THE GEOLOGICAL SOCIETY OF AMERICA®

Integrated stratigraphic, geochemical, and paleontological late Ediacaran to early Cambrian records from southwestern Mongolia: Reply

E.F. Smith[1,2,†], F.A. Macdonald[3], T.A. Petach[4], and U. Bold[5]

[1]*Smithsonian Institution, P.O. Box 37012, MRC 121, Washington, DC 20013-7012, USA*
[2]*Department of Earth and Planetary Sciences, Johns Hopkins University, 3300 San Martin Drive, Baltimore, Maryland 21218, USA*
[3]*Department of Earth and Planetary Sciences, Harvard University, 20 Oxford Street, Cambridge, Massachusetts 02138, USA*
[4]*School of Civil and Environmental Engineering, Cornell University, 220 Hollister Hall, Ithaca, New York 14853, USA*
[5]*Department of Earth and Planetary Science, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan*

In their comment, Landing and Kruse disagree with some of our discussion and, at times, use blanket statements to incorrectly summarize from the Smith et al. (2016) paper. This is not the venue for a discussion and rehashing of the details discussed at length in the text of the publication. Here, we respond only to what we were able to identify as the key questions and issues raised in the comment.

In the Zavkhan Basin, the regional geologic context is essential to any discussion of biostratigraphy. Using geologic mapping, stratigraphy, structure, a new age model, detrital zircon geochronology, and the presence of a tectonic mélange, we have demonstrated that latest Ediacaran through early Cambrian strata in the Zavkhan terrane were deposited in a foreland basin (Macdonald et al., 2009; Smith et al., 2016; Bold et al., 2016a), and not, as Landing and Kruse wrote, in a forearc. Major lateral facies changes over short spatial distances in what was a tectonically active basin render lithostratigraphic correlations—the correlation method that, by and large, was previously used for biostratigraphic studies in this basin (i.e., Brasier et al., 1996; Khomentovsky and Gibsher, 1996)—insufficient for intrabasinal correlation. Particularly, previous correlations used early diagenetic phosphorite horizons, which are diachronous across the basin. Further complicating any biostratigraphic study of this basin is Paleozoic tectonism (Bold et al., 2016a). Many of the previously studied areas were mismapped or not mapped at all, and as a result, some of the fossil horizons were misplaced in a stratigraphic context. The data for our new structural interpretations and geologic maps are discussed in the text. One of the goals of this project was, through detailed geologic mapping and a basinwide facies model, to use sequence-stratigraphic and chemostratigraphic correlations to place early Cambrian small shelly fossil horizons into a stratigraphic and geologic framework and construct a new age model for fossil horizons that is independent of the previous, inherently circular lithostratigraphic and biostratigraphic age model.

After establishing a regional stratigraphic and geologic framework, we used carbon isotope chemostratigraphy for global correlation and to construct an age model. Despite Landing and Kruse's claims, we never asserted that the Zavkhan strata lack discontinuities. In fact, a major contribution of our studies has been to refine the nature and duration of hiatuses within the succession (Macdonald et al., 2009; Smith et al., 2016; Bold et al., 2016a, 2016b). While we do believe the entire succession (Zuun-Arts through Khairkhan Formations) was deposited relatively rapidly in a single basin-forming event, with the flysch and mélange of the Khairkhan Formation marking the closure of the foreland basin, there are many disconformities—some of which are very subtle—at sequence boundaries, particularly in the more proximal sections. We do, however, assert that the section at Orolgo Gorge (E1220, E1223) is the most distal, the most carbonate-dominated, and the most continuous section preserved in the basin. Because of this, it is this stratigraphic section that forms the backbone of our chemostratigraphic correlations and age model (see column A in Smith et al., 2016, fig. 11).

After clarifying the stratigraphic and geologic questions raised by Landing and Kruse, we can now address their specific biostratigraphic concerns. We organize the rest of our response into what we have identified as their three main categories of comments: (1) archaeocyath biostratigraphy, (2) small shelly fossil biostratigraphy, and (3) *Treptichnus pedum* and the placement of the Ediacaran-Cambrian boundary in the Zavkhan Basin.

