THE UNIVERSITY *of* EDINBURGH

Edinburgh Research Explorer

Doushantuo-type microfossils from latest Ediacaran phosphorites of northern Mongolia

Citation for published version:

Anderson, RP, Macdonald, FA, Jones, DS, McMahon, S & Briggs, DEG 2017, 'Doushantuo-type microfossils from latest Ediacaran phosphorites of northern Mongolia', *Geology*, vol. 45, pp. 1079-1082. <https://doi.org/DOI:10.1130/G39576.1>

Digital Object Identifier (DOI):

[DOI:10.1130/G39576.1](https://doi.org/DOI:10.1130/G39576.1)

Link:

[Link to publication record in Edinburgh Research Explorer](#)

Document Version:

Peer reviewed version

Published In:

Geology

General rights

Copyright for the publications made accessible via the Edinburgh Research Explorer is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy

The University of Edinburgh has made every reasonable effort to ensure that Edinburgh Research Explorer content complies with UK legislation. If you believe that the public display of this file breaches copyright please contact openaccess@ed.ac.uk providing details, and we will remove access to the work immediately and investigate your claim.

Geology

Doushantuo-type microfossils from latest Ediacaran phosphorites of northern Mongolia --Manuscript Draft--

Manuscript Number:	G39576R1
Full Title:	Doushantuo-type microfossils from latest Ediacaran phosphorites of northern Mongolia
Short Title:	Latest Ediacaran Doushantuo-type microfossils from Mongolia
Article Type:	Article
Keywords:	Ediacaran; Doushantuo; fossil embryos; acritarchs; phosphatization
Corresponding Author:	Ross Peter Anderson Yale University New Haven, Connecticut UNITED STATES
Corresponding Author Secondary Information:	
Corresponding Author's Institution:	Yale University
Corresponding Author's Secondary Institution:	
First Author:	Ross Peter Anderson
First Author Secondary Information:	
Order of Authors:	Ross Peter Anderson Francis Alexander Macdonald David S Jones Sean McMahon Derek Ernest Gilmor Briggs
Order of Authors Secondary Information:	
Manuscript Region of Origin:	MONGOLIA
Abstract:	Phosphorites of the latest Ediacaran upper Khesen Formation in the Khuvsgul Group of northern Mongolia preserve a newly discovered, three-dimensionally phosphatized Doushantuo-type microfossil assemblage. Eight genera include the second occurrence of the putative multicellular fossil animal embryo <i>Megasphaera</i> outside South China, the Doushantuo-Pertatataka-type acanthomorphic acritarchs <i>Appendisphaera</i> , <i>Cavaspina</i> , and <i>Variomargosphaeridium</i> , and the possible alga <i>Archaeophycus yunnanensis</i> . The assemblage occurs in the lowermost phosphorite horizon in foreland basin deposits on the Khuvsgul terrane; lithostratigraphic and ^{13}C correlation with the Zavkhan terrane of southwestern Mongolia establish a latest Ediacaran age for the fossiliferous phosphorites. Thus, this is the youngest Doushantuo-type assemblage yet reported. It extends the range of <i>Megasphaera</i> , filling a gap in the record of phosphatized embryo-like forms between the ~600 Ma Doushantuo Weng'an Biota and Cambrian examples. The Khesen fossil assemblage emphasizes the potential of Mongolian phosphorites to provide new paleontological data on the Ediacaran-Cambrian transition, and to resolve the phylogenetic debate surrounding <i>Megasphaera</i> embryo-like taxa.
Response to Reviewers:	Response to reviewer's comments Line 116. I believe that the specimens in Fig. 3B and 3C represent <i>Cavaspina acuminata</i> . They have too short and small processes to be <i>Tanarium</i> . We have removed the reference to <i>Tanarium</i> . However, our fossils most closely resemble <i>Cavaspina basiconica</i> from the Doushantuo Formation (Xiao et al., 2014, J. Paleo.) which has larger numbers of more densely packed processes and can reach

larger sizes more similar to those of our specimens than to the type material of *Cavaspina acuminata* from Siberia. Please see lines 102–108 in the revised manuscript.

Line 137. Correct the citation: it is fig. 103 parts 6, 7, and 18 in Liu et al., 2014 (not fig. 117).

We have corrected the citation as suggested. Please see lines 126–127 in the revised manuscript.

Lines 162-164. The morphologically complex acanthomorphic microfossils of the Pertatataka-Doushantuo type are actually known from the late Ediacaran strata in Siberia and were reported by Moczydlowska and Nagovitsin (2012 in *Precambrian Research* 198-199, 1-24) and Moczydlowska (2015, *Palynology online*, and 2016 *Palynology* 40, 1, 83-121). The cited publication Golubkova et al., 2015, deals with the East European Platform, Baltica, record of microfossils.

