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Project on Quaternary Geology of the Turgen Uul Area, Northern Altay, Western Mongolia (Tavan Har), Mongolia ; Summer, 2003

The Study Abroad Research Context

The very idea of going to Mongolia, much less spending a month living and working with Mongolians, had never crossed my mind until the fall of 2002, when I read about the research trip to Mongolia being led by the Keck Geology Consortium. Made up of twelve small liberal arts colleges in the U.S., the goal of Keck is to provide high quality, field-based summer research experiences for undergraduate students. The fieldwork led by faculty from within and outside the consortium, serves as the first step in a year-long independent study project, which culminates for many students in a senior undergraduate thesis. Although Keck has taken many students abroad to do research in the past, this was their first international research expedition to include a multinational group of participants and to use geology fieldwork as a basis for cross-cultural exchange. American and Mongolian students conducted fieldwork together, and co-authored 4-page abstracts, as research summaries, for the Consortium.

As a student intensely interested in studying both environmental geology and international relations, I saw this project as an opportunity to apply my multidisciplinary education to a foreign experience. I departed for Mongolia with many questions: What will be the logistics of doing fieldwork in a remote desert? How will I decide on and complete a project given a limited amount of time in a place I have never been? How will we all work together, when many of the Americans have not met before, and only two of the participants are conversant in both Mongolian and English?

The field season lasted one month, from July 14 to August 14, 2003. After two days of travel, the 16 Americans met with the 20 Mongolian project participants in Ulaan Baatar, the capital of Mongolia.[1] A. In addition, there were five drivers, two cooks, a doctor and several field assistants. The research conditions are well-described on the Keck website: "Students … must be able to work under harsh conditions in a setting remote from any modern conveniences. Fieldwork for this project will include nearly four weeks at a primitive base camp, although there will be plenty of water for drinking and cooling, it is unlikely there will be water for washing clothes or bathing (other than a sponge bath). Meals will feature sheep and goat."[2]

We spent four days driving to our field area in rebuilt Russian vans, following a pair of tire tracks that we were told lead eventually to Beijing. Our field area, known as Tavan Har, covers about 1800 square kilometers and is located 60 kilometers south of the town of Saynshand. Following several days of field reconnaissance, the students had sixteen days to complete their fieldwork before heading back to the capital.

Throughout the expedition, I saw interaction between the Mongolian and American participants as an essential part of a successful project. In brief, I found that how well the people from these two very different cultures communicated and learned from each other over this relatively short time period depended on our ability to communicate across cultural and linguistic barriers, and the Americans' willingness to adapt to unfamiliar customs, combined with the Mongolian project leader's awareness of what would make the Americans feel more "at home."

In my opinion, we fell short of our goal of coordinating and completing projects with paired American and Mongolian students. This was due in large part to the language barrier, but also because the two groups had different expectations for their projects. In general, the Mongolian students were interested in natural resources that might be found there, while the American students wanted to unravel the geologic history of the area. In addition, the Americans seemed to perceive themselves as doing original research to develop what is known about the geology of the field area, while the Mongolians appeared to see the area as already more-or-less understood, and their research as a way to apply what they had learned in classes. I think that these contrasting views and priorities stemmed partly from cultural difference, but were also similar to trends that might be seen between groups of liberal arts students and university students, or between people visiting an entirely new continent and people who are exploring a new part of their own country.

Even though this aspect of the project was not a success, I would argue that the multinational character of the project made it a much more valuable experience. The two groups shared skills, resources and knowledge that made the project logistically and scientifically possible. In addition, by overcoming the intimidation of a language barrier and by being somewhat immersed in another culture, I think that each of the participants will now be more likely to participate in and benefit from similar multinational projects. For myself, I not only gained valuable international research experience, but also I learned firsthand how international politics, language, and geography can affect the scientific process.

[1] The American students s came from Beloit College, Carleton College, Colorado College, Franklin & Marshall College , Pomona College, Whitman College and the University of Utah. The Mongolian students and faculty all came from the Mongolian University of Science and Technology (MUST). In total, there were 19 students and four faculty leaders , including Professors Bob Carson and Kevin Pogue (Whitman College), Cari Johnson (University of Utah), and A. Bayasgalan (MUST).

[2] See the Keck Geology Consortium website: http://keck.wooster.edu/

Sedimentation History and Provenance Analysis of a Late Mesozoic Rifting Event at Tavan Har, East Gobi, Mongolia

Introduction

The East Gobi Basin (EGB), which covers over 1.5 million square kilometers in southeastern Mongolia, is one of several basins in eastern China and Mongolia that was formed by extension and intracontinental rifting (a "pulling apart" of the continent) during the late Mesozoic (or from about 161 to 100 Ma) (Watson, et al, 1987; Johnson, et al, 2001). For reasons that are poorly understood, the continental lithosphere covering areas that are now known as eastern China and Mongolia underwent extension and thinning, which led to normal faulting and the creation of areas of subsidence — basins — within the continent.

Due to its remote location and to political factors, few field-based studies have been completed in the EGB, and even fewer are available in the English language (Lamb & Badarch, 1997). For decades, the area was essentially closed to people from non-Soviet countries as a result of the Cold War. As geologists have attempted to reconstruct the geologic history of northeastern Asia, they continue to point to a lack of detailed, internationally consistent information as an obstacle to further understanding ([a]engör et al, 1993; Lamb and Badarch, 1997; Heubeck, 2001). The most likely sources for these data are the extensional basins within the region, including the EGB, where the layers of sediment that have been deposited serve as a record of the region's history and have yet to be fully documented.

This study contributes to the amount of primary field data and quantitative analyses available on the Mesozoic sedimentary deposits within the EGB, focusing on the syn-rift (deposited during intracontinental rifting) rock units that were extensive in our particular field area. This is the first study to focus on the source rock of sandstones in the EGB. In addition, the data provide a basis for reconstructing the paleogeography and paleoenvironment of late Mesozoic rifting event. The conclusions of this study, when placed within the context of the geology of Asia, help us to better understand rift processes and basin evolution in different parts of the world.

Regional Geologic Background

Paleozoic History (542–251 Ma)

The composition of basement rock in Asia differs from that of many well-studied continents such as Europe and North America, as a result of tectonic evolution during the Paleozoic. Typically, continents are considered to be composed primarily of extensive fragments of quartz-rich continental lithosphere. Much of Asia, like the Rocky Mountains in the US, is composed of many relatively small continental terranes (microcontinents) and complexes of remnant volcanic island chains and former seafloor ([a]engör and others, 1993; Traynor and Sladen, 1995). These fragments surround several major cratons, including the Siberian, South China, East European Platform, Arabian, and Indian cratons (Heubeck, 2001).

Several models have combined available geologic data in order to reconstruct the Paleozoic tectonic accretion and continental evolution of Asia ([a]engör et al, 1993; Heubeck, 2001). Growth of the continent occurred primarily in the mid- to late-Paleozoic. At that time, small continental blocks and one or more volcanic island arcs (Lamb and Badarch, 1997), separated by wedges of volcanic and oceanic sediment deposited in the depressions between them, converged (Figure 1). Oceanic lithosphere subducted northwards, closing several oceans that used to separate what are now eastern Europe and central Asia, Mongolia and Siberia, and Mongolia and northern China. Present-day Mongolia has been fully within the continent since the late Paleozoic (around 250 Ma) (Sladen and Traynor, 2000). Present-day Mongolia, northern China and Central Asia are made up predominantly of this atypical continental material (Watson and others, 1987; [a]engör et al, 1993; Heubeck, 2001).

