Paleontology of the Neoproterozoic Uinta Mountain Group

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ABSTRACT

Sedimentary rocks of the Uinta Mountain Group (northeastern Utah) preserve fossils deposited in a marine setting during middle Neoproterozoic time. Although well preserved, species diversity is much lower than many other midddle Neoproterozoic siliciclastic deposits. Microfossil assemblages are mostly limited to *Leiosphaeridia* sp., *Bavlinella faveolata*, and filaments. Diverse ornamented acritarchs, vase-shaped microfossils, and the macroscopic compression fossil *Chuaria circularis,* also occur, but are much more rare. Although the Uinta Mountain Group does not preserve as wide a range of facies as other middle Neoproterozoic units – the unit is carbonate-free – it is unlikely that preservation alone can account for its relatively limited fossil diversity. Rather, the Uinta Mountain Group likely records deposition in an environment that was inimical to most eukaryotes.

INTRODUCTION

The Uinta Mountain Group (UMG) is one of several western North American successions that provide a glimpse of middle Neoproterozoic life (Link and others, 1993). Other successions from this region have yielded important insight into this critical interval, including the earliest evidence for eukaryotic biomineralization (Horodyski and Mankiewicz, 1990; Porter and others, 2003), evidence that heterotrophic protists were abundant and diverse components of middle Neoproterozoic ecosystems (Porter and Knoll, 2000; Porter and others, 2003), and evidence for the persistence of complex microbiotas in shallow water environments during snowball Earth times (Corsetti and others, 2003). In contrast, the paleontological studies of the UMG have largely been limited to minor reports noting the presence of one or few fossil taxa (Hofmann, 1977; Nyberg and others, 1980; Nyberg, 1982a, 1982b; Vidal and Ford 1985; see Horodyski in Link and others, 1993). Here we provide a synthesis of UMG paleontology, relying on data both from previous work (see table 1) and from recent studies of our own (see table 2). We find that although the UMG is fossiliferous throughout its stratigraphic and geographic range, (appendix A) fossil assemblages are, for the most part, taxonomically depauperate, limited to just one or a few morphologically simple species. This probably reflects, at least in part, the limited range of taphonomic windows preserved in the UMG, but also suggests that much of the UMG was deposited in an environment inimical to high species diversity.

GEOLOGY

The Uinta Mountain Group is exposed throughout the Uinta Mountains of northeastern Utah. It is composed of 4–7 km of sedimentary deposits, primarily sandstones and shales (Hansen 1965, Wallace and Crittenden 1969), that were deposited in a marine-deltaic to braided fluvial setting (Dehler and others, in press) in an intracratonic rift basin that was open to the south, and could have been connected south to the Grand Canyon region and west to the Death Valley region (CHUMP hypothesis, see Dehler and others, 2001; Condie and others, 2001).

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The Uinta Mountain Group is readily differentiated into western and eastern regions, although it is unclear how the two are stratigraphically related (Dehler and others, in press). In the western region, the UMG has been divided into four units. At the top lies the most fossiliferous of the group: the Red Pine Shale, a ≤1200-m-thick unit comprising gray to black laminated organic-rich shales with medium to coarse sandstone interbeds (Dehler and others, in press). Below the Red Pine Shale, in descending order lie the formation of Hades Pass the Mount Watson Formation (and equivalents), and the formation of Moosehorn Lake (and equivalents). Fossils have been reported from the last two units.

In the eastern region, the majority of the UMG is undescribed and therefore undivided. This 'undivided UMG' unit consists predominantly of sandstones with local mudstones and conglomerates. Its thickness is not known, but may be between 4 and 7 km. Beneath the 'undivided UMG' is the

Table 1. *Summary of fossil occurrences from previous paleontological studies of the Uinta Mountain Group. (There has been no previous paleontological work on the eastern UMG.) The taxa Kildinosphaera sp., Trachysphaeridium sp., and Kildinella sp. have been subsumed here in the genus, Leiosphaeridia sp. (Jankauskas and others, 1989). Questionable fossils are noted by a "?". Also see Horodyski in Link and others (1993).*

Region	Unit	Fossil	Localities	References
Western UMG	Red Pine Shale	*Chuaria circularis*	Yellowstone Creek†; Setting Road*; Moon Lake§	Hofmann, 1977; Nyberg and others, 1980; Nyberg, 1982a; Vidal and Ford, 1985
		Siphonophycus sp.	Yellowstone Creek†	Nyberg, 1982a
		Taeniatum sp. and other filaments	Gardner's Fork§; Setting Road*	Nyberg, and others, 1980; Nyberg, 1982a; Vidal and Ford, 1985
		Leiosphaeridia sp.	various§; Setting Road*	Nyberg, 1982a; Vidal and Ford, 1985
		Valeria lophostriata	Setting Road*	Vidal and Ford, 1985
		cf. *Stictosphaeridium* sp.	Setting Road*	Vidal and Ford, 1985
		Trachysphaeridium sp. A	Setting Road*	Vidal and Ford, 1985
		Trachysphaeridium laminaritum	Setting Road*	Vidal and Ford, 1985
		Trachysphaeridium laufeldi	Setting Road*	Vidal and Ford, 1985
		Tasmanites rifeiicus	Setting Road*	Vidal and Ford, 1985
		vase-shaped microfossils	Red Pine Creek§	Nyberg, 1982a,b
		Tuberculosiphon uintaensis n.gen. n. sp.	Gardner's Fork§	Nyberg, 1982a
		?*Anguloplanina rhombica*	Gardner's Fork§	Nyberg, 1982a
	Mount Watson Formation	*Leiosphaeridia* sp.	South of Bald Mountain*	Vidal and Ford, 1985
		Trachysphaeridium laufeldi	South of Bald Mountain*	Vidal and Ford, 1985
	formation of Moosehorn Lake	?vase-shaped microfossil	Mirror Lake§	Nyberg, 1982a
		Taeniatum sp.	Mirror Lake§	Nyberg, 1982a
		Leiosphaeridia sp.	Mirror Lake§	Nyberg, 1982a

