gypsum-rich parent rock has been noted before (e.g., Bockheim, 2014; Casby-Horton and others, 2015). Gypsic soils also contain gypsum nodules that may be up to several centimeters in diameter (Carter, 1984). In the Ralston Creek, these nodules occur in mudstone, siltstone, and fine-grained sandstone, and may coalesce into discontinuous irregular beds (e.g., figure 6C and 6D).

Based on the 152 Ma radiometric dates high in the Salt Wash and Ralston Creek Members (see above), the ancestral Rocky Mountains must have acted as a topographic barrier between the two depositional systems (see Craig and others, 1977). As described above, conglomerates in the western outcrops of the Ralston Creek indicate low gradient alluvial fans on the eastern side of the remnant mountains, and the isopleth map of grain-size distribution given by Craig and others (1955, figure 27) shows a decrease in sorting in the eastern-most portions of the Salt Wash. A similar decrease in sorting was cited by them as evidence for proximity of the Salt Wash in south-central Utah and northeastern Arizona to a source area. Thus, the eastern-most Salt Wash must have been deposited near a source area, which would have been the western side of the ancestral Rockies.

Termination of Ralston Creek deposition was marked by overtopping of the ancestral Rockies as evidenced by the sandstone-mudstone facies of the typical Morrison in unconformable contact with Precambrian granites along the Wet Mountains (Brady, 1967), in the present day intermountain basins (e.g., North and Middle Park, Wellborn, 1977; South Park, Fisher, 1977; Fraser Basin, Shroba and others, 2010; Webster Park, De Ford, 1929), and in the conformable contact of the

unnamed member with the underlying Ralston Creek Member across eastern Colorado and western Kansas. The termination of gypsum deposition was gradual as the overtopping Morrison facies was deposited progressively farther eastward through time as evidence by the stratigraphic position of the gypsum facies relative to a tuff marker bed (Cramer, 1962). This sedimentary change was undoubtedly accompanied by a change in groundwater chemistry, which probably resulted in formation of a welded chert zone. The progressive eastward shift in facies explains the observation by Frederickson and others (1956) and Prince (1988) that the welded cherts are time transgressive.

The change in groundwater chemistry at this time may explain the abundant lacustrine carbonates in the lower part of the Morrison Formation in eastern Colorado (Giltner, 1953; Prince, 1988; Dunagan, 1998). What would have been playa lakes depositing gypsum, were now freshwater lakes maintained by groundwater (Dunagan, 1998). A shift in the outflow/inflow ratios during droughts may explain the presence of the occasional evaporites and temporary playa lakes (Giltner, 1953; Sweet, 1984a, 1984b; Dunagan, 1998).

As is typical for modern playa areas, eolian sand grains (frosted, unimodal, and usually rounded) occur in the Ralston Creek Member, with the thickest eolian deposits downwind on the east side of the basin (Merriam, 1955; Frederickson and others, 1956). Some of the grains are probably recycled from the older eolian Entrada Sandstone. De Lay (1955) reported chert ventifacts near the base of the Ralston Creek in the western part of the Cañon City embayment. The presence of microbial mats, stromatolites, etc. (de Albuquerque, 1988) indicates the presence of more permanent brine lakes. These microbialites form in the strandline (Warren, 2016).

## THE UNNAMED MEMBER

The unnamed member of the Morrison Formation in the GPNL is what has traditionally been referred to as the Morrison Formation since the introduction of the term “Ralston Formation” into the Cañon City embayment by DeLay (1955) and Saylor (1955) for the gypsiferous facies. The unnamed member is predom-



inantly gray-green to rusty red mudstone, with many sandstone lenses, mostly discontinuous, but with a few thicker, more persistent beds (figure 4A; Evanoff and Carpenter, 1998). Color variations of the mudstone beds are in part stratigraphic and in part reflect the oxidation state of the contained iron. In the vicinity of Fourmile Creek, gray-green is the dominant color of the lower part of the member, and various shades of reddish color in the upper part (figure 2). This allows the member to be subdivided informally here into lower and upper parts. This two-part color separation is absent in the eastern portion of GPNL (“Green Acres” area, figure 9) and to the west in the Shaws Park area (figure 5A). A cyclical sandstone-mudstone unit lies at the base of the unnamed member along Fourmile Creek (figure 9B), which can be traced to below Felch Quarry 1 (figure 2A). All detrital rocks in the unnamed member are predominately clay, quartz, and potassic feldspar in varying quantities, and with, or without, calcite cement. Thin limestone beds are also present in the lower part, with one prominent bed in “Egg Gulch” (figure 1). The different lithologies are discussed further below. Trujillo and Kowallis (2015) report a single-crystal  $^{40}\text{Ar}/^{39}\text{Ar}$  laser probe date of  $152.29 \pm 0.27$  Ma from a bentonite mine in “Green Acres.” This mine is about 56 m above the Ralston Creek Member (Peterson and Turner, 1998, figure 5 place the mine at 8 m above the Ralston Creek, which is well below the bentonitic mudstone beds that occur above the local clay change).

All of the historic dinosaur quarries in Garden Park occur in the unnamed member of the Morrison Formation (see Carpenter, 1998b; Monaco, 1998). Therefore, we discuss its sedimentology further. As noted above, the unnamed member west of Fourmile Creek can be informally subdivided based on color. The lower part consists predominantly of pastel gray-green mudstone and light grayish-white to pastel green sandstone, which make up to 13% to 14% in the measured sections. Gray or green mudstone clasts from bank collapse are common in some sandstone beds, such as Felch Quarry 1, showing that the gray and green colors of the mudstone are primary in origin. The upper part of the unnamed member consists of predominately reddish to maroon mudstone, with lenses of green to greenish-gray paleosols (figure 2B; Carpenter, 2019). The mudstones are predominately smectitic, but with an illite-kaolinite assemblage (see below). Tabular reddish-white to yellowish-colored sandstone also occurs (figures 2B and 4A). Correlations within the Morrison throughout Garden Park are difficult due to the discontinuous, lency nature of the sandstone and limestone beds, and to Quaternary cover and landslide deposits that are mostly developed on the smectitic clays. A stratigraphic map and cross section that features the entire stratigraphic section of the Morrison Formation west of Fourmile Creek is shown on figure 10.

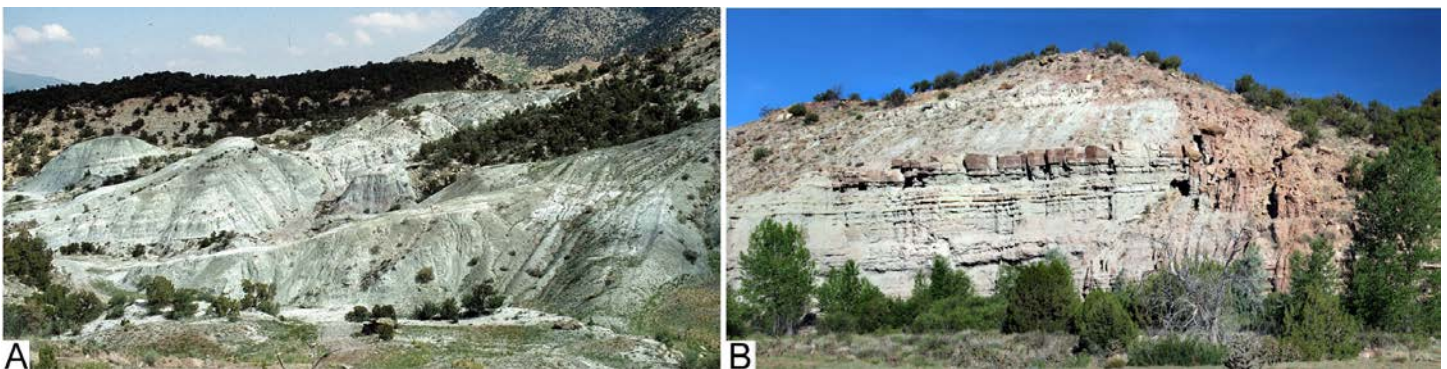


Figure 9. (A) Bentonitic green-gray mudstone beds of the middle and upper part of the unnamed member as exposed in “Green Acres.” A bentonite mine 250 m to the left out of frame produced an  $^{40}\text{Ar}/^{39}\text{Ar}$  date of  $152.29 \pm 0.27$  Ma (Trujillo and Kowallis, 2015). Two quarries in the area produced partial skeletons of *Diplodocus longus* and *Camarasaurus grandis*. (B) alternating beds of thin sandstone and mudstone of the lower part of the unnamed member as exposed near the Fourmile Creek bridge. Felch Quarry 1 is on the other side of the hill (see figure 2A). Photograph courtesy of Dan Grenard (retired, Bureau of Land Management).