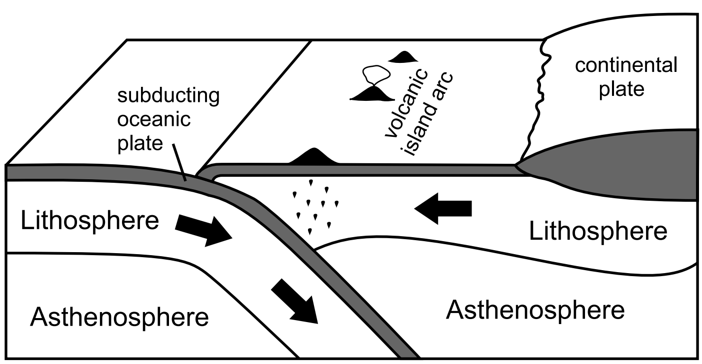

Figure 1. Diagram showing the relationship between subducting plates and volcanic island arcs (modified) from Skinner and Porter, 1995)

While this general explanation for the Paleozoic evolution of Asia is understood, much of the detail is not. Major questions that remain are the type and extent of fault movement, (ªengör and others, 1993; Heubeck, 2001), the locations of former plate boundaries (Carroll and others, 1995; Heubeck, 2001), the timing of ocean closure (Lamb and Badarch, 1997), and the extent of large continental blocks and regional tectonic frameworks (Heubeck, 2001).

Mesozoic Deformation (251–65.5Ma)

The Paleozoic amalgamation of northern Asia was followed in the Mesozoic by deformation within the continent that has been expressed in various ways throughout Asia, and that has continued to the present (Watson and others, 1987; Hendrix and others, 2001). In the regions of Asia that are not made up of major continental cratons — including much of Mongolia — tectonic reactions to regional stresses have been controlled largely by weaknesses along the suture zones between microcontinents, volcanic island chains, and sedimentary wedges (Allen and others, 1995; Sladen and Traynor, 2000). Within China and Mongolia, variations in the deformation styles that formed basins during the Mesozoic occur between the west and east (Hefu, 1986; Watson and others, 1987; Johnson and others, 2001) (Figure 2).

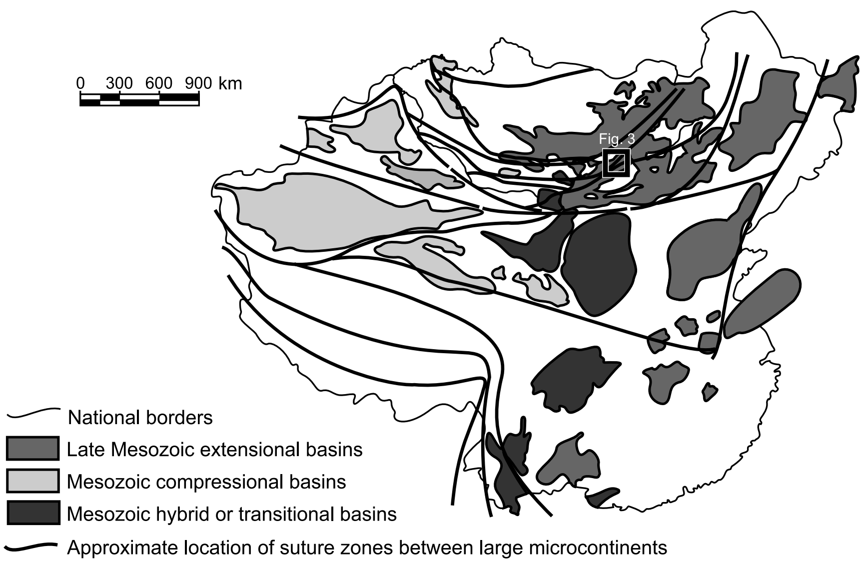

Figure 2. Map showing Mesozoic sedimentary basins of China and Mongolia and how they generally were formed, along with the boundaries between major continental fragments that make up Asia (modified from Watson and others, 1987; Traynor and Sladen, 2000; Johnson and others, 2001).

In the west, deformation began in the early Mesozoic (Hendrix et al, 2001; Johnson and others, 2001) as a result of recurring collisions along the southwestern edge of the continent (Watson et al, 1987; Allen et al, 1995). This regional compression led to the formation of several east-west trending basins (Watson et al, 1987). Within eastern China and Mongolia, deformation commenced in the late Mesozoic (Johnson and others, 2001). As a result of extensional stresses, north-south trending extensional basins developed (Watson et al, 1987).

The exact origins of Mesozoic intracontinental extension and rifting in Mongolia and China are poorly understood, due to a lack of data (Lamb and Badarch, 1997; Sladen and Traynor, 2000; Hendrix et al, 2001). The most accepted theory is that extension took place in a back-arc setting — on the landward side of a volcanic island arc — as the Pacific plate subducted under the north China plate (Watson et al, 1987; Sladen and Traynor, 2000; Graham et al, 2001). This theory is questioned, however, due to the fact that Mongolia was located well within the Asian continent (>1000 km from the Pacific Ocean) by the Mesozoic, and not directly landward of an island chain as this basin terminology suggests (Graham et al, 2001).

Several other regional factors that may have controlled the extensional tectonics of the late Mesozoic, and the cause was most likely some combination of stresses within the continent (Traynor and Sladen, 1995; Graham et alrs, 2001). More broadly, late Mesozoic rifting in northeast Asia can be associated with rifting that was taking place worldwide during the Mesozoic (Sengör, 1995), concurrent with the breakup of the supercontinent Pangea (Bond et al, 1995). As researchers look for evidence of the mechanism for and tectonic and structural evolution of extension, perhaps the most sought after data are detailed sedimentary and structural field data from the sedimentary basins in the region (Watson et al, 1987; Hendrix et al, 2001).

Geology of the East Gobi Basin

History

In southeast Mongolia, the youngest preserved marine deposition is Late Permian (around 260 Ma), and marks the completion of continental assembly in the region. Continuing compression, as microcontinents accreted onto the southern edge of Asia, led to the formation of a mountain chain in the Early Triassic (~251-245 Ma) that spread across what is today the Gobi. During the Late Triassic (~228-200 Ma), compression led to igneous processes including volcanism and the intrusion of bodies of magma (Sladen and Traynor, 2000). The mountain chain eroded throughout the Triassic and into the Early Jurassic (~200 Ma).

By the end of the Jurassic, the development of intracontinental rift basins showed evidence for regional extension. A belt of basins covered southern and eastern Mongolia and northeast China (Sladen and Traynor, 2000), with sediments depositing into these new depressions in the landscape. These basins are characterized by their asymmetric "half-graben" shape, with faults along two sides, and by rapid changes in the sediments and the ways in which they were deposited within them; these are all distinguishing features of sedimentation in non-marine environments that are undergoing rifting (Miall, 1984; Sladen and Traynor, 2000).