†Locality described in Hofmann (1977)
§Localities described in Nyberg (1982a)
*Localities described in Vidal and Ford (1985)

Table 2. *Paleontological data for samples collected for this study (see also Dehler and others, in press). An em dash (—) means no identifiable fossils were found.*

Region	Unit	Locality	Sample #	Fossils
Western UMG	Red Pine Shale	Tunnel Section	TS03-1	—
		Aspen Grove	AG03-2	*Leiosphaeridia* sp.; filaments
		White Rocks	WR03-1	*Bavlinella faveolata*
		White Rocks	WR03-2	*Bavlinella faveolata*
		White Rocks	WR03-4	*Bavlinella faveolata*
		White Rocks	WR100101-2	*Bavlinella faveolata*
		White Rocks	WR100101-3	*Bavlinella faveolata*
		Henry's Fork	HF-3	*Satka colonialica*; filaments
		Henry's Fork	HF-7	*Leiosphaeridia* sp.; filaments; ?VSMs
		Ashley Creek	AC04-3	—
		Ashley Creek	AC04-5	—
		Ashley Creek	AC-1	*Leiosphaeridia* sp.; filaments
		Type Section	RP04-3	*Leiosphaeridia* sp.; filaments
		Type Section	RP04-10	*Leiosphaeridia* sp.; filaments
		Type Section	RP00B-8	*Leiosphaeridia* sp.
		Type Section	RP00B-32	*Leiosphaeridia* sp.
		Type Section	RP00B-40	VSMs
		Hades	RP03B-1	—
		Hades	RP03B-24	*Chuaria circularis*
		Hades	RP03B-25	*Leiosphaeridia* sp.
		Lower Hades	RP01A-50	*Leiosphaeridia* sp.; filaments; *Bavlinella faveolata*
		Lower Hades	RP01A-63	*Leiosphaeridia* sp.; filaments
		Lower Hades	RP01A-68	*Leiosphaeridia* sp.; filaments
		Lower Hades	RP01A-70	*Leiosphaeridia* sp.; filaments
		Lower Hades	RP01A-85	*Bavlinella faveolata*
		Hoop Lake	HL04-04	—
		Hoop Lake	HL04-10	*Leiosphaeridia* sp.; filaments; *Bavlinella faveolata*
		Hoop Lake	HL04-22	filaments
	formation of Moosehorn Lake	Bald Mountain	BM03-2	filaments
Eastern UMG	undivided UMG	Leidy Peak	LP10-03-01-2	ornamented acritarchs; filaments; ?VSMs
		Leidy Peak	LP10-03-01-4	*Leiosphaeridia* sp.; filaments
		Leidy Peak	LP10-03-01-6	*Leiosphaeridia* sp.; filaments
		Dutch John	DJ04-02	—
		Dutch John	DJ04-07	*Leiosphaeridia* sp.; filaments
		Carter Creek	CTR04-01	—
		Sheep Creek	SHC04-01	filaments
		Pit Draw	PDUMG-C	*Leiosphaeridia* sp.; filaments
	Jesse Ewing Canyon Fm.	Jesse Ewing Canyon	JEC04-02	*Leiosphaeridia* sp.; filaments

Jesse Ewing Canyon Formation, a ~225 m thick conglomeratic unit with intervals of shale. Fossils are known from both the undivided strata and the Jesse Ewing Canyon Formation. (See De Grey and Dehler; and Waanders and Sprinkel, this volume, for further details on sedimentology, stratigraphy, and paleontology of the eastern UMG).

A maximum age of ~770 Ma has recently been reported from detrital zircons collected near the middle of the UMG in the eastern region (Fanning and Dehler, 2005). This is consistent with paleomagnetic data from the Flaming Gorge region of the eastern UMG that suggest a date of 800-750 Ma (Weil and others, in press), and with bio- and chemostratigraphic constraints that suggest correlation with the ~770-740 Ma Chuar Group (see Dehler and others, in press, and references cited therein).

MATERIALS AND METHODS

UMG microfossils are found in organic-rich, non-oxidized, gray, green, and black shales. Some samples exhibit mm-scale laminations, but there is no apparent correlation between degree or scale of lamination and fossils. Shale samples were immersed in 48% hydrofluoric acid, which dissolves silicate minerals and thereby frees preserved organic matter. Acid residues were then neutralized and sieved at <10 µm, 10 – 25 µm, and > 25 µm mesh sizes. Sieved material was mounted on slides and viewed with a transmitted light microscope. Few microfossils are found in the size fractions less than 25 µm, thus efforts were concentrated on the >25µm size fraction.