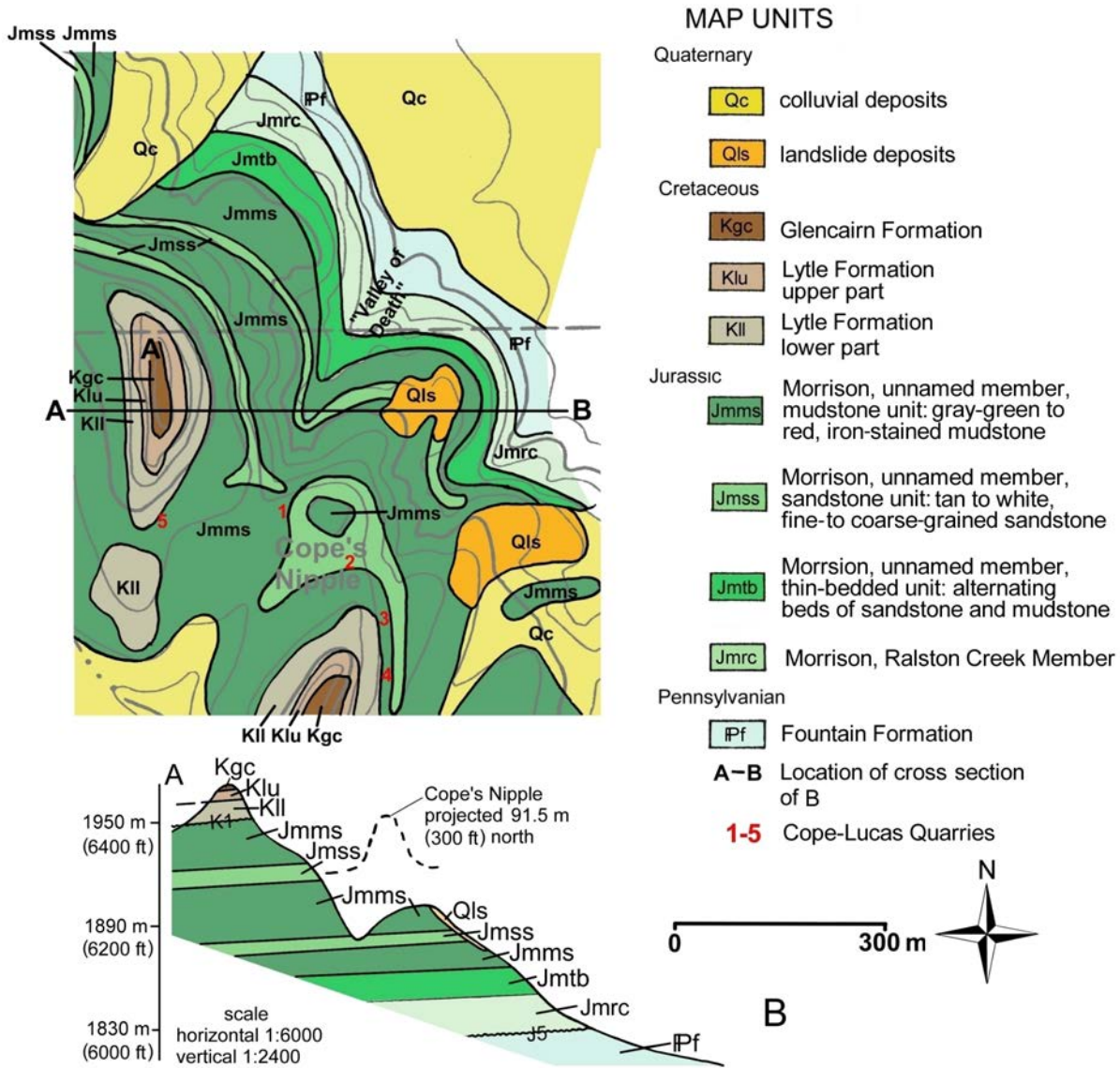


Figure 10. Geologic map and cross section showing stratigraphy and distribution of lithofacies in the area around Cope's Nipple. Line labeled A-B is location of cross section. Geologic map by E. Lindsey.

## Description of Lithofacies

### Thin-bedded unit (Jmtb)

This basal unit of crevasse splay deposits onto a floodplain is composed of thin alternating beds of gray mudstone to siltstone and sandstone exposed below Felch Quarry 1 (figure 2A) and near Fourmile Creek bridge (figure 9B). Individual beds are rarely more than 2 m thick and most are less than 0.75 m thick. All beds are calcareous. The mudstone-siltstone beds are 50% clay, 50% quartz plus feldspar, with quartz and feldspar

content about equal. Feldspars are potassic and most show incipient clay alteration. The sandstone beds have identical mineralogy, but clay content is only about 20%. Grain size ranges from clay to fine sand and individual grains are angular to subrounded. This unit is about 16.5 m thick.

### Sandstone Unit (Jmss)

The geometry of the sandstone bodies in the sandstone unit is predominately shoestring channels and sheet sands of crevasse splays in the lower portion, es-



pecially near Felch Quarry 1 (Evanoff and Carpenter, 1998), and tabular sheets of sandstone in the upper portion, especially in the vicinity of Cope's Nipple. Twelve samples of sandstone were collected and examined. The mineralogy is the same as the mudstone except that clay content is only about 10% to 15% of the rock, whereas quartz plus feldspar comprises 85% to 90% of the total. Quartz dominates in all samples and quartz:feldspar ratios vary between 75:25 and 90:10. All feldspar fragments are potassic and all display some degree of clay alteration. Brady (1967, 1969) reported about 1% plagioclase feldspars in sandstone north of Cope's Nipple. As in the mudstone beds, calcite cements the sandstone beds in the lower 73 m of the unnamed member. Many sand grains are subrounded and frosted, a point also noted by Hassinger (1959). The frosting was attributed to etching by the carbonate cement. Alternatively, is the reworking of older, eolian sedimentary rocks.

A thin section was made from the sandstone capping the 1830-m bench near Cope's Nipple. Grain size is about 0.2 mm in diameter, subangular to subrounded, and cemented by a clay and iron oxide mixture. There are very scarce patches of calcite cement. This sandstone was shown lithologically to have produced the holotype of the crocodylomorph *Hallopus victor* (Ague and others, 1995).

Calcareous sandstone occurs on the east side of Garden Park, in the Green Acres area. It also occurs sporadically to the west in "Stegosaurus Gulch," a west-trending gully containing the Small *Stegosaurus* Quarry (Carpenter, 1998a). The rock is a gray- to brown-weathering coarse-grained sandstone. In thin section, it appears to contain about 30% calcite cement whereas quartz grains comprise about 60% of the rock, and potassic feldspar grains are 5% or less. A small amount of clay and opaque minerals are also present. Grain sizes range from 0.1 mm to 0.2 mm and they are subangular to subrounded.

### **Mudstone Unit (Jmms)**

Mudstone comprises about 70% to 80% of the unnamed member in the Garden Park area. The mudstone is typically massive and variegated, and along Fourmile Creek, consist of alternating bands of greenish-gray, olive-gray, purple, and grayish-red beds in the lower part,

and grayish-red, pale-red, reddish-brown, and yellowish-gray beds in the upper part. Some of these colors appear differently in the unweathered profile. For example, purple weathered mudstone beds are usually blackish red (Munsell Color 5R2/2) when excavated, whereas gray weathered mudstone is often a dusky brown (5YR2/2). Many colored bands have diffuse contacts with other bands, but some have an abrupt upper or lower contact (e.g., figure 2B). Mottling is common in the mudstone, usually as various shades of green in the upper part, and greens and reds in the lower part. Pedotubules and carbonate nodules are common, and small (5 mm) ferruginous nodules in the upper red beds.

Fifteen samples of mudstone in Garden Park were collected and analyzed (see figure 11 for sample locations). Clay content ranges from 60% to 95%, decreasing upward. The quartz:feldspar ratios vary between 60:40 and 90:10. Feldspars are potassic and most show some clay alteration. Some quartz and feldspar grains are extremely small and are angular to subangular. Calcite cement is present in the lower 73 m of the unnamed member. In "Green Acres" east of Fourmile Creek, calcite cement is present in the lower 82 m. Above these measured levels calcite is absent. The distribution and vertical succession of clay minerals is depicted in figure 11. Sample density is sparse in the Garden Park area, but the vertical distribution of clay minerals in the unnamed member duplicates that found by Brady (1967) in a measured section 3.2 km north of Cope's Nipple involving 14 samples. In the mudstone beds of the unnamed member, clay minerals form unique assemblages with smectite generally dominant throughout, but with significant illite in the lowermost assemblage. Kaolinite, with illite, appears near the top of the section. In the lower middle part of the section Brady (1967) reported an 8-m interval is exclusively smectite, whereas near Cope's Nipple two samples in the upper middle part of the section are exclusively smectite. Detailed clay mineral analyses are given in table 1. Paleoenvironmental interpretation of the mudstone is discussed below.

