Geology

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Geology 2009;37;123-126
doi:10.1130/G24797A.1

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THE GEOLOGICAL SOCIETY OF AMERICA

Stratigraphic and tectonic implications of a newly discovered glacial diamictite–cap carbonate couplet in southwestern Mongolia

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ABSTRACT

We report here the discovery of a new end-Cryogenian glacial diamictite and an overlying basal Ediacaran cap carbonate within the Tsagaan Oloom Formation of southwestern Mongolia. The identification of the Cryogenian-Ediacaran boundary, coupled with new $\delta^{13}C$ chemostratigraphic profiles, facilitates the integration of the Neoproterozoic stratigraphy of Mongolia with records elsewhere. These correlations indicate that a previously unrecognized, –16‰ Cryogenian $\delta^{13}C$ anomaly is present in the newly defined Tayshir member (informal) of the Tsagaan Oloom Formation. Furthermore, chemostratigraphic and lithostratigraphic relationships suggest an ~35 m.y. depositional hiatus below the phosphorite-bearing Zunne Arts member (informal) of the upper Tsagaan Oloom Formation and that subsidence renewed in the latest Ediacaran–Early Cambrian. We propose that the lower ~1500 m of the Tsagaan Oloom Formation was deposited on a thermally subsiding passive margin after Rodinia-age rifting, whereas the Zunne Arts member and the overlying ~1600 m of Early Cambrian strata were deposited in a foredeep basin that formed as the southern margin of the Dzabkhan terrane was subducted beneath the Khantayshir-Dariv arc.

INTRODUCTION

The Dzabkhan basin of southwestern Mongolia hosts glacial deposits, phosphorites, and copious trace fossils, all within carbonate-dominated strata (Khomentovsky and Gibsher, 1996). Previous studies have only described early Cryogenian diamictites at the base of the succession (Lindsay et al., 1996) and have failed to identify any pronounced negative $\delta^{13}C$ anomalies between these glacial deposits and Early Cambrian strata (Brasier et al., 1996), leaving correlations with Neoproterozoic strata elsewhere ambiguous. Understanding the timing of deposition facilitates the placement of this record into a global context and provides constraints on tectonic models for the Paleozoic accretion of Central Asia.

The Dzabkhan terrane is a composite Precambrian terrane, hosting a heterogeneous Archean and Proterozoic crystalline basement intruded by ca. 800 Ma continental arc volcanism (Badarch et al., 2002). The Dzabkhan basin and the adjacent Khubsugul basin to the north (Fig. 1A) formed on segments of a ribbon continent that rifted away from Siberia in the late Neoproterozoic (Kuzmichev et al., 2001). Based on similarities in the Neoproterozoic stratigraphy, radiometric ages in the underlying basement, and the continuity of aeromagnetic anomalies associated with the fringing Neoproterozoic ophiolites, the southwestern margin of the Dzabkhan basin can be traced to the western margin of the Khubsugul basin along the Tuva-Mongolia border (Fig. 1A). The eastern boundary of the Dzabkhan terrane is obscured by Paleozoic intrusions, and consequently pre-Ordovician connections with the Baidrag terrane are ambiguous. Overlap assemblages indicate that the Dzabkhan, Khubsugul, Baidrag, and Tarvagatay terranes had amalgamated into a single continental mass by the Devonian (Badarch et al., 2002).

STRATIGRAPHY

The Tsagaan Oloom Formation consists of as much as 1500 m of Neoproterozoic platform carbonates with minor glacial diamictites and clastic deposits. Previous studies have focused on sections at Bayan Gol and Tsagaan Gol (Brasier et al., 1996; Khomentovsky and Gibsher, 1996), where ~200 m of stratigraphy in the middle of the Tsagaan Oloom Formation is faulted out and poorly exposed, respectively. Here we report measured stratigraphic sections from several localities that lack tectonic complications (Figs. 1B and 2). We also introduce informal member names to distinguish the major sequences within the Tsagaan Oloom Formation.

The Maikhan Ul member is composed of glacigenic diamictites and clastic sediments varying in thickness from 6 to 500 m. The stratigraphy of the Maikhan Ul was described at Tsagaan Gol (Lindsay et al., 1996), where two ~100-m-thick massive unstratified diamictites are separated by weakly bedded siltstone and very coarse unsorted sandstone. Clast size ranges from gravel to boulders with clasts of the underlying volcanics, granite, gneiss, carbonate, and sandstone. A glacial origin of the Maikhan Ul diamictites is indicated by bed penetrating dropstones and striated clasts. On the Khongoryn block (Fig. 1B, section F708), clastic units between the Maikhan Ul diamictites contain rare volcanic cobble lonestones, suggesting that they are also of glacial origin. A proglacial environment for the clastic units and the upper diamictite is inferred from the presence of mud cracks and 0.5-m-thick carbonate beds.

