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Andrew P. de Wet
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Lara Heister
Symposium Convenor
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Project Directors: ***CONSTANCE M. SOJA***: Colgate University
**CHULUUN MINJIN:** Mongolian University of Science and Technology
Project Faculty: ***PAUL MYROW***: The Colorado College
***D. JEFFREY OVER***: State University of New York at Geneseo

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***UYANGA BOLD***: Mongolian University of Science and Technology
Research Advisor: Chuluun Minjin

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Research Advisor: Chuluun Minjin

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Research Advisor: Chuluun Minjin

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Faculty Advisor: D. Jeffrey Over

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***ZOE VULGAROPULOS*:** Oberlin College
Research Advisor: Dennis Hubbard

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Keck Geology Consortium
Franklin & Marshall College
PO Box 3003, Lancaster Pa, 17603
Keckgeology.org

# PALEOZOIC PALEOENVIRONMENTAL RECONSTRUCTION OF THE GOBI-ALTAI TERRANE, MONGOLIA

Project Directors:
**CONSTANCE M. SOJA**: Colgate University
**CHULUUN MINJIN**: Mongolian University of Science and Technology

Project Faculty:
**PAUL MYROW**: The Colorado College
**D. JEFFREY OVER**: State University of New York at Geneseo

## INTRODUCTION

Central Asia experienced dynamic crustal growth in the late Paleozoic–early Mesozoic through the protracted accretion of allochthonous terranes onto Asia's cratonic core. Situated at its geographic heart, Mongolia is an important key for unlocking the complex geologic history of this vast region (Hendrix and Davis, 2001; Heubeck, 2001; Badarch et al., 2002; Poier et al., 2002; Windley et al., 2003; Lamb et al., 2008). Characterized by a nearly complete record of Paleozoic deposits, Mongolia is distinguished from most of central Asia where pre-Devonian rocks have limited exposure or are poorly preserved (Heubeck, 2001). Closure of the paleo-Asian Ocean in the late Permian sandwiched Mongolia between Siberia, Tarim, and the Sino-Korean craton. As a tectonic mosaic configured of microcontinents, island arcs, and other terranes, Mongolia thus became the nucleus of the Eurasian landmass. Mesozoic accretion also welded to it Baltica, S. China (after its amalgamation with other blocks), and eventually Siberia (Pruner, 1992; Heubeck, 2001; Windley et al., 2002; Xiao and Windley, 2003; Tomurtogoo et al., 2005).

Multiple ideas have been proposed to explain Mongolia's complicated geologic past, as a microcontinent united with Tuva, for example, (Pruner, 1992; Gusev and Khain, 1995; Lamb and Badarch, 1997; Takahashi et al., 2001; Dobretsov et al., 2003; Yolkin et al., 2003; Yoshida et al., 2003) or as a single, long-lived volcanic arc system later dissected by faults (Sengör et al., 1993; Lamb and Badarch, 1997, 2001; Buchan et al., 2001). Recent studies recognize as many as 44 individual tectonic entities that amalgamated onto a core of Precambrian "preaccretionary" terranes (Fig. 1). Of the 44 terranes identified, island arcs (25%), slivers of continents and passive margins (~20%), backarc-forearc basins (18%), accretionary complexes (16%), metamorphic terranes of unknown derivation (~14%), and ophiolites (7%) are believed to have accreted *seriatim* during the closure of ocean basins from the Neoproterozoic to the Triassic (Badarch et al., 2002; Windley et al., 2002, 2003; Xiao et al., 2004a, 2004b).