### **Limestone Unit (not mapped on figure 10)**

Thin, discontinuous limestone beds comprise 5% of the Morrison Formation in Garden Park, especially in

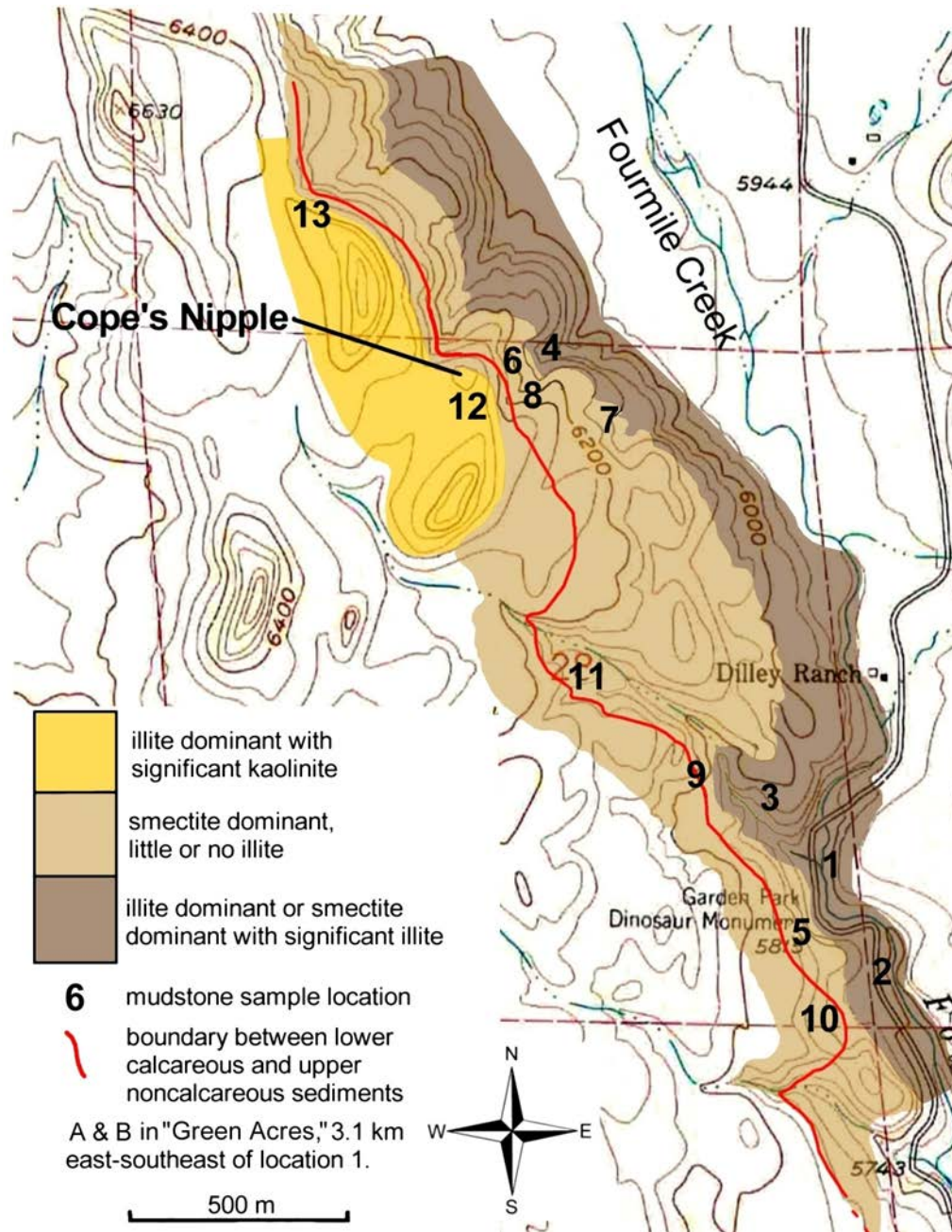


Figure 11. Map showing distribution of clay mineral zones in the study area west of Fourmile Creek. Mudstone (clay) sample sites labeled 1 to 13. The zone is stratigraphically arranged as shown in the legend.

the lower part above the Ralston Creek Member. However, limestone beds also occur in the unnamed member as noted below. These limestone beds are dense, brown to gray, and microcrystalline. They are probably chemical precipitates rather than organic accumulations, and invertebrate fossils, especially ostracods and aquatic mollusks, are present (Evanoff and others, 1998; Schudack and others, 1998). These invertebrate fossils

are fresh water forms indicating a lacustrine environment. Ostracods in the limestone beds often have both shells in a closed position, suggesting the animals had enclosed themselves to exclude unfavorable water conditions, such as increased salinity due to seasonal evaporation of the lacustrine waters. This stress may also explain the generally small, stunted size of the gastropods as well. Most of these fossils are silicified bright orange.



Table 1. Clay breakdown stratigraphically given in percentages. Sample locations shown on figure 7.

Sample	Sample Size (μ)	Illite	Chlorite or Kaolinite	Kaolin	Mixed-layer Illite/Smectite	Mixed-layer % Composition (expandable/collapsed)
13	<2	45		24	31	730/70
	2-8	38		23	38	
12	<2	22		11	67	70/30
	2-8	33		10	57	
11	<2	1		0	99	-
	2-8	1		0	99	
10	<2	0			100	70/30
	2-8	0			100	
9	<2	1	1		99	65/35
	2-8	1	1		99	
8	<2	0		0	100	-
	2-8	-		-	100	
7	<2	12			87	70/30
	2-8	15		1	83	
6	<2	13		0	87	60/40
	2-8	14	2		84	
5	<2	1			99	70/30
	2-8	1			99	
4	<2	9		0	91 (smect)	-
	2-8	9		1	90	
3	<2	4	<1		96	65/35
	2-8	5	<1		95	
2	<2	60			40	?
	2-8	85			15	
1	<2	8		0	92	-
	2-8	8		0	92	
A	<2	46		23	31 (mixed)	-
	2-8	50		35	15	
B	<2	1		0	99 (smect)	-
	2-8	2		0	98	

The thickest, most laterally extensive limestone in Garden Park occurs near Egg Gulch (near sample site 10, figure 11). It is about 1 m thick and extends north-south about 450 m. Stratigraphically, it is near the middle of the unnamed member, in the smectite-dominant clay assemblage. This rock, informally the “Egg Gulch limestone,” has many hallmarks of a calcrete; it is extensively brecciated, has calcite and chalcedony lined cavities, red chert, and a rhizoliths. However, the presence of silicified, bright orange aquatic gastropods shows that the limestone was initially lacustrine in origin, and that it was later altered by pedogenesis. Most of the gastropods are very small, being less than 5 mm in diameter. One exceptionally rich concentration of gastropods was seen within a branching burrow. The large diameter of the burrow, about 3 cm, suggests that it might have been that of a crayfish.

Another limestone, about 2 m thick, occurs near the bridge crossing at Fourmile Creek below Felch Quarry 1 (SE¼NE¼SE¼ section 28, T. 17 S., R. 70 W.). Most of it is a stage III calcrete (Retallack, 1988) consisting of a continuous layer formed by coalescing nodules. The nodules are light-gray (N7) micrite, with splotches of brownish-gray (5YR4/1) color. Bright red diagenetic

chalcedony occurs as small globular masses or splotches of welded chert (King and Merriam, 1969) and as linings in cavities between the nodules. These cherts have been used to correlate lower part of the unnamed member with the Tidwell Member on the Colorado Plateau by Turner and Peterson (1992). However, these welded cherts are not confined to the base of the unnamed member at Garden Park and depending on the definition of the contact (see section on the Ralston Creek Member Contact), they occur in the Ralston Creek Member and as high as 1 m below the upper part of the unnamed member near Cope’s Nipple. Most often, these cherts are associated carbonate beds and are secondary replacement of calcite (Hassinger, 1959; Cramer, 1962; Enciso, 1981; Sweet, 1984a). In a few places, the upper calcrete is a stage IV carbonate showing weakly developed lamellar structure. Downwards in the bed, the nodules become more distinct and are blocky, calcareous siltstone. The nodules are mottled greenish-gray (10GY5/2) and moderate-red (5R5/4) to grayish-red (5R4/2) in color. A limonitic yellowish-orange stain occurs on the surfaces of the nodules.

### Paleosols in the Unnamed Member

The existence of paleosols in the Morrison Formation is now well established (e.g., Mantzios, 1986; Retallack, 1990; Demko and others, 2004; Tanner and others, 2014). Laterally extensive colored banding of mudstones is an important (but not exclusive) feature in the field recognition of paleosols (Retallack, 1983; Bown and Kraus, 1986; Tabor and Myers, 2015) and this is true of the Morrison Formation at Garden Park as well. Color bands tend to lighten toward channel bodies reflecting less mature paleosols, the protosols of Mack and others (1993). These lighter sediments are also typically coarser grained, being silty or sandy, and probably represent levee and splay deposits. Cementation is usually better in the sandier facies resulting in irregular sandstone sheets up to 1 m thick. Most sandstone sheets, however, are much thinner, being 10 to 20 cm thick. A basal conglomerate of matrix-supported angular to subangular carbonate nodules and clay balls is also present in many of the channel sandstone beds. The conglomerates originate from fluvial entrainment of bank collapse and

show that the formation of soil nodules in the floodplain sediments occurred early in pedogenesis (Karcz, 1969, 1972; Mather and others, 2008; Carpenter, 2013). Remnants of termite nests are also present in the sandstone beds showing infestation of tree roots (figure 12; Hasiotis and Demko, 1998).

Most of the paleosols in Garden Park are calcic argillisols based on the calcareous nature of the mudstones B horizons enriched with argillans, or clay skins; calcareous nodules are present and widely scattered throughout the lower portion. The A horizon is typically a blackish-red (5R2/2) color and often shows an extensive network of grayish-green (5G3/2) root casts. At the Small *Stegosaurus* Quarry located in a former pond, there is an abundance of organic carbon, including fusain (Rougier and others, 2015). Elsewhere, the in-situ presence of dinosaur eggs provides additional clues to identifying the A horizon. At Egg Gulch, the eggs occur in a nonswelling, gray-weathering mudstone that, when fresh, is a mottled blackish-red (5R2/2) and grayish-green (5G3/2), blocky, calcareous mudstone with slickensides. Medium gray (N5) micritic nodules are present and these have a very light ferruginous coating or dusting. The stratigraphically higher eggs at Tim's Site near Egg Gulch occur in a swelling, grayish-weathering mudstone that was partially in a blackish-red (5R2/2) mudstone, with tiny (1 mm) grayish-orange pink spots (5YR7/2), and partially in a yellowish-gray (5Y7/2) mudstone.