The Maikhan Ul member is overlain in a knife-sharp contact by the Tayshir member, which consists of ~570 m of limestone that records three supersequences. The base of the first supersequence is defined by a tan weathering, dark gray when fresh, millimeter-laminated limestone that is succeeded by ~100 m of limestone marl and rhythmite, shallowing upsection to ~10 m of grainstone. The second sequence begins with ~10 m of limestone marl and rhythmite followed by ~200 m of massively bedded blue grainstone. The third transgression begins with ~50 m of limestone rhythmite and debris flows with numerous black chert beds and nodules, and shallows upsection to ~200 m of dark fetid limestone, microbial laminite, and grainstone with giant ooids (>0.5 cm diameter).

More than 20 m of a previously unreported diamictite (herein referred to as the Khongorgyn diamictite) is exposed on the Khongoryn and Tsagaan blocks (Fig. 1B, section F708; Fig. 3A). The Khongoryn diamictite is composed of carbonate clasts in weakly stratified shale, siltstone, and marl matrices (Fig. 3B). Clasts range from gravel to boulder in size and are typically subangular to subrounded. The basal contact of the diamictite is an erosional surface, cutting down into the underlying Tayshir member.

The Khongoryn diamictite is overlain by the Ol cap carbonate, which begins with 7–40 m of buff to pink colored, largely recrystallized, micropeloidal dolostone. Low-angle cross-stratification (Aitken, 1991), tubestone stromatolites (Corsetti and Grotzinger, 2005), and giant wave ripples (Allen and Hoffman, 2005) are also present in the Ol cap dolomite (Fig. 3C). The transgressive tract of the Ol member continues upward into limestone ribbonite and then rhythmite with ~5-cm-tall former aragonite crystal fans present just above the limestone-dolostone transition. Crystal fans are present both as individual crystals growing upward into the sediment, similar to the Hayhook Member in the Mackenzie Mountains of Canada (Aitken, 1991), and as crystal fan shrubs that are >10 cm across, as seen in northern Namibia (Hoffman and Halverson, 2008). Above the postglacial transgression, the Ol member shallows upward from gray limestone rhythmite into ~10 m of grainstone.

Near the Khongoryn Range (Fig. 1B, section F708), the overlying Ulaan Bulagyn member begins with a transgression consisting of pink marl and shallows upsection to limestone ribbonite with chert nodules and then >500 m of massive weathering dolomite. In more distal sections, the Ulaan Bulagyn member thins to less than 100 m and contains both limestone and dolostone.

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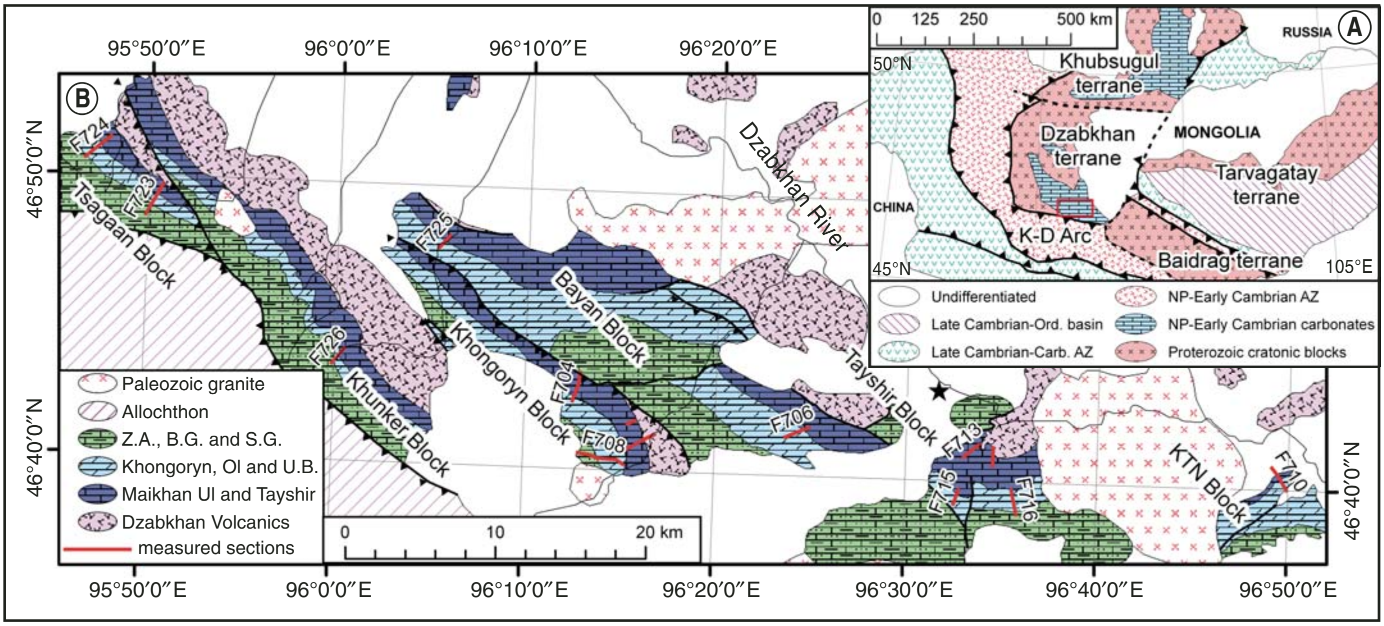