Landing and Kruse raise three interrelated concerns regarding the archaeocyath biostratigraphy presented in Smith et al. (2016). The first is that they generally disagree with the chemostratigraphic age model used for the Salaagol Formation in Smith et al. (2016); the second, and related point, is that, based on previous archaeocyath biostratigraphy, they contest the claim that the archaeocyaths in the Zavkhan Basin are the oldest ones globally; and third, they contend that similarities between the archaeocyath genera and species in Siberia and southwest Mongolia indicate extensive faunal exchange between the two regions.

Landing and Kruse disagree with the chemostratigraphic age model for the Salaagol Formation presented in Smith et al. (2016) because it is in contradiction with the regional archaeocyath biostratigraphic framework from Siberia with which they are most familiar. They suggest that the extremely positive $\delta^{13}C$ excursion (+5‰–7‰) in the Salaagol Formation is a "local expression of the IV excursion within the lower Atdabanian of Siberia," an excursion which typically has $\delta^{13}C$ values of +2‰–3‰ (Kouchinsky et al., 2007; Landing et al., 2013), without offering an explanation or mechanism for why this single excursion in southwest Mongolia would be so unusually ^{13}C-enriched in Mongolia. We emphasize that the late Nemakit-Daldynian and Nemakit-Daldynian–Tommotian boundary is the only time interval in all of the Cambrian Period in which global $\delta^{13}C$ values are so heavy (i.e., Saltzman and Thomas, 2012). The Steptoean positive carbon isotope excursion (SPICE) event, with $\delta^{13}C$ values that reach +4‰–5‰ in the Furongian (Upper Cambrian), is the only other excursion in the Cambrian that comes close to having such ^{13}C-enriched $\delta^{13}C$ values (Saltzman, 2005). It is difficult to imagine a local or diagenetic effect that would selectively affect the $\delta^{13}C$ values of only the Salaagol

†smithef@si.edu

GSA Bulletin; doi: 10.1130/B31763.1.

Formation carbonates to generate such unusual ^{13}C enrichment in all stratigraphic sections across the basin. Carbon isotope chemostratigraphic correlations can sometimes be ambiguous and difficult to interpret, but these enriched values of the Salaagol Formation carbonates are distinctive, and therefore they make this specific correlation relatively straightforward.

Landing and Kruse also disagree with our discussion on the significance of a thick sandstone unit below the Salaagol archaeocyath reefs and sandstone and conglomerate beds within the Salaagol Formation. Despite their portrayal of our discussion of this in their comment, we also recognized the thick sandstone unit below the base of the Salaagol Formation in all of our measured sections. We referred to this unit as "BG5/6," the top member of the Bayangol Formation in figures 8 and 9 of Smith et al. (2016). In the more proximal sections, there is evidence that there is some time missing at the base of this coarse siliciclastic unit. We even demonstrate the diachronous nature of this unconformity in figure 9, in which the basal Salaagol Formation in the most proximal section (see section E1325) only captures the end of the positive δ^{13}C excursion. We do not dispute that there is time missing at the base of the Salaagol Formation, but we disagree with Landing and Kruse over the duration of this hiatus. Furthermore, in the most distal measured section in the basin in Orolgo Gorge (E1220, E1223 *in* Smith et al., 2016, fig. 9), the upper Bayangol Formation is characterized by a mixed carbonate and siliciclastic succession that is correlative with the siliciclastic units "BG5" and "BG6" in other sections in the basin; the distal, carbonate-rich section in Orolgo Gorge provides confidence that, regionally, there is not a major hiatus at the basal contact of the Salaagol Formation.