In the text we note that Doushantuo-Pertatataka-type acanthomorphs are generally known from strata deposited prior to or synchronously with carbon isotope excursions interpreted to be equivalent to the Shuram carbon isotope excursion. The fossils reported in the publications of the reviewer come from the Ura and Chench Formation in Siberia. The younger of these, the Chench, was deposited synchronously with the Shuram isotope excursion (see Pokrovskii et al. 2006, *Lithology and Mineral Resources for carbon isotope stratigraphy*). In contrast the fossils of Golubkova et al. (2015) may be in the “high horizons of the Upper Vendian (Ediacaran)” presumably above the Shuram excursion. Xiao et al. (2016, *Episodes*), in their review of acanthomorph biostratigraphy for the Subcommittee on Ediacaran Stratigraphy, detail this stratigraphic arrangement: “Doushantuo-Pertatataka-type acanthomorphs as a whole seem to be restricted to the lower Ediacaran System, below the Gaskiers-age Moelv diamictite in southern Norway and below negative 13C excursions in South China, South Australia, and Siberia that are interpreted as equivalent to the Shuram excursion. However, as mentioned above, recent reports of elements of Doushantuo- Pertatataka-type acanthomorphs in terminal Ediacaran rocks (Golubkova et al., 2015) need to be assessed critically.”

We have altered the text to make clear that the Doushantuo-Pertatataka-type assemblage is “generally” found prior to “or synchronously with carbon isotope excursions interpreted to be equivalent to the Shuram carbon isotope excursion”. Please see lines 157–160 in the revised manuscript.

We have also corrected the text by stating that the Golubkova et al. (2015) publication refers to the East European Platform rather than Siberia. Please see lines 154–156 in the revised manuscript.

Lines 165-166. I would rather say “predate the Shuram excursion” not the end of the excursion. The “end of the Shuram excursion” means that the successions of the EN3/Shuram excursion intervals contain the microfossils. In fact only the terminal Ediacaran member IV of the Doushantuo Formation is devoid insofar of the Doushantuo type microfossils in China. In Siberia and the EEP, and now in Mongolia, this type of microfossils occurs in the terminal Ediacaran strata. I agree that the record in Mongolia may be the youngest.

We have reworded this sentence to read: “Elsewhere in the world Doushantuo-Pertatataka-type acanthomorphs occur generally in rocks that predate or are synchronous with carbon isotope excursions interpreted to be equivalent to the Shuram carbon isotope excursion (Zhou et al., 2007; Xiao et al., 2016; Zhou et al., 2017)” for the reasons detailed in our response to the comment on lines 162-164 above. Please see lines 157–160 in the revised manuscript.

Line 166. I would add the recent reference to Zhou et al, 2017, *Precambrian Research*

288, 23-38.

We have added the reference as suggested. Please see lines 160 and 335–339 in the revised manuscript.

Lines 171-173. Absolutely, in Siberia and EEP, and now in Mongolia at the latest Ediacaran.

Please see our responses above to the reviewer's comments on lines 162–164 and 165–166.

Line 272. Incorrect reference. The paper by Liu et al., 2014 is published in Palaeontology Memoir 72, 1-133.

We have corrected the reference as suggested. Please see lines 261–264 in the revised manuscript.

Publisher: GSA
Journal: GEOL: Geology
DOI:10.1130/G39576.1

1 Doushantuo-type microfossils from latest Ediacaran
2 phosphorites of northern Mongolia

3 **Ross P. Anderson^{1*}, Francis A. Macdonald², David S. Jones³, Sean McMahon¹, and**
4 **Derek E.G. Briggs¹**

5 ¹*Department of Geology and Geophysics, Yale University, 210 Whitney Avenue, New*
6 *Haven, Connecticut 06511, USA*

7 ²*Department of Earth and Planetary Sciences, Harvard University, 20 Oxford Street,*
8 *Cambridge, Massachusetts 02138, USA*

9 ³*Geology Department, Amherst College, 11 Barrett Hill Road, Amherst, Massachusetts*
10 *01002, USA*

11 *E-mail: ross.anderson@yale.edu

12 **ABSTRACT**

13 Phosphorites of the latest Ediacaran upper Khesen Formation in the Khuvsgul
14 Group of northern Mongolia preserve a newly discovered, three-dimensionally
15 phosphatized Doushantuo-type microfossil assemblage. Eight genera include the second
16 occurrence of the putative multicellular fossil animal embryo *Megasphaera* outside South
17 China, the Doushantuo-Pertatataka-type acanthomorphic acritarchs *Appendisphaera*,
18 *Cavaspina*, and *Variomargosphaeridium*, and the possible alga *Archaeophycus*
19 *yunnanensis*. The assemblage occurs in the lowermost phosphorite horizon in foreland
20 basin deposits on the Khuvsgul terrane; lithostratigraphic and $\delta^{13}\text{C}$ correlation with the
21 Zavkhan terrane of southwestern Mongolia establish a latest Ediacaran age for the
22 fossiliferous phosphorites. Thus, this is the youngest Doushantuo-type assemblage yet

reported. It extends the range of *Megasphaera*, filling a gap in the record of phosphatized embryo-like forms between the ~600 Ma Doushantuo Weng'an Biota and Cambrian examples. The Khesen fossil assemblage emphasizes the potential of Mongolian phosphorites to provide new paleontological data on the Ediacaran–Cambrian transition, and to resolve the phylogenetic debate surrounding *Megasphaera* embryo-like taxa.