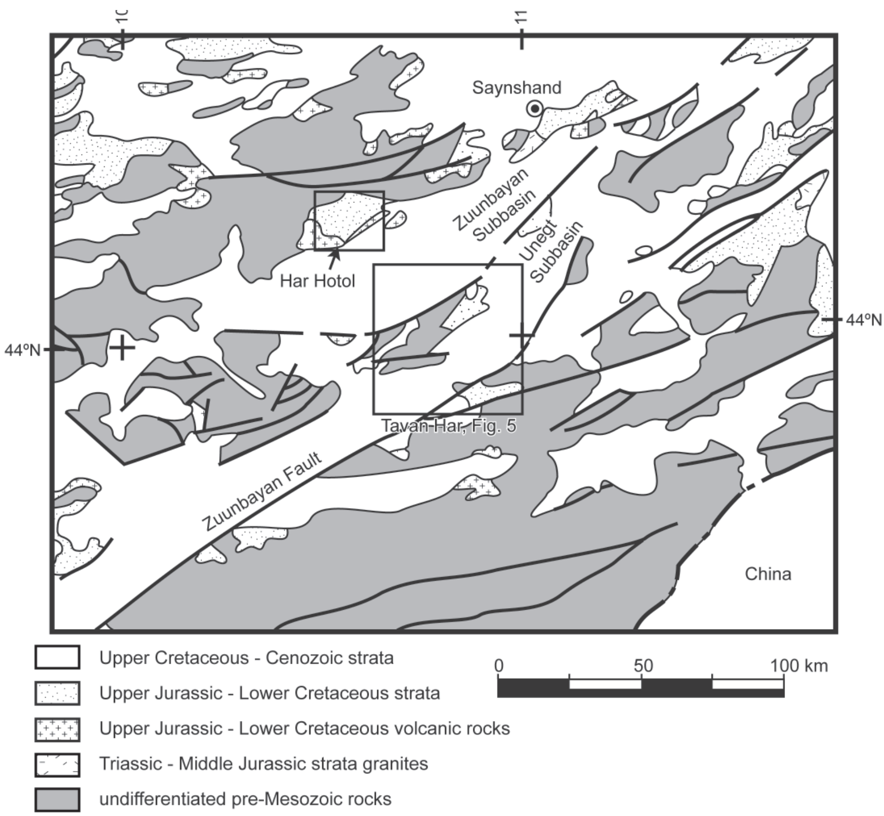

Figure 3. Geologic map emphasizing Mesozoic rock units in the region around Tavan Har, northeast EGB, Mongolia (modified from Johnson and Graham, 1997).

Extensional faulting and rift-related deposition lasted until the middle Cretaceous (~100 Ma). In the Gobi region of Mongolia, the faults bounding the basins were reactivated, but this time as a result of compression, which meant that faults moved in the opposite direction, tilting the layers of sediment that had deposited within the basins. The post-rift sedimentation followed in layers on top of these tilted beds (Shuvalov, 2000; Sladen and Traynor, 2000).

Structure

The East Gobi basin is an elongate basin trending northeast-southwest, which is divided into several subbasins by northwest-southeast-trending faults (Johnson and others, 2001) (Figure 3). These subbasins range from 100 to several hundred kilometers in length and 20–50 km in width, and contain 1–3 km of rift-related and post-rift sedimentary strata (Graham and others, 2001).

Within the East Gobi basin, Johnson and others (2001) have recognized two types of Cretaceous extensional basin formation. The Tavan Har study area is located in the northeast, where low-strain extension was characterized by faulting and basin formation. Along its southeastern border, the EGB is separated from the contemporaneous Erlian basin (for more on the Erlian basin, see Li and others, 1997; Lin and others, 2001) by a block of basement rocks and by the Zuunbayan fault. The Zuunbayan fault was probably active during early Mesozoic basin formation, but the type and extent of faulting is not well understood. The northern edge of the basin is bounded by a series of Late Jurassic (~175-145 Ma) faults that were caused by extension and then were reactivated by compression in the mid-Cretaceous (105 Ma) (Johnson and others, 2001). A third major fault zone, referred to as the North Zuunbayan Fault Zone, splits the basin into two major regions of deposition (Johnson, 2004).

Stratigraphy

There is no complete exposure of the sequence of sedimentary layers, or stratigraphy, that was deposited in the Gobi Basin during the Mesozoic (251-65.5 Ma) (Jerzykiewicz and Russell, 1991). This, in combination with the EGB's remote location and a lack of fossils from widespread flora and fauna that could be used to constrain the age of rocks, has impeded stratigraphic correlation within the basin and the region (Graham and others, 2001). However, extensive exposure of Mesozoic sedimentary rocks in subbasins has allowed the general stratigraphy to be understood.

An additional cause for confusion in understanding Mongolian stratigraphy is due to differences in the terminology used by American and Russian researchers.

In the early 1900s, American scientists used the term “formation” to refer to visibly distinguishable rock units, without necessarily correlating the ages of these units. Later on, Russian scientists defined stratigraphy by “svita,” a term that refers to lithology and age, and that assumes that the timing and type of deposition are equal throughout the “svita” (Jerzykiewicz, 2000). Although stratigraphic nomenclature has become somewhat more consistent in recent decades, it is likely that different interpretations of unit definitions persist (Johnson, 2002).

The most common nomenclature for Mesozoic units was first used in the 1950s by Mongolian and Russian petroleum geologists (Shuvalov, 2000). This terminology was reclassified by Traynor and Sladen (1995), who divided the stratigraphy of Mongolia into five chronologic megasequences based on tectonic and sedimentary characteristics. Figure 4 shows the distribution of rift-sequence

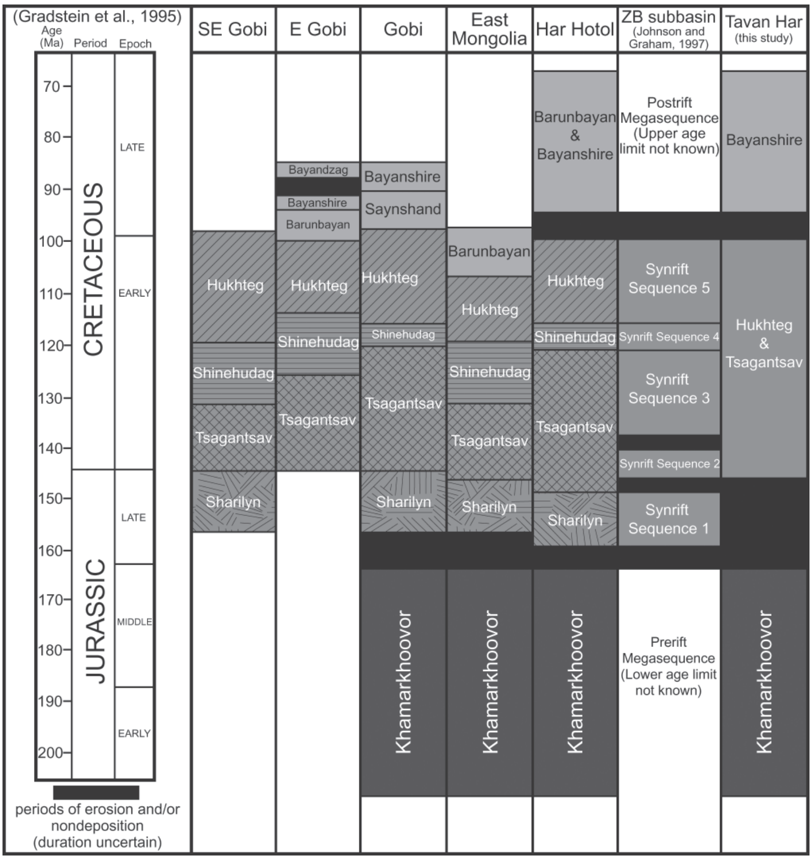

Figure 4. Names of major Mesozoic sedimentary rock units, based on relative age, from different regions of southern and eastern Mongolia, modified from Graham et al. (2001). The Tavan Har column was added using data from this study.

formations throughout the Gobi, correlated to the geologic time scale. My study uses the older formation names; however, as the figure shows, the two classification systems correlate fairly well to each other. Rift sequence units exposed in the field area include the Khamarkhoovor Formation (pre-rift), the Tsagantsav and Hukhteg Formation (syn-rift), and the Bayanshire Formation (post-rift).