The C horizon is best developed in the Temple Canyon area, 17 km southwest of Garden Park, where the Morrison discordantly overlies Precambrian granite and metamorphic rocks. Here, the Precambrian rocks are deeply weathered, with feldspars altered to clays. The basal part of the Morrison is frequently a calcite-cemented, conglomeratic sandstone, with boulders up to 1 m in diameter. Locally, however, a light-green mudstone is present.

Brady (1967, 1969), in his work north of Cope's Nipple, found the lower 15.6 m of the mudstone beds in the unnamed member to be illitic, the middle 31.1 m to be smectitic, and the upper 55.8 m to be mixed illitic-kaolinitic. A similar succession occurs near Cope's Nipple, although the thicknesses of the three assemblages differ. A three-fold division also occurs at the reference sec-



Figure 12. The vertical orientation of a fossil termite nest indicates a formerly infested tree root. Sandstone is in the unnamed member of the Morrison Formation from the west side of Felch Quarry 1. Height is about 50 cm.

tion of the Morrison Formation, but with a kaolinite- and illite-dominated lower and middle sections, and a smectitic-dominated (as montmorillonite) upper section (Keller 1953). A three-fold division is also present in the Morrison of the Colorado Plateau (Keller, 1962); it is present, although not as well developed near Dillon, Colorado (Wahlstrom, 1966) where secondary illite has been identified (Bell, 1986). Turner and Fishman (1991) have hypothesized that some illite may form at low syn-depositional temperatures, but most illite is believed to be detrital (Keller, 1962). Whether the illite at Garden Park is primary or secondary is not known at this time. The percentage of illite in the samples is shown in table 1.

Smectitic clays are most likely the product of devitrification of volcanic ash because glass shards are identified throughout the section (Keller, 1962; Brady, 1969).



The source of this ash was most likely along the southern California, Nevada, and Arizona border (Rogers and others, 1974; Kowallis and others, 2001; Christiansen and others, 1994, 2015). The percentage of smectite in Garden Park is shown in table 1.

Much of the clay in the unnamed member is a illite-smectite mixed layer (table 1). This clay is widespread through the Morrison Formation in the Western Interior (Turner and Peterson, 1999; Trujillo, 2006). This mixed layer clay may form by smectite illitization through the input of potassium ions (Rask and others, 1997; Cuadros, 2006). The potassium may derive from feldspars, which are ubiquitous in the Morrison (Keller, 1962).

Kaolinite appears in the upper part of the upper unnamed member at elevation 1830 m, and on the east side near Green Acres at elevation 1975 m. Tabbutt and others (1989) suggest that kaolinite in the Morrison is detrital in origin, whereas Tank (1956) and Mantzoi (1986) believe the kaolinite is produced by weathering potassic feldspar in low pH (acidic) environments. The absence of calcium carbonate cement in the upper member of the Morrison supports the possibility that low pH environments did exist and that kaolinite was produced there. Kaolinite is also present low in the Salt Wash Member of the Colorado Plateau, in the lower portions at the type section of the Morrison, near Golden, Colorado, in the lower part of the Morrison at Blue Mesa Reservoir, Colorado, in the upper portions of the Morrison near Dillon, Colorado, and the Black Hills of Wyoming and South Dakota (Keller, 1953, 1962; Tank, 1956; Wahlstrom, 1966; Fiorillo and McCarty, 1996).

The upward succession of clay mineral assemblages and the distribution of vertebrate fossils leads to contradictory conclusions regarding paleoclimate, a point also noted by Tanner and others (2014) in western Colorado (but not addressed by Demko and others, 2004). Based upon clay mineral stability at low pressures and temperatures described by Singer (1980), the predominance of illite and smectite in the lower portion of the unnamed member at Garden Park suggests that waters in the environment were alkaline, with a relatively high cation concentration and a relatively low Eh. Such conditions would occur on a mature surface with low to moderate rainfall, which would result in slow moving

rivers, large and numerous paludal areas, and with devitrifying volcanic ash supplying large amounts of cations to the waters. The appearance of kaolinite in the upper portion implies altered conditions, including a slightly acid pH, increased Eh, and dilution of the cation concentration. Such conditions could arise from increased rainfall, consequent increased river flow velocities, and flushing and diluting the paludal areas. However, as reported elsewhere (Carpenter, 1998b), the aquatic vertebrates and invertebrates are comparatively scarcer in the upper part of the Morrison at Garden Park as compared with the lower part. This scarcity does not appear to be due to taphonomic loss in an acidic environment because of the lack of dissolution features on the abundant dinosaur specimens and the few rare turtle bones found by us.

## CONCLUSIONS

The Morrison Formation along Fourmile Creek in Garden Park, Colorado, is subdivided into the reassigned Ralston Creek Member and overlying unnamed member. The Morrison rests on the J-5 unconformity at the base of the Ralston Creek that can be traced along the Front Range and the rest of the Denver Basin. The Ralston Creek Member has several facies. The most widespread facies is characterized by gypsum that was predominantly deposited as gypsisols and in lesser amounts subaquatically in playa lakes. The non-gypsum facies preserved on the west side of the Ralston Creek depositional basin represent alluvial fans from the remnants of the ancestral Rocky Mountains. These mountains were only tens to hundreds of meters high, but formed a topographical barrier that separated the Ralston Creek and the Salt Wash depositional basins for about 4 million years. Eventually erosion and deposition buried the mountains allowing the unnamed member to be deposited over the Ralston Creek sediments. The change in groundwater chemistry halted gypsum deposition and gave rise to the welded chert zone.

The upper unnamed member of the Morrison Formation on the west side of Fourmile Creek can be subdivided into a lower part composed predominantly of green and gray smectite, dominated by smectite-illite mudstone and sandstone, and lesser amounts of la-

custrine limestone. Paleosols are well developed in the lower part as shown by pedogenic features (brecciated calcrete, welded cherts, a carbonaceous A horizon with rhizoliths, clay skins, and calcareous nodules in the B horizon). The upper part of the unnamed member is composed predominantly of purple and red smectite-dominant mudstone with little or no illite content. Sandstone and limestone beds are less abundant here than in the lower part. At the top of the formation, illite is again present and kaolinite occurs for the first time in the clay mineral assemblage. Sandstone beds in this upper part, while less abundant, are more continuous. Paleosol development in this upper part are not as well defined, although clay skins and ferruginous nodules occur in the B horizon. The paleosols in Garden Park are mostly calcic argillisol and gypsisols.

## ACKNOWLEDGMENTS

Field photographs to replace those lost by Carpenter were made available to us by Dan Grenard (retired, Bureau of Land Management, Cañon City, Colorado) and Vicki Garrisi (True West Properties, Woodland Park, Colorado). Paul Myrow (Colorado College, Colorado Springs, Colorado) shared images taken along the Purgatoire River, Colorado. We thank Dan, Vicki, and Paul for their use. William Benzel (Marathon Oil Company) analyzed the clay samples and his assistance is greatly appreciated. Thin sections were prepared at the U.S. Geological Survey facility, Denver Federal Center. Air photos, used in the geologic mapping project, were supplied gratis by the Bureau of Land Management. Thanks to Fred Peterson (U.S. Geological Survey, Denver, Colorado) and Emmett Evanoff (University of Northern Colorado, Greeley, Colorado) for discussions in the field. Thanks to Bruce Schumacher (U.S. Forest Service, La Junta, Colorado) for sharing the report on radiometric dates for the Jurassic strata in the Purgatoire River valley. Review comments of earlier drafts by Emmett Evanoff, John Foster (Utah Field House of Natural History State Park Museum), Kelli Trujillo (Laramie County Community College), and my wife, Yvonne Wilson are appreciated. Finally, field work in the Garden Park National Natural Landmark was conducted under Bureau of Land Management permit C-49819(c).

## REFERENCES

- Ague, J., Carpenter, K., and Ostrom, J., 1995, Solution to the *Halolopus enigma?*: *American Journal of Science*, v. 295, p. 1–17.
- Alf, K., 1998, Preliminary study of an eggshell site in the Morrison Formation of Colorado, *in* Carpenter, K., Chure, D., and Kirkland, J.I., editors, *The Upper Jurassic Morrison Formation—an interdisciplinary study, part II: Modern Geology*, v. 23, p. 241–248.
- Al-Youssef, M., 2014, Gypsum crystals formation and habits, Umm Said Sabkha, Qatar, *in* Khan, M.A., Böer, B., Öztürk, M., Al Abdessalaam, T.Z., Clüsener-Godt, M., and Gul, B., editors, *Sabkha ecosystems, volume IV—cash crop halophyte and biodiversity conservation: Tasks for Vegetation Science*, v. 47, p. 23–54.
- Anderson, J.L., and Cullers, R.L., 1999, Paleo- and Mesoproterozoic granite plutonism of Colorado and Wyoming: *Rocky Mountain Geology*, v. 34, no. 2, p. 149–164.
- Anderson, O.J., and Lucas, S.G., 1994, Middle Jurassic stratigraphy, sedimentation and paleogeography in the southern Colorado Plateau and southern High Plains, *in* Caputo, M.V., Peterson, J.A., and Franczyk, K.J., editors, *Mesozoic systems of the Rocky Mountain region, USA: Denver, Rocky Mountain Section SEPM (Society for Sedimentary Geology)*, p. 299–314.
- Baghai-Riding, D.K., Hotton, C., Myrow, P., and Dangles, L., 2014, Palynomorphs from the base of the Late Jurassic Morrison Formation, Colorado Springs, Colorado, U.S.A. [abs.]: *Botany, 2014 Electronic Abstracts* <http://www.2014.botanyconference.org/engine/search/index.php?func=detailandaid=529> (accessed July 25, 2017).
- Bell, T.E., 1986, Microstructure in mixed-layer illite/smectite and its relationship to the reaction of smectite to illite: *Clays and Clay Minerals*, v. 34, p. 146–154.
- Bockheim, J.G., 2014, *Soil geography of the USA—a diagnostic-horizon approach: Switzerland*, Springer International Publishing, 320 p.
- Boos, C.M., and Boos, M.F., 1957, Tectonics of eastern flank and foothills of Front Range, Colorado: *American Association of Petroleum Geologists Bulletin*, v. 41, no. 12, p. 2603–2676.
- Bown, T., and Kraus, M., 1986, Integration of channel and floodplain suites, I—developmental sequence and lateral relations of alluvial paleosols: *Journal of Sedimentary Petrology*, v. 57, p. 587–601.
- Brady, L.L., 1967, Stratigraphy and petrology of the Morrison Formation (Jurassic) in the vicinity of Cañon City, Colorado area: *Lawrence, University of Kansas, M.S. thesis*, 111 p.
- Brady, L.L., 1969, Stratigraphy and petrology of the Morrison Formation (Jurassic) of the Cañon City, Colorado area: *Journal of Sedimentary Petrology*, v. 39, p. 632–648.



