Journal of Paleontology, page 1 of 8

Published by Cambridge University Press
on behalf of The Paleontological Society
0022-3360/24/1937-2337
doi: 10.1017/jpa.2023.82

JOURNAL OF PALEONTOLOGY A PUBLICATION OF THE Paleontological SOCIETY

Cambrian trilobites and associated fossils from the Uinta Mountains of Utah (USA)

John R. Foster,[1*] Frederick A. Sundberg,[2] and James W. Hagadorn[3]

[1]Utah Field House of Natural History State Park Museum, 496 East Main Street, Vernal, Utah 84078, USA <johnfoster@utah.gov>
[2]Earth and Planetary Science, University of New Mexico, Albuquerque, New Mexico 87131, USA <sundbergfred@gmail.com>
[3]Denver Museum of Nature and Science, 2001 Colorado Boulevard, Denver, Colorado 80205, USA <james.hagadorn@dmns.org>

Non-technical Summary.—New trilobites from the Ophir Formation of the western Uinta Mountains in northern Utah represent some of the first identifiable and biostratigraphically useful fossils in the range, outside of Dinosaur National Monument. The fossils indicate that the Ophir Formation is similar in age to the Lodore Formation.

Abstract.—Fossils are rare in Cambrian strata of the Uinta Mountains of northeastern Utah, and are important because they can help integrate our understanding of laterally adjacent but discontiguous rock units, e. g., the Tintic Quartzite of Utah and the Lodore Formation of Utah-Colorado. New body fossils from strata previously mapped as Tintic or Cambrian Undifferentiated, but here interpreted as the Ophir Formation, include indeterminate hyoliths and hyolithids, brachiopods including a linguloid, and the trilobites *Trachycheilus* Resser, 1945 and *Elrathiella* Poulsen, 1927. The last two assign these strata to the *Ehmaniella* Biozone (uppermost Wuliuan Stage; Miaolingian Series) or traditional Laurentian middle Cambrian. These data, together with fossil occurrences elsewhere in Utah, require that the Tintic Quartzite was deposited prior to and/or during the early Wuliuan, and suggest that the unit could be correlative to much of the Lodore Formation of Utah and Colorado.

Introduction

The Uinta Mountains, locally known as the Uintas, are an east-west trending Laramide uplift in northeastern Utah and northwestern Colorado. Cambrian strata in this region include the Tintic Quartzite and overlying Ophir Formation in the west and the Lodore Formation in the east (Fig. 1.1). Each succession lies unconformably atop the Neoproterozoic Uinta Mountain Group and is disconformably overlain by the Mississippian Madison Limestone (Hansen et al., 1983; Bryant, 1992; Sprinkel, 2006), except where local depositional remnants of Devonian strata are preserved (e.g., Herr, 1979; Soule, 1992; Myrow et al., 2023a, b). Tintic Quartzite and Ophir Formation outcrops in the western part of the Uinta Mountains are separated from Lodore outcrops in the east by a ∼75 km gap in which there are no Cambrian strata preserved and the Madison lies directly on the Uinta Mountain Group (Fig. 1.1, 1.2; Stokes and Madsen, 1962; Sprinkel, 2006). Tintic-Ophir strata thin eastward toward this gap and the Lodore Formation thins westward toward it. This gap is hypothesized to result from erosion of Cambrian sediments before deposition of the Mississippian Madison Limestone (Williams, 1957; Robison, 1964; Hansen, 1965; Lochman-Balk, 1972). In the Uinta Mountains, the upper Tintic and Ophir units are Miaolingian (Williams, 1957; Robison, 1964) and the Lodore Formation was previously considered mostly upper Cambrian (Furongian; Untermann and Untermann, 1949, 1954; Williams, 1953; Halgarth, 1959; Robison, 1964; Herr et al., 1982), although recent data indicate that the middle portion is Miaolingian (Myrow et al., 2023b).

These Uinta Mountains Cambrian rocks contain no datable volcanic units, lack unique populations of detrital zircons, and historically have lacked biostratigraphically useful fossils. Thus, it has been challenging to test the hypothesis that the Tintic-Ophir and the Lodore successions might be similar in age, or that they represent erosional remnants of the same depositional system. To help resolve this knowledge gap, here we present a specimen-rich but low diversity fauna from the Tintic-Ophir succession of the Uinta Mountains and employ it to refine the age and biostratigraphic position of these strata.

Geologic setting and localities

Cambrian rocks are exposed along the southern flank of the Uinta Mountains and include the Tintic Quartzite and overlying Ophir Formation in the western part of the range, east of Salt Lake City (Bryant, 1992; Fig. 1.1, 1.2), and the Lodore Formation as far east as Juniper Mountain, Colorado (Sprinkel, 2006). Due to high-angle reverse faulting, Cambrian rocks are not exposed on the surface along the northern flank of the Uintas, except for a small outcrop of the Tintic Quartzite at the Long Park Reservoir dam in Daggett County, Utah (Sprinkel, 2006).

The Cambrian succession in the western Uintas is usually up to ∼200 m thick and dominated by gray to brown quartzite and sandstone, which is locally conformably overlain by an up to ∼70 m thick, easily weathered interval characterized by

*Corresponding author.