Given the unusually ^{13}C-enriched chemostratigraphic values of the lower Salaagol Formation, discussed in the preceding paragraphs, the lower to middle Salaagol Formation cannot be Atdabanian or Botomian in age. As we point out in the paper, the middle to upper part of the Salaagol Formation is characterized by δ^{13}C values of –1‰ to –2‰, values which are not diagnostic of any time interval. Thus, if there are Atdabanian and Botomian archaeocyaths in the Salaagol Formation, then they are in this middle to upper part of the formation, and there must be an intraformational unconformity (p. 462). We tentatively reject this model because it necessitates a more complicated, multistage subsidence model, and, as Landing and Kruse themselves point out, there is little sedimentological evidence other than the intraformational conglomerates in SE Khukh Davaa that support this model. Moreover, no trilobites or trilobite hash were found in any of the hundreds of meters of heterolithic strata of the Salaagol Formation, consistent with a pretrilobite age (Smith et al., 2016). A more thorough discussion of the implications of the new age model is on page 462 (Smith et al., 2016).

Although Landing and Kruse contend that similarities between the archaeocyath genera and species in Siberia and southwest Mongolia indicate extensive faunal exchange between the two regions, there is very little data that would suggest robust ties between the Siberian and Mongolian terranes during the Paleozoic. As they themselves point out, southwest Mongolia is known to have been separate from the Siberian Platform during the early Cambrian (Evans et al., 1996; Wilhem et al., 2012). Previously, Cambrian trilobites (e.g., Cocks and Torsvik, 2007) and Ordovician to Silurian brachiopods (Wang et al., 2011) were used to suggest Paleozoic paleogeographic ties between the two regions, but, more recently, these biostratigraphic links have been disproven. Although no trilobites have been identified on the Zavkhan terrane, trilobites from the adjacent Tuva-Mongolia terrane have been shown to be distinct from those of Siberia (Atashkin, 1995; Korobov, 1980, 1989). Additionally, the distinctive *Tuvaella* brachiopod is only present on "peri-Siberian" terranes and not Siberia (Wang et al., 2011), and the geographic distributions of other brachiopod assemblages (Harper et al., 2013) and crinoids (Webster and Ariunchimeg (2004) are distinctly different between Mongolian terranes and Siberia. Moreover, recent paleomagnetic constraints have demonstrated that the Zavkhan terrane was independent from Siberia for much of the Paleozoic (Kilian et al., 2016). There is no robust geologic, paleomagnetic, or biogeographic evidence to suggest that there could have been extensive archaeocyath faunal exchange between Siberia and Mongolia.

Landing and Kruse further contest that the archaeocyaths in Mongolia are among some of the oldest globally. It appears that some of the concerns about the first appearance datum (FAD) of archaeocyaths are due in part to confusion regarding the nomenclature and the unofficial subdivisions of the early Cambrian. The Tommotian in Siberia is generally considered correlative with Stage 2 of the Terreneuvian Series, but neither the upper nor the lower boundary of Stage 2 has yet been defined. The FAD of the archaeocyaths in the Salaagol Formation is within the younger of the two highly ^{13}C-enriched excursions. Because we interpret this extremely positive δ^{13}C excursion followed by a downturn to values of ~–2‰ as unique to the Nemakit-Daldynian–Tommotian boundary (see Maloof et al., 2010), we interpret the archaeocyaths from the Salaagol Formation in Mongolia as only *slightly* older than the oldest archaeocyaths from Siberia. It is also relevant to note that at the Selinde River section, archaeocyath debris has been found stratigraphically below the last large positive δ^{13}C excursion (Kouchinsky et al., 2005), leading some to argue that there are Siberian archaeocyaths in the latest Nemakit-Daldynian (Khomentovsky et al., 1990; Khomentovsky and Karlova, 1993). Based on these discrepancies, we suggest that much of the existing global archaeocyath taxonomy and biostratigraphy needs to be revisited, revised, and integrated with independent chronostratigraphy. In future biostratigraphic studies, radioisotopic and relative age models are critical to avoiding circular arguments that rely only on regional biostratigraphic ranges.