- Bray, E.S., and Hirsch, F.F., 1998, Egg shell from the Upper Jurassic Morrison Formation, in Carpenter, K., Chure, D., and Kirkland, J.I., editors, The Upper Jurassic Morrison Formation—an interdisciplinary study, part II: Modern Geology, v. 23, p. 219–240.
- Briere, P.R., 2000, Playa, playa lake, sabkha—proposed definitions for old terms: Journal of Arid Environments, v. 45, p. 1–7.
- Brill, K., and Carpenter, K., 2001, A baby ornithopod from the Morrison Formation of Garden Park, Colorado, in Tanke, D., and Carpenter, K., editors, Mesozoic vertebrate life: Bloomington, Indiana University Press, p. 197–205.
- Carpenter, K., 1998a, Armor of *Stegosaurus stenops*, and the taphonomic history of a new specimen from Garden Park, Colorado, in Carpenter, K., Chure, D., and Kirkland, J.I., editors, The Upper Jurassic Morrison Formation—an interdisciplinary study, part II: Modern Geology, v. 23, p. 127–144.
- Carpenter, K., 1998b, Vertebrate biostratigraphy of the Morrison Formation near Cañon City, Colorado, in Carpenter, K., Chure, D., and Kirkland, J.I., editors, The Upper Jurassic Morrison Formation—an interdisciplinary study, part II: Modern Geology, v. 23, p. 407–426.
- Carpenter, K., 1999, The Cañon City dinosaur sites of Marsh and Cope: Society of Vertebrate Paleontology Fieldtrip Guidebook, Denver, Colorado, Denver Museum of Nature and Science, 14 p.
- Carpenter, K., 2013, History, sedimentology, and taphonomy of the Carnegie Quarry, Dinosaur National Monument: Annals of Carnegie Museum, v. 81, p. 153–232.
- Carpenter, K., 2019, History and geology of the Cope's Nipple Quarries in Garden Park, Colorado, Morrison Formation, type locality of giant sauropods: Geology of the Intermountain West, v. 6, p. 31–53.
- Carpenter, K., and Tidwell, V., 1998, Preliminary description of a *Brachiosaurus* skull from Felch Quarry 1, Garden Park, Colorado, in Carpenter, K., Chure, D., and Kirkland, J.I., editors, The Upper Jurassic Morrison Formation—an interdisciplinary study, part II: Modern Geology, v. 23, p. 69–84.
- Carter, M.H., 1984, Paleoenvironmental analysis of the Ralston Creek Formation within the Cañon City embayment, Cañon City, Colorado: Norman, University of Oklahoma, M.S. thesis, 90 p.
- Casby-Horton, S., Herrero, J., and Rolong, N.A., 2015, Gypsum soils—their morphology, classification, function, and landscapes: Advances in Agronomy, v. 130, p. 231–290.
- Chivas, A.R., 2007, Terrestrial evaporites, in Nash D.J., and McLaren, S.J., editors, Geochemical sediments and landscapes: Oxford, England, Blackwell Publishing Ltd, p. 330–364.
- Christiansen, E.H., Kowallis, B.J., and Barton, M.D., 1994, Temporal and spatial distribution of volcanic ash in Mesozoic sedimentary rocks of the Western Interior—an alternative record of Mesozoic magmatism, in Caputo, M.V., Peterson, J.A., and Franczyk, K.J., editors, Mesozoic systems of the Rocky Mountain region, USA: Denver, Rocky Mountain Section SEPM (Society for Sedimentary Geology), p. 73–94.
- Christiansen, E.H., Kowallis, B.J., Dorais, M.J., Hart, G.L., Mills, C.N., Pickard, M., and Parks, E., 2015, The record of volcanism in the Brushy Basin Member of the Morrison Formation—implications for the Late Jurassic of western North America, in Anderson, T.H., Didenko, A.N., Johnson, C.L., Khanchuk, A.I., and MacDonald, J.H., Jr., editors, Late Jurassic margin of Laurasia—a record of faulting accommodating plate rotation: Geological Society of America Special Paper 513, p. 399–439.
- Chure, D.J., 2001, The second record of the African theropod *Elaphrosaurus* (Dinosauria, Ceratosauria) from the Western Hemisphere: Neues Jahrbuch für Geologie und Paläontologie Monatshefte, v. 9, p. 565–576.
- Cody, R.D., and Cody, A.M., 1988, Gypsum nucleation and crystal morphology in analog saline terrestrial environments: Journal of Sedimentary Petrology, v. 58, p. 247–255.
- Cohen, K.M., Finney, S.C., Gibbard, P.L., and Fan, J., 2013, The ICS international chronostratigraphic chart: Episodes, v. 36, no. 3, p. 199–204, URL:<http://www.stratigraphy.org/ICSchart/ChronostratChart2018-08.pdf>.
- Committee on Stratigraphic Nomenclature, 1933, Classification and nomenclature of rock units: American Association of Petroleum Geologists Bulletin, v. 17, no. 7, p. 843–868.
- Craig, L.C., Holmes, C.N., Cadlgan, R.A., Freeman, V.L., Mullens, T.B., and Weir, G.W., 1955, Stratigraphy of the Morrison and related formations, Colorado Plateau region—a preliminary report: U.S. Geological Survey Bulletin 1009-E, p. 125–168.
- Craig, L.C., Holmes, C.N., Cadlgan, R.A., Freeman, V.L., Mullens, T.B., and Weir, G.W., 1977, Sheet 1 – isopach and facies map of Salt Wash Member of the Morrison Formation—maps showing thickness of the Morrison Formation and thickness and generalized facies of the members of the Morrison Formation in the Colorado Plateau region: U.S. Geological Survey Open-File Report 77–516, 5 sheets, scale 1:1,000,000.
- Cramer, J.A., 1962, The Jurassic Ralston Formation in the southern Colorado Front Range: Lawrence, University of Kansas, M.S. thesis, 117 p.
- Czaja, A., Estrada-Rodríguez, J.L., and Olvera, H.F., 2014, The gypsum dunes of Cuatrociénegas valley, Mexico—a secondary sabkha ecosystem with gypsophytes, in Khan, M.A., Böer, B., Öztürk, M., Al Abdessalaam, T.Z., Clüsener-Godt, M., and Gul, B., editors, Sabkha ecosystems, volume 4—cash crop halophyte and biodiversity conservation: Tasks for Vegetation Science, v. 47, p. 81–92.
- Cross, W., 1894, Description of the Pikes Peak sheet: U.S. Geological Survey, Geologic Atlas of the United States, Pikes Peak Folio, Colorado, 17 p.