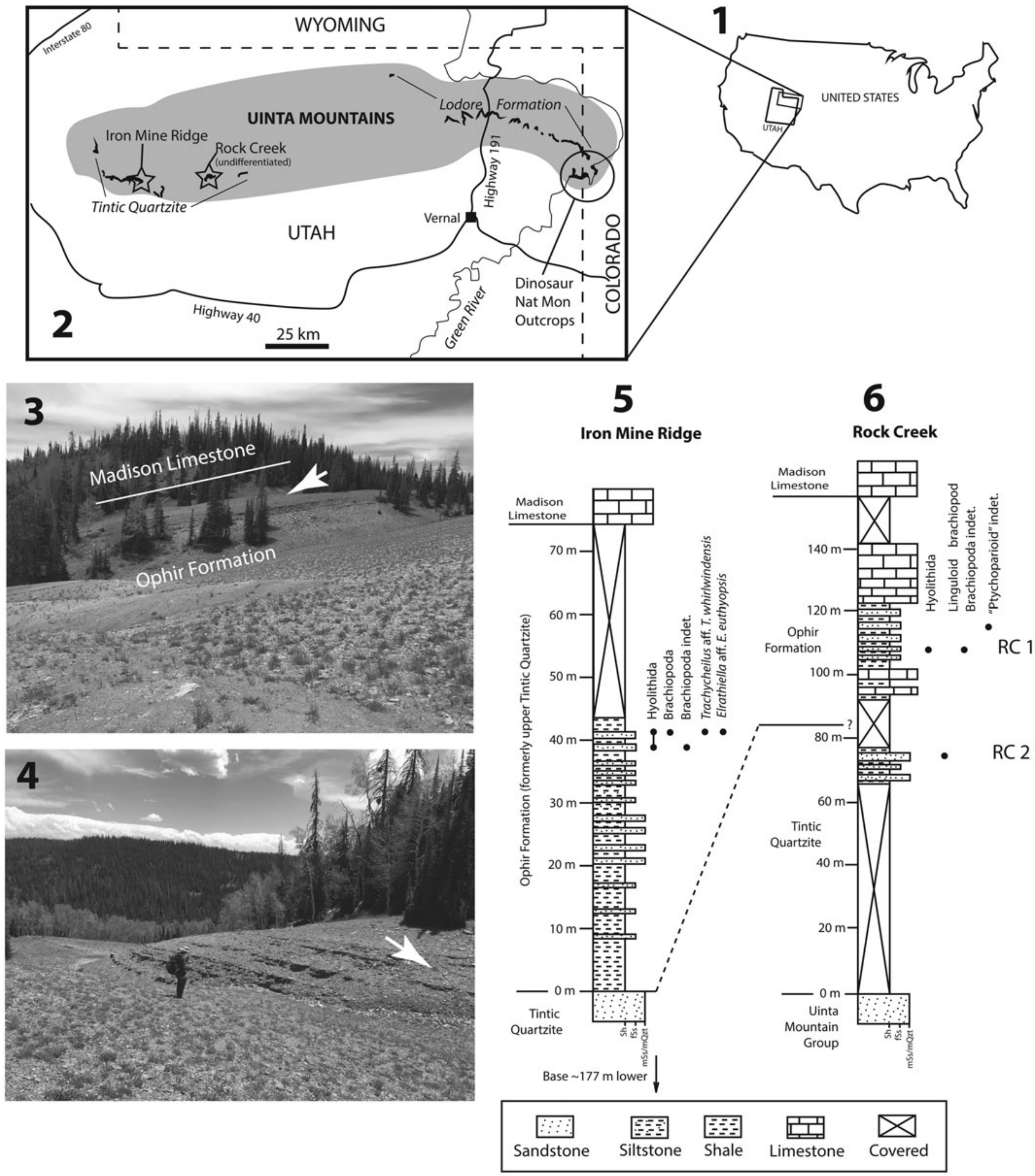

Figure 1. Context of fossils studied herein. (**1**) Location of study area in northeastern Utah, western United States. (**2**) Map of Uinta Mountains and Cambrian localities studied here (stars). Outcrop exposures in black lines around southern rim of mountains. Western outcrops mapped as Tintic Quartzite but include Ophir Formation studied here; eastern outcrops assigned to the Lodore Formation. Outcrops based on geologic maps by Bryant (1992), Hansen et al. (1983), and Sprinkel (2006). (**3, 4**) Photographs of Iron Mine Ridge section of upper 74 m of Cambrian rocks (Ophir Formation): (**3**) looking west-southwest diagonally down dip and across strike, with approximate Ophir-Madison contact labeled; white arrow indicates approximate level of fossil layers; (**4**) looking southeast showing upper Ophir Formation layers and with fossil layers level shown by white arrow. (**5**) Stratigraphic section of Ophir Formation at Iron Mine Ridge locality showing distributions of fossil taxa. (**6**) Stratigraphic section of Tintic Quartzite and Ophir Formation at Rock Creek showing distributions of fossil taxa.

https://doi.org/10.1017/jpa.2023.82 Published online by Cambridge University Press

alternating sandstone and shale. Although these upper rocks are mapped as Tintic Quartzite, the upper ∼70 m portion of the succession has been interpreted by some stratigraphers to represent the Ophir Formation (Williams, 1953, 1957; Lochman-Balk, 1955). This dichotomy between map unit names and stratigraphic assignment could be because, in the Uintas, the ∼70 m of finer-grained strata that cap or overlie the Tintic are too thin and limited in geographic extent to be mapped separately as a distinct unit. For comparison, near its type area ∼125 km to the southwest, the Ophir Formation alone ranges up to ∼130 m in thickness (Hintze, 1988).

In the eastern Uinta Mountains, the Lodore Formation ranges up to 180 m in thickness and is dominated by feldspathic to quartzitic sandstone with minor shale and conglomerate (Hansen, 1977; Herr, 1979). In places where the Lodore is not capped by Devonian or younger erosional remnants (Herr, 1979; Soule, 1992; Myrow et al., 2023a), the succession is similar in appearance to the Tintic-Ophir succession. The upper portion of the Lodore consists of alternating glauconitic shale, sandstone, and minor sandy dolostone—lithologies that are comparable to portions of the Dotsero Formation to the east in Colorado (see synthesis by Myrow et al., 2003) or perhaps the 'transition beds' between the cliff-forming Tapeats Sandstone and the overlying Bright Angel Formation of the Grand Canyon region (McKee and Resser, 1945; Karlstrom et al., 2020).

Iron Mine Ridge.—The Iron Mine Ridge site (Fig. 1.2–1.5) is near Iron Mine Mountain in Wasatch County, Utah, at ∼3,015 m elevation (Fig. 1.2). The succession consists of ∼250 m of comparatively well-exposed dark-colored sandstones, well-indurated quartz sandstones, siltstones, and shales (Fig. 1.5). Outcrops are mapped as Tintic Quartzite at Iron Mine Ridge (Bryant, 1992), despite recognition that the upper portion of the succession is likely the Ophir Formation or transitional between the two (Williams, 1953). This upper portion of the section consists of 38.6 m of tan to medium-brown siltstones and 15–30 cm of thick, orange, cross-bedded sandstones with thin, interbedded, light-green, platy shales, overlain by a 35.6 m covered interval immediately below the Mississippian-age Madison Limestone (Fig. 1.3). Fossils described below come from the upper portion of the mapped Tintic succession, in what is here considered the Ophir Formation.

Rock Creek 1 and 2 (Hell's Ten Miles and Dave's Brach Frags).—Two superjacent localities (Fig. 1.2, 1.6) ∼1,300 m apart form a composite measured section through partially covered Cambrian strata, ∼29–30 km east of Iron Mine Ridge. These exposures are in the vicinity of Rock Creek (a named topographic horizontal control station on a peak of ∼3,464 m elevation, north of a Rock Creek stream), in Duchesne County, Utah. The sites near the Rock Creek station are in rocks mapped as Cambrian Undifferentiated (Bryant, 1992). The lower half of this succession is lithologically equivalent to the Tintic exposures near its type area, but the upper half of the succession contains substantial limestone interbedded with thin siltstone, shale, and sandstone (Fig. 1.6) and is here considered the Ophir Formation. In this respect, the Rock Creek 1 and 2 section differs from the majority of other Tintic exposures in the Uinta Mountains. The outcrops at Rock Creek occur between mapped Tintic outcrops immediately to the west and east (Bryant, 1992; Fig. 1.2). Lochman-Balk (1955, fig. 1b, column 13) interpreted the Cambrian section here as consisting of Tintic Quartzite overlain by 'cf. Ophir.' We concur with her assessment and tentatively ascribe the upper portion of the section here to the Ophir Formation.