Figure 1. A: Tectonic map of western Mongolia modified from Badarch et al. (2002) and Windley et al. (2007). Teeth on faults indicate the inferred dip of subduction zones. K-D Arc— Khantayshir-Dariv Arc; AZ—accretionary zone including arcs, metamorphic rocks, and ophiolites; NP—Neoproterozic; Ord—Ordovician; Carb—Carboniferous; U.B.—Ulaan Bulagyn. Red box outlines position of B. B: Geological map of Tayshir region. Blue map units include entire Tsagaan Oloom Formation with exception of Zunne Arts (Z.A.) member. Green map unit includes Zunne Arts member of Tsagaan Oloom Formation, and Bayan Gol (B.G.) and Salaany Gol (S.G) Formations.

The Zunne Arts member begins with distinct pink-colored columnar stromatolites (*Boxonia grumulosa*) that overlie a karstic surface with meter-scale relief. The *Boxonia* bioherms are flooded by 10–20 m of violet and green shales that are variably phosphatized and interbedded with lenses of dolomite and microcrystalline to nodular phosphorite. These shale beds are succeeded by >200 m of blue limestone rhythmite and ribbonite that include nodular black chert and bed-parallel meandering ichnogenera (Goldring and Jensen, 1996).

Above the Tsagaan Oloom Formation, the Early Cambrian Bayan Gol Formation is composed of ~1000 m of mixed carbonate and siltstone with a rich diversity of ichnogenera (Goldring and Jensen, 1996), small shelly fossils, and calcimicrobial patch reefs (Kruse et al., 1996). An additional 400 m of carbonates containing archeocyathid reefs are present in the overlying Salaany Gol Formation. Deposition in the Dzabkhan basin terminates in the Botomian to Toyonian with ~200 m of conglomerates, black shales, and sandstones of the Khayrkhan Formation (Khomentovsky and Gibsher, 1996).

CHEMOSTRATIGRAPHY

During our mapping we collected samples for $\delta^{13}C$ and $\delta^{18}O$ analyses within measured stratigraphic sections. The samples were processed and analyzed using standard laboratory procedures (see supplemental data in the GSA Data Repository[1]).

Carbon isotope values in the black laminated limestone above the Maikhan Ul diamictites are moderately negative, with values increasing upsection through the overlying pink marls to +8‰. These values plummet abruptly at the third transgression in the Tayshir member, reaching a low of −7.5‰. From this nadir (herein referred to as the Tayshir anomaly), $\delta^{13}C$ values increase smoothly to +9‰, where they remain for the rest of the Tayshir member.

[1]GSA Data Repository item 2009035, Figure DR1 (chemo- and litho-stratigraphy of the end Cryogenian Khongoryn diamictite and the overlying basal Ediacaran Ol member) and Table DR1 (carbon- and oxygen-isotope data tables with description of methods), is available online at www.geosociety.org/pubs/ft2009.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

Overlying the upper diamictite, $\delta^{13}C$ profiles through the Ol member form a sigmoidal pattern that reaches a nadir of –6‰. This profile has been reproduced at 3 localities in the Dzabkhan basin spanning 75 km (see the Data Repository). Negative values continue for another ~100 m through the overlying limestone strata in the succeeding highstand and basal transgression of the Ulaan Bulagyn member, then return to positive values with an abrupt increase to ~+3‰, where they remain for most of the member. Above the shales and phosphorite of the Zunne Arts member, $\delta^{13}C$ values are more variable, oscillating between +2‰ and –5‰ over ~200 m of stratigraphy.