We examined 25 samples from 7 localities of the Red Pine Shale (21 of which were fossiliferous), 11 samples from 6 localities in the eastern undivided UMG (8 of which were fossiliferous), and a single sample from both the formation of Moosehorn Lake and the Jesse Ewing Canyon Formation (both fossiliferous).

Grade of preservation varies from exceptional to very poor across the samples examined, although most samples exhibit average to good preservation. Thermal alteration (inferred from coloration, which darkens with increasing alteration as described in Martin 1993) also ranges from sample to sample.

PALEONTOLOGY

For the most part, UMG rocks preserve low diversity assemblages comprising morphologically simple fossils (see tables 1 and 2). Most samples preserve *Leiosphaeridia* sp., *Bavlinella faveolata*, an array of filaments, or some combination of these three. Diverse ornamented acritarchs, *Chuaria circularis*, and vase-shaped microfossils also occur but are much rarer. In the following sections, we discuss the fossils found in the UMG.

Leiosphaeridia sp.

Acritarchs of the genus *Leiosphaeridia* (figures. 1L-O and 2A-C) are unornamented, smooth-walled sphaeromorphs that range in diameter from tens to hundreds of micrometers. Species within the genus are identified on the basis of size and wall thickness (Jankauskas and others, 1989). Although there is evidence that this ad hoc species taxonomy may actually have some biological significance (Butterfield and others, 1994), it is likely that the genus itself represents a collection of unrelated organisms, united primarily on the basis of their lack of characters. Because of their simplicity, their biological affinities are problematic. Some may be the outer envelopes of more complex acritarchs, while others may represent cysts – or resting stages – of protists. Evidence for the latter comes from the presence of medial splits (figures. 2A-B) that likely represent excystment structures (see Butterfield and others, 1994 for a discussion of biologically vs. taphonomically produced splits). [During adverse conditions, some protists enclose themselves within a resistant wall that ruptures -- via the excystment structure -- to release the cell once conditions become suitable again. Prokaryotes do not produce excystment structures (Javaux and others, 2003)]. It is also possible that some represent vegetative cells of single-celled protists like green algae (Tappan, 1980; Martin 1993), or disarticulated parts of a larger plant (Butterfield, 2004).