Biostratigraphy

Previous work and historical context.—Most of the Tintic Quartzite in its type area, in the Tintic mining district ∼125 km southwest of the western Uintas, has been considered early to medial Cambrian (Series 2 to Miaolingian) in age (Peterson, 1953; Lochman-Balk, 1976), whereas at its top in the Uinta Mountains it is thought to be younger, perhaps representing deposition during the early portion of the Miaolingian Epoch (early Wuliuan, *Glossopleura* Biochron; Robison, 1976). This age determination was necessarily based on inference, and on fossils that were too poorly preserved or lacked sufficient stratigraphic control to be of biostratigraphic utility. For example, the only figured body fossil ascribed to the Tintic is a single partial trilobite (erroneously reported as *Olenellus*? Hall, 1862; Peterson, 1953, fig. 5; Lochman-Balk, 1955) collected in float from the uppermost portion of the Tintic Formation at Long Ridge—a hillside that is littered with trilobite-bearing slabs sliding downhill from basal exposures of the overlying Ophir Formation. Trace fossils from the Tintic in the Wasatch and Lakeside ranges of Utah, although useful for regional correlation (Magwood, 1996), do not provide age control for the unit.

In the Uinta Mountains, unfigured specimens from the Ophir Formation include two unidentifiable trilobite fragments and a suite of 'longuloid' or 'obolid' brachiopods (*Westonia* Walcott, 1901) collected by Williams (1953) from exposures at Iron Mine Mountain. In the type area of the Ophir to the southwest, Robison (1976) stated that the Ophir Formation contains trilobites of the *Glossopleura walcotti* Biozone (Wuliuan, Miaolingian; Palmer, 1954; Lochman-Balk, 1955) and the overlying *Ehmaniella* Biozone, but did not figure or describe them. Although the Ophir Formation contains more fossils than the Tintic, few specimens have been figured that can be tied with any confidence to stratigraphy or locality, and most of these are syntypic materials of *Glossopleura producta* (Hall and Whitfield, 1877) from the Oquirrh Range southwest of Salt Lake City (Hall and Whitfield, 1877; Walcott, 1886, 1916; Palmer, 1954).

The Lodore Formation has a similar history. Prior to recent work in the Dinosaur National Monument area (Myrow et al., 2023a, b), the formation was considered early late Cambrian (Dresbachian) or, in modern terms, latest Miaolingian in age. That age, however, was based on the occurrence of simple 'ptychoparioid' trilobites, brachiopods, hyoliths, and 'tiny coiled gastropods,' none of which were illustrated or tied to detailed measured sections (Untermann and Untermann, 1954; Halgarth, 1959). All were from the upper half of the unit but apparently lacked sufficient detail to permit biostratigraphic assignment. Lodore Formation trace fossils and K-Ar dating of glauconite in the unit also have not permitted accurate age assessment (Herr, 1979; Herr et al., 1982). Myrow et al. (2023b) reported

https://doi.org/10.1017/jpa.2023.82 Published online by Cambridge University Press

several species of *Elrathiella* Poulsen, 1927 tied to a stratigraphic section within Dinosaur National Monument, Utah, and assigned the Lodore Formation to the *Ehmaniella* Biozone and provisionally to the *Altiocculus* Subzone.

New fossils.—There are two fossiliferous horizons in the Ophir Formation at our Iron Mine Ridge section (Fig. 1.4, 1.5). The lowest is a gray sandstone with heavy bioturbation and abundant white fossil fragments and rare valves of acrotheloid brachiopods and impressions of hyoliths and hyolithids (Fig. 2). Approximately 1.5 m above this horizon is a 2–5 cm thick, dark gray to tan sandstone with abundant trilobites plus rarer brachiopods and hyoliths (Fig. 1.5). Trilobites collected include *Elrathiella* aff. *Elrathiella euthyopsis* Sundberg, 1994 and *Trachycheilus* aff. *T. whirlwindensis* Sundberg, 1994. The majority of specimens are preserved as molds or casts on the bedding surfaces and within the beds. The combined sample of trilobites and other taxa from both beds at this site contained >615 specimens, with most from the upper bed and ∼93.5% of specimens being trilobites.

In the Rock Creek area, there are three productive horizons. The highest one (∼114 m, Rock Creek 1; Figs. 1.6, 2.4) is in a bioturbated siltstone, where one indeterminate ‘ptychoparioid’ trilobite was found. Five meters below this horizon, a hyolith and several brachiopods were found (Fig. 1.6). Lower in the section, at the nearby Rock Creek 2 locality, abundant brachiopod fragments and at least one possible species of *Lingulella* Salter, 1866 occurred in a medium to coarse reddish sandstone (∼77 m; Figs. 1.6, 2.6).

Interpretation and implications.—Species of *Elrathiella*, like those from the Ophir Formation at Iron Mine Ridge, were reported by Sundberg (1994) to range from the *Elrathiella* to basal *Ehmaniella* subzones of the *Ehmaniella* Biozone in Utah and Nevada. *Elrathiella euthyopsis* is also known from the Whirlwind Formation, Drum Mountains, and House Range, Utah. Species of *Trachycheilus* Resser, 1945 range through the entire *Ehmaniella* Biozone (*Proehmaniella*–*Altiocculus* Subzones; Sundberg, 1994). *Trachycheilus whirlwindensis* is from the *Elrathiella* to *Ehmaniella* subzones of the Whirlwind Formation, Drum Mountains; Shadscale Formation, Dugway Range, Utah; and Member E, Pole Canyon Limestone, Patterson Pass, Nevada. These two trilobite species suggest that, in the western Uintas, deposition of the Ophir Formation occurred during the middle portion of the *Ehmaniella* Biochron, Topazan Age (late international Wuliuan Age, Miaolingian Epoch), ∼503 Ma (Karlstrom et al., 2020; Sundberg et al., 2020).