DISCUSSION: STRATIGRAPHIC CORRELATIONS AND TECTONIC IMPLICATIONS

The black laminated cap carbonate above the Maikhan Ul diamictites harbors a modest negative $\delta^{13}C$ anomaly that is typical of early Cryogenian cap carbonates (Brasier et al., 1996; Halverson et al., 2005; Shields et al., 2002). The −16‰ Tayshir anomaly may be correlative with the Trezona anomaly (Halverson et al., 2002; McKirdy et al., 2001); however, this would imply that stratigraphy bearing the positive values of the upper portion of the Tayshir member was nearly uniformly removed by glacial erosion to just above the Trezona anomaly at several sites in Namibia, Canada, and Australia. Alternatively, this anomaly could be correlative with negative values in the exposure-riddled Gruis Formation of Namibia (Halverson et al., 2005), and not recorded in the clastic portions of the Cryogenian strata in Canada and Australia. We prefer the latter interpretation, particularly as the extremely positive values of the uppermost Tayshir member are reminiscent of the positive isotopic interval in Canada referred to as the Keele Peak (Kaufman et al., 1997). The presence of hundreds of meters of carbonates above the Tayshir anomaly with positive $\delta^{13}C$ values highlights the fact that the composite Neoproterozoic $\delta^{13}C$ curve is a work in progress.

The cap carbonate of the Ol member is composed of fine-laminated micropeloids and contains tubestone stromatolites, giant wave ripples, and pseudomorphosed crystal fans. These peculiar sedimentary structures, their specific order, and the distinct sigmoidal $\delta^{13}C$ profile are characteristic of basal Ediacaran cap carbonates globally (Hoffman et al., 2007). This suggests that the underlying Khongoryn diamictite is an end-Cryogenian glacial deposit. The base of the Ediacaran is bracketed