Leiosphaeridia sp. are found throughout the UMG (see tables 1 and 2), with the exception of the little-studied formation of Moosehorn Lake (Nyberg and others, 1982a; Vidal and Ford, 1985; Dehler and others, in press; this study). They are a common
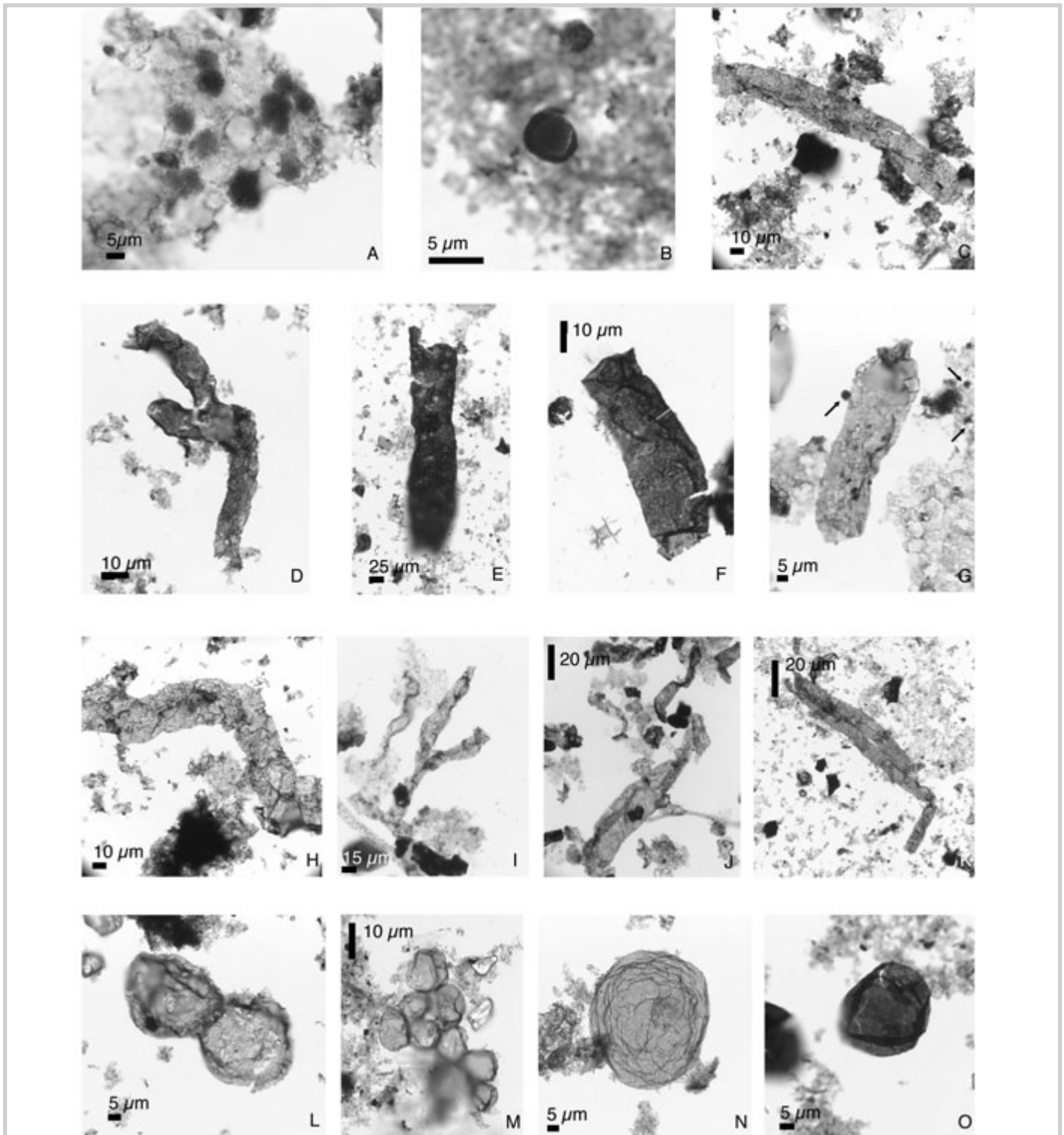
Figure 1. *Representative microfossils from the Uinta Mountain Group; A – Bavlinella faveolata aggregates (HL04-10, K37); B - Bavlinella faveolata spheroid, note possible outer membrane (WR100101-2, P26-2); C – Filament with one curved end cf. Botuliform fossils (LP10-03-01-6, K39); D – a branching filamentous form (LP10-03-01-6, K47-3); E – robust filament exhibits very little compaction or folding (LP10-03-01-6, J43); F – a compressed filament or abandoned sheath (RP04-10, G33-3); G – Botuliform fossil, note overall elliptical shape, arrows indicate B. faveolata spheroids; H – filament (HF03-3, W22); I – branching structure, appears to be a single flat layer (HL04-10, H38-3); J – multiple filaments demonstrating size range and varying grades of preservation (HL04-10, N34-2); K – two filaments, note curved Botuliform-like end on lower specimen, it is unclear weather association is biologic or taphonomic, also note the Leiosphaeridia sp. at the center of the left-hand side of the image (LP10-03-01-6, T43-3); L – two attached Leiosphaeridia sp. (LP10-03-01-6, G26-3); M – monospecific cluster of Leiosphaeridia sp. (LP10-03-01-6, N36-3); N – a thin-walled Leiosphaeridia sp., note wrinkles and folds (LP10-03-01-6, H46); O – a thick-walled Leiosphaeridia sp., note compressional folds and radial cracks (LP10-03-01-6, N37-3); scale bar is 5 μm in A, B, G, L, N, and O, 10 μm in C, D, F, H, and M, 15μm in I, 20 μm in J and K, and 25μm in E; sample numbers indicated refer to acid macerations housed in the Earth Sciences at the University of California, Santa Barbara; England Finder coordinates refer to location of specimen on slide with labeled edge to the left and England Finder oriented so that text appears right-side up through the microscope.*
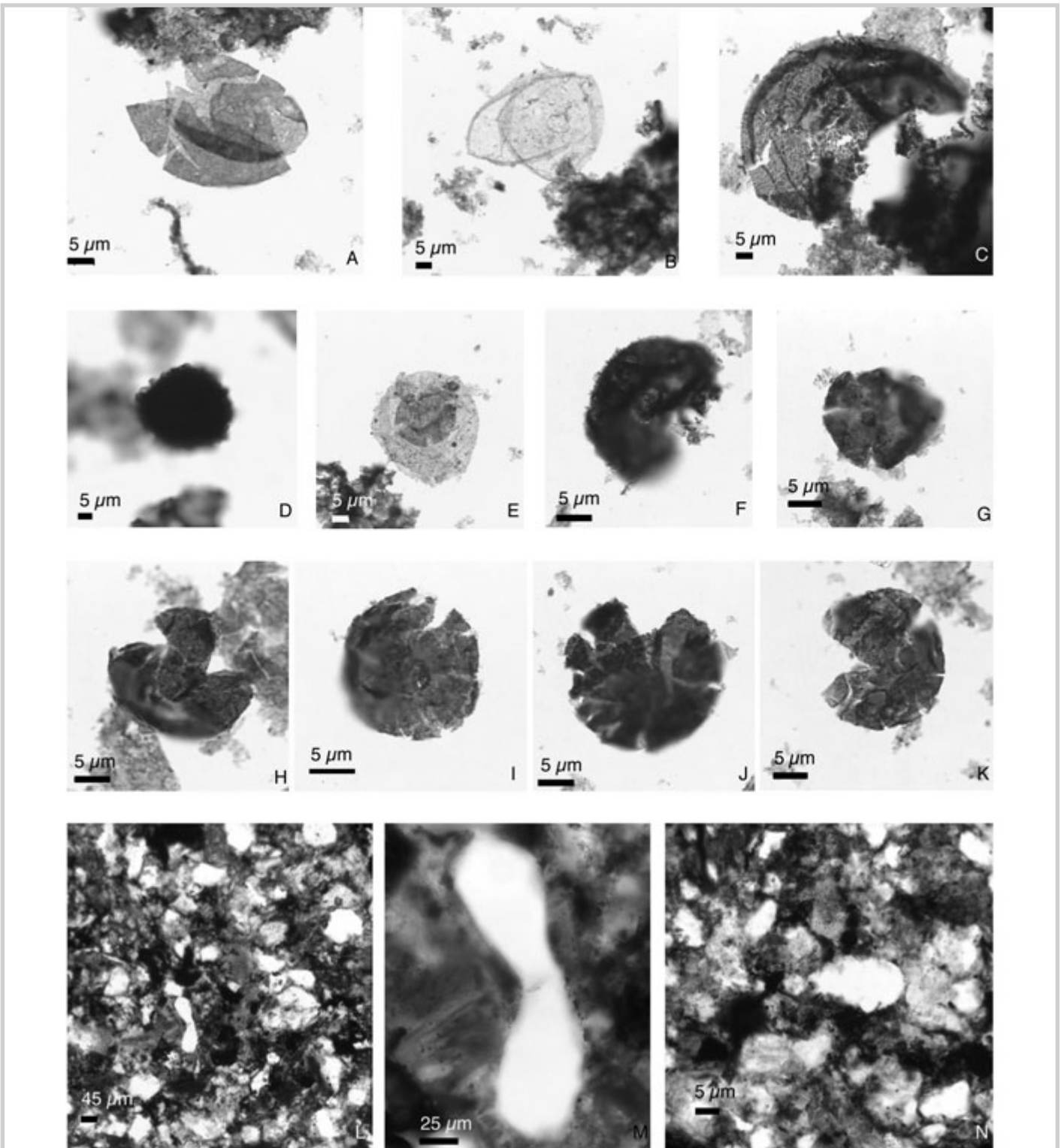
Figure 2. *Acritarchs and vase-shaped microfossils from the Uinta Mountain Group; A – thin-walled Leiosphaeridia sp. with a clear medial split (LP10-03-01-6, M36); B – a very thin-walled Leiosphaeridia sp. with a medial split (LP10-03-01-6, R34); C – an unidentified acritarch with unusual wall sculpture, possibly a taphonomically altered Leiosphaeridia sp. (LP10-03-01-6, M41-2); D – an unidentified acritarch (LP10-03-01-6, J40-4); E – Pterospermopsimorpha sp. (LP10-03-01-6, M35-4); F – acritarch with hair-like processes (especially visible along the upper left edge of the specimen), processes <1µm (LP10-03-01-6, P33-1); G – a smooth-walled acritarch with a round granular structure (possibly an excystment operculum) towards the center (LP10-03-01-6, N25-1); H&I – acritarchs with small, cone-like processes (LP10-03-01-6, coordinates unavailable and Y16-2, respectively); J&K – acritarchs with blunt, cylindrical processes (LP03-01-6, J30-4 and P29-3, respectively); L&M – VSMs preserved with their apertures attached; M is a closer view of L (RP00B-40, Z30-3); N – a single VSM (RP00B-40, K30); scale bars are 5 µm in A-K and N, 45 µm in L, and 25 µm in M; A-K are acid macerations, L-O are thin sections. All are housed in the Earth Sciences at the University of California, Santa Barbara.*