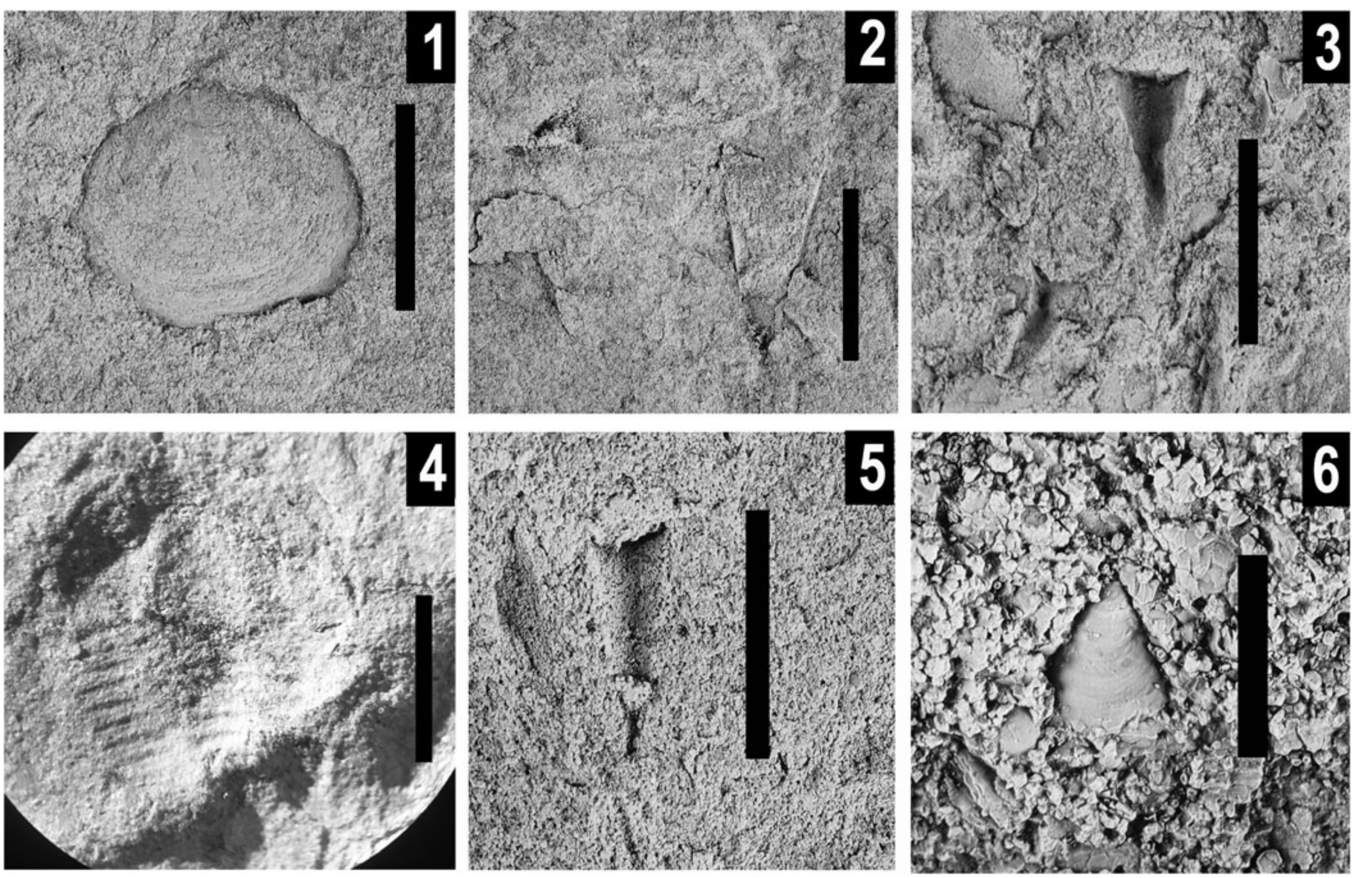

Figure 2. Associated fossil material from the Ophir Formation at the Iron Mine Ridge locality (formerly upper Tintic Quartzite) and Rock Creek locality (formerly Cambrian Undifferentiated). (**1–3**) Fossils from Iron Mine Ridge (see Fig. 1.5): (**1**) brachiopod (FHPR 11151) from 40.5 m; (**2**) two hyoliths (FHPR 11155) from 40.5 m; (**3**) molds of two indeterminate hyoliths (FHPR 11153) from 39 m. (**4–6**) Fossils from Cambrian layers at Rock Creek (see Fig. 1.6): (**4**) mold of articulated dorsal exoskeleton of an indeterminate ‘ptychoparioid’ trilobite (FHPR 18457) from 114 m (Ophir Formation); (**5**) mold of a hyolithid hyolith (FHPR 18458) from 109 m (Ophir Formation); (**6**) linguloid brachiopod (FHPR 18460) from 77 m (Tintic Quartzite). Scale bars = 1 cm (**1–5**); 5 mm (**6**).

https://doi.org/10.1017/jpa.2023.82 Published online by Cambridge University Press

Materials and methods

Fossils were collected by splitting weathered slabs at exposures on U.S.D.A. Forest Service land in the western Uinta Mountains near Iron Mine Mountain and near Rock Creek peak. Fossils were logged, collected, and reposited at the Utah Field House of the Natural History State Park Museum. Fossils occur as molds or casts on weathered sandstone bedding planes and were split out of the sandstones by splitting or breaking off corners. In total, ~575 trilobite cranidia, some pygidia, and 40 brachiopods and hyoliths were collected from Iron Mine Ridge; one articulated trilobite mold, a hyolith impression, and many fragments of brachiopods were collected from Rock Creek.

Illustrated trilobite specimens were coated with colloidal graphite and then ammonium chloride sublimate. Specimen orientation for photography and measurements was primarily with the cranidial anterior border and/or palpebral lobes, librigenal border, or pygidial border in a horizontal plane.

Repositories and institutional abbreviations.—DMNS, Denver Museum of Nature and Science, Denver, Colorado; FHPR, Utah Field House of Natural History State Park Museum, Vernal, Utah; USNM, National Museum of Natural History, Smithsonian Institution, Washington, DC.

Systematic paleontology

Phylum Arthropoda Gravenhorst, 1843
Class Trilobita Walch, 1771
Order Unknown (see Sundberg and Webster, 2022)
Family Alokistocaridae Resser, 1939
Subfamily Alokistocarinae Hupé, 1955

Remarks.—Sundberg (1994) recognized two subfamilies: Ehmaniellinae and Altiocculinae. With the recognition that Ehmaniellidae and Alokistocaridae are synonymous, the subfamily Ehmaniellinae is synonymous with Alokistocarinae (see Esteve et al., 2012).

Genus *Elrathiella* Poulsen, 1927

Type species.—*Elrathiella obscura* Poulsen, 1927, Pemmican River Formation, Inglefield, Greenland, by original designation.