Landing and Kruse also raise concerns about the revised FAD of small shelly fossils in the Zavkhan Basin. Here, the problem is an issue of what we interpret as mismapping and miscorrelation rather than interpretations regarding a chemostratigraphic age model. Our data supporting this are described in part below. The lowest reports of anabaritids from Brasier et al. (1996) and Khomentovsky and Gibsher (1996) are reported from the Zuun-Arts Formation in Orolgo Gorge (or what they refer to as "Orolchayn Gol"), but these fossils were initially discovered by Endonzhamts and Lkhasuren (1988; see small shelly fossil horizon "b" in figure 5 and "8323" in figure 6 *of* Brasier et al., 1996; figure 13 *in* Khomentovsky and Gibsher, 1996). The small shelly fossils from this locality are very obvious in outcrop (Smith et al., 2016, fig. 3H) and are immediately above a phosphatic shale interval. No dissolutions are required to see these fossils. In Brasier et al. (1996), this horizon was placed into a composite measured section using lithostratigraphic correlation. However, the Zuun-Arts Formation is almost entirely faulted out at this locality (Smith et al., 2016, fig. 6E). What previous workers considered the basal Zuun-Arts Formation in this gorge is actually the basal Bayangol Formation; there is no lower to middle Zuun-Arts Formation present anywhere in this gorge. The small shelly fossil horizon that was previously reported from this locality is above the phosphatic shale in the basal Bayangol Formation, not the phosphatic shale in the basal Zuun-Arts Formation, as was previously assumed. A similar mapping and correlation problem exists for small shelly fossil beds "8305," "8325," and "8326" (see Khomentovsky and Gibsher, 1996, fig. 13); these fossils are all part of the Endonzhamts and Lkhasuren (1988) collection and were later placed into what we believe is an incorrect stratigraphic framework. None of the small shelly fossils from the Zuun-Arts Formation was collected or first reported by any of the authors in the series of 1996 *Geological Magazine* publications that were part of the International Geoscience Programme (IGCP) Project 303, "Late Precambrian–Cambrian Event Stratigraphy." In Smith et al. (2016), the small shelly fossils beds that were previously placed in the Zuun-Arts Formation have been shifted up into the Bayangol Formation. It is possible that, globally, there are small shelly fossils below the large negative basal Cambrian $\delta^{13}C$ excursion (BACE); however, there is no evidence to support that in the Zavkhan Basin in southwest Mongolia.

Finally, Landing and Kruse misrepresent our discussion of the FAD of *T. pedum* and the placement of the Ediacaran-Cambrian boundary in Mongolia. The point we make in the abstract and later on in the text is that because of the apparent facies dependence of the preservation of *T. pedum*, this trace fossil is not useful in identifying the Ediacaran-Cambrian boundary in the Zavkhan Basin (Smith et al., 2016, p. 459). In southwest Mongolia, there are more useful secondary chronostratigraphic markers (i.e., FAD of small shelly fossils and the large negative $\delta^{13}C$ excursion near the top of the Zuun-Arts Formation) that suggest that the Ediacaran-Cambrian boundary is at or near the contact between the Zuun-Arts and Bayangol Formations. We do state that the negative excursion at the top of Zuun-Arts Formation correlates to the "W excursion" of Brasier et al. (1996) and globally with the BACE (Smith et al., 2016, p. 459), so on this point, there is no disagreement. The broader question we raised in the discussion of *T. pedum* and the placement of the Ediacaran-Cambrian boundary in the Zavkhan Basin is the utility of *T. pedum* as a global chronostratigraphic marker for one of the most important boundaries in Earth history. In southwest Mongolia, with its mixed siliciclastic-carbonate succession that preserves a wide range of depositional environments, *T. pedum* is found hundreds of meters above the FAD of small shelly fossils, the BACE, and other Cambrian trace fossils, and, as a result, we suggest that the biostratigraphic marker for this global boundary could be reconsidered.

One of the main goals of this work was to move beyond traditional and often circular biostratigraphic correlations to create an independent chronology of biological and environmental events across the Proterozoic-Phanerozoic transition. Landing and Kruse take the traditional biostratigraphic view of the Paleozoic that has persisted for over 150 yr and has left us with no explanation for the apparently rapid expansion of diversity in the early Cambrian fossil record. With new tools coupled with more extensive field studies, we have the opportunity to move beyond this static view of early animal evolution and to construct records of evolution that keep time as an independent variable. We challenge the notion that paleontological constraints are robust without an independent method of telling time in the rock record.