INTRODUCTION

The Ediacaran Period represents a critical juncture in Earth's history with the emergence of macroscopic eukaryotic communities with animal components (e.g., Xiao et al., 2016). Ornamented spheroidal microfossils, known as Doushantuo-Pertatataka-type acanthomorphic acritarchs, are found in Ediacaran successions globally (see Cohen and Macdonald, 2015, and references therein). The discovery of similar fossils preserved in phosphorites of the Doushantuo Formation at Weng'an in South China has yielded critical insights into Ediacaran paleobiology (e.g., Xiao et al., 2014a). Some of the Doushantuo fossils may be the oldest fossil animals, resembling embryonic forms, although their phylogenetic affinities, even after ~20 years of study, remain controversial—none of the characters used to marshal the evidence for an animal affinity are unequivocally diagnostic (Cunningham et al., 2017). Similar phosphatized fossils have been recovered recently elsewhere in South China (Zhang and Zhang, 2017). However, despite the importance of Doushantuo-type preservation to studies of Ediacaran diversity and animal evolution, few phosphatized fossils have been reported from other global Ediacaran successions with the exception of the Biskopås Formation, Norway and the Chambaghat Formation, India. Although the Biskopås Formation has yielded a variety of acanthomorphs, embryo-like forms have not been discovered (see

Vidal, 1990, and references therein), and possible embryo-like forms reported from the Chambaghat Formation (Shome et al., 2014) are not preserved with the same fidelity as those of the Doushantuo Formation. Here we report new Ediacaran phosphatized microfossils, which include Doushantuo-Pertatataka-type acanthomorphs and most notably multicellular embryo-like forms, from the upper Khesen Formation, Mongolia.

GEOLOGICAL SETTING

The Khesen Formation of the Khuvsgul Group (Fig. 1) is exposed discontinuously along a 250 km north-south belt on the western margin of Lake Khuvsgul in northern Mongolia (Macdonald and Jones, 2011). During Neoproterozoic and Cambrian time, the Khuvsgul and Zavkhan terranes formed one contiguous margin (Fig. 1A). Both terranes are characterized by ~800 Ma arc-volcanic rocks overlain by late Tonian rift-related strata, Cryogenian–early Ediacaran carbonate platforms interrupted by two Snowball Earth intervals, and latest Ediacaran to early Cambrian foreland basin successions (Macdonald et al., 2009; Kuzmichev and Larionov, 2011; Macdonald and Jones, 2011; Bold et al., 2016a; Bold et al., 2016b; Smith et al., 2016).

The Khesen Formation is divided into informal lower and upper members by a major unconformity (Fig. 1D, 1E, and 1F) that separates Marinoan glacial deposits and a basal Ediacaran cap carbonate succession from latest Ediacaran to early Cambrian carbonate, shale, and phosphorite deposits (Donov et al., 1967; Ilyin, 1973; Ilyin et al., 1986; Osokin and Tyzhinov, 1998; Macdonald and Jones, 2011). An equivalent unconformity is present on the Zavkhan terrane (Fig. 1C), separating early Ediacaran carbonates of the Ol and Shuurgat formations from latest Ediacaran phosphorite and carbonate of the terminal Ediacaran Zuun-Arts Formation (Bold et al., 2016b; Smith et

al., 2016). Latest Ediacaran–Terreneuvian phosphorite-bearing foreland basins formed on the Khuvsgul and Zavkhan terranes as the result of the collision of the Khantaishir-Agradag arc (Bold et al., 2016a; Smith et al., 2016). On both terranes, two phosphorite-rich successions bracket the Proterozoic–Phanerozoic boundary and additional phosphorite is present in overlying early Cambrian strata (Ilyin, 2004; Smith et al., 2016). The sediment-starved carbonate succession of the upper Khesen Formation preserves reworked granular phosphorite grainstone beds and massive replacive phosphate beds (Fig. 1). A minimum age constraint for the upper Khesen Formation is provided by Cambrian archaeocyathids and trilobites in the overlying Erkhelnur Formation (Ilyin and Zhuraveleva, 1968; Korobov, 1980).

A NEW FOSSIL ASSEMBLAGE

Eight genera of phosphatized microfossils (Figs. 2 and 3) were recovered from the lowermost phosphorite horizon of the upper Khesen Formation (see supplementary information for occurrences) with 5 genera confined to just two samples (Yale Peabody Museum YPM 536747 and 536748) from granular phosphorites along the ridgeline east of Urandush Uul (at 21 and 22 m, Fig. 1F). Probable cyanobacteria are found in most fossiliferous samples. Filaments of *Siphonophycus* occur as clusters of a few individuals, patchworks of hundreds of criss-crossing individuals, and clasts of microbial mat several hundred micrometers in maximum dimension. A few individuals of the possible oscillatoriacean cyanobacterium *Obruchevella* are also present (Fig. 3F).