Dating

The most well-studied exposure of the Khamarkhoovor Formation is located ~70 km north-northeast of Tavan Har. It is non-marine (Jerzykiewicz and Russell, 1991), similar to strata found in other regions of Mongolia and neighboring parts of China that have been dated as Lower to Middle Jurassic (200-161 Ma) (Graham et al, 2001). Regionally, this unit has been dated using fossil correlations (Jerzykiewicz and Russell, 1991).

Graham, et al, (2001) completed radiometric dating of early Mesozoic volcanic rocks at Har Hotol, located ~45 km northwest of Tavan Har. A distinctive layer of volcanic ash within the Sharilyn Formation was dated at 155 ± 1 Ma (Late Jurassic), and basalts at the base of the Tsagantsav Formation were dated at 126 ± 1 and 131 ± 1 Ma (Early Cretaceous).

The Shinehudag Formation, which typically overlies the Tsagantsav, is thought to not crop out at Tavan Har, and instead the additional Lower Cretaceous units are mapped as the Hukhteg Formation. In the northeast part of the EGB, the Hukhteg is constrained by stratigraphy and fossil assemblages to be 100 Ma or older (Johnson, 2004).

The Bayanshire Formation is dated as Upper Cretaceous due to its location overlying tilted Lower Cretaceous beds, and the dinosaur fossils found within it. The fault activity that tilted the syn-rift formations is constrained to 95-100 Ma by deposits that have known ages and were deposited before and after the faulting (Johnson, 2004).

Past Research in the East Gobi Basin

The results of past geologic research in the vicinity of the EGB have defined several parameters that I used as a context for this study. Paleontologists have compiled and analyzed late Mesozoic paleontology and stratigraphy within the Gobi Basin, and correlated these data with those from other regions of Mongolia (Jerzykiewicz and Russell, 1991; Jerzykiewicz, 2000; Shuvalov, 2000). Studies of sedimentology and stratigraphy have helped to interpret late Mesozoic extension-related faulting (Graham and others, 2001; Johnson and others, 2001).

In addition to these basin-wide studies, several studies have looked specifically at the region around our field area, Tavan Har. Subsurface data, collected through seismic reflection profiles, well logs (Johnson, 2004), and a 600 m borehole core that was collected from ~60 km northeast of Tavan Har (Johnson, 2002) have added to what is known about the majority of Mesozoic basin-fill, which is not exposed at the surface (Johnson, 2004). Other research has included basin modeling of the Zuunbayan subbasin (Johnson, 2004) and geochemical analyses of source rocks (Johnson et al, 2003).

Structure of Field Area

The Tavan Har field area is located at the northeastern end of a northeast-southwest-trending topographic high of basement rock that forms a distinguishing landmark on topographic maps and satellite images. This basement rock has been uplifted on either side by faults that are understood to be pieces of the North Zuunbayan Fault. These faults extend to the northeast beyond the exposed basement, dividing the area into the Unegt subbasin in the northwest and the Zuunbayan subbasin in the southeast (Johnson, 2004).

Methods

I, along with Cari Johnson (assistant professor, University of Utah) and Justin Gosses (student, Franklin and Marshall College), completed field research for this study during July and August, 2003, as part of the larger geologic expedition led by the Keck Geology Consortium and the Mongolian University of Science and Technology (MUST). We completed the fieldwork at Tavan Har, located between 109°15'-110°15'E and 43°50'-44°10'N. During our time at the site, we located exposures of Jurassic and Cretaceous sedimentary units deposited before, during and after the late Mesozoic rifting event using an unpublished map provided by MUST, as well as by observation during field reconnaissance (Figure 5). In addition, we were able to spend a day ~38 km north of our field area, at Har Hotol, and obtain samples from the Sharilyn Formation (pre-rift), which has not been found exposed at Tavan Har.

At each location, we completed statistical counts of major rock types represented in conglomerates and collected samples of medium-grained sandstones to use for compositional analysis. Where possible, we measured rock beds and pebble alignment that indicated current direction at the time of deposition (paleocurrents). Descriptions were made of the Khamarkhoovor (pre-rift), Sharilyn, Hukhteg, Tsagantsav (syn-rift) and Bayanshire (post-rift) Formations that we visited in the field. In addition, we measured and described sections from within the Hukhteg Formation at Locations 1, 2, and 5, and the Tsagantsav Formation at Locations 3, 4, 5, and 6.

Fourteen sandstone samples were thin sectioned for analysis, and the composition of 500 grains on each slide was counted using a common point-counting method (Ingersoll and others, 1984). Using this method, known as the Gazzi-Dickinson method, I moved the slide a set distance between counts and identified the grain directly under the crosshairs of the microscope as either a mineral or, if it was too fine-grained to identify a mineral, as a sedimentary or volcanic lithic. Samples were collected from all major outcrops of units deposited before, during and after the rifting event in and north of the field area, and therefore provide a complete, if preliminary, representation of the rift basin sedimentary sequence.

Results

Point-Count Data

Point-count results were tabulated into percentages of monocrystalline quartz (Qm), feldspar (F) and lithics (Lt), and of polycrystalline quartz (Qp), volcanic and metamorphosed volcanic lithics (Lvm), and sedimentary and

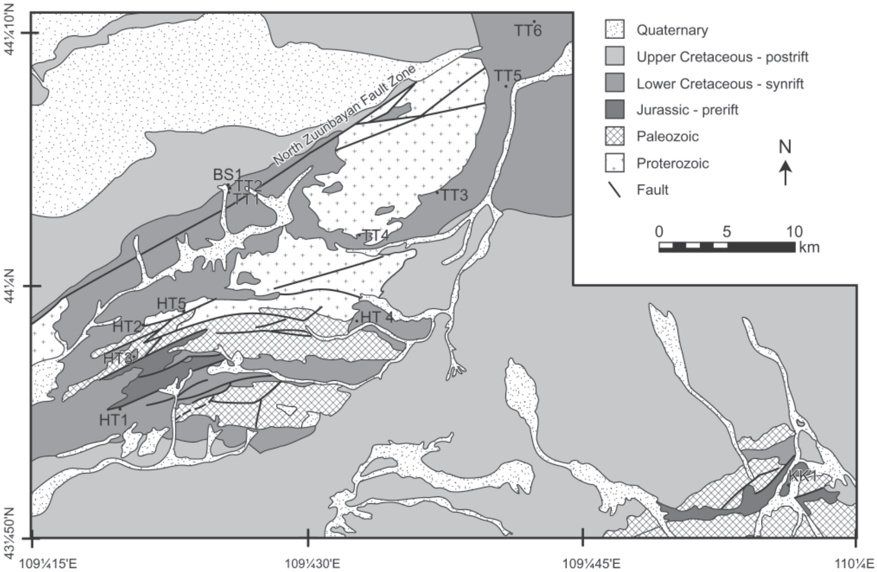

Figure 5. Geologic map of the Tavar Har field area, showing the distribution of late Mesozoic rift-related sedimentary units and the locations referred to in this study (modified from unpublished map from MUST). KK=Khamarkoovor (pre-rift); TT=Tsagantsav (syn-rift); HT=Hukhteg (syn-rift); GS=Bayanshire (post-rift).

metamorphosed sedimentary lithics (Lsm), which are plotted on ternary diagrams (Figure 6). Counts of pore space or any other minerals are excluded from these models. The fields on the ternary diagrams shown were developed by Dickinson and Suczek (1979) to estimate the tectonic setting of sand deposition in tectonically active areas.