REFERENCES CITED

Atashkin, V.A., 1995, The Cambrian System of the Foldbelts of Russia and Mongolia: Correlation Chart and Explanatory Notes: International Union of Geological Sciences Publication 32, 132 p.

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 Mongolia: Implications for continental growth in the Central Asian orogenic belt: Lithosphere, v. 8, no. 6, p. 729–750, doi:10.1130/L549.1.

Bold, U., Smith, E.F., Rooney, A.D., Bowring, S.A., Buchwaldt, R., Dudás, F.Ő., Ramezani, J., Crowley, J.L., Schrag, D.P., and Macdonald, F.A., 2016b, Neoproterozoic stratigraphy of the Zavkhan terrane of Mongolia: The backbone for Cryogenian and early Ediacaran chemostratigraphic records: American Journal of Science, v. 316, no. 1, p. 1–63, doi:10.2475/01.2016.01.

Brasier, M.D., Shields, G., Kuleshov, V.N., and Zhegallo, E.A., 1996, Integrated chemo- and biostratigraphic calibration of early animal evolution: Neoproterozoic–early Cambrian of southwest Mongolia: Geological Magazine, v. 133, no. 4, p. 445–485, doi:10.1017/S0016756800007603.

Cocks, L.R.M., and Torsvik, T.H., 2007, Siberia, the wandering northern terrane, and its changing geography through the Palaeozoic: Earth-Science Reviews, v. 82, no. 1–2, p. 29–74, doi:10.1016/j.earscirev.2007.02.001.

Endonzhamts, Z., and Lkhasuren, B., 1988, Stratigrafiya pogranichnykh tolshch dokembriya i kembriya Dzabkhanskoy zony, *in* Khomentovsky, V.V., and Shenfil', V.Yu., eds., Pozdniy Dokembriy i Ranniy Paleozoy Sibiri, Rifey i Vend: Novosibirsk, SSSR, Institut Geologii i Geofiziki, Sibirskoe Otdelenie, Akademiya Nauk: SSSR, p. 150–162.

Evans, D.A., Zhuravlev, A.Y., Budney, C.J., and Kirschvink, J.L., 1996, Palaeomagnetism of the Bayan Gol formation, western Mongolia: Geological Magazine, v. 133, p. 487–496.

Harper, D.A., Rasmussen, C.M., Liljeroth, M., Blodgett, R.B., Candela, Y., Jin, J., Percival, I.G., Rong, J.Y., Villas, E., and Zhan, R.B., 2013, Biodiversity, biogeography and phylogeography of Ordovician rhynchonelliform brachiopods, *in* Harper, D.A.T., and Servais, T., eds., Early Palaeozoic Biogeography and Palaeogeography: Geological Society [London] Memoir 38, p. 127–144.

Khomentovsky, V.V., and Gibsher, A.S., 1996, The Neoproterozoic–Lower Cambrian in northern Govi-Altay, western Mongolia: Regional setting, lithostratigraphy and biostratigraphy: Geological Magazine, v. 133, no. 4, p. 371–390.

Khomentovsky, V.V., and Karlova, G.A., 1993, Biostratigraphy of the Vendian–Cambrian beds and the lower Cambrian boundary in Siberia: Geological Magazine, v. 130, no. 1, p. 29–45, doi:10.1017/S0016756800023700.

Khomentovsky, V.V., Val'Kov, A.K., and Karlova, G.A., 1990, Novye dannye po biostratigrafii perekhodnykh vend-kembrijskikh sloev v bassejne srednego techeniya r. Aldan. [New data on the biostratigraphy of transitional Vendian–Cambrian strata in the middle reaches of the River Aldan], in Khomentovsky, V.V., and Gibsher, A.S., eds., Pozdnij Dokembrij i Rannijpaleozoj Sibiri, Voprosy Regional'noj Stratigrafii: Novosibirsk, Institut geologii i geofiziki, Sibirskoe otdelenie, Akademiya nauk SSSR, p. 3–57.

Kilian, T.M., Swanson-Hysell, N.L., Bold, U., Crowley, J., and Macdonald, F.A., 2016, Paleomagnetism of the Teel basalts from the Zavkhan terrane: Implications for Paleozoic paleogeography in Mongolia and the growth of continental crust: Lithosphere, v. 8, no. 6, p. 699–715.