- Curtis, B.F., 1963, Jurassic stratigraphic relationships in the northern Denver Basin, *in* Katich, P.J., and Bolyard, D.W., editors, *Geology of the northern Denver Basin and adjacent uplifts: Rocky Mountain Association of Geologists*, p. 111–118, online, [archives.datapages.comml.org/data/rmag/geol-northden63/curtis.html](http://archives.datapages.comml.org/data/rmag/geol-northden63/curtis.html), accessed June 30, 2017.
- Cuadros, J., 2006, Modeling of smectite illitization in burial diagenesis environments: *Geochimica et Cosmochimica Acta*, v. 70, p. 4181–4195.
- Dangles L.N., Myrow, P.M., Chen, J., Baghal-Riding, N., Hotton, C.L., Schumacher, B., and Hager, A., 2014, Triassic-Jurassic strata of the Colorado Springs region and associated palynoflora [abs.]: *Geological Society of America Abstracts with Programs*, v. 46, no. 5, p. 25.
- de Albuquerque, J.S., 1988, Stratigraphy and depositional environments of the Middle Jurassic (Callovian) Ralston Creek Formation, Beulah-Wetmore area, south-central Colorado: Hays, Fort Hays State University, M.S. thesis, 114 p.
- De Ford, R.K., 1929, Surface structure, Florence oil field, Fremont County, Colorado, *in* Powers, S., editor, *Structure of typical American oil fields, volume II: American Associations of Petroleum Geologists Special Publication 4*, p. 75–92.
- De Lay, J.M., 1955, Late Paleozoic and early Mesozoic stratigraphy of the western Cañon City embayment, Colorado: Norman, University of Oklahoma, M.S. thesis, 105 p.
- Demko, T.M., Currie, B.S., and Nicoll, K.A., 2004, Regional paleoclimatic and stratigraphic implications of paleosols and fluvial/overbank architecture in the Morrison Formation (Upper Jurassic), Western Interior, USA: *Sedimentary Geology*, v. 167, no. 3, p. 115–135.
- Dunagan, S.P., 1998, Lacustrine and palustrine carbonates from the Morrison Formation (Upper Jurassic), east-central Colorado, USA—implications for depositional patterns, paleoecology, paleohydrology, and paleoclimatology: Knoxville, University of Tennessee, Ph.D. dissertation, 275 p.
- Dunkle, D.H., 1942, A new fossil fish of the family Leptolepidae: *Scientific Publications of the Cleveland Museum of Natural History*, v. 8, p. 61–64.
- Enciso, G., 1981, Paleoenvironmental analysis of the Morrison Formation in the Cañon City, Colorado, area: Lawrence, University of Kansas, M.S. thesis, 89 p.
- Ethridge, G.H., 1896. Mesozoic geology, *in* Emmons, S.F., Cross, W., and Eldridge, G.H., contributors, *Geology of the Denver Basin in Colorado: U.S. Geological Survey Monograph 27*, p. 51–149.
- Eugster, H.P., and Hardie, L.A., 1978, Saline lakes, *in* Lerman, A., editor, *Lakes—chemistry, geology, physics: New York, Springer-Verlag*, p. 237–293.
- Evanoff, E., and Carpenter, K., 1998, History, sedimentology, and taphonomy of Felch Quarry 1 and associated sandbodies, Morrison Formation, Garden Park, Colorado, *in* Carpenter, K., Chure, D., and Kirkland, J.I., editors, *The Upper Jurassic Morrison Formation—an interdisciplinary study, part I: Modern Geology*, v. 22, p. 145–169.
- Evanoff, E., Good, S.C., and Hanley, J.H., 1998, An overview of the freshwater mollusks from the Morrison Formation (Upper Jurassic, Western Interior, USA), *in* Carpenter, K., Chure, D., and Kirkland, J.I., editors, *The Upper Jurassic Morrison Formation—an interdisciplinary study, part I: Modern Geology*, v. 22, p. 423–450.
- Finlay, G.I., 1916, Description of the Colorado Springs quadrangle, Colorado: U.S. Geological Survey Geologic Atlas of the United States Folio, Colorado Springs folio, no. 203, 17 p.
- Fiorillo, A.R., and McCarty, D.K., 1996, Paleopedological evidence for a humid paleoenvironment in the lower part of the Brushy Basin Member, Morrison Formation, of Curecanti National Recreation Area, Colorado, *in* Morales, M., editor, *The continental Jurassic: Museum of Northern Arizona Bulletin 60*, p. 575–580.
- Fisher, T., 1977, Subsurface correlation in South Park, Colorado, *in* Irwin, D., chairman, *Colorado Stratigraphic Cross Sections: Rocky Mountain Association of Geologists Special Publication No. 2*, p. 37–39.
- Foster, J.R., 2003, Paleoecological analysis of the vertebrate fauna of the Morrison Formation (Upper Jurassic), Rocky Mountain region, U.S.A: *New Mexico Museum of Natural History and Science Bulletin 23*, 95 p.
- Frederickson, A., Delay, J., and Saylor, Q., 1956, Ralston Formation of the Cañon City embayment: *American Association of Petroleum Geologists Bulletin*, v. 40, p. 2120–2148.
- Furquim, S.A.C., Barbiero, L., Graham, R.C., de Queiroz Neto, J.P., Ferreira, R.P.D., and Furian, S., 2010, Neof ormation of micas in soils surrounding an alkaline-saline lake of Pantanal wetland, Brazil: *Geoderma*, v. 158, no. 3, p. 331–342.
- Giltner, R.F., 1953, Petrology of the Morrison limestones of central Colorado: Ames, Iowa State College, M.S. thesis, 90 p.
- Gong, J., 1986, Evolution of the Canon City embayment, Colorado: Stillwater, Oklahoma State University, M.S. thesis, 146 p.
- Grose, L.T., 1960, Geologic formations and structure of Colorado Springs area, Colorado, *in* Weimer, R.J., and Haun, J.D., editors, *Guide to the geology of Colorado: Geological Society of America, Rocky Mountain Association of Geologists, and Colorado Scientific Society*, p. 188–195.
- Hager, A.O., 2015, The geochronology and stratigraphy of Comanche National Grasslands, CO: Colorado Springs, Colorado College, Senior thesis, Online, [digitalcc.coloradocollege.edu/islandora/object/coccc%3A11241](http://digitalcc.coloradocollege.edu/islandora/object/coccc%3A11241) (accessed June 6, 2017).
- Harris, J.D., 1998, Dinosaur footprints from Garden Park, Colo-



- rado, in Carpenter, K., Chure, D., and Kirkland, J.I., editors, *The Upper Jurassic Morrison Formation—an interdisciplinary study, part II: Modern Geology*, v. 23, p. 291–307.
- Harris, J., and Carpenter, K., 1996, A large pterodactyloid from the Morrison Formation (Late Jurassic) of Garden Park, Colorado: *Neues Jahrbuch für Geologie und Paläontologie Monatshefte* 9, p. 473–484
- Hasiotis, S.T., and Demoko, T.M., 1998, Ichnofossils from Garden Park Paleontological Area, Colorado—implications for paleoecologic and paleoclimatic reconstructions of the Upper Jurassic, in Carpenter, K., Chure, D., and Kirkland, J.I., editors, *The Upper Jurassic Morrison Formation—an interdisciplinary study, part II: Modern Geology*, v. 23, p. 461–479.
- Hassinger, R., 1959, Stratigraphy of the Morrison Formation of the Cañon City embayment, Colorado: Norman, University of Oklahoma, M.S. thesis, 116 p.
- Hatcher, J.B., 1902, The Jurassic dinosaur deposits near Canyon City, Colorado: *Annals of Carnegie Museum*, v. 1, p. 327–341.
- Heaton, R.L., 1939, Contribution to Jurassic stratigraphy of Rocky Mountain region: *American Association of Petroleum Geologists Bulletin*, v. 23, no. 2, p. 1153–1177.
- Heaton, R.L., 1950, Late Paleozoic and Mesozoic history of Colorado and adjacent areas: *American Association of Petroleum Geologists Bulletin*, v. 34, no. 8, p. 1659–1698.
- Imlay, R.W., 1952, Correlation of the Jurassic formations of North America, exclusive of Canada: *Geological Society of America Bulletin*, v. 63, no. 9, p. 953–992.
- Imlay, R.W., 1980, Jurassic paleobiogeography of the conterminous United States in its continental setting: U.S. Geological Survey Professional Paper 1062, 134 p.
- Imlay, R.W., 1982, Jurassic (Oxfordian and Late Callovian) ammonites from the Western Interior region of the United States: U.S. Geological Survey Professional Paper 1232, 44 p.
- Jacobson, G., and Jankowski, J., 1989, Groundwater-discharge processes at a central Australian playa: *Journal of Hydrology*, v. 105, p. 275–295.
- Joeckel, R.M., Ludvigson, G.A., Wally, K.D., and Doveton, J.H., 2007, Preliminary analysis of the Upper Jurassic Morrison Formation in the Rebecca Bounds Core, western Kansas [abs.]: *Geological Society of America Abstracts with Programs*, v. 39, no. 6, p. 338.
- Johnson, J.S., 1991, Stratigraphy, sedimentology and depositional environments of the Upper Jurassic Morrison Formation, Colorado Front Range: Lincoln, University of Nebraska, Ph.D. dissertation, 171 p.
- Johnson, R.B., 1959, Geology of the Huerfano Park area, Huerfano, and Custer Counties, Colorado: U.S. Geological Survey Bulletin 1071-D, p. 87–119.
- Johnson, R.B., 1962, The Ralston Creek (?) Formation of Late Jurassic age in the Raton Mesa region and Huerfano Park, south-central Colorado: U.S. Geological Survey Professional Paper 450-C, p. C49–C54.
- Karcz, I., 1969, Mud pebbles in a flash floods environment: *Journal of Sedimentary Research*, v. 39, p. 333–337.
- Karcz, I., 1972, Sedimentary structures formed by flash floods in southern Israel: *Sedimentary Geology*, v. 7, p. 161–182.
- Keller, W.D., 1953, Clay minerals of the type section of the Morrison Formation: *Journal of Sedimentary Petrology*, v. 23, p. 93–105.
- Keller, W.D., 1958, Glauconitic mica in the Morrison Formation in Colorado: Clays and Clay Minerals, Fifth Annual Conference Proceedings, National Academy of Sciences – National Research Council Publication 566, p. 120–128.
- Keller, W.D., 1962, Clay minerals in the Morrison Formation of the Colorado Plateau: U.S. Geological Survey Bulletin 1150, 90 p.
- King, R., and Merriam, D., 1969, Origin of the “welded chert,” Morrison Formation (Jurassic), Colorado: *Geological Society of America Bulletin*, v. 80, no. 6, p. 1141–1148.
- Kirkland, J.I., 1998, Morrison fishes, in Carpenter, K., Chure, D., and Kirkland, J.I., editors, *The Upper Jurassic Morrison Formation—an interdisciplinary study, part II: Modern Geology*, v. 23, p. 503–533.
- Kirkland, J.I., and Madsen, S.K., 2007, The Lower Cretaceous Cedar Mountain Formation, eastern Utah—the view up an always interesting learning curve, in Lund, W.R., editor, *Field guide to geological excursions in southern Utah: Geological Society of America Rocky Mountain Section 2007 Annual Meeting, Grand Junction Geological Society, and Utah Geological Association Publication 35*, p. 1–108, compact disk.
- Kirkland, J.I., Suarez, M., Suarez, C., and Hunt-Foster, R., 2016, The Lower Cretaceous in east-central Utah—the Cedar Mountain Formation and its bounding strata: *Geology of the Intermountain West*, v. 3, p. 101–228.
- Kirkland, J.I., Carpenter, K., Hunt, A.P., and Scheetz, R.D., 1998, Ankylosaur (Dinosauria) specimens from the Upper Jurassic Morrison Formation, in Carpenter, K., Chure, D., and Kirkland, J.I., editors, *The Upper Jurassic Morrison Formation—an interdisciplinary study, part II: Modern Geology*, v. 23, p. 145–177.
- Kowallis, B.J., Christiansen, E.H., Deino, A.L., Zhang, C., and Everett, B.H., 2001, The record of Middle Jurassic volcanism in the Carmel and Temple Cap Formations of southwestern Utah: *Geological Society of America Bulletin*, v. 113, p. 373–387.
- Kues, B.S., and Lucas, S.G., 1987, Cretaceous stratigraphy and paleontology in the Dry Cimarron Valley, New Mexico, Colorado, and Oklahoma, in Lucas, S.G., and Hunt, A.P., editors, *Northeastern New Mexico: New Mexico Geological Society Guidebook 38*, p. 167–198.