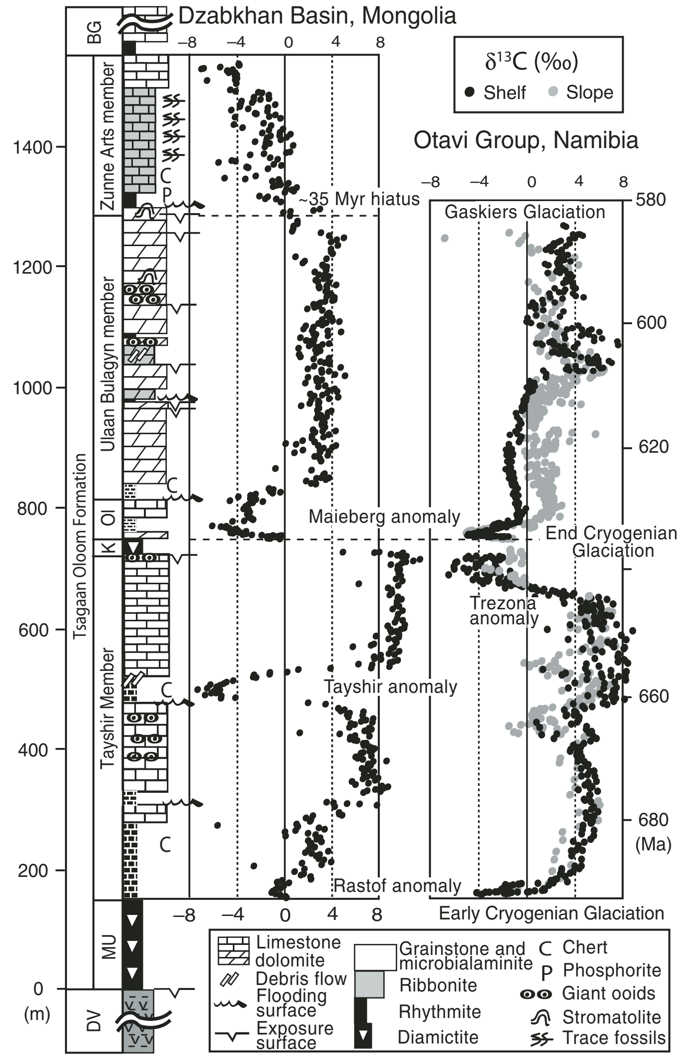

Figure 2. Carbon isotope chemostratigraphy and lithostratigraphy of Tsagaan Oloom Formation (sections F704, F708, and F709) compared to composite δ13C curve of Otavi Group in Namibia. Isotopic data from the Ediacaran Tsumeb Subgroup and from shelf sections of Cryogenian Abeneb Subgroup are from Halverson et al. (2005). Abeneb slope data are courtesy of Paul Hoffman. For the Tsumeb, the ~1400 m shelf data have been stretched to fit the ~475 m slope data, and for the Abeneb, ~500-m-thick shelf sections have been stretched to fit the lower 150 m of the ~300-m-thick slope sections. This correlation rests on interpretation that Trezona anomaly has been removed by glacial erosion from shelf sections in Mongolia. DV—Dzabkhan volcanics; MU—Maikhan Ul member; K—Khongoryn member: Ol—Ol member; BG—Bayan Gol Formation.

by U-Pb ages of 635.5 ± 0.6 Ma (Hoffmann et al., 2004) and 635.51 ± 0.54 Ma (Condon et al., 2005).

Above the Ol cap carbonate, $\delta^{13}C$ values oscillate around +3‰ for most of the Ulaan Bulagyn member. These values are typical of the middle (pre–580 Ma) Ediacaran (Halverson et al., 2005). These new correlations also place earlier $^{87}Sr/^{86}Sr$ measurements (Brasier et al., 1996) in a tighter temporal context. Strontium isotope values of least-altered samples from the Tayshir member are typical of Cryogenian carbonates, and below the 0.7075 threshold of basal Ediacaran carbonates (Halverson et al., 2007). The high $^{87}Sr/^{86}Sr$ values (near 0.7085) of Brasier et al. (1996) in the Zunne Arts member are characteristic of those near the Precambrian-Cambrian boundary (Derry et al., 1994; Halverson et al., 2007), supporting the idea of a major hiatus below the phosphorites. The assignment of the Zunne Arts member to the latest Ediacaran or Early Cambrian is also consistent with the oscillatory $\delta^{13}C$ profiles similar to those in Morocco (Maloof et al., 2005), and the presence of small shelly fossils (Brasier et al., 1996) and trace fossils (Goldring and Jensen, 1996).

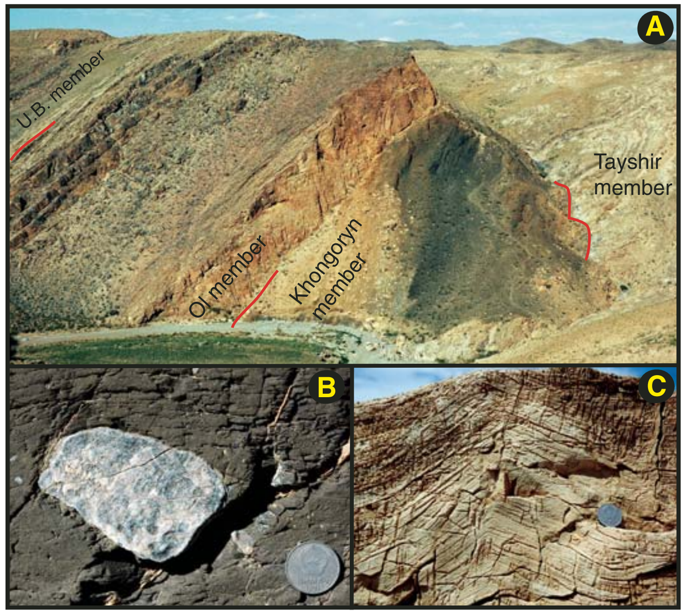

Figure 3. A: Khongoryn diamictite and Ol cap carbonate sequence south of the Khongoryn Range (section F708) looking west. At this locality diamictite is 21.7 m thick and Ol cap dolostone is 7.1 m thick. B: Lonestone in Khongoryn diamictite south of Bayan Gol from the creek bed in A (section F708). Clast is cobble-sized limestone with limestone gravel in weakly laminated black marl matrix. Coin is 2.25 cm in diameter. C: Giant wave ripple in the Ol cap dolostone south of Tayshir (section F716). Coin is 2.25 cm in diameter.