Elrathiella aff. *Elrathiella euthyopsis* Sundberg, 1994
Figure 3

Occurrence.—Iron Mine Ridge, Ophir Formation (formerly upper Tintic Quartzite), Wasatch County, Utah.

Materials.—Numerous cranidia and a pygidium.

Remarks.—The specimens assigned to *Elrathiella* aff. *Elrathiella euthyopsis* are similar to *Elrathiella euthyopsis* in having an elongated glabella (73–79% cranidial length vs. 70–80% described by Sundberg in 1994 in the Whirlwind Formation of central Utah) that is moderately to strongly tapered and with a strongly rounded frontal lobe; anterior border strongly convex, deep anterior border furrow; moderately tapered; possible moderately coarse granular ornamentation (new material preserved in sandstone, presence of granular ornamentation cannot be firmly established). The material from the Iron Mine Ridge locality differs from the material from the Whirlwind Formation in having an anterior border that is shorter (vs. 45–55% of the frontal area length vs. 55–65%) and evenly curved; slightly narrower fixigenal width (40–50% glabellar width vs. 55–60%); a pygidium with a longer axis, and less pronounced pleural furrows. These specimens are left in open nomenclature due to their preservation as molds or casts in a medium-grained sandstone and the lack of detailed features of the exoskeleton surface.

A single pygidium (Fig. 3.18) that co-occurred with the cranidia has a more transversely elongated outline with more anteriorly located anterolateral corners. This specimen is questionably assigned to this species.

Genus *Trachycheilus* Resser, 1945

Type species.—*Trachycheilus typicale* Resser, 1945, upper portion of the Bright Angel Formation or lowermost Muav Limestone (USNM loc. 73b; loc. 15 of Resser, 1945), Kwagunt Valley, Grand Canyon, Arizona, by original designation.

Trachycheilus aff. *T. whirlwindensis* Sundberg, 1994
Figure 4

Occurrence.—Iron Mine Ridge, Ophir Formation (formerly upper Tintic Quartzite), Wasatch County, Utah.

Materials.—Two cranidia.

Remarks.—Cranidia referred to *Trachycheilus* possess the tapered glabella, convexity, curved relatively wide (tr.) and short (sag.) anterior border, glabellar furrows, relatively short palpebral lobes, and a small medial sulcus in the front of the glabella typical of that genus. The larger cranidium (Fig. 4.1–4.4) from the Iron Mine Ridge locality is similar to *T. whirlwindensis* in its tapered glabella with a rounded frontal lobe, narrow fixigena, relatively short palpebral lobes, and convex, curved anterior border. Distinction between the two forms is that the former has a more tapered glabella and a longer preglabellar area than the two subspecies of *T. whirlwindensis*. The two cranidia also show no surface granules typical of *T. granulosus* Sundberg, 1994. The Iron Mine Ridge specimens also differ from the single cranidium of the type species *T. typicale* Resser, 1945 in having a longer preglabellar area and lacking the medium swelling and inbend of the anterior border. The smaller specimen (Fig. 4.5–4.7) has a narrower prefrontal area, wider fixigena, and less tapered glabella with a medial sulcus in the frontal lobe. In these features, this smaller specimen is more like *T. whirlwindensis*, however, these features could be the result of allometric changes during ontogeny. These two cranidia are left in open nomenclature due to their preservation as molds or casts in sandstone, the lack of details on their exoskeleton surface, and the absence of additional sclerites.

https://doi.org/10.1017/jpa.2023.82 Published online by Cambridge University Press