- Lee, W.T., 1902, The Morrison shales of southeastern Colorado and northern New Mexico: *Journal of Geology*, v. 10, p. 36–58.
- Lee, W.T., 1920, Type section of the Morrison Formation: *American Journal of Science*, 4th series, v. 49, p. 183–188.
- LeRoy, L.W., 1944, Stratigraphy of the Golden-Morrison area, Jefferson County, Colorado: Golden, Colorado School of Mines, Ph.D. dissertation, 186 p.
- LeRoy, L.W., 1946, Stratigraphy of the Golden-Morrison area, Jefferson County, Colorado: *Colorado School of Mines Quarterly*, v. 41, p. 1–115.
- Lockley, M.G., McCrea, R.T., and Buckley, L.G., 2015, A review of dinosaur track occurrences from the Morrison Formation in the type area around Dinosaur Ridge: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 433, p. 10–19.
- Lucas, S.G., Kietzke, K.K., and Hunt, A.P., 1985, The Jurassic System in east-central New Mexico, in Lucas, S.G., and Zidek, J., editors, Santa Rosa, Tucumcari region: *New Mexico Geological Society Guidebook 36*, p. 213–242.
- Mack, G.H., James, W.C., and Monger, H.C., 1993, Classification of paleosols: *Geological Society of America Bulletin*, v. 105, p. 129–136.
- Macumber, P.G., 1991, Interaction between groundwater and surface systems in northern Victoria: Melbourne, Department of Conservation and Environment, unpaginated, Online, [vro.agriculture.vic.gov.au/dpi/vro/vrosite.nsf/pages/water-gw-nv\\_docs/\\$FILE/interaction\\_groundwater\\_surface.pdf](http://vro.agriculture.vic.gov.au/dpi/vro/vrosite.nsf/pages/water-gw-nv_docs/$FILE/interaction_groundwater_surface.pdf), accessed July 27, 2017.
- Mantzios, C., 1986, The paleosols of the Upper Jurassic Morrison and Lower Cretaceous Cloverly Formations, northeast Big-horn Basin, Wyoming: Ames, Iowa State University, M.S. thesis, 127 p.
- Martin, C.A., 1965, Denver Basin: *American Association of Petroleum Geologists Bulletin*, v. 49, p. 1908–1925.
- Mateer, N., 1987, The Dakota Group of northeastern New Mexico and southern Colorado, in Lucas, S.G., and Hunt, A.P., editors, *Northeastern New Mexico: New Mexico Geological Society Guidebook 38*, p. 223–236.
- Mather, A., Stokes, M., Pirrie, D., and Hartley, R., 2008, Generation, transport and preservation of armoured mudballs in an ephemeral gully system: *Geomorphology*, v. 100, p. 104–119.
- McIntosh, J.S., and Carpenter, K., 1998, The holotype of *Diplodocus longus*, with comments on other specimens of the genus, in Carpenter, K., Chure, D., and Kirkland, J.I., editors, *The Upper Jurassic Morrison Formation—an interdisciplinary study, part II: Modern Geology*, v. 23, p. 85–110.
- McWhinney, L., Carpenter, K., and Rothschild, B., 2001, Dinosaurian humeral periostitis—a case of a juxtacortical lesion in the fossil record, in Tanke, D., and Carpenter, K., editors, *Mesozoic vertebrate life*: Bloomington, Indiana University Press, p. 364–377.
- Merriam, D.F., 1955, Jurassic rocks in Kansas: *American Association of Petroleum Geologists Bulletin*, v. 39, p. 31–46.
- Metz, J.P., 1959, A petrologic study of some Jurassic (?) sediments located at North Creek, Custer and Pueblo Counties, Colorado: Manhattan, Kansas State College, M.S. thesis, 35 p.
- Monaco, P.E., 1998, A short history of dinosaur collecting in the Garden Park Fossil Area, Cañon City, Colorado, in Carpenter, K., Chure, D., and Kirkland, J.I., editors, *The Upper Jurassic Morrison Formation—an interdisciplinary study, part II: Modern Geology*, v. 23, p. 465–480.
- Mook, C.C., 1916, A study of the Morrison Formation: *Annals of the New York Academy of Sciences*, v. 27, p. 39–191.
- North American Commission on Stratigraphic Nomenclature, 2005, North American stratigraphic code: *American Association of Petroleum Geologists Bulletin*, v. 89, no. 11, p. 1547–1591.
- Ogden, L., 1954, Rocky Mountain Jurassic time surface: *American Association of Petroleum Geologists Bulletin*, v. 38, p. 914–916.
- Oriel, S.S., and Craig, L.C., 1960, Lower Mesozoic rocks in Colorado, in Weimer, R.J., and Haun, J.D., editors, *Guide to the geology of Colorado*: Denver, Rocky Mountain Association of Geologists, p. 43–58.
- Oriel, S.S., and Mudge, M.R., 1956, Problems of lower Mesozoic stratigraphy in southeastern Colorado, in McGinnis, C.J., editor, *Guidebook to the geology of the Raton Basin, Colorado*: Denver, Rocky Mountain Association of Geologist, p. 19–24.
- O’Sullivan, R.B., 1992, Jurassic Wanakah and Morrison Formations in the Telluride-Ouray-western Black Canyon area of southwestern Colorado: *U.S. Geological Survey Bulletin 1927*, 24 p.
- Pattemore, G.A., Rigby, J.F., and Playford, G., 2014, *Palissya*—a global review and reassessment of Eastern Gondwanan material: *Review of Palaeobotany and Palynology*, v. 210, p. 50–61.
- Peck, R.E., 1957, North American Mesozoic Charophyta: *U.S. Geological Survey Professional Paper 294-A*, p. 1–44.
- Peterson, F., 1994, Sand dunes, sabkhas, streams, and shallow seas—Jurassic paleogeography in the southern part of the Western Interior Basin, in Caputo, M.V., Peterson, J.A., and Franczyk, K.J., editors, *Mesozoic systems of the Rocky Mountain region, USA*: Denver, Rocky Mountain Section SEPM (Society for Sedimentary Geology), p. 233–272.
- Peterson, F., and Turner, C.E., 1998, Stratigraphy of the Ralston Creek and Morrison Formations (Upper Jurassic) near Denver, Colorado, in Carpenter, K., Chure, D., and Kirkland, J.I., editors, *The Upper Jurassic Morrison Formation—an interdisciplinary study, part I: Modern Geology*, v. 22, p. 3–38.
- Pipiringos, G.N., and O’Sullivan, R.B., 1976, Stratigraphic sections