Previous studies have proposed that the Dzabkhan basin formed in a backarc setting (Khomentovsky and Gibsher, 1996); however, this is inconsistent with the age of the continental arc volcanism, the position of the accretionary wedge and ophiolites on the northern margin of the fringing Khantayshir-Dariv arc (Khain et al., 2003), and the north-vergent thrusting in the accretionary zone, all of which indicate that the subducting plate dipped to the south. Furthermore, chemostratigraphic and lithostratigraphic correlations presented here suggest that most of the Tsagaan Oloom Formation accumulated slowly on a passive margin, during the post-rift thermal subsidence stage, for ~140 m.y. (ca. 720–580 Ma).

Remarkably consistent U/Pb zircon ages near 570 Ma have been obtained from plagiogranite dikes in the inner belt of ophiolites in western Mongolia. To the south of the Dzabkhan basin, the Khantayshir ophiolite has yielded a date of 568 ± 4 Ma (Khain et al., 2003); to the southwest the Dariv ophiolite gives an age of 573 ± 6 Ma (Khain et al., 2003); and to the northwest the Agardag ophiolite has been dated as 569 ± 1 Ma (Pfander et al., 1998). The Dariv and Khantayshir ophiolites appear to have formed in a suprasubduction setting via intraarc spreading (Khain et al., 2003), and thus these arcs were active ca. 570 Ma. Our chemostratigraphic correlations indicate the presence of a hiatus during this time, and that when deposition resumed in the latest Ediacaran, ~2 km of strata were accommodated in ~20 m.y. These observations are consistent with the Zunne Arts member and the overlying Early Cambrian formations being accommodated via flexure as the south-dipping margin was pulled into the trench.

We suggest that the phosphorites of the Dzabkhan basin, and perhaps correlative phosphorites in the Khubsugul Group, formed in the latest Ediacaran during the initial foredeep transgression. This setting for phosphogenesis is similar to that of the Ediacaran–Early Cambrian phosphorites of West Africa (Flicoteaux and Trompette, 1998), and analogous to the Superior-type iron formations that are present in the primary transgression in several of the Early Proterozoic foredeep basins of Canada (Hoffman, 1987). Perhaps downdip magmatism provided iron hydroxides to the margin on which phosphorous could be adsorped and effectively shuttled to the basin (Froelich et al., 1982). Thus, the paleoceanographic significance of the Vendian–Cambrian phosphorite peak (Cook and Shergold, 1984) could be in the combination of iron delivery and passing a threshold of oxidizing power in the oceans.

CONCLUSION

The identification of the ca. 635 Ma basal Ediacaran cap carbonate in the Ol member along with the underlying Khongoryn diamictite facilitates the integration of the Dzabkhan basin stratigraphy into the global record of Neoproterozoic environmental change. Using the early and end Cryogenian glaciations as tie lines, the new high-resolution composite $\delta^{13}C$ profile can be incorporated into global composite $\delta^{13}C$ curves. These correlations indicate that the Tayshir anomaly is a large, previously unidentified, mid-Cryogenian, −16‰ $\delta^{13}C$ anomaly. These new age constraints can also be incorporated into a new basin subsidence model, in which most of the Tsagaan Oloom Formation was deposited on a rifted passive margin, and the Zunne Arts member and the overlying Early Cambrian strata formed after an ~35 m.y. hiatus in a foredeep basin. These correlations further suggest that the late Ediacaran–Early Cambrian phosphorites were deposited during the initial transgression as the Dzabkhan terrane was pulled into the trench. Further work is necessary to incorporate the other Neoproterozoic and early Paleozoic terranes of Mongolia into this model and better understand the relationships between ophiolite obduction, foredeep formation, and phosphogenesis.

ACKNOWLEDGMENTS

We thank our field assistants, Baata, Erdenebayar Oyun, Tsolomon Adiya, Jaavka Otgonhuu, and Uyanga Bold. We thank Jonathan Husson for preparing samples and Greg Eischeid for help with the mass spectrometry. We also thank Bayassa and Altan Amaglaan for help with logistics. We thank Jessica Creveling, Graham Shields, John Lindsey, and an anonymous reviewer for their comments on this manuscript. We are grateful to Paul Hoffman and National Science Foundation grant EAR-0417422 (to Hoffman) for support of this work.

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Manuscript received 21 January 2008
Revised manuscript received 23 September 2008
Manuscript accepted 6 October 2008

Printed in USA