Despite the various tectonic models proposed, the complete geologic history of Mongolia's tectonic collage is still unknown. Most, if not all, terranes are presumed to have been located south of Siberia, north of the Tarim and Sino-Korean cratons, and east of Baltica in the Paleozoic, as they are now (Shangyou et al., 1990; Badarch et al., 2002; Cocks and Torsvik, 2002) (Figs. 1-2). However, the paleogeographic setting of Mongolia and individual terranes is poorly constrained. Limited paleomagnetic, paleoclimate, and paleobiogeographic data are available that would help determine paleolatitudinal placement of terranes and amalgamation histories. Moreover, unraveling the sequence and timing of terrane accretion is complicated by an incomplete knowledge of multiple deformational events, which have been variously related to Caledonide, Hercynian, and unidentified periods of orogenesis (Kepezhinskas et al., 1991; Gusev and Khain, 1995; Badarch et al., 2002; Chen and Jahn, 2002; Poier et al., 2002; Kovalenko et al., 2003; Dobretsov et al., 2003; Torsvik and Cocks, 2004).

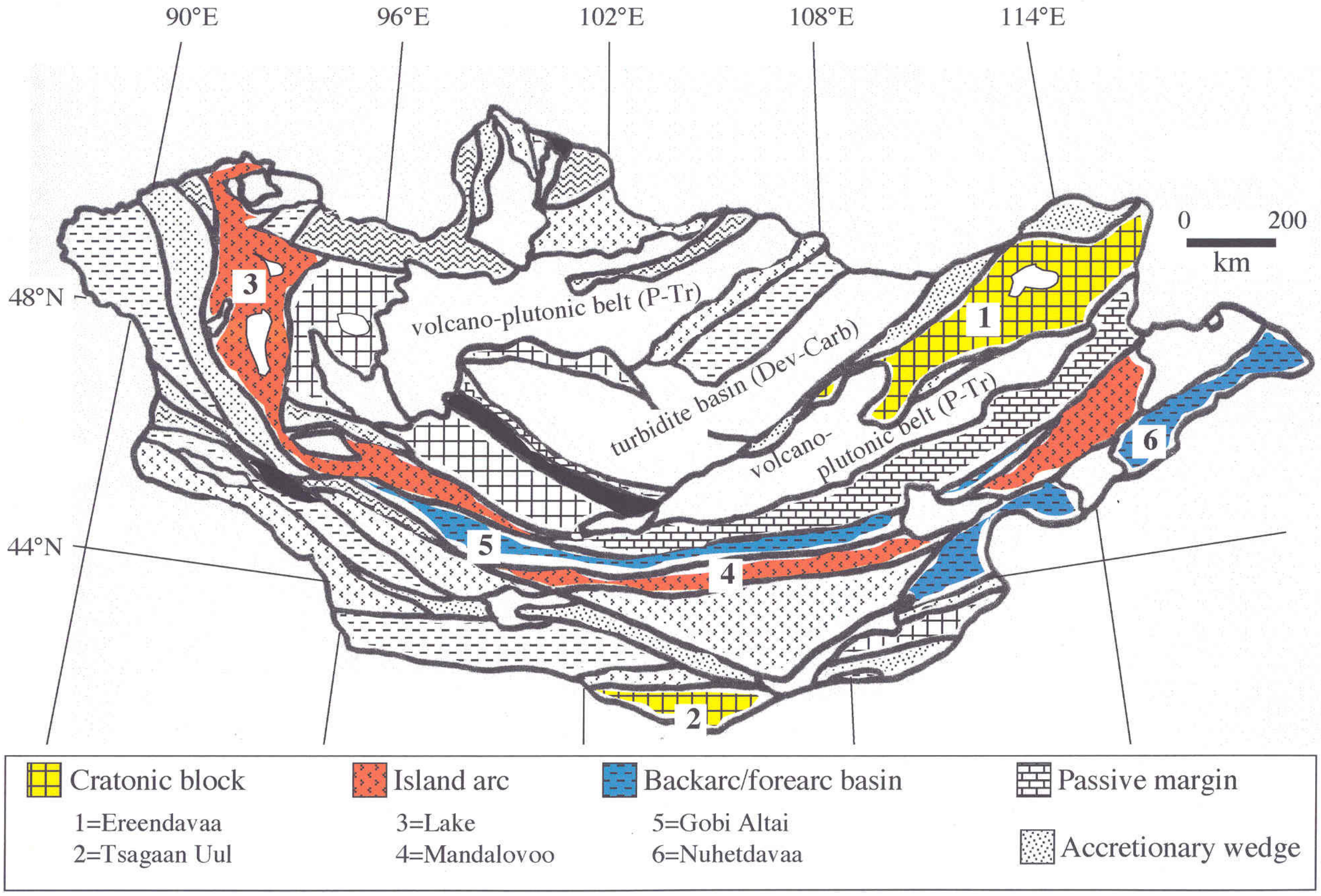


*Figure 1. Terrane map of Mongolia showing where research was undertaken on Ordovician to Devonian rocks in the Gobi-Altai terrane (terrane 5). Modified from Badarch et al. (2002).*

Reconnaissance and more detailed geological investigations in Mongolia have documented the general stratigraphy, paleontology, and structural geology of many areas (with a focus to date mainly on Devonian and younger siliciclastic and volcanic units) (Lamb and Badarch, 1997, 2001; Minjin, 1998, 2000, 2001, 2002; Badarch et al., 2002; Lamb et al., 2008). Yet incomplete documentation of sedimentary environments and faunas of Ordovician–Devonian age in Mongolia has precluded the analysis of paleobiogeographic patterns that could help determine the location of Mongolian terranes in space and time. Some of the biostratigraphic data collected on brachiopods, corals, and bryozoans can be used to correlate sections from one area in Mongolia to another, but these need to be reassessed for areas that are now believed to represent