The pre-rift and syn-rift sandstones plot closest to a volcanic island arc or "magmatic arc" setting on both the Qm-F-Lt and Qp-Lvm-Lsm diagrams. Post-rift sediments plot within a "continental block" setting on the Q-F-Lt diagram. On the Qp-Lvm-Lsm diagram, the post-rift samples indicate mixed sources.

Conglomerate Lithologies

In the field, we noted the pebble lithographies of a; with conglomeratic units. At some locations there was a single dominant pebble lithography; at locations with several different lithologies, we completed clast counts of randomly chosen clasts to estimate composition. Overall, the vast majority of syn-rift clasts were classified as metavolcanic or metasedimentary. Some lithographies were correlated to basement rocks seen by the other students or me in the area.

Stratigraphic Sequences

The Lower to Middle Jurassic, pre-rift Khamarkhoovor Formation (between 200 and 161 million years old) grades from sandstone and conglomerate beds into fine-grained sequences of shale, sandstone, and coal seams (Graham and others, 2001). In other parts of the basin, this unit contains beds of volcanic rocks (Jerzykiewicz and Russell, 1991) that do not occur here (Graham and

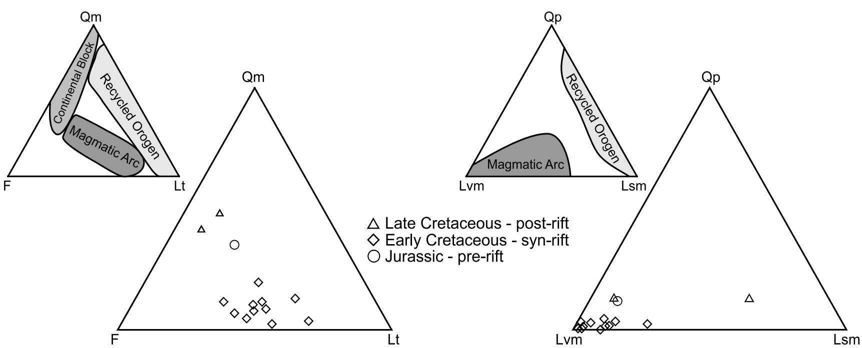

Figure 6. Ternary plots of the compositino of sandstone samples taken from throughout the late Mesozoic rift sequence at Tavan Har, along with fields developed by Dickinson and Suczek (1979) to estimate the tectonic setting of deposition. Qm=monocrystalline quartz, F=total fedspar, Lt=total lithics, Qp=polycrystalline quartz, Lvm=lithic volcanic and metavolcanic grains, Lsm=lithic sedimentary plus lithic metamorphic grains.

others, 2001). We found one exposure of this formation, in the southeast corner of our field area, consisting of 10-15 m of alternating beds of conglomerate and sandstone, each less than 1 m thick.

The conglomerate here probably represents deposition at the bottom of a slope during storm events. The lack of any distinctive structures in the coarse sandstones suggests that these beds were also deposited in periodic high-energy events, in which sediments were carried farther than usual.

The Upper Jurassic, early syn-rift Sharilyn Formation (deposited 161-145 Ma) was deposited on top of the Khamarkhoovor after a period of erosion and/or deposition. Grain size fines upward from a massive conglomerate made up primarily of large pebbles to interbedded mudstone and fine-grained sandstone. The Sharilyn Formation has not been found at Tavan Har, however we were able to visit two exposures of this unit ~38 km to the north at Har Hotol. There, the unit consists mostly of fine-grained sandstones.

These sedimentary rocks were likely deposited in river channels and lakes. At one of the locations, extensive exposure and study have led to an interpretation that the area was at first in a deep-water environment, which gradually became shallower until it became a delta and later a system of rivers (Graham and others, 2001).

Several outcrops of the Lower Cretaceous, syn-rift Tsgantsav Formation (145-100 Ma) were found at Tavan Har, mostly in the northern part of the study area. It is marked at its base by basalt and ash layers or by a distinctive blue-green basaltic breccia. Beds of conglomerate are often interbedded with layers of coarse sandstone. The upper part of the formation contains lacustrine deposits, such as fine-grained sandstone, thin white shale, siltstone and mudstone. In addition, these beds include waterlain ash and fossils of fish, bivalves, gastropods and plants. At some locations, the coarse-grained and fine-grained sediments alternate, showing multiple cycles of coarse conglomerate beds grading up to very fine-grained mudstone beds.

Two lines of evidence suggest that the source rock of the breccia beds must be close to where they were deposited. First, most of the coarse material appears to be made of the same source rock; second, these fragments of rock are made up of basalt, which is very fine-grained and tends to break down as it is transported. These coarse deposits probably represent deposition that took place after faulting events, which created newly uplifted areas that eroded rapidly into the new depressions in the landscape. The finer-grained beds deposited after and between these events show a gradual creation of new lakes and drainage systems as subbasins developed.

The Lower Cretaceous, syn-rift Hukhteg Formation (also 145-100 Ma) outcrops in the southern part of the study area. It is characterized by conglomerate, primarily volcanic, that grades into finer-grained lacustrine deposits. In the lower part of the unit, tilted beds have created a landscape with thick layers of conglomerate beds forming erosion-resistant hills between valleys that are most likely made up of finer-grained sedimentary rock. In the upper part of the formation, beds consist of fine-grained white material thought to be ash, as well as sandstone and conglomerate with smaller, more rounded pebbles and a wider variety of rock types than those at the base of the unit. These layers also contain plant fossils, including petrified wood.

The conglomerates exposed at the base of this unit represent deposition during episodic, rapid erosional events that likely occurring after periodic faulting and uplift along the border of the subbasin. The later, finer-grained beds show the development of river channels and lakes after the extensive faulting in the area had ended.

Exposures of the Upper Cretaceous, post-rift Bayanshire Formation (deposited between 100 and 66 Ma) were found overlying the Tsagantsav Formation in the northwest, and also ~20 km northeast of the study area. This unit contains conglomerate and medium to coarse-grained sandstone. The conglomerate beds contain pebbles that are smaller and more rounded than those in the syn-rift units. In some places, the sandstone beds contain dinosaur bones and petrified wood.

While some of the sandstone beds appear to have been deposited in rivers or shallow lakes, the environment appears overall to have become more arid. Red sandstone beds found in the unit specifically indicate an arid environment; in addition, there are no deep-water sediments, and fossils show the presence of terrestrial/continental plants and animals.

Discussion

Provenance

Sandstone composition

Sandstone composition is a result of a number of factors, including the composition of the source rock, climate, topography, dispersal paths, transport processes, and post-depositional changes (Dickinson and Suczek, 1979; Ingersoll et al, 1984; Zuffa, 1985). In tectonically active contexts, tectonic processes can be assumed to be the dominant control on these factors, and sediment composition will primarily reflect the source rock's lithology (Dickinson, 1970). Dickinson and Suczek (1979) compiled point-count data for sandstones from known plate tectonic regimes and located the regions on ternary diagrams where sandstones from "continental block", "magmatic arc", and "recycled orogen" source areas plotted. These frameworks were thought of as "useful inferences to be made relating framework modes to tectonic setting for any given basin" (Dickinson and Suczek, 1979, p. 2179).