Most of the fossil diversity in the assemblage is made up of probable eukaryotes. Simple leiosphaerid acritarchs are present in almost all fossiliferous samples. *Archaeophycus yunnanensis* occurs as solitary cells, or dyad, triad, tetrad, and octad

clusters (Figs. 2A and 3A). The tetrad form of this fossil was previously compared (as *Paratetraphycus giganteus*) to carposporangia of the modern bangialean alga *Porphyra* but convergent evolution among cyanobacteria and other algae cannot be ruled out (Xiao et al., 1998; Dong et al., 2009; Xiao et al., 2014a). In addition to these simple forms, the lower phosphorites yield a variety of Doushantuo-Pertatataka-type acanthomorphic acritarchs, most notably *Appendisphaera* (Fig. 2B), *Cavaspina* (Figs. 3B and 3C), and *Variomargosphaeridium* (Figs. 2C, 2D, 2E, and 2F). *Appendisphaera* is characterized by a spheroidal vesicle with densely spaced, long, hollow, unbranched processes (Moczydlowska et al., 1993; Moczydlowska, 2005). Three species are identified in the Khesen phosphorites: *A. grandis*, *A. fragilis*, and *A. tenuis*. An area of dense, dark organic matter can be present between the processes (Fig. 2B). Several Khesen fossils are tentatively identified as *Cavaspina*, which has conical processes that are commonly <10% of vesicle diameter (Moczydlowska et al., 1993). The Khesen specimens have larger vesicle sizes (>250 μm) than most reported examples of this genus, however, and the length of their processes, while commonly <10% of vesicle diameter, can reach ~13%. They most closely resemble *C. basiconica* from the Doushantuo Formation (cf. Fig. 8 parts 1–4 in Xiao et al., 2014b) in the number of processes and larger vesicle size. The most abundant acanthomorph (tens of specimens) is assigned to *Variomargosphaeridium gracile*. *Variomargosphaeridium* is characterized by heteromorphic, hollow, multi-branched processes (e.g., Fig. 2E); *V. gracile* is small (vesicle 30–150 μm in maximum diameter) with thin processes (9–21 μm in length). Some of the Khesen specimens contain numerous cell-like structures (Fig. 2C) allowing *V. gracile* to be added to a growing list of Ediacaran acanthomorphs which display

possible multicellular features (Xiao et al., 2014b). A number of specimens (<10 individuals) with branching processes that are <10% of the vesicle diameter may represent a new species of *Variomargosphaeridium* (Fig. 2F).

Most notably, the assemblage includes the second reported occurrences (~50 specimens of which <10 are well-preserved) of the multicellular fossil *Megasphaera* outside South China, where it occurs in the Doushantuo and Denying phosphorites (Xiao et al., 2014b; Zhang and Zhang, 2017). The Khesen fossils (Figs. 2G, 2H, 2I, 3D, and 3E) are readily accommodated by the emended diagnosis of *Megasphaera* (Xiao et al., 2014b), which calls for a large vesicle without long processes and enclosing one or more internal cells. However, the Khesen specimens also bear morphological similarities to leiosphaerid acritarchs from the upper Khesen Formation, to “leiospheres with cellular inclusions” from cherts of the Doushantuo Formation (cf. Fig. 103 parts 6, 7, and 18 in Liu et al., 2014), and to *Clonophycus* from other cherts of Ediacaran and Cambrian age in South China (Nantuo and Taozichong formations) (Oehler, 1977, 1978; Luo et al., 1982). They differ from *Leiosphaeridia* in the upper Khesen Formation in the presence of internal structures, are intermediate in size between species of *Megasphaera* found elsewhere and Doushantuo leiospheres with cellular inclusions, and are significantly larger than *C. guizhouensis*, the largest species of *Clonophycus*. The thick vesicle wall (Fig. 3D and 3E) supports our identification of these fossils as *Megasphaera*.

THE AGE OF THE KHESEN ASSEMBLAGE

Macdonald and Jones (2011) interpreted the age of the fossil-bearing lowermost phosphorite unit of the upper Khesen Formation as latest Ediacaran based on lithostratigraphic correlation with the Zuun-Arts Formation of southwestern Mongolia,

138 which preserves the Proterozoic–Phanerozoic boundary (Smith et al., 2016), and with the
139 Zabit Formation of Siberia, which yields the latest Ediacaran fossil *Cloudina*
140 (Kherzaskova and Samygin, 1992). The stratigraphy of the upper Khesen Formation is
141 remarkably similar to that of the Zuun-Arts Formation and the basal Bayangol Formation
142 (also southwestern Mongolia), comprising fossiliferous lower granular phosphorite beds,
143 limestone, and upper bedded phosphorites (Macdonald and Jones, 2011; Smith et al.,
144 2016). This correlation implies that the carbon isotope excursion between the
145 phosphorite-rich successions in the upper Khesen Formation (Ilyin, 2004; Vishnevskaya
146 and Letnikova, 2013, and Figure 1 herein) represents the Proterozoic–Phanerozoic
147 boundary as it does in the Zuun-Arts Formation (Smith et al., 2016; Fig. 1). Such a
148 correlation is consistent with the geodynamics of foreland basin development (Sinclair
149 and Naylor, 2012) in which the migration of loads can create diachronous deposition over
150 a few million years but not over tens of millions of years, as would be required for an
151 early Ediacaran (i.e., older than the Shuram carbon isotope excursion) age for the Khesen
152 fossils. Thus, geological evidence, as well as chemostratigraphic data, suggest that the
153 Khesen fossil assemblage lies immediately below the Proterozoic–Phanerozoic boundary.
154 This inference is consistent with recent reports of Doushantuo-Pertatataka-type
155 acanthomorphs from possible late Ediacaran strata on the East European Platform
156 (Golubkova et al., 2015).