separate terranes. For example, the provincial affinities of Silurian brachiopods cannot be closely allied with other fossil assemblages from areas outside of Mongolia. Instead the faunas are interpreted to have evolved in an isolated, endemic center within the Mongolo-Okhotsk Subprovince of the Uralian-Cordilleran Region (Rozman, 1999). Rozman (1999) assigned these communities to "inner shelf" and "outer shelf" facies that bear no correspondence to terrane boundaries recognized by Badarch et al. (2002).

In essence, before models by Badarch et al. (2002) (Fig. 2) and others (Lamb and Badarch, 2001) can be refined, a more detailed understanding of the sedimentary history of stratigraphic deposits needs to be integrated with available geologic evidence. This will be necessary to establish the spatial and biogeographic relationships that terranes may have shared with each other and continental areas.

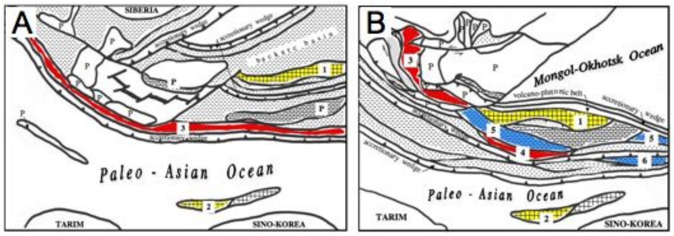


*Figure 2. Research will add new data to test terrane reconstructions for the Neoproterozoic–early Paleozoic (A) and establish baseline data for the Devonian–Carboniferous (B), as postulated by Badarch et al. (2002). Terrane numbers and symbols correspond to those in Fig. 1; P=pre-accretionary terrane.*

## PROJECT OBJECTIVES

### Introduction

Lower Paleozoic rocks exposed in the Gobi-Altai terrane of southern Mongolia are particularly well suited for detailed analyses that should yield data critical for refining terrane reconstructions (Minjin, 2001, 2002; Soja et al., 2006; Soja, 2009). Ordovician–Silurian marine successions are overlain by Devonian–Triassic volcanic-sedimentary rocks. Together these comprise one of the least deformed and most continuous stratigraphic sections in Mongolia. Magnificent, unvegetated exposures reveal rocks that are well preserved and generally richly fossiliferous. Badarch et al. (2002) tentatively suggest that the Gobi-Altai terrane formed as a backarc basin to the Mandalovoo arc terrane (Fig. 1), but a preponderance of shallow-water facies suggests that the terrane could be a dismembered part of that arc (Soja et al., 2006).