Because continents are typically known to be made up of light-colored, igneous materials (Strahler, 1998), it follows accordingly that sedimentation within continents is considered to be made up of quartz and feldspar, the most common minerals in these types of rocks (Dickinson and Suczek, 1979). Therefore, because the EGB is known to have been fully within the Asian continent by the Jurassic, the apparent "magmatic arc," or volcanic island arc, source setting of much of this sedimentation appears anomalous. However, these results can be explained by recognizing that much of the basement rock in southern Mongolia is made of volcanic islands that were accreted between microcontinents and wedges of oceanic sediments. One can therefore interpret the volcanic sands as coming from older rocks that were exposed and eroded during the late Mesozoic. This conclusion is supported by the identification of metamorphosed volcanic basement rock while we were in the field. In addition, similar results have been found in provenance studies in northwest China (Carroll and others, 1995; Hendrix, 2000), western China (Graham and others, 1993), and southern Mongolia (Hendrix and others, 2001). The implications of these results for sandstone provenance schemes in nonmarine basins are discussed below.

Sample size

Another aspect of sandstone composition relevant to this study is sample size. Ingersoll and others (1993) distinguish three levels of sedimentation scale: first-order, which includes local drainages and piles of deposition at the base of hills or mountains; second-order, which includes streams and rivers that drain large topographic highs; and third-order, which includes large rivers, deltas, and marine environments. They point out that earlier research of source-rock settings studied third-order settings, and that studying first- and second-order settings may have results that do not follow models as well as expected.

In my study, much of the coarse-grained material likely came from first-order settings, and the lacustrine deposition was probably closest to second-order. Because the EGB is divided into several small subbasins, it may be difficult to find third-order settings, which would allow for more accurate source-rock estimates. The largest-scale late Mesozoic depositional environment exposed in the area is probably the delta sequence at Har Hotol that has been studied by Graham and others (2001).

Hukhteg – Tsagantsav Correlation

Currently, the Hukhteg and Tsagantsav Formations are divided into two formations that are thought to have been deposited consecutively. Based on evidence from this field work, combined with what little is known about Lower Cretaceous deposition in the Tavan Har field area, a simpler explanation of the lithological differences between the Hukhteg and Tsagantsav Formations at Tavan Har is that they are separated geographically, rather than chronologically.

Two field observations specifically support this conclusion. First, the two units are geographically separate throughout Tavan Har. All Hukhteg Formation outcrops are located in the southern part of the northeast section of Tavan Har, whereas all Tsagantsav Formation outcrops are found in the northernmost part of the area. This means that there is no evidence of Tsagantsav being deposited before Hukhteg (as the stratigraphic names suggest) or vice versa. Further, we found discrepancies with the current interpretation: at one location we noted that the Bayanshire Formation was found directly overlying the Tsagatsav Formation — had they been deposited one after the other, the Hukhteg Formation should have been seen between them. At another location, the Hukhteg Formation was found directly overlying pre-Mesozoic strata without any evidence of the Tsagantsav Formation ever having been present.

Second, in description and in outcrop, the two units show generally comparable sediment types and depositional environments. Both have coarse conglomerates at their base, with primarily volcanic composition, and then grade into lacustrine sequences. While in the field, this was a source of confusion, as the two units have similar compositional and structural sedimentary characteristics.

The major difference between the two units is the presence of extensive ash deposits, as well as distinctive blue breccia and conglomerate beds, found in the Tsagantsav Formation but not the Hukhteg Formation. However, an explanation simpler than a large chronological difference can account for this variation. According to the most current mapping of the area, the characteristic basal conglomerate in the Tsagantsav Formation could be attributed to differences in source rock (see Figure 5). Exposures of the Hukhteg Formation and Tsagantsav Formation surround two separate basement rock types. In addition, considering the lack of exposure within measured Hukhteg sections,

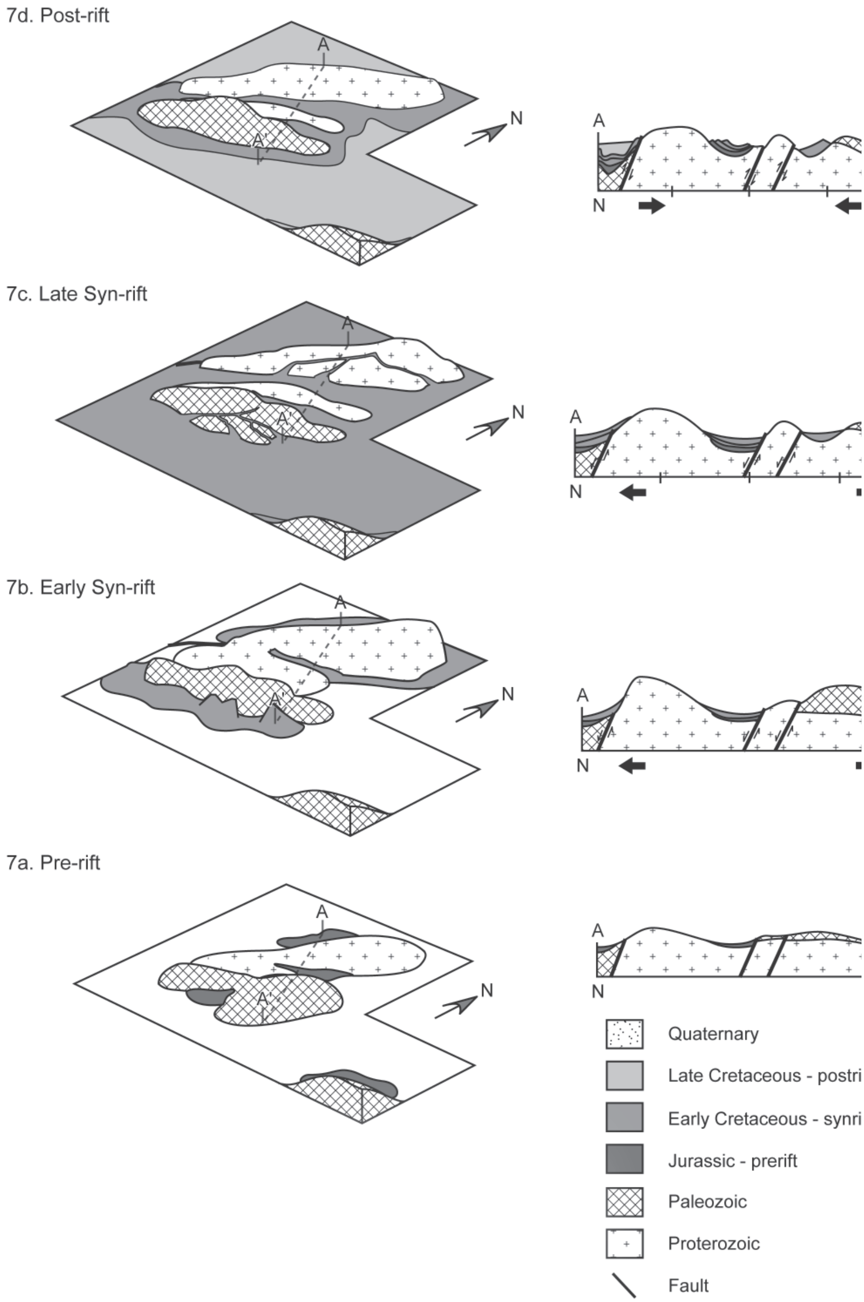

Figure 7. Diagrams showing the palcogeographic sedimentary and structural evolution of Tavan Har before, during, and after the late Mesozoic rifting event.

it is likely that more ash beds are present in the section but cannot be seen at the surface. Within outcrops of the lacustrine sequence of the Hukhteg, fine-grained, light colored siltstones and mudstones look identical to ash units studied in the Tsagantsav (Gosses and Bat-Erdene, 2004).