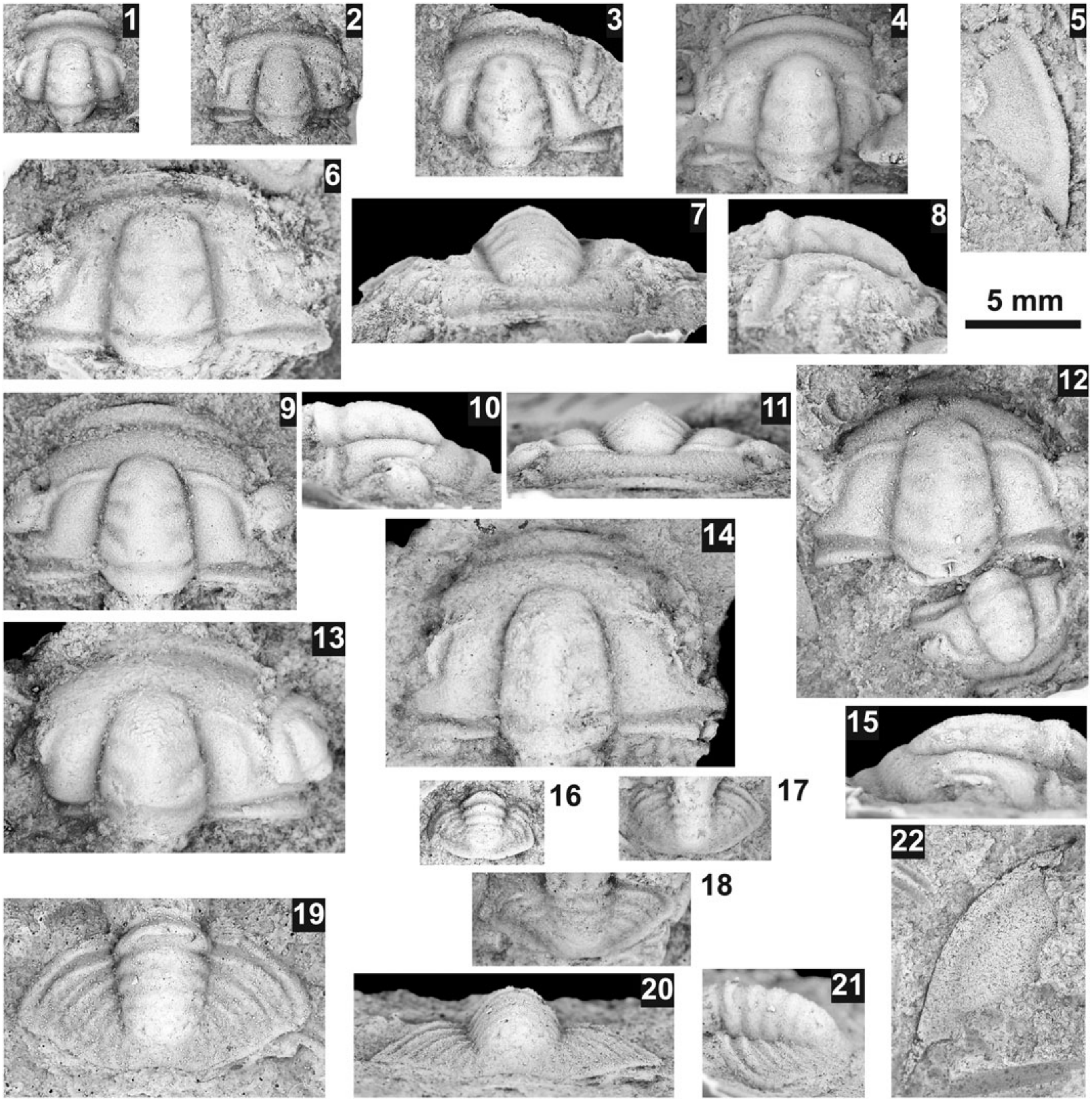

Figure 3. *Elrathiella* aff. *E. euthyopsis* Sundberg, 1994 from the Ophir Formation: (**1**) cranidium, FHPR 11094-3; (**2**) cranidium, FHPR 11094-2; (**3**) cranidium, FHPR 11148; (**4**) cranidium, FHPR 11093c; (**5**) librigena, FHPR 11147; (**6–8**) cranidium, FHPR 11132a, dorsal, anterior, and lateral views, respectively; (**9–11**) cranidium, FHPR 11098, dorsal, lateral, and anterior views, respectively; (**12**) cranidium, FHPR 11094a, b (smaller specimen); (**13**) cranidium, FHPR 11132-2; (**14, 15**) cranidium, FHPR 11101, dorsal and lateral views, respectively; (**16**) pygidium with articulated thoracic segment, FHPR 11146; (**17**) pygidium, FHPR 11093b; (**18**) pygidium, FHPR 11093a, questionably assigned to this species; (**19–21**) pygidium, FHPR 11147a, dorsal, posterior, and lateral views, respectively; (**22**) librigena, FHPR 11059, internal mold (not latex). All photos are of latex casts, unless otherwise noted. All specimens are from 40.5 m in the Iron Mine Ridge section (Fig. 1.5; Wasatch County, Utah).

Indeterminate 'ptychoparioid'
Figure 2.4

Occurrence.—Rock Creek 1, Ophir Formation (formerly Cambrian Undifferentiated), Duchesne County, Utah.

Materials.—Natural external mold of a single articulated and nearly complete individual in bioturbated fine-grained sandstone.

Remarks.—Preservation too poor to allow a more precise identification than indeterminate 'ptychoparioid' based on short glabella.

https://doi.org/10.1017/jpa.2023.82 Published online by Cambridge University Press

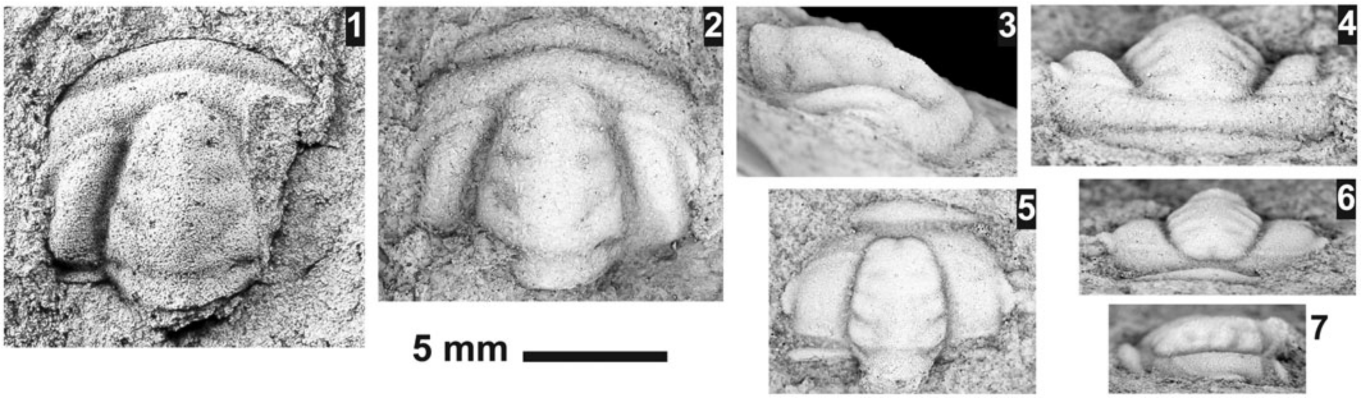

Figure 4. *Trachycheilus* aff. *T. whirlwindensis* Sundberg, 1994 from the Ophir Formation: (**1–4**) cranidium, FHPR 11139a, dorsal internal mold, dorsal, lateral, and anterior views, respectively; (**5–7**) cranidium, FHPR 11102, dorsal, anterior, and lateral views, respectively. All specimens are from 40.5 m in the Iron Mine Ridge section (Fig. 1.5). All images are of latex casts unless otherwise noted.

Discussion

These Ophir Formation fossils provide the first upper-age constraints on deposition of the Tintic Quartzite in the Uinta Mountains, with the occurrence of *Elrathiella* and *Trachycheilus* requiring that local deposition of the Tintic ceased by or during early medial Cambrian time (*Ehmaniella* Biochron, Wuliuan Age, Miaolingian Epoch). These fossils also suggest that much of the Ophir Formation in the region was marine—a finding consistent with the presence of exclusively marine trace fossils in the unit and in the upper half of the conformably underlying Tintic Quartzite elsewhere (Magwood, 1996; personal communication, A. Ekdale, 2017).

A similar upper limit on deposition (*Ehmaniella* Biozone, Miaolingian) and environmental interpretation appears to exist in the eastern Uintas for the Lodore Formation (Myrow et al., 2023b). Together with the eastward stratigraphic thinning of the Tintic and Ophir, the eastward disappearance of the typical cliff-forming quartzites of the Tintic, and the thermal exposure history (see review by Herr et al., 1982), these fossil occurrences lend support to the hypothesis that the top of the Cambrian succession in this region was eroded and locally reflects a composite unconformity like those that occur atop the Sawatch Quartzite of Colorado (e.g., Myrow et al., 2003). These data also permit us to hypothesize that the Tintic and lower Lodore are age equivalent and that, with comparable lithologies, they formed through similar depositional processes.

Based on the fossil material, the Ophir Formation of the Uinta Mountains appears to be broadly similar in age (*Ehmaniella* Biozone, Miaolingian) to the upper Lodore Formation of the eastern Uintas, as well as to the Wolsey Shale in Wyoming and Montana (Lochman-Balk, 1957; Schwimmer, 1973; Sundberg, 1994), and the upper Bright Angel to lower Muav formations of the Grand Canyon (Karlstrom et al., 2020).