constituent of the fossil assemblage, ranging in size from 5-100µm, occurring both as solitary unicells (figures. 1N-O and 2A-C) and colonial aggregates (figures. 1L-M). Several specimens exhibit medial splits (figures. 2A-B), suggesting that they are fossilized cysts. In addition, the unornamented acritarch, *Satka colonialica* (a large spherical to oval envelope that records impressions of cells no longer inside) has also been recorded in the Red Pine Shale (table 2).

Bavlinella faveolata

Bavlinella faveolata (figures 1A-B) is an aggregate of <1 µm coccoid subunits. [The fossil is also referred to in the literature as *Sphaerocongregus variabilis*, now regarded as a junior synonym of *Bavlinella faveolata* (see Gaucher and others, 2003)]. The aggregates themselves are usually sphereoidal, although amorphously clustered and elongated forms are also occasionally noted. Spheroidal aggregates are ~5-20 µm in diameter. An outer membrane is sometimes found surrounding the aggregate (figure. 1B; Cloud and others, 1975; Moorman, 1974; R.M. Nagy, personal observation), although the fact that clearly abiogenic mineral crystals may also be observed with a similar coating (R.M. Nagy, personal observation) suggests these "membranes" may be taphonomic artifacts. The fossil appears superficially similar to framboidal pyrite (Javor and Mountjoy, 1976), and indeed specimens are often pyritized or permineralized with iron oxides (S.M. Porter, personal observation; Gaucher and others, 2003). Others clearly are organic-walled, however; as argued by Knoll and others (1981; and references therein) *B. faveolata* is not simply framboidal pyrite.