As described earlier, the current classification of formation names and ages in the field area, as in the entire region, is by no means definite. Moreover, non-marine basins are known for containing complex stratigraphic variations as a result of small-scale, rapid changes in deposition, particularly in lacustrine environments (Miall, 1984). Further research could be done to support or refute this conclusion about these two units. Seismic imaging of the subsurface would easily show the presence or absence of two thick syn-rift sections. Closer analysis of possible ash deposits in the Hukhteg would allow comparison with ashes in the Tsagantsav. Dating of the two units within Tavan Har would also provide more concrete evidence of their relative ages.

Reconstruction of the Rift Event

Keeping the above analyses in mind, my interpretation of the field descriptions can be incorporated with regional events within the EGB to reconstruct the paleoenvironment and paleogeography of the rift sequence within the Tavan Har field area.

Pre-rift (~200-161 Ma)

Deposition in the EGB during the Early-Middle Jurassic was due to erosion of a regional mountain chain (Traynor and Sladen, 1995). To the north of the Tavan Har field area, pre-rift deposition reflects high-energy braided streams that later shifted to lower-energy meandering streams and swamps (Graham et al, 2001). This suggests the continuing erosion of topographic highs in a humid climate. In the southeast part of our field area, the environment was probably similar: at Khamarkhoovor Location 1, deposition took place during periodic storm events. The relatively quartz and feldspar-rich composition of sandstone beds suggest that they were likely deposited in a warm and humid environment, where feldspar-rich sediments eroded rapidly from local uplifts before significant weathering could take place (Boggs, 1995). Sandstone composition during this period suggests multiple erosion cycles of Paleozoic arc sequences and possibly granitic crust. The pre-rift period ended with a period of erosion (Figure 7a).

Early Syn-rift (~161–145 Ma)

Extensional tectonics commenced throughout the Gobi Region in the Late Jurassic (Traynor and Sladen, 1995), with faults most likely forming along weak zones between accreted microcontinents, volcanic islands, and sedimentary sequences. In the northeast EGB, newly exposed remnant volcanic arc materials were carried by braided stream and alluvial systems, leaving coarse conglomerate and sandstone deposits in the developing basin. North of Tavan Har, at Har Hotol, fluvial and lacustrine systems developed; coarse-grained pebble and ash deposition shows the initiation of rift processes (Graham et al, 2001).

In our field area, the Tavan Har basement rock was most likely already uplifted when extension commenced. This hypothesis is supported by at least two lines of evidence: first, syn-rift deposition directly overlies Permian basement rock at Hukhteg Location 5, meaning it must have been already exposed when this deposition took place. Second, Graham et al (2001) found evidence that Tavan Har, one of two major basement highs in the EGB (Johnson, 2004), separated the Unegt (NW) and Zuunbayan (SE) subbasins during at least parts of the rifting event.

The earliest syn-rift deposits at Tavan Har are very coarse-grained conglomerates. Based on what is exposed at the surface, the majority of this coarse deposition appears to be on the southwest and northeast ends of the Tavan Har uplift. This could be because a) the steepest relief of the Tavan Har basement was along its northwest and southeast ends, or b) coarse basal rocks are buried under later deposits in other parts of the area.

In the northeast, much of the coarse-grained deposition is composed of redeposited volcanic flows. The original source of this extrusive igneous material could be contemporaneous volcanism or pre-Mesozoic arc basement; I assume at least some of it is rift-related volcanic material, because in-place basaltic and ash units are present. A proximal source for the original flow deposits can be inferred from the homogeneity and coarseness of the basal conglomerate units (Figure 7b).

Late Syn-rift(~145–100 Ma)

At Tavan Har, more texturally mature conglomerate overlies the earliest syn-rift deposits. Sandstone continues to be lithic-rich, implying continued erosion of volcanic arc-related basement, but coarse units have more of a sandy matrix, and pebbles are smaller and more rounded. This change probably resulted from the continued erosion of topographic highs with shallower slopes.

Intermittent ash beds were deposited as volcanic processes continued some distance from Tavan Har.

Much of the upper-Lower Cretaceous deposition consists of fine-grained fluvial and lacustrine beds. The development of finer-grained fluvial and lacustrine systems, also present to the north (Johnson, 2002; Graham et al, 2001), indicate an increase in water supply, due to some combination of basin subsidence relative to surrounding relief, a shift in drainage patterns, and an increase in precipitation throughout the region.

Based on the locations of fine-grained lacustrine deposits in the area, the lake was probably bounded on the northeast along the North Zuunbayan Fault splay. It also likely surrounded the same two major topographic highs of Tavan Har basement that still exist today, as well as another basement high ~30 km to the southeast. Exposed lacustrine units lie along the east flank of the northeastern point of Tavan Har and on the north side of the southeastern Tavan Har uplift. High-energy deposits at Tsagantsav Location 4 imply that the current valley between the two Tavan Har uplifts may have existed or been eroded out during this time (Figure 7c).

Post-rift (younger than 100 Ma)

In the mid-Cretaceous, regional compression led to a reactivation of faults throughout many parts of Mongolia, with fault movement reversing its direction from during the rifting event (Traynor and Sladen, 1995). In the EGB, this faulting deformed syn-rift strata (Johnson and Graham, 1997; Graham et al, 2001). This event was followed by post-rift deposition throughout the region (Traynor and Sladen, 1995), and a shift to a more arid climate (Jerzykiewicz and Russell, 1991; Shuvalov, 2000).

In the Tavan Har field area, flatter terrain in the area led to more mature sediment deposition in less humid, fairly high-energy systems. In much of the area, non-deposition or erosion occurred, leaving synrift deposits exposed. Red beds and terrestrial fossils at Bayanshire Location 2 are representative of similar deposits across southern Mongolia (Jerzykiewicz and Russell, 1991) (Figure 7d).

Implications for the Study of Non-marine Basins

A number of geologists who study in Asia have called attention to the fact that current basin classifications and sandstone source setting schemes are not applicable to the study of Asian basins (Marsaglia and Ingersoll, 1992; Graham et al, 1993; Hendrix, 2000; Sjostrom et al, 2001). Hendrix (2000) notes that while sandstones in basins of North America are generally rich in quartz and feldspar, reflecting the erosion of granitic uplifted basement rocks, few sandstones in western China share this composition. Graham and others (1993) recognize that current classification schemes were derived from well-studied basins, most of which are in the Americas and Europe, and that using these models for basins in western China will lead to inaccurate interpretations of tectonic setting. Studies of western and southern Mongolia have had to address similar sandstone composition results (Sjostrom et al, 2001; Hendrix et al, 2001).