Future work

To test such hypotheses, we recommend focusing on the carbonate portion of the section at Rock Creek because it could have potential through crackout and dissolution-based treatments to identify additional fossils of biostratigraphic utility, and to couple fossils with $\delta^{13}C$ chemostratigraphy. Similarly, the prevalence of young detrital zircon populations in Cambrian sandstones of this age in both northern Utah and adjacent areas in Colorado and Wyoming (Matthews et al., 2017; Karlstrom et al., 2018, 2020; Cothren et al., 2022; Holm-Denoma, 2022) suggests that there is potential for obtaining a basal-age constraints for the Tintic Quartzite and the Lodore Formation. Such work would permit testing of the hypothesis that the units represent isochronous components of the same depositional system. By pairing such data with emerging biostratigraphy such as that presented here, there is opportunity to learn if/how deposition of the Tintic and Lodore is related to larger-scale Cambrian processes, e.g., Sauk-related deposition of other western epicratonic sandstones, ranging from the Flathead Sandstone of Wyoming to the Sawatch Quartzite of Colorado and beyond.

Acknowledgments

Field work was facilitated by U.S.D.A. Forest Service permit R4-ANF-MGM-FY20-001 and the Forest Service's D. Herron and J. Wilkins. Special thanks for assistance in the field to T. Howells, M.B. Bennis, D. Gray, and D. Herron. We are grateful for funding from the National Science Foundation (EAR 1954634, 1955115), David B. Jones Foundation, and patrons of the DMNS Department of Earth Sciences. We greatly appreciate the reviews of J. Taylor, G. Geyer, and an anonymous reviewer, whose comments greatly improved the manuscript.

Declaration of competing interests

The authors declare none.

References

Bryant, B., 1992, Geologic and structure maps of the Salt Lake City 1° x 2° quadrangle, Utah and Wyoming: U.S. Geological Survey Miscellaneous Investigations Map I-1997, scale 1:125,000, 3 sheets.

Cothren, H.R., Farrell, T.P., Sundberg, F.A., Dehler, C.M., and Schmitz, M.D., 2022, Novel age constraints for the onset of the Steptoean Positive Isotopic Carbon Excursion (SPICE) and the late Cambrian time scale using high-precision U-Pb detrital zircon ages: Geology, v. 50, p. 1415–1420, https://doi.org/10.1130/G50434.1.

Esteve, J., Sundberg, F.A., Zamora, S., and Gozalo, R., 2012, A new Alokistocaridae Resser, 1939 (Trilobita) from the middle Cambrian of Spain: Geobios, v. 45, p. 275–283, https://doi.org/10.1016/j.geobios.2011.10.003.

Gravenhorst, J.L.C., 1843, Vergleichende Zoologie: Wroclaw, Poland, Graß, Barth, and Company, 687 p.

Halgarth, W.E., 1959, Stratigraphy of Paleozoic rocks in northeastern Colorado: U.S. Geological Survey Oil and Gas Investigations Chart OC-59, 1 sheet.

Hall, J., 1862, Supplementary note to the thirteenth report of the Regents of the State Cabinet: Albany, 15th Annual Report of the New York Cabinet for Natural History, p. 113–119.

Hall, J., and Whitfield, R.P., 1877, Paleontology: United States Geological Exploration of the 40th Parallel Report, v. 4, p. 199–231.

Hansen, W.R., 1965, Geology of the Flaming Gorge Area Utah-Colorado-Wyoming: U.S. Geological Survey Professional Paper, v. 490, 196 p.

Hansen, W.R., 1977, Geologic map of the Canyon of Lodore south quadrangle, Moffat County, Colorado: U.S. Geological Survey Map GQ-1403, scale 1:24,000, 1 sheet.

Hansen, W.R., Rowley, P.D., and Carrara, P.E., 1983, Geologic map of Dinosaur National Monument and vicinity, Utah and Colorado: U.S. Geological Survey Map I-1407.

Herr, R.G., 1979, Sedimentary petrology and stratigraphy of the Lodore Formation (upper Cambrian), northeast Utah and northwest Colorado [unpublished M.S. thesis]: Salt Lake City, University of Utah, 130 p.

Herr, R.G., Picard, M.D., and Evans, S.H., 1982, Age and depth of burial, Cambrian Lodore Formation, northeastern Utah and northwestern Colorado: Rocky Mountain Geology, v. 21, p. 115–121.

Hintze, L.F., 1988, Geologic history of Utah: Brigham Young University Geology Studies, Special Publication, v. 7, p. 1–202.

Holm-Denoma, C.S., Matthews, W.A., Soar, L.K., Longman, M.W., and Hagadorn, J.W., 2022, Provenance of Devonian–Carboniferous strata of Colorado: the influence of the Cambrian and the Proterozoic: Rocky Mountain Geology, v. 57, p. 1–21.

Hupé, P., 1955, Classification des trilobites: Annales de Paléontologie, v. 41, p. 91–325.

Karlstrom, K., Hagadorn, J., Gehrels, G., Matthews, W., Schmitz, M., et al., 2018, Cambrian Sauk transgression in the Grand Canyon region redefined by detrital zircons: Nature Geoscience, v. 11, p. 438–443, https://doi.org/10.1038/s41561-018-0131-7.

Karlstrom, K.E., Mohr, M.T., Schmitz, M., Sundberg, F.A., Rowland, S., et al., 2020, Redefining the Tonto Group of Grand Canyon and recalibrating the Cambrian timescale: Geology, v. 48, p. 425–430, https://doi.org/10.1130/G46755.1.

Lochman-Balk, C., 1955, Cambrian stratigraphy of the south and west margins of Green River Basin, *in* Guidebook, Wyoming Geological Association, Annual Field Conference, 10th, Rock Springs, Wyoming: Casper, Wyoming Geological Association, p. 29–37.

Lochman-Balk, C., 1957, Paleoecology of the Cambrian in Montana and Wyoming: Geological Society of America Memoirs, v. 67, p. 117–162.

Lochman-Balk, C., 1972, Cambrian system, *in* Mallory, W.W., ed., The Geologic Atlas of the Rocky Mountain Region: Denver, Colorado, Rocky Mountain Association of Geologists, p. 60–75.

Lochman-Balk, C., 1976, The Cambrian section of the central Wasatch Mountains, *in* Hill, J.G., ed., Geology of the Cordilleran Hingeline, Rocky Mountain Association of Geologists, 1976 symposium: Denver, Rocky Mountain Association of Geologists, p. 103–108.

Magwood, J.P.A., 1996, Solutions to ichnological problems recognized in lower Cambrian strata, Basin and Range Province, U.S.A. [unpublished Ph.D. thesis]: Salt Lake City, University of Utah, 212 p.