Although biogeographic, magnetostratigraphic, and chemostratigraphic data have not been collected systematically in the terrane, many important lithologic and taxonomic studies have been published, which document the basic stratigraphic relationships of Phanerozoic formations exposed across a broad region (Minjin, 1998, 2000, 2001, 2002; Minjin and Tumenbayer, 2001; Rozman and Rong, 1993; Rozman, 1999; Wang et al., 2005; Lamb et al., 2008). Ordovician to Lower Devonian deposits exceed 3000 m in thickness and reveal abundant shallow-water indicators, including oncoidal limestone, cross-bedded sandstone, and biohermal limestone. These are overlain by Lower Devonian breccia and conglomerate. Recent work provides more details about the terrane's crustal growth associated with volcanic arc activity in the Devonian–Carboniferous, accretion in the late Paleozoic–Mesozoic, and multiple episodes of deformation in the Mesozoic and Cenozoic (Lamb et al., 2008).

Although still to be resolved, Mongolia may have been positioned near the eastern end of the Uralian Seaway during the early to middle Paleozoic, then rotated clockwise to become wedged between Siberia, Kazakhstan, and Sino-Korea in the late Paleozoic–Mesozoic (Fig. 3). That seaway was an important early to middle Paleozoic marine corridor in the Northern Hemisphere. Localized areas of carbonate sedimentation and reef growth enabled "stepping stone" migration of stromatolite-related biotas between northern Laurentia, eastern Baltica, and Siberia in the Late Silurian (Soja and Antoshkina, 1997; Soja et al., 2000; Antoshkina and Soja, 2006). Skeletal grains coated by microbial encrusters associated with algae and locally abundant stromatolites are present in the Silurian and Devonian sections in the Gobi-Altai terrane (Soja et al., 2006). This suggests that similar environmental conditions may have extended across the Uralian Seaway to its eastern extremity or beyond. That seaway's eastern margin may have been enclosed by volcanic islands and arc-related terranes that later would become consolidated into Mongolia.

Building on these foundational studies, our overall objective was to provide more complete documentation of the early Paleozoic history of southern Mongolia. Our three main goals were to: (1) develop a depositional-tectonic model that explains the dynamics of terrestrial and marine sedimentation through time; (2) determine the paleoecology and evolutionary history of marine benthic communities; and (3) establish regional biogeographic correlations. Compiling detailed petrologic, petrographic, geochemical, and paleontologic evidence would allow us to reconstruct the paleoenvironments, depositional history, and tectonic setting. Careful study of the sequence stratigraphy and conodont age