The current explanation and classification schemes for basins throughout the world only date back a few decades, since the acceptance of plate tectonic theory (Miall, 1984). Therefore, it is not surprising that unique characteristics of basins in less-studied parts of the world have not yet been incorporated into the majority of literature on basin studies. One popular basin tectonic textbook (Busby and Ingersoll, 1995) notes that modelers have not yet considered some basin types that remain relatively unstudied. There are no substantial data on the composition of accreted terranes in Asia or their corresponding sediments, and until these data — as well as detailed information on the tectonic evolution of the continent — are collected and compiled, it will be difficult to classify and compare basins in Asia as accurately as basins in other parts of the world.

Several existing basin models could potentially help to describe the EGB. Two of these — the divergent continental rift and backarc basin models — may come the closest. I will present these and assess the extent to which they characterize the EGB and our field area, and discuss the possible development of new basin models.

Divergent Rift

Divergent continental rifts occur within continental crust, and are often associated with volcanism. In our case, rifting was probably passive rather than active: passive rifting is driven by tensional stress due to plate tectonic processes in the asthenosphere, as opposed to lithosphere-driven mantle upwelling that occurs in active rifts (Busby and Ingersoll, 1995). Intracontinental rift models state that the tectonic reaction to tensional stresses will tend to take place along weak zones in the crust, such as older rifts or sutures (Miall, 1984). Faulting in rifted areas generally forms asymmetrical basins that are bordered by a single major fault zone (Busby and Ingersoll, 1995).

Basin formation is characterized by rapid subsidence and deposition, as the newly uplifted border of the basin erodes (Miall, 1984). The development of coarse-grained alluvial fans along the border fault (Busby and Ingersoll,

1995) and river systems on fault scarps or along basin axes is likely, and lakes may develop (Miall, 1984). Deposition within intracontinental rift basins can be highly varied, and may commonly include conglomerate, sandstone, and shale, as well as turbidites, carbonates, coal and evaporates (Boggs, 1995). These often show repeated fining-upward sequences that record recurring uplift and erosion (Busby and Ingersoll, 1995).

The general composition of sediments reflects that of the uplifted basement rock as well as any overlying units. A large-scale study by Dickinson and Suczek (1979) showed that sand deposition where uplifted basement is the source rock most commonly consists of quartz and feldspar-rich sands. Where lithic-rich sands occurred, these were interpreted to generally reflect the erosion of sedimentary or metamorphic rock units covering the basement gneisses and granites. They did note recent volcanic arc-related erosion in four intracontinental sandstone sample sets from Alaska and California. However, these samples appear to have been largely overlooked, due to the fact that they did not match the overall trends seen in the other sandstones that were studied (discussed below).

Overall, the divergent intracontinental rift model describes well the basic tectonic and sedimentary processes that characterize the evolution of the EGB and Tavan Har. Although basin formation — in the EGB complicated by complex basement structures — and sandstone composition do not fit into the most "common" basins of this type, the model does seek to explain this variability. Busby and Ingersoll (1995) note that basin evolution is controlled primarily by the type of substratum and location of nearby plate boundaries, and Dickinson and Suczek (1979) do acknowledge the possibility of arc-related sediment sources. Despite this, it seems significant that the compositional and structural characteristics of the EGB and much of Asia are considered atypical, since Asia is currently the largest continent in the world.

Convergent Backarc Basin

Backarc basins form in either oceanic or continental lithosphere on the landward side of volcanic arc systems. The continental type can form when a volcanic arc is on the continent margin; sometimes, the hinge of the subducting plate shifts back into the ocean, and a new volcanic arc develops above the new, further oceanward, subduction zone. This creates a sedimentary basin between the old and newly active arcs (Miall, 1984). However, as mentioned earlier, the intracontinental location of the EGB — over 1000 km from the subduction zone — at the time of rifting makes it difficult to argue that extension was due to stress directly landward of any subduction-related volcanic arc (Graham et al, 2001).

Deposition in backarc basins was found by Dickinson and Suczek (1979) to range in composition from lithic- and plagioclase feldspar-rich volcanic detritus to quartz and feldspar-rich granitic material. While this is similar to the sandstone compositions found at Tavan Har, the deposition in our field area is primarily a result of basement volcanic arc material and only partly due to materials derived from contemporaneous volcanism; therefore an interpretation of sediment source based on this model would be inaccurate.

Based on fieldwork as well as research of late Mesozoic rifting throughout the region, the divergent rift model adds somewhat to the understanding of rift initiation and basin-forming processes. But neither of these models seems to explain directly the tectonic, structural, or compositional characteristics of the EGB. Because many of these characteristics are common throughout all of Asia, this indicates a lack of representative understanding of non-marine basins worldwide.

New Basin Model Development

In the coming years, it is likely that continuing studies in Asia will lead to a better understanding of basin-forming processes in the region and the development of new models that more accurately account for the continental makeup of Asia. Already, studies on basin types have focused on Chinese basins (Hefu, 1986; Graham et al, 1993). Marsaglia and Ingersoll (1992) have sought specifically to address the varied interpretations of volcanic-arc source settings in sandstones.

It is also important to reiterate that Asia is not the only part of the world where continents have been formed by accretionary processes. For example, somewhat analogous, although younger, continental composition and structure is found in western North America (this was reflected in the sample suites from Alaska and California that Dickinson and Suczek (1979) used in the study noted above) If further field studies are completed in basins in Asia, as well as these other areas, this continental make-up will come to be understood as an important context for basin formation and basin model development.

Conclusions

At the Tavan Har field area, the Hukhteg and Tsagantsav Formations are more likely distributed geographically, rather than chronologically. Studies of the source setting of sandstones in the rift units in the EGB and throughout

Asia show that non-marine sediments have similar depositional styles to but different compositions than those in more thoroughly studied regions, with important implications for interpreting basin histories worldwide. In addition, detailed studies in relatively small areas, such as Tavan Har, can provide a great deal of data on the local as well as regional tectonic and sedimentary history. Numerous such studies within central Asia could provide much of the information needed to identify and constrain explanations of late Mesozoic deformation.

I would suggest three additional types of studies that could add to the understanding of the area. First, detailed studies on the rift-related volcanic rocks could provide information about the type of igneous processes that were taking place during the Mesozoic, and would elucidate the relative effect of different possible drivers of extension. Second, further subsurface studies — including seismic imaging and research on additional sample cores — in the Tavan Har area would be helpful for understanding the boundaries between and amount of deposition within the subbasins, and would confirm whether there are one (as I suggest) or two (as is currently thought) major synrift sequences in the area. Third, more dating of rocks in the area would provide support for or determine changes to the currently accepted stratigraphy in the region, by clarifying differences between interpretations of local and regional formations that are based on sedimentary characteristics and those based on the relative timing of deposition.

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Postscript

My fieldwork in Mongolia, combined with a semester spent abroad in Turkey, has unquestionably affected my current interests and goals. In part because of my experiences abroad studying both geology and international relations, I am now interested in working and researching in the fields of hydrogeology and water resources management, specifically in developing countries and in regions where water resources are shared by multiple states. In these areas, a lack of knowledge or communication about what water is available and how it is being used and developed can lead to environmental, social, and national security problems.

Completing research abroad helped me to recognize the challenges involved with translating ideas between different languages, institutional cultures, and geographic regions. It also helped me to realize how important these translations are to collecting information and developing theories that accurately reflect this world. So far as I can tell, this is as true in almost any other field as it is in geology. With so much research being done in the US, and so much literature available in English, it is easy for American college students to overlook the missing or inaccurate data that results from poor communication between regions and countries. The best way for students to see these challenges, and their practical and academic effects, is to study abroad.