157 Elsewhere in the world Doushantuo-Pertatataka-type acanthomorphs occur
158 generally in rocks that predate or are synchronous with carbon isotope excursions
159 interpreted to be equivalent to the Shuram excursion (Zhou et al., 2007; Xiao et al., 2016;
160 Zhou et al., 2017). The similarity between the Khesen assemblage reported here and that

of the older Doushantuo Formation includes the presence of *Appendisphaera grandis* and *A. tenuis*, *Cavaspina ?basiconica*, *Megasphaera*, and *Variomargosphaeridium gracile* (Xiao et al., 2014b). Such similarities can be accounted for by conditions favoring similar preservation in phosphate rather than coeval deposition, and imply longer ranges than previously recorded for some taxa. Thus, the Khesen fossils suggest that Doushantuo-Pertatataka-type acanthomorphs are not confined to pre-Shuram strata, but extend into latest Ediacaran time.

DISCUSSION AND CONCLUSIONS

The fossils of the upper Khesen Formation represent a new discovery of embryo-like forms (e.g., *Megasphaera*) in Ediacaran phosphorites, adding to those of the Doushantuo and Denying Formations, South China (Xiao et al., 2014b; Zhang and Zhang, 2017) and the Chambaghat Formation, India (Shome et al., 2014). *Megasphaera* is >200 μm in diameter in China and India (Shome et al., 2014; Xiao et al., 2014b; Zhang and Zhang, 2017). The Khesen fossils (Figs. 2G, 2H, 2I, 3D, and 3E) include specimens with a maximum diameter as low as 80 μm and probably represent a new species. The spheroidal cellular inclusions are rarely in contact, presumably due to some degradation and shrinkage. The number in each vesicle ranges from 20 to 106 but thin sections do not reveal them all. Although this new material does not settle the question of whether or not *Megasphaera* represents the earliest animal fossils, the exceptional preservation, diversity of form, and age range provide new constraints on the paleobiology of this iconic taxon.

The discovery of possible fossil embryos in latest Ediacaran strata fills the gap in exceptional phosphatic preservation between the older South China occurrences (and possible equivalents in India) and unequivocal embryos in Cambrian successions (e.g.,

Donoghue et al., 2006; Brasier and Callow, 2007; Muscente et al., 2015). Doushantuo-type preservation involves the concentration of phosphate and organic matter through siliciclastic sediment starvation and the Doushantuo Formation at Weng'an comprises phosphatic grainstones resulting from reworking and winnowing (Xiao et al., 1998; Xiao and Knoll, 1999; Muscente et al., 2015). The Khesen assemblage is preserved in similar facies, with both massive replacive and granular phosphorites preserved within a condensed sediment-starved carbonate succession. The preservation of the Khesen fossils rivals that in the Doushantuo Formation: cell-division is evident in extracted specimens of *Archaeophycus yunnanensis* (Fig. 3A), and processes on other acanthomorphs are preserved with exceptional fidelity (Figs. 2C, 2D, 3B, and 3C). This similarity emphasizes the potential of Mongolian phosphorites to provide new paleontological data on the Ediacaran–Cambrian transition, and to resolve the phylogenetic debate surrounding *Megasphaera* embryo-like taxa.

ACKNOWLEDGMENTS

S. Butts and J. Utrup managed collections. U. Bold helped with logistics in Mongolia. This work was supported by a GSA ExxonMobil Student Grant, the NASA Astrobiology Institute [NNA13AA90A], a NASA Earth and Space Science Fellowship [NNX14AP10H], and the Yale Institute for Biospheric Studies and Peabody Museum. We thank Malgorzata Moczydlowska, Shuhai Xiao, and an anonymous reviewer for helpful comments.

REFERENCES CITED

Bold, U., Crowley, J.L., Smith, E.F., Sambuu, O., and Macdonald, F.A., 2016a, Neoproterozoic to early Paleozoic tectonic evolution of the Zavkhan terrane of

- 207 Mongolia: Implications for continental growth in the Central Asian orogenic belt:
208 Lithosphere, v. 8, p. 729–750, <https://doi.org/10.1130/L549.1>.
- 209 Bold, U., Smith, E.F., Rooney, A.D., Bowring, S.A., Buchwaldt, R., Dudás, F.Ö.,
210 Ramezani, J., Crowley, J.L., Schrag, D.P., and Macdonald, F.A., 2016b,
211 Neoproterozoic stratigraphy of the Zavkhan Terrane of Mongolia: The backbone for
212 Cryogenian and early Ediacaran chemostratigraphic records: American Journal of
213 Science, v. 316, p. 1–63, <https://doi.org/10.2475/01.2016.01>.
- 214 Brasier, M.D., and Callow, R.H.T., 2007, Changes in the patterns of phosphatic
215 preservation across the Proterozoic–Cambrian transition: Memoirs of the Association
216 of Australasian Palaeontologists, v. 34, p. 377–389.
- 217 Cohen, P.A., and Macdonald, F.A., 2015, The Proterozoic record of eukaryotes:
218 Paleobiology, v. 41, p. 610–632, <https://doi.org/10.1017/pab.2015.25>.
- 219 Cunningham, J. A., Vargas, K., Yin, Z., Bengtson, S., and Donoghue, P. C. J., 2017, The
220 Weng'an Biota (Doushantuo Formation): An Ediacaran window on soft-bodied and
221 multicellular microorganisms: Journal of the Geological Society (London),
222 doi:10.1144/jgs2016-142.
- 223 Dong, L., Xiao, S., Shen, B., Zhou, C., Li, G., and Yao, J., 2009, Basal Cambrian
224 microfossils from the Yangtze Gorges Area (South China) and the Aksy Area (Tarim
225 Block, Northwestern China): Journal of Paleontology, v. 83, p. 30–44,
226 <https://doi.org/10.1017/S0022336000058108>.
- 227 Donoghue, P.C.J., Kouchinsky, A., Waloszek, D., Bengtson, S., Dong, X., Val'kov, A.K.,
228 Cunningham, J.A., and Repetski, J.E., 2006, Fossilized embryos are widespread but