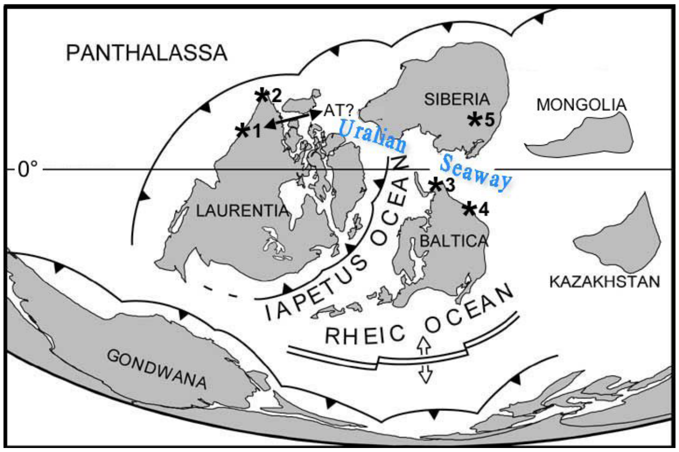


*Figure 3. Map showing possible paleogeographic placement of Mongolia (terranes are clustered together) near the eastern extent of the Uralian Seaway in the Silurian. Stars show occurrence of Upper Silurian stromatolite reefs: (1) Alexander terrane (AT) and its possible Silurian location in the Uralian Seaway; (2) Farewell terrane in sw Alaska; (3) Pay-Khoy; (4) Ural Mountains; and (5) Salair. Modified from Silurian basemap of Scotese (2001) and from paleogeographic models in Sengör et al. (1993), Lamb and Badarch (1997), Landing and Johnson (1998), Scotese (2001), Cocks and Torsvik (2002), Yolkin et al. (2003), Soja et al. (2000), and Torsvik and Cocks (2004).*

zonation, lithologic compositions, primary excursions in chemostratigraphic carbon isotopic data, facies relationships, and the nature and timing of deformational events might permit regional correlations between terranes. Detrital zircons and geochemical indicators could be used to track changes in sediment sources or terrane locations through time. Paleoecologic analyses would provide the basis for future documentation of the provincial affinities of the biotas. In essence, our new data would allow us to interpret the patterns of Ordovician to Devonian faunal succession in a comprehensive evolutionary, paleoenvironmental, and tectonic framework.

## Field Work

In July–August 2009, eight students and three faculty from the U.S. engaged in joint field research with our Mongolian colleague and four students from Mongolian University of Science and Technology. Our work consisted of field mapping of Ordovician through Devonian deposits exposed near Shine Jinst in southern Mongolia's Gobi-Altai terrane. Students also undertook systematic sampling of sedimentary rocks (primarily limestone but also interbedded siliciclastic and volcanic units) and fossils from measured and photographed stratigraphic sections. They identified litho- and biofacies on the basis of sedimentary textures and structures, stratigraphic relationships, as well as changes in rock constituents. Some fossils, specifically conodonts, brachiopods, and trilobites, were collected in bulk samples to establish better constraints on age relationships and to document species abundance and richness. Bulk collections of sandstone were made from key siliciclastic beds so that detrital zircons could be used to determine the age and provenance of source materials.

## Laboratory Analysis

Approximately 600 kg of rock and fossils were shipped to the U.S. for further study in the lab. Samples were prepared as thin-sections and polished slabs for petrographic analysis. Point counts enabled students to determine the sediment and fossil composition of carbonate and interbedded siliciclastic units. Fossils and detrital zircons were extracted from bulk samples. Students relied on detrital zircons, taphonomic aspects of fossils, and the composition, size, shape, sphericity, and sorting of siliciclastic grains, including clasts in conglomerate, to better ascertain provenance and depositional conditions. Powdered samples were analyzed for carbon and oxygen isotopes, magnetic susceptibility, and by XRD to determine the presence of dolomite and non-carbonate minerals.

## Gmail Account

During the academic year, students submitted weekly progress reports to our gmail account. This account was invaluable because it allowed all participants, including our Mongolian colleagues and the research advisors, to post and have access to references; "how to" guides for preparing thin-sections, samples for geochemical analysis, point counts, etc.; field photographs and photomicrographs; spreadsheets for recording data; stratigraphic logs; latest results; and other information that would help students collaborate on completing their projects.

## RESULTS

Fossiliferous rocks of Ordovician to Devonian age exposed in the Gobi-Altai terrane provided an exceptional opportunity for students to integrate paleontological, sedimentological, and geochemical data. Students' documentation of the bathymetric distribution of organisms along environmental gradients through time integrated with geochemical and other data have allowed them to interpret paleocommunity patterns in an ecologic context. This interdisciplinary approach forms the basis for understanding the influence of tectonism, sea-level change, and environmental factors on marine benthic paleoecology and community evolution. The students' projects are summarized below; please refer to each student's paper in this volume for more detailed discussions of results.