Matthews, W., Guest, B., and Madronich, L., 2017, Latest Neoproterozoic to Cambrian detrital zircon facies of western Laurentia: Geosphere, v. 14, p. 243–264, https://doi.org/10.1130/GES01544.1.

McKee, E.D., and Resser, C.E., 1945, Cambrian history of the Grand Canyon region: Carnegie Institution of Washington, Publication 563, 232 p.

Myrow, P.M., Taylor, J.F., Miller, J. F., Ethington, R.L., Ripperdan, R.L., and Allen, J., 2003, Fallen arches: dispelling myths concerning Cambrian and Ordovician paleogeography in the Rocky Mountain region: GSA Bulletin, v. 115, p. 695–713, https://doi.org/10.1130/0016-7606(2003)115<0695:FADMCC>2.0.CO;2.

Myrow, P.M., Hasson, M., Taylor, J.F., Tarhan, L., Fike, D.A., et al., 2023a, Revised Paleozoic depositional history of the central Rocky Mountains (Utah and Colorado): Sedimentary Geology, v. 449, n. 106373, https://doi.org/10.1016/j.sedgeo.2023.106373.

Myrow, P.M, Hasson, M., Taylor, J.F., Tarhan, L.G., Ramirez, G., Fowlkes, G., and Chen, J., 2023b, Structural control of Cambrian paleotopography and patterns of transgressions in western Laurentia: Geology, v. 51, p. 521–526, https://doi.org/10.1130/G51055.1.

Palmer, A.R., 1954, An appraisal of the Great Basin middle Cambrian trilobites described before 1900: U.S. Geological Survey Professional Paper, v. 264D, p. 53–85.

Peterson, D.O., 1953, Structure and stratigraphy of the Little Valley area, Long Ridge, Utah [unpublished M.S. thesis]: Provo, Utah, Brigham Young University, 96 p.

Poulsen, C, 1927, The Cambrian, Ozarkian and Canadian faunas of northwest Greenland: Meddelelser om Grønland, v. 70, p. 233–343.

Resser, C.E., 1939, The Spence Shale and its fauna: Smithsonian Miscellaneous Collections, v. 97, 29 p., 6 pls.

Resser, C.E., 1945, Part II, Cambrian fossils of the Grand Canyon, *in* McKee, E.D., and Resser, C.E., eds., Cambrian History of the Grand Canyon Region: Carnegie Institution of Washington, Publication 563, p. 171–232, pls. 16–27.

Robison, R.A., 1964, Cambrian of the Uinta Mountains, *in* Sabatka, E.F., ed., Guidebook to the Geology and Mineral Resources of the Uinta Basin: Utah's Hydrocarbon Storehouse, Annual Field Conference, 13th, 16–19 September 1964: Salt Lake City, Intermountain Association of Petroleum Geologists, p. 63–66.

Robison, R.A., 1976, Middle Cambrian trilobite biostratigraphy of the Great Basin: Brigham Young University Geology Studies, v. 23, p. 93–109.

Salter, J.W., 1866, On the fossils of North Wales, *in* Ramsay, A.C., ed., The Geology of North Wales: Memoirs of the Geological Survey of Great Britain and of the Museum of Practical Geology 3, p. 239–381, pls. 1–26.

Schwimmer, D.R., 1973, The middle Cambrian biostratigraphy of Montana and Wyoming [unpublished Ph.D. dissertation]: Stony Brook, State University of New York, 452 p.

Soule, J.M., 1992, Precambrian to earliest Mississippian stratigraphy, geologic history, and paleogeography of northwestern Colorado and west-central Colorado: U.S. Geological Survey Bulletin 1787, 35 p.

Sprinkel, D.A., 2006, Interim geologic map of the Dutch John 30' x 60' quadrangle, Daggett and Uintah counties, Utah, Moffat County, Colorado, and Sweetwater County, Wyoming: Utah Geological Survey, Open-File-Report 491DM, 3 pls.

Stokes, W.L., and Madsen, J.H., 1962, Geologic map of Utah (northeast quarter): Utah Geological and Mineralogical Survey, scale 1:250,000, 1 p.

Sundberg, F.A., 1994, Corynexochida and Ptychopariida (Trilobita, Arthropoda) of the *Ehmaniella* Biozone (middle Cambrian), Utah and Nevada: Los Angeles County Museum of Natural History, Contributions in Science 446, 137 p.

Sundberg, F.A., and Webster, M., 2022, Trilobite faunas of the Harkless Formation and Mule Spring Limestone (Cambrian Series 2, Stage 4), Clayton Ridge, Nevada: pt. 2 Ptychoparioids: Journal of Paleontology, v. 96, p. 1–35.

Sundberg, F.A., Karlstrom, K.E., Geyer, G., Foster, J.R., Hagadorn, J.W., Mohr, M.T., Schmitz, M.D., Dehler, C.M., and Crossey, L.J., 2020, Asynchronous trilobite extinctions at the early to middle Cambrian transition: Geology, v. 48, p. 441–445, https://doi.org/10.1130/G46913.1.

Untermann, G.E., and Untermann, B.R., 1949, Geology of Green and Yampa River canyons and vicinity, Dinosaur National Monument, Utah and Colorado: AAPG Bulletin, v. 33, p. 683–694.

Untermann, G.E., and Untermann, B.R., 1954, Geology of Dinosaur National Monument and vicinity, Utah-Colorado: Utah Geological and Mineralogical Survey, Bulletin 42, 221 p.

Walch, J.E.I., 1771, Die Naturgeschichte der Versteinerungen, Dritter Theil: Nuremberg, Paul Jonathan Felstecker, 235 p.

Walcott, C.D., 1886, Second contribution to the studies on the Cambrian faunas of North America: United States Geological Survey Bulletin, v. 30, p. 1–369.

Walcott, C.D., 1901, Cambrian Brachiopoda: *Obolella*, subgenus *Glyptias*; *Bicia*, *Obolus*, subgenus *Westonia*; with descriptions of new species: Proceedings of the United States National Museum, v. 23, p. 669–695.

Walcott, C.D., 1916, Cambrian geology and paleontology III—Cambrian trilobites: Smithsonian Miscellaneous Collections, v. 64, no. 5, p. 303–456.

Williams, N.C., 1953, Late Pre-Cambrian and early Paleozoic geology of western Uinta Mountains, Utah: Bulletin of the American Association of Petroleum Geologists, v. 37, p. 2734–2742.

Williams, N.C., 1957, Cambrian stratigraphy of the south flank of the Uinta Mountains, *in* Seal, O.G., ed., Guidebook to the Geology of the Uinta Basin, Annual Field Conference, 8th, 20–22 June 1957: Salt Lake City, Intermountain Association of Petroleum Geologists, p. 53–55.

Accepted: 4 October 2023