- 229 the record is temporally and taxonomically biased: *Evolution & Development*, v. 8,
230 p. 232–238, <https://doi.org/10.1111/j.1525-142X.2006.00093.x>.
- 231 Donovan, N.A., Edemsky, H.B., and Ilyin, A.V., 1967, Cambrian phosphorites of Mongolia
232 Popular Republic: *Sovetskaya Geologia*, v. 3, p. 55–60.
- 233 Golubkova, E.Y., Zaitseva, T.S., Kuznetsov, A.B., Dovzhikova, E.G., and Maslov, A.V.,
234 2015, Microfossils and Rb-Sr age of glauconite in the key section of the Upper
235 Proterozoic of the northeastern part of the Russian Plate (Keltmen-1 Borehole):
236 *Doklady Earth Sciences*, v. 462, p. 547–551,
237 <https://doi.org/10.1134/S1028334X15060045>.
- 238 Ilyin, A.V., 1973, Khubsugul phosphorite-bearing basin: Moscow, *Geologicheskiy Institut*,
239 *Doklady Akademii Nauk SSSR*, p. 167.
- 240 Ilyin, A.V., 2004, The Khubsugul phosphate-bearing basin: New data and concepts:
241 *Lithology and Mineral Resources*, v. 39, p. 454–467,
242 <https://doi.org/10.1023/B:LIMI.0000040735.76025.80>.
- 243 Ilyin, A.V., Zaitsev, N.S., and Bjamba, Z., 1986, Proterozoic and Cambrian phosphorites
244 — deposits: Khubsugul, Mongolian People's Republic, *in* Cook, P. J., and Shergold,
245 J. H., eds., *Phosphate deposits of the world*: Cambridge, Cambridge University
246 Press, p. 162–174.
- 247 Ilyin, A.V., and Zhuraveleva, I.T., 1968, On the boundary between the Cambrian and the
248 Precambrian at Prikhubsugulie (Mongolian PR): *Doklady Akademii Nauk SSSR*,
249 v. 182, p. 1164–1166.

- 250 Kherzaskova, T.N., and Samygin, S.G., 1992, Tectonic conditions in the East Sayan
251 Vendian–Middle Cambrian terrigenous carbonate association: *Geotectonics*, v. 26,
252 p. 445–458.
- 253 Korobov, M.N., 1980, Lower Cambrian biostratigraphy and miomeroid trilobites of the
254 Lower Cambrian of Mongolia, *in* Menner, V. V., and Meyen, S. V., eds., *Lower*
255 *Cambrian and Carboniferous biostratigraphy of Mongolia*, Volume 26: Moscow,
256 *Trudy Sovmestnou Sovetsoko-Mongol-skoy Paleontologicheskoy Exspeditsii*, p. 5–
257 108.
- 258 Kuzmichev, A.B., and Larionov, A.N., 2011, The Sarkhoi Group in East Sayan:
259 Neoproterozoic (~770–800 Ma) volcanic belt of the Andean type: *Russian Geology*
260 *and Geophysics*, v. 52, p. 685–700, <https://doi.org/10.1016/j.rgg.2011.06.001>.
- 261 Liu, P., Xiao, S., Yin, C., Chen, S., Zhou, C., and Li, M., 2014, Ediacaran
262 acanthomorphic acritarchs and other microfossils from chert nodules of the Upper
263 Doushantuo Formation in the Yangtze Gorges Area, South China: *Paleontology*
264 *Memoir*, v. 72, p. 1–139, <https://doi.org/10.1666/13-009>.
- 265 Luo, Q., Wang, F., and Wang, Y., 1982, Uppermost Sinian–lowest Cambrian age
266 microfossils from Qingzhen-Zhijin County, Guizhou Province: *Bulletin Tianjin*
267 *Institute of Geology and Mineral Resources: Chinese Academy of Sciences*, v. 6,
268 p. 23–41.
- 269 Macdonald, F.A., and Jones, D.S., 2011, The Khubsugul Group, northern Mongolia, *in*
270 Arnaud, E., et al., eds., *The Geological Record of Neoproterozoic Glaciations:*
271 *Geological Society, London, Memoirs*, v. 36, p. 339–345.