**Sara Oser** (University of Cincinnati) and **Madelyn Mette** (Macalester College) studied the Upper Ordovician (Caradoc–Ashgill) Daravgai and Gushuunovoo formations. Oser compared those rocks with coeval sequences exposed in the Cincinnatian region. Her evidence shows that the cyclic deposition of fossiliferous limestone and shale in the Gobi-Altai terrane records sea level fluctuations that correspond to patterns of global eustasy in the Late Ordovician. Mette's magnetic susceptibility and carbon isotopic data complement Oser's litho- and biofacies evidence in suggesting that tectonic activity contributed to regression and the influx of terrigenous sediment in the Gobi-Altai terrane in the Late Ordovician (Ashgill).

**Munkh-Od Purevtseren** (Mongolian University of Science and Technology) worked with Mette and Oser at Scharchuluut, producing a geologic map that shows east-to-west facies transitions in the Lower Silurian Scharchuluut Formation. He mapped sandstone and volcanic rocks that are interbedded with limestone rich in coral, crinoids, bryozoans, stromatoporoids, and brachiopods. **Uyanga Bold** (Mongolian University of Science and Technology) did research at Yamaan-Us along with **Nicholas Sullivan** and measured a 160 m thick section of the Lower Silurian Scharchuluut Formation, noting an abundance of stromatoporoids and coral that formed a massive reef. **Badral Khurelbaatar** (Mongolian University of Science and Technology) assisted Uyanga Bold at Yamaan-Us on collecting Lower Silurian brachiopods from the Scharchuluut Formation for future study. **Bilguun Dalaibaatar** (Mongolian University of Science and Technology) completed a geologic map of the Lower Silurian Scharchuluut Formation where it is exposed at "Wenlock Hill." Limestone composed of massive stromatoporoids and coral represent a biohermal reef. Together the work accomplished by these students across a broad area provides new insights into the Scharchuluut Formation, specifically that diverse shallow-water communities, including reefs, evolved in the Gobi-Altai terrane during ongoing volcanism and tectonic pulses in the Early Silurian (Llandovery–Wenlock).

**Nadine Reitman** (Vassar College) and **Zoe Vulgaropulos** (Oberlin College) investigated the Upper Silurian(?)–Lower Devonian Tsagaanbulag and Amansair formations. Their analysis of richly fossiliferous wackestone and packstone interbedded with siliciclastic deposits reveals that complex ecosystems characterized by the differentiation of trophic levels flourished on a shallow-marine shelf, which was affected by fluctuations in sea level and episodic storms. A stratigraphic increase in the predominance of subangular quartz, highly fragmented fossils, and cross bedding reflects regression in the Gobi-Altai terrane in the Early Devonian (Lockhovian).

**Timothy Gibson** (The Colorado College) examined the limestone conglomerate, siltstone, volcaniclastic sandstone, rhyolitic tuff and flows, and minor carbonate of the Lower Devonian Tsakhir Formation. The massive conglomerate at the base of the formation, abundance of siliciclastic strata, and interbedded volcanic rock indicate that the Gobi-Altai terrane experienced a significant tectonic event in the Early Devonian (Lochkovian–Pragian). Clast compositions and other data suggest that debris flows and fanglomerate prograded from subaerial to nearshore marine environments following the uplift and erosion of Ordovician–Lower Devonian rocks in the terrane. His analysis of the first detrital zircons to be extracted from the Gashuunovoo, Tsakhir, and Chuluun formations reveals that the Gobi-Altai terrane was in proximity to a continent or deeply eroded volcanic arc from the Late Ordovician to the Early Devonian.