The random bedding-plane distribution of *B. faveolata* suggests a planktonic habit (Vidal and Nystuen 1990). Interestingly, *B. faveolata* is rare or absent in the relatively diverse microfossil assemblages that characterize shallow water environments during Neoproterozoic time (Knoll and others, 1981 and references therein). Instead, it usually occurs by itself in dense concentrations in deeper water settings (Knoll and others, 1981; Vidal and Nystuen, 1990; Butterfield and Chandler, 1992). This suggests that *B. faveolata* may represent an opportunistic taxon that creates blooms in stressed environmental conditions (Knoll and others, 1981).

B. faveolata has been interpreted by many as an endosporulating cyanobacteria, consistent with the possible presence of an outer membrane surrounding reproductive 'spores' (Moorman, 1974; Cloud and others, 1975; Knoll and others, 1981; Vidal, 1981; Mansuy and Vidal, 1983; Vidal and Knoll, 1983; Knoll and Swett, 1985). Alternatively, Vidal and Nystuen (1990) have suggested *B. faveolata* represents the remains of an anoxygenic, photosynthetic bacterium. This is consistent with its occurrence in deeper-water, organic- and sulfide-rich facies (Vidal and Nystuen, 1990; Butterfield and Chandler 1992; S.M. Porter personal observation), and with the fact that aerobic eukaryotes are absent (excluded?) from *B. faveolata* assemblages (see above; Vidal and Nystuen, 1990). It is also possible *B. faveolata* represents two or more prokaryotic species living together in a consortium (e.g., Orphan and others, 2001), although the presence of a membrane, if confirmed, would falsify this hypothesis.

B. faveolata occurs in monospecific assemblages in the Red Pine Shale, where it is associated with black, sulfur-rich shales (table 2). It also occurs in association with abundant filaments and *Leiosphaeridia* sp. in one exceptionally preserved sample from the Red Pine Shale at the Hoop Lake locality (figures 1A, 1G, and 1J). In all cases, *B. faveolata*–bearing samples from the UMG are thought to have been deposited in deep water, low energy conditions.

Assorted filaments

A variety of simple, strip- or tube-like fossils (figures 1C-K), collectively referred to here as 'filaments', are common in UMG sediments (see tables 1 and 2). They range from 5 to 20 µm in width, and up to >100 µm in length (most are broken at either end, preventing their full lengths to be determined). Some appear to be composed of a single layer (figures 1C, G-K) and thus have a 'strip-like' morphology; others are clearly double-walled (figure. 1D-F) and thus were probably once hollow tubes. Extremely rare specimens (<1%) exhibit branching (figure. 1D, I); other, similarly rare specimens have rounded ends (figures. 1C, K), and are comparable to botuliform fossils like *Navifusa* (e.g., Hofmann and Jackson,

1994). Earlier workers (Nyberg and others, 1980; Nyberg, 1982a; Vidal and Ford 1985) also noted the presence of a variety of filamentous fossils in the UMG, including *Taeniatum* sp., *Siphonophycus* sp., possible oscillatoriacean trichomes, and a new species, *Tuberculosiphon uintaensis* Nyberg 1982, characterized by nonseptate branched filaments with bulbous terminations.

Like *Leiosphaeridia* sp. these fossil filaments probably represent an assortment of taxa, but their simple morphology precludes confident assignment to any specific modern clade. Similar filaments from other successions are often compared with filamentous cyanobacteria (e.g., Hofmann and Aitken, 1979), although a eukaryotic affinity cannot, in principle, be ruled out.

Ornamented acritarchs

Acritarchs are acid-resistant organic-walled vesicles of unknown taxonomic affinities that range in size from <10µm to >1000µm (although taxa from the UMG tend to be restricted to between 10 and 100 µm).

Ornamented acritarchs including *Valeria lophostriata, Tasmanites rifejicus*, cf. *Stictosphaeridium* sp., *Trachysphaeridium laminaritum, Trachysphaeridium laufeldi,* and *Trachysphaeridium* sp. 'A' were first reported from a single sample of the Red Pine Shale by Vidal and Ford (1985) (table 1). (They also found a single corroded specimen -- possibly reworked -- of *Trachysphaeridium laufeldi* in a sample from the Mount Watson Formation.) One particularly fossiliferous sample from green shale at the Leidy Peak locality yields a similar acritarch assemblage (table 2), with notable acritarchs from the genus *Pterospermopsimorpha* (figure 2E), several taxa that exhibit a diversity of processes (figures 2F-K), and three specimens with a morphology distinct from any previously described acritarch taxa (figure. 2D). Although there is a variety of process-bearing acritarchs, those with outer membranes are notably absent in the sample.

Acritarchs are interpreted by most to be the abandoned cysts of eukaryotic, unicellular planktonic algae, in particular of green algae or dinoflagellates (see Dorning, 2005 and Martin, 1993 for further details on acritarch morphology, classification, and

interpretation). Although smooth-walled acritarchs are known from Paleoproterozoic rocks (e.g., Zhang, 1986), ornamented acritarchs first appear in the early Mesoproterozoic Era (Javaux and others, 2001). They continue to diversify through the Neoproterozoic Era, with diversity reaching an acme in the middle Ediacaran Period (<580 Ma). Following a late Ediacaran extinction event, they rediversify in the early Cambrian Period (Knoll, 1994; Vidal and Moczydlowska-Vidal, 1997; Grey and others, 2003).