- 272 Macdonald, F.A., Jones, D.S., and Schrag, D.P., 2009, Stratigraphic and tectonic
273 implications of a newly discovered glacial diamictite-cap carbonate couplet in
274 southwestern Mongolia: *Geology*, v. 37, p. 123–126,
275 <https://doi.org/10.1130/G24797A.1>.
- 276 Moczydlowska, M., 2005, Taxonomic review of some Ediacaran acritarchs from the
277 Siberian Platform: *Precambrian Research*, v. 136, p. 283–307,
278 <https://doi.org/10.1016/j.precamres.2004.12.001>.
- 279 Moczydlowska, M., Vidal, G., and Rudavskaya, V.A., 1993, Neoproterozoic (Vendian)
280 phytoplankton from the Siberia platform, Yakutia: *Palaeontology*, v. 36, p. 495–521.
- 281 Muscente, A.D., Hawkins, A.D., and Xiao, S., 2015, Fossil preservation through
282 phosphatization and silicification in the Ediacaran Doushantuo Formation (South
283 China): A comparative synthesis: *Palaeogeography, Palaeoclimatology,*
284 *Palaeoecology*, v. 434, p. 46–62, <https://doi.org/10.1016/j.palaeo.2014.10.013>.
- 285 Oehler, D.Z., 1977, Microflora of the H. Y. C. Pyrite Shale Member of the Barney Creek
286 Formation (McArthur Group), middle Proterozoic of northern Australia: *Alcheringa*,
287 v. 1, p. 315–349, <https://doi.org/10.1080/03115517708527768>.
- 288 Oehler, D.Z., 1978, Microflora of the middle Proterozoic Balbrini Dolomite (McArthur
289 Group) of Australia: *Alcheringa*, v. 2, p. 269–309,
290 <https://doi.org/10.1080/03115517808527785>.
- 291 Osokin, P.V., and Tyzhinov, A.V., 1998, Precambrian tilloids of the Oka-Khubsugul
292 phosphorite-bearing basin (Eastern Sayan, Northwestern Mongolia): *Lithology and*
293 *Mineral Resources*, v. 33, p. 142–154.

- 294 Sinclair, H., and Naylor, M., 2012, Foreland basin subsidence driven by topographic
295 growth versus plate subduction: Geological Society of America Bulletin, v. 124,
296 p. 368–379, <https://doi.org/10.1130/B30383.1>.
- 297 Shome, S., Mathur, V.K., Nath, S., Xiao, S., and Broce, J., 2014, Occurrence of
298 Neoproterozoic animal embryos in the Chambaghat Formation of Himachal Lesser
299 Himalaya, India: Current Science, v. 106, p. 813–815.
- 300 Smith, E.F., Macdonald, F.A., Petach, T.A., Bold, U., and Schrag, D.P., 2016, Integrated
301 stratigraphic, geochemical, and paleontological late Ediacaran to early Cambrian
302 records from southwestern Mongolia: Geological Society of America Bulletin,
303 v. 128, p. 442–468, <https://doi.org/10.1130/B31248.1>.
- 304 Vidal, G., 1990, Giant acanthomorphic acritarchs from the upper Proterozoic in southern
305 Norway: Palaeontology, v. 33, p. 287–298.
- 306 Vishnevskaya, I.A., and Letnikova, E.F., 2013, Chemostratigraphy of the Vendian–
307 Cambrian carbonate sedimentary cover of the Tuva-Mongolian microcontinent:
308 Russian Geology and Geophysics, v. 54, p. 567–586,
309 <https://doi.org/10.1016/j.rgg.2013.04.008>.
- 310 Xiao, S., and Knoll, A.H., 1999, Fossil preservation in the Neoproterozoic Doushantuo
311 phosphorite Lagerstätte, South China: Lethaia, v. 32, p. 219–238,
312 <https://doi.org/10.1111/j.1502-3931.1999.tb00541.x>.
- 313 Xiao, S., Muscente, A.D., Chen, L., Zhou, C.-M., Schiffbauer, J.D., Wood, A.D., Polys,
314 N.F., and Yuan, X.-L., 2014a, The Weng'an biota and the Ediacaran radiation of
315 multicellular eukaryotes: National Science Review, v. 1, p. 498–520,
316 <https://doi.org/10.1093/nsr/nwu061>.

- 317 Xiao, S., Narbonne, G.M., Zhou, C.-M., Laflamme, M., Grazhdankin, D.V.,
318 Moczydłowska-Vidal, M., and Cui, H., 2016, Towards an Ediacaran Time Scale:
319 Problems, Protocols, and Prospects: Episodes, v. 39, p. 540–555,
320 <https://doi.org/10.18814/epiiugs/2016/v39i4/103886>.
- 321 Xiao, S., Zhang, Y., and Knoll, A.H., 1998, Three-dimensional preservation of algae and
322 animal embryos in a Neoproterozoic phosphorite: Nature, v. 391, p. 553–558,
323 <https://doi.org/10.1038/35318>.
- 324 Xiao, S., Zhou, C., Liu, P., Wang, D., and Yuan, X., 2014b, Phosphatized
325 acanthomorphic acritarchs and related microfossils from the Ediacaran Doushantuo
326 Formation at Weng'an (South China) and their implications for biostratigraphic
327 correlation: Journal of Paleontology, v. 88, p. 1–67, <https://doi.org/10.1666/12-157R>.
- 328 Zhang, Y., and Zhang, X., 2017, New *Megasphaera*-like microfossils reveal their
329 reproductive strategies: Precambrian Research, v. 300, p. 141–150,
330 <https://doi.org/10.1016/j.precamres.2017.08.006>.
- 331 Zhou, C., Xie, G., McFadden, K.A., Xiao, S., and Yuan, X., 2007, The diversification
332 and extinction of Doushantuo-Pertatataka acritarchs in South China: Causes and
333 biostratigraphic significance: Geological Journal, v. 42, p. 229–262,
334 <https://doi.org/10.1002/gj.1062>.
- 335 Zhou, C., Xiao, S., Wang, W., Guan, C., Ouyang, Q., and Chen, Z., 2017, The
336 stratigraphic complexity of the middle Ediacaran carbon isotope record in the
337 Yangtze Gorges area, South China, and its implications for the age and
338 chemostratigraphic significance of the Shuram excursion: Precambrian Research, v.
339 288, p. 23–38, <https://doi.org/10.1016/j.precamres.2016.11.007>.