**Adam Pellegrini** (Colgate University) studied the basal limestone member of the Chuluun Formation, which formed in the late Early Devonian (Emsian) as the first widespread carbonate to accumulate in the wake of Lochkovian–Pragian tectonism. His research shows that after prolonged intervals of siliciclastic influx and volcanic activity, massive stromatoporoids, colonial corals, and bryozoans dominated in level-bottom, non-reefal habitats. The low diversity biotas suggest that isolation, lack of accommodation space, or other factors limited the ecologic succession of the earliest organisms to colonize the newly submerged shelf.

Research accomplished by **Jennifer Peteya** (Mt. Union College) on the Tsagaankhaalga Formation shows that diverse invertebrate communities dominated by bryozoans and crinoids evolved in the Gobi-Altai terrane in the Middle Devonian (Eifelian). Fossiliferous limestone that comprises coarse-grained or mostly articulated skeletal material accumulated on a quiet-water shelf during marine transgression. She has made the first preliminary identification of proetid trilobites in the Gobi-Altai terrane.

**Nicholas Sullivan** (State University of New York at Geneseo) used magnetic susceptibility and microfossil data to ascertain the approximate location of the Eifelian Givetian boundary in the Tsakhir basin. He extracted conodonts from limestone beds in a section that is dominated by siliciclastic and volcanic rocks. Noting the presence of polygnathid conodonts, the overall positive trend in magnetic susceptibility upsection, and similarities to Middle Devonian sections in Morocco and New York State, he suggests that the Eifelian Givetian boundary occurs within the lower member of the Govialtai Formation.

## CONCLUSIONS

The students involved in this project acquired important new geologic data about Mongolia's Gobi-Altai terrane, including its sedimentary history, invertebrate communities, and tectonic setting in the early to middle Paleozoic. Their research has produced the first correlation tools based on sequence stratigraphy, carbon isotope chemostratigraphy, magnetic susceptibility profiles, and detrital zircon geochronology for rocks exposed in the Gobi-Altai terrane. Building on others' research, their results document the influence of physical, biological, and tectonic factors on Ordovician–Devonian sedimentation processes and paleoecological patterns in the Gobi-Altai terrane.

In particular, the students' research results support the general model proposed by Lamb and Badarch (2001) that: (a) Ordovician–Lower Devonian sedimentary deposits in the Gobi-Altai terrane accumulated in a shallow-marine setting adjacent to cratonic or arc-related sources of siliciclastic detritus, and (b) a significant disruption in carbonate platform deposition occurred in the Early Devonian as a result of tectonic uplift, erosion, and terrigenous sedimentation. However contrary to Lamb and Badarch (2001), interbedded volcanic rocks indicate that volcanism did occur episodically in the Ordovician and Silurian before becoming more prominent in the Early Devonian. Similarity in the stratigraphy of the Mandalovoo and Gobi-Altai terranes (Badarch et al., 2002), including the presence of Lower Devonian conglomerate in both regions, suggests that these crustal slivers may have experienced the same mid-Paleozoic tectonic event as part of a single, large volcanic arc complex. Future research in the Mandalovoo and adjacent terranes will enable detailed comparisons to be made with the data we have compiled on the depositional environments, paleocommunities, sequence stratigraphy, chemostratigraphy, magnetic susceptibility, and detrital zircon geochronology of Ordovician–Devonian rocks in the Gobi-Altai terrane.

In summary, this valuable work provides the basis for future research that will compare the sedimentary history of the Gobi-Altai terrane with that of other terranes to establish paleogeographic correlations. Our collaboration with Dr. Minjin and his students has produced detailed documentation of geologically significant deposits and provided the opportunity for an important and mutually beneficial international collaboration. Our joint field work allowed us to amplify and revise geologic maps; strengthen and extend regional stratigraphic correlations; collect rock and fossil samples for laboratory analyses; supervise student research; help students develop important scientific and professional skills; and synthesize data to explore the geologic implications of the Paleozoic rocks exposed across a large region in southern Mongolia. Cooperative aspects of the proposed research have been particularly beneficial in contributing new data that will enhance an overall understanding of the tectonic evolution of central Asia.

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