Chuaria circularis

Specimens of *Chuaria circularis*, a megascopic carbonaceous compression that forms mm-scale disk-shaped impressions on bedding planes, were first reported from the UMG by Hofmann (1977), Nyberg and others (1980), Nyberg (1982a), and Vidal and Ford (1985). Their walls are psilate to finely chagrinate on both the interior and exterior surfaces (Talyzina, 2000), and exhibit distinctive concentric folds. The homogeneous, unilamellar wall is occasionally perforated by degradational holes and cavities, and ranges in thickness from 0.5-5.4 µm (Talyzina, 2000). *C. circularis* was the first Precambrian fossil described (Walcott, 1899), and its biological affiliations have been widely speculated in the past century. Walcott (1899) first suspected it to be a brachiopod, and it has since been interpreted as a gastropod (Talyzina, 2000 and references therein), an inorganic pseudofossil (Talyzina, 2000 and references therein), a trilobite egg (Ford and Breed 1974), and a non-calcareous Foraminifera (Ford and Breed 1974), although an algal affinity is now commonly accepted (Butterfield and others, 1994; Talyzina 2000). *C. circularis* is widespread in early to middle Neoproterozoic rocks that predate 'snowball Earth' glaciation (Talyzina, 2000). Another species, *C. pendjariensis,* characterized by a thick, multi-layered wall (although see Talyzina, 2000), occurs in shales that overlie Marinoan-equivalent tillites in West Africa (Amard, 1992; Porter and others, 2004).

Vase-Shaped Microfossils

The term 'vase-shaped microfossil' (VSM) refers to a diversity of fossil species that possess tear-drop-

shaped or hemispherical tests with an opening, or 'aperture', at one end (e.g., Porter and others, 2003). VSMs are widespread and abundant in middle Neoproterozoic rocks, where they are often found in association with organic-rich layers in microbial mats (Porter and Knoll, 2000). A particularly dense accumulation (>109 specimens) is preserved in secondary diagenetic dolomite nodules in shale from the upper Chuar Group, Grand Canyon. This assemblage contains at least ten species, some with test characters that allow confident attribution to the filose and lobose testate amoebae (Porter and Knoll, 2000; Porter and others, 2003). [Despite their similar tests, these two groups are not closely related to each other. The filose testate amoebae are members of the Rhizaria, a group that also includes the Foraminifera and most Radiolaria. The lobose testate amoebae are part of the Amoebozoa, a group that also includes the slime molds and most naked amoebae (see Baldauf 2003; Simpson and Roger 2004).]

VSMs are preserved as internal molds (figures. 2L-N) in a silicified, organic-rich mudstone located ~360 m above the base of the type section of the Red Pine Shale (see also Nyberg, 1982a,b). Included in this assemblage are two specimens with their apertures attached (figures 2L-M); these are thought to have been undergoing asexual reproduction when they died (Porter and others, 2003). The occurrence of VSMs elsewhere in the UMG is in question. Nyberg (1982a) reported VSMs with flat bases and elongated necks from the formation of Moosehorn Lake, but the two specimens illustrated are not convincingly biological. Dehler and others (in press) report possible VSMs from the formation of Moosehorn Lake and the undivided strata in the eastern UMG, but the specimens are too poorly preserved to allow confident assignment.

DISCUSSION

Overall, UMG rocks yield low diversity fossil assemblages consisting of morphologically simple taxa. In contrast, other units of similar age host much more diverse assemblages (e.g., Vidal, 1976; Knoll and others, 1989, 1991; Butterfield and others, 1994). Some of this difference is due to availability of preservational facies; silicified carbonates, which provide an important taphonomic window on

Precambrian life, are notably absent from the UMG. But even in comparison with other shale-facies assemblages, the UMG seems species-poor. The Chuar Group, for example, preserves relatively diverse assemblages of acritarchs throughout its thickness (R.M. Nagy, personal observation). This difference is not simply due to different qualities of preservation; as with the Chuar Group, very delicate fossils may be beautifully preserved in the UMG. Instead, the taxonomically depauperate, morphologically simple fossil assemblages that characterize the UMG probably reflect a taxonomically depauperate, morphologically simple biota that lived in UMG seas ~750 million years ago.

Interestingly, UMG fossil assemblages are comparable to those of the similarly aged Hedmark Group of southern Norway, which records turbidite deposition in an intracratonic rift basin (Vidal and Nystuen, 1990). Vidal and Nystuen (1990) envisioned the Hedmark basin to be similar to the Black Sea today (Repeta and others, 1989), where below a very shallow chemocline, anoxygenic photosynthetic bacteria bloom in sulfide-rich, anoxic waters. Assuming that the similar fossil assemblages imply similar environments, we suggest a similar scenario for UMG life: filamentous bacteria – perhaps sulfate reducers – formed mats on the seafloor; anoxygenic photosynthetic bacteria bloomed in the water column; and simple, single-celled eukaryotes lived in the uppermost (oxygenated) layer of water, producing cysts when times got tough. Diverse, complex eukaryotes were, for the most part, excluded from the basin, surviving perhaps in shallow water benthic habitats only occasionally recorded by UMG strata. This environmental scenario is consistent with facies interpretations by Dehler and others (in press), who suggest that the Red Pine Shale, and other shale in the UMG, represent different parts of a marine deltaic system in an intracratonic rift setting.