FIGURE CAPTIONS

Figure 1. Geological setting of the Khesen fossil assemblage. A: Map showing the extent of the Khuvsgul (Khuv.) and Zavkhan (Zav.) terranes. B: Geological map of the western margin of Lake Khuvsgul. C: Simplified stratigraphy of the Tsagaan Olom Group of the Zavkhan Basin (MU = Maikhan-Uul, BG = Bayangol). D: Simplified stratigraphy of the Khuvsgul Group (phos. = phosphorite). E: Khesen Formation at Ongoluk Gol with carbon isotope record. F: Khesen Formation stratigraphy from the ridgeline east of Urandush Uul.

Figure 2. Paleontology of the Khesen Formation in thin-sections. A: *Archeophycus yunnanensis*, YPM 536754. B: *Appendisphaera grandis*, YPM 536755. C: *Variomargosphaeridium gracile* with possible internal structures, YPM 536772. D: *V. gracile*, YPM 536800. E: *V. gracile* showing distal end of processes to the upper left, YPM 536802. F: *V. sp.*, YPM 536787. G–I: *Megasphaera sp.*. G: YPM 536794. H: YPM 536784. I: YPM 536766. Scale bars 50 µm.

Figure 3. Paleontology of the Khesen Formation revealed by 20% acetic acid maceration. A: *Archaeophycus yunnanensis* showing T cell-division, YPM 538070. B–C: *Cavaspina ?basiconica*. B: YPM 538071 C: YPM 538072. D–E: *Megasphaera sp.*. D: YPM 538073. E: YPM 538074. F: *Obruchevella magna*, YPM 538075. Scale bars 100 µm.

363 1GSA Data Repository item 2017xxx, xxxxxxxx, is available online at
364 <http://www.geosociety.org/datarepository/2017/> or on request from
365 editing@geosociety.org.

Figure 2

Figure 3

[Click here to download](#)

Supplementary Information

Doushantuo-type microfossils from latest Ediacaran phosphorites of northern Mongolia

Ross P. Anderson, Francis A. Macdonald, David S. Jones, Sean McMahon, Derek E.G. Briggs

Email: ross.anderson@yale.edu

Methods

The Khesen fossils were examined in thin-section and by scanning electron microscopy following 20% acetic acid maceration. All materials are deposited in the Yale Peabody Museum of Natural History (YPM). Carbon isotope ratios of micro-drilled carbonate powders were measured following methods described in Macdonald et al. (2009).

Biostratigraphy

Khesen Gol

YPM 536746 and 536748 are at 0 and 3 m respectively in Fig. 1E.

Urandush Uul

YPM 536747 and 536748 are at 21 and 22 m respectively in Fig. 1F.

	Khesen Gol		Urandush Uul	
	YPM 536746	YPM 536749	YPM 536747	YPM 536748
Cyanobacteria				
<i>Obruchevella delicata</i>	R			
<i>Obruchevella magna</i>			R	R
<i>Obruchevella parvissima</i>				R
<i>Obruchevella</i> sp.				R
<i>Siphonophycus</i> spp.	C	C	C	C
?Algae				
<i>Archaeophycus yunnanensis</i>			R	
Acritarchs				
<i>Appendisphaera grandis</i>			R	
<i>Appendisphaera fragilis</i>		R		R
<i>Appendisphaera tenuis</i>			R	
<i>Cavaspina ?basiconica</i>			R	
<i>Leiosphaeridia</i> spp.	R	R	C	C
<i>Megasphaera</i> sp.			C	C
<i>Variomargosphaeridium gracile</i>			C	C
<i>Variomargosphaeridium</i> sp.				R

Table S1: Biostratigraphy of the upper Khesen Formation showing reported taxa from the four most diverse samples and their relative abundance within the assemblage. R = rare (isolated individuals, only a few specimens). C = common (10s of individuals). In the case of *Megasphaera* 10s of individuals are reported but only a few are preserved with enough fidelity to confidently interpret internal structures. YPM sample numbers are given for reference.

Figure S1: Expanded stratigraphy showing relationships between Khesen, Ongoluk, and Urandush Uul localities. See Figure 1 for locality information.

References

Macdonald, F.A., Jones, D.S., and Schrag, D.P., 2009. Stratigraphic and tectonic implications of a newly discovered glacial diamictite-cap carbonate couplet in southwestern Mongolia: *Geology*, v. 37, p. 123–126, <https://doi.org/10.1130/G24797A.1>.