Korobov, M.N., 1980, Biostratigrafiya i miomernye trilobity nizhnego kembriya Mongolii [Biostratigraphy and miomerid trilobites from the Lower Cambrian of Mongolia]: The Joint Soviet-Mongolian Scientific-Research Geological Expedition Transactions, v. 26, p. 5–108.

Korobov, M.N., 1989, Biostratigraphy and Lower Cambrian polymerid trilobites of Mongolia: Joint Soviet-Mongolian Scientific Research Geological Expedition Transactions, v. 48, p. 1–202.

Kouchinsky, A., Bengtson, S., Pavlov, V., Runnegar, B., Val'kov, A., and Young, E., 2005, Pre-Tommotian age of the lower Pestrotsvet Formation in the Selinde section on the Siberian platform: Carbon isotopic evidence: Geological Magazine, v. 142, no. 4, p. 319–325, doi:10.1017/S0016756805000865.

Kouchinsky, A., Bengtson, S., Pavlov, V., Runnegar, B., Torssander, P., Young, E., and Ziegler, K., 2007, Carbon isotope stratigraphy of the Precambrian–Cambrian Sukharikha River section, northwestern Siberian platform: Geological Magazine, v. 144, no. 4, p. 609–618, doi:10.1017/S0016756807003354.

Landing, E., Geyer, G., Brasier, M.D., and Bowring, S.A., 2013, Cambrian evolutionary radiation: Context, correlation, and chronostratigraphy—Overcoming deficiencies of the first appearance datum (FAD) concept: Earth-Science Reviews, v. 123, p. 133–172, doi:10.1016/j.earscirev.2013.03.008.

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, no. 2, p. 123–126, doi:10.1130/G24797A.1.

Maloof, A.C., Porter, S.M., Moore, J.L., Dudás, F.Ö., Bowring, S.A., Higgins, J.A., Fike, D.A., and Eddy, M.P., 2010, The earliest Cambrian record of animals and ocean geochemical change: Geological Society of America Bulletin, v. 122, no. 11–12, p. 1731–1774.

Saltzman, M.R., 2005, Phosphorus, nitrogen, and the redox evolution of the Paleozoic oceans: Geology, v. 33, no. 7, p. 573–576, doi:10.1130/G21535.1.

Saltzman, M.R., and Thomas, E., 2012, Carbon isotope stratigraphy, *in* Gradstein, F.M., Ogg, J.G., Schmitz, M., and Ogg, G., eds., The Geologic Time Scale, Volume 1: The Netherlands, Elsevier, p. 207–232.

Smith, E.F., Macdonald, F.A., Petach, T.A., Bold, U., and Schrag, D.P., 2016, Integrated stratigraphic, geochemical, and paleontological late Ediacaran to early Cambrian records from southwestern Mongolia: Geological Society of America Bulletin, v. 128, no. 3–4, p. 442–468, doi:10.1130/B31248.1.

Wang, T., Zheng, Y., Zhang, J., Zeng, L., Donskaya, T., Guo, L., and Li, J., 2011, Pattern and kinematic polarity of late Mesozoic extension in continental NE Asia: Perspectives from metamorphic core complexes: Tectonics, v. 30, no. 6, TC6007, doi:10.1029/2011TC002896.

Webster, G.D., and Ariunchimeg, Y.A., 2004, The northernmost Emsian crinoids known, a Devonian fauna from the Chuluun Formation, Shine Jinst area, southern Mongolia: Geobios, v. 37, no. 4, p. 481–487, doi:10.1016/j.geobios.2003.07.001.

Wilhem, C., Windley, B.F., and Stampfli, G.M., 2012, The Altaids of Central Asia: A tectonic and evolutionary innovative review: Earth-Science Reviews, v. 113, p. 303–341.

Science Editor: Bradley S. Singer

Manuscript Received 3 February 2017
Revised Manuscript Received 18 March 2017
Manuscript Accepted 4 April 2017

Printed in the USA