CONCLUSIONS

In comparison with other Neoproterozoic units, the paleontology of the UMG at first appears relatively uninteresting. UMG fossils are morphologically simple; UMG fossil assemblages record low taxonomic diversity. But it is precisely because of its simple biota that the UMG deserves

closer study. Eukaryotes are diversifying during UMG time; biomarkers and body fossils indicate that nearly every major clade was present by the middle Neoproterozoic Era (Porter, 2004). Thus, the fact that we do not find diverse eukaryotes in UMG rocks suggests that they were excluded from the basin. It has been suggested that adverse environmental conditions delayed eukaryotic diversification until the end of the Mesoproterozoic Era (e.g. Anbar and Knoll, 2001); these conditions may have persisted in the UMG basin, preventing eukaryotes from gaining a foothold in prokaryote-dominated communities.

ACKNOWLEDGEMENTS

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Appendix A. *Information on localities where paleontological samples were collected. 'NA' = information not available.*

		Locality	GPS	Latitude & Longitude	Description	Lithology	References
Western UMG	Red Pine Shale	Tunnel Section	NA	NA	Along cliffs west of Hades campground	Coarse-grained (probably proximal pro-delta), blackish gray sandy siltstones	C. Dehler (pers. comm.); SMP
		Aspen Grove	NA	NA	Roadcut near the Aspen Grove campground, in the north fork Duchesne River Valley	Fractured and faulted, finely laminated mudstones and sandstones	C. Dehler (pers. comm.); SMP
		White Rocks	NA	NA	Roadcut along Utah State 191, near Red Springs campground	Black shales weathering to yellow (sulfur rich?), very fissile	C. Dehler (pers. comm.); SMP
		Henry's Fork	NA	NA	At trailhead of Henry's Fork Trail	Conglomerates and dark shales	C. Dehler (pers. comm.); SMP
		Ashley Creek	NA	NA	West, across Ashley Creek, from Red Pine Trail	Shales and interbedded sandstones	C. Dehler (pers. comm.); SMP
		Type Section	NA	NA	Red Pine Creek off of Smith and Moorehouse Creek	Gray to black shales	C. Dehler (pers. comm.) SMP
		Lower Hades	NA	NA	From the Hades campground, near Beaver Dam	Claystones, mudstones, and sandstones	C. Dehler (pers. comm.); SMP
		Yellowstone Creek	NA	40°36'49"N 110°22'04"W	Southwest facing cliff on Yellowstone Creek, 2.3 km upstream of Swift Creek	Sandstones, siltstones, and dark gray to greenish gray laminated shales	Hofmann, 1977
		Setting Road	NA	NA	Setting Road, c. 16 km east of kamas along Utah State 150	Thinly bedded gray shales	Vidal and Ford, 1985
	Moosehorn Lake Shale	Bald Mountain	NA	NA	Roadcut between Bald Mountain and Mudstone Mountain	Black, silty shales	C. Dehler (pers. comm.); SMP

Appendix A. *continued*

		Locality	GPS	Latitude & Longitude	Description	Lithology	References
Eastern UMG	Undivided UMG	Leidy Peak	NA	NA	Base of Leidy Peak	Green to gray shales	C. Dehler (pers. comm.); SMP
		Dutch John	N0633290 E4533324	NA	Roadcut on the north side of Utah State 191, along Mustang Ridge, just north of Dutch John	Variegated to gray to green shales, many with mm-scale laminations and black organics on bedding plane; interbedded with sandstones and pebble-sized conglomerates	C. Dehler (pers. comm.); RMN
		Carter Creek	N0610893 E4524420	NA	Roadcut on the south side of Utah State 191, just west of Flaming Gorge reservoir, at Carter Creek	Green shales with mudcracks, ripple marks, and rip-up clasts	C. Dehler (pers. comm.); RMN
		Hoop Lake	NA	NA	>100 m of measured section on the north side of the road to Hoop Lake in the eastern Uintas	Gray shales weathering to brown	C. Dehler (pers. comm.); RMN
		Sheep Creek	N0603734 E4526933	NA	The eastern end of the road through the Sheep Creek Geologic Loop in the eastern Uintas	Laminated dark gray to green shales	C. Dehler (pers. comm.); RMN
		Swallow Canyon	NA	NA	East of Rye Grass Canyon	Green to gray shales	C. Dehler (pers. comm.); RMN
		Pit Draw	NA	NA	East of Crouse Canyon	Green to gray shales	C. Dehler (pers. comm.); RMN
	Jesse Ewing Canyon Formation	Jesse Ewing Canyon	N0656796 E4531959	NA	Exposed along Jesse Ewing Canyon road into Brown's Park	Laminated gray to greenish gray shales	C. Dehler (pers. comm.); RMN