- of some Triassic and Jurassic rocks from Douglas, Wyoming, to Boulder, Colorado: U.S. Geological Survey Oil and Gas Investigations Chart OC-69, 1 sheet, scale 1:2,222,000.
- Pipiringos, G.N., and O'Sullivan, R.B., 1978, Principal unconformities in Triassic and Jurassic rocks, Western Interior United States—a preliminary survey: U.S. Geological Survey Professional Paper 1035A, p. A1–A29.
- Prince, N.K., 1988, Lacustrine deposition in the Jurassic Morrison Formation, Purgatoire River region, southeastern Colorado: Denver, University of Colorado at Denver, M.S. thesis, 182 p.
- Rask, J.H., Bryndzia, L.T., Braunsdorf, N.R., and Murray, T.E., 1997, Smectite illitization in Pliocene-age Gulf of Mexico mudrocks: *Clays and Clay Minerals*, v. 45, p. 99–109.
- Retallack, G., 1983, Late Eocene and Oligocene paleosols from Badlands National Park, South Dakota: Geological Society of America Special Paper 193, 82 p.
- Retallack, G., 1988, Field recognition of paleosols, in Reinhardt, J., and Sigleo, W., editors, *Paleosols and weathering through geologic time*: Geological Society of America Special Paper 216, p. 1–20.
- Retallack, G., 1990, *Soils of the past*: Boston, Unwin Hyman, 520 p.
- Richardson, J.L., 1987, Analysis of the sedimentary geology of the Jurassic Ralston Creek Formation as it is exposed in the vicinity of Cañon City, Colorado: Stillwater, Oklahoma State University, M.S. thesis, 147 p.
- Rogers, J., Burchfiel, B., Abbott, E., Anepohl, J., Ewing, A., Koehnken, P., Novitsky-Evans, J., and Talukdars, S., 1974, Paleozoic and lower Mesozoic volcanism and continental growth in the Western United States: Geological Society of America Bulletin, v. 85, p. 1913–1924.
- Rosen, M.R., 1994, The importance of groundwater in playas—a review of playa classifications and the sedimentology and hydrology of playas, in Rosen, M.R., editor, *Paleoclimate and basin evolution of playa systems*: Geological Society of America Special Paper 289, p. 1–18.
- Rosen, M.R., and Warren, J.K., 1990a, New interpretation of vertically aligned gypsum fabrics—implications for gypsum depositional environments and diagenesis [abs.]: American Association of Petroleum Geologists Annual Convention, San Francisco, California, online, [searchanddiscovery.com/abstracts/html/1990/annual/abstracts/0751d.htm](http://searchanddiscovery.com/abstracts/html/1990/annual/abstracts/0751d.htm) (accessed July 23, 2017).
- Rosen, M.R., and Warren, J.K., 1990b, The origin and significance of groundwater-seepage gypsum from Bristol Dry Lake, California, USA: *Sedimentology*, v. 37, no. 6, p. 983–996.
- Rougier, G.W., Sheth, A.S., Carpenter, K., Appella-Guiscafre, L., and Davis, B.M., 2015, A new species of *Docodon* (Mammaliaformes: Docodonta) from the Upper Jurassic Morrison Formation and a reassessment of selected craniodental characters in basal mammaliaforms: *Journal of Mammalian Evolution*, v. 22, p. 1–16.
- Sackett, D.H., 1961, *Geology of the Garden Park Area, Fremont County, Colorado*: Lawrence, University of Kansas, M.S. thesis, 38 p.
- Saylor, W.W., 1955, Late Paleozoic and early Mesozoic stratigraphy of the eastern Cañon City embayment, Colorado: Norman, University of Oklahoma, M.S. thesis, 104 p.
- Schaeffer, B., and Patterson, C., 1984, Jurassic fishes from the western United States, with comments on Jurassic fish distribution: *American Museum of Natural History Novitates*, no. 2796, 86 p.
- Schudack, M.E., Turner, C.E., and Peterson, F., 1998, Biostratigraphy, paleoecology and biogeography of charophytes and ostracods from the Upper Jurassic Morrison Formation, Western Interior, USA, in Carpenter, K., Chure, D., and Kirkland, J.I., editors, *The Upper Jurassic Morrison Formation—an interdisciplinary study*, part I: *Modern Geology*, v. 22, p. 379–414.
- Schulze, J.D., 1954, The Pre-Dakota geology of the northern half of the Cañon City embayment, Colorado: Norman, University of Oklahoma, M.S. thesis, 163 p.
- Schultze, H.P., and Enciso, G., 1983, Middle Jurassic age of the fish-bearing horizon in the Cañon City embayment, Colorado: *Journal of Paleontology*, v. 57, p. 1053–1060.
- Scott, G.R., 1962, *Geology of the Littleton quadrangle, Jefferson, Douglas, and Arapahoe Counties, Colorado*: U.S. Geological Survey Bulletin 1121-L, p. L1–L53.
- Scott, G.R., 1963, *Bedrock geology of the Kassler quadrangle, Colorado*: U.S. Geological Survey Professional Paper 421-B, p. 71–125.
- Scott, G.R., Taylor, R., Epis, R., and Wobus, R., 1978, *Geologic map of the Pueblo 1° x 2° quadrangle, south-central Colorado*: U.S. Geological Survey Miscellaneous Investigations Series Map I-1022, 2 sheets, scale 1:250,000.
- Shroba, R.R., Bryant, B., Kellogg, K.S., Theobald, P.K., and Brandt, T.R., 2010, *Geologic map of the Fraser 7.5-minute quadrangle, Grand County, Colorado*: U.S. Geological Survey Scientific Investigations Map SIM-3130, 26 p., 1 plate, scale 1:24,000.
- Singer, A., 1980, The paleoclimatic interpretation of clay minerals in soils and weathering profiles: *Earth Science Reviews*, v. 15, p. 303–326.
- Small, B.J., and Carpenter, K., 1997, Upper Jurassic microvertebrates from the “Small Quarry,” Garden Park, Colorado [abs.]: *Journal of Vertebrate Paleontology*, v. 17, supplement to no. 3, p. 76–77A.
- Sweet, R., 1984a, A sedimentary analysis of the Upper Jurassic Morrison Formation as it is exposed in the vicinity of Cañon City, Colorado: Stillwater, Oklahoma State University, M.S. thesis, 210 p.

- Sweet, R., 1984b, Evidence for playa sedimentation in the Morrison Formation, Cañon City, Colorado [abs.]: Geological Society of America Abstracts with Program, v. 7, p. 672.
- Tabbutt, K., Barreiro, B., and Reynolds, R., 1989, Variation in clay mineral and REE composition of shales from some Mesozoic terrestrial clastics in the Western Interior [abs.]: Geological Society of America Abstracts with Program, v. 7, p. A335.
- Tabor, N.J., and Myers, T.S., 2015, Paleosols as indicators of paleoenvironment and paleoclimate: Annual Review of Earth and Planetary Sciences, 43, p. 333–361.
- Tank, R., 1956, Clay mineralogy of the Morrison Formation, Black Hills area, Wyoming and South Dakota: American Association of Petroleum Geologists Bulletin, v. 40, p. 871–878.
- Tanner, L.H., Galli, K.G., and Lucas, S.G., 2014, Pedogenic and lacustrine features of the Brushy Basin Member of the Upper Jurassic Morrison Formation in western Colorado—reassessing the paleoclimatic interpretations: *Volumina Jurassica*, v. 12, no. 2, p. 115–130.
- Tidwell, V.A., and Carpenter, K., 1998, A new look at the sauropods of Garden Park, Colorado [abs.]: Journal of Vertebrate Paleontology, v. 18, supplement to no. 3, p. 82A.
- Trujillo, K.C., 2006, Clay mineralogy of the Morrison Formation (Upper Jurassic–?Lower Cretaceous), and its use in long distance correlation and paleoenvironmental analysis, in Foster, J.R., and Spencer, G.L., editors, Paleontology and geology of the Upper Jurassic Morrison Formation: New Mexico Museum of Natural History and Science Bulletin 36, p. 17–23.
- Trujillo, K.C., and Kowallis, B.J., 2015, Recalibrated legacy  $^{40}\text{Ar}/^{39}\text{Ar}$  ages for the Upper Jurassic Morrison Formation, Western Interior, U.S.A.: Geology of the Intermountain West, v. 2, p. 1–8.
- Turner, C.E., and Fishman, N.S., 1991, Jurassic Lake T'oodi-chi'—a large saline lake, Morrison Formation, eastern Colorado Plateau: Geological Society of America Bulletin, v. 103, no. 4, p. 538–558.
- Turner, C.E., and Peterson, F., 1992, Stratigraphic framework for the Jurassic Morrison Formation, southern Rocky Mountain region, and implications for Late Jurassic dinosaur chronology [abs.]: Geological Society of America Abstracts with Program, v. 7, p. A359.
- Turner, C.E., and Peterson, F., 1999, Biostratigraphy of dinosaurs in the Upper Jurassic Morrison Formation of the Western Interior, U.S.A., in Gillette, D.D., editor, Vertebrate paleontology of Utah: Utah Geological Survey Miscellaneous Publication 99-1, p. 77–114.
- Van Horn, R., 1957, Ralston Creek Formation, new name for Ralston Formation of LeRoy (1946): American Association of Petroleum Geologists Bulletin, v. 41, p. 755–756.
- Wahlstrom, E., 1966, Geochemistry and petrology of the Morrison Formation, Dillon, Colorado: Geological Society of America Bulletin, v. 77, p. 727–740.
- Waldschmidt, W., and LeRoy, L., 1944, Reconsideration of the Morrison Formation in the type area, Jefferson County, Colorado: Geological Society of America Bulletin, v. 55, p. 1097–1114.
- Warren, J.K., 2016, Evaporites—a geological compendium: Switzerland, Springer, 1813 p.
- Wellborn, R., 1977, Subsurface correlation in the North Park-Middle Park Basin, Colorado, in Irwin, D., chairman, Colorado stratigraphic cross sections: Rocky Mountain Association of Geologists Special Publication No. 2, p. 13–14.
- Wobus, R., Chase, R., Scott, G., and Taylor, R., 1985, Reconnaissance geological map of the Cooper Mountain quadrangle, Fremont County, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-1762, 1 sheet, scale 1:24,000.
- Wood, W.W., and Sanford, W.E., 1990, Ground-water control of evaporite deposition: Economic Geology, v. 85, no. 6, p. 1226–1235.
- Yen, T.C., 1952, Molluscan fauna of the Morrison Formation: U.S. Geological Survey Professional Paper 233-B, p. 21–51.

