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Franklin & Marshall College

Dr. Stan Mertzman
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Franklin & Marshall College

Kelly Erb
Keck Consortium Administrative Assistant

Diane Kadyk
Academic Department Coordinator
Department of Earth & Environment
Franklin & Marshall College

Keck Geology Consortium
Franklin & Marshall College
PO Box 3003, Lancaster PA 17604-3003
717 291-4132 keckgeology.org

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Students: GARRISON LOOPE: Oberlin College; DOUGLAS MERKERT: Union College; JOHN LINDEN NEFF: Amherst College; NANCY PARKER: Lafayette College; KYLE TROSTLE: Franklin & Marshall College; BEVERLY WALKER: Colgate University

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A. BAYASGALAN: Mongolian University of Science and Technology
KURT L. FRANKEL: Georgia Institute of Technology
KARL W. WEGMANN: North Carolina State University

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GANBAYAR RAGCHAASUREN: Mongolia University of Science and Technology

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**Esukhei Ganbold:** Mongolia University of Science and Technology

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**Tamir Battogtokh:** Mongolia University of Science and Technology

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**Brittany Gaudette:** Mount Holyoke College
Research Advisors: Al Werner
**Delgerstseg Burendelger:** Mongolia Univ. of Science and Technology

Visitors:
- Tsolman Amgaa: Mongolia University of Science and Technology
- Steven Boettcher: University of Bayreuth
- Laura Gregory: Oxford University
- Richard Walker: Oxford University

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

The Höh Serh Range is a subrange of the Mongolian Altai in western Mongolia (Fig. 1). Using satellite imagery, PIs noted three lines of evidence that there has been a recent component of vertical motion and uplift of the Höh Serh along the transpressional Höh Serh Fault (HSF) on the western flanks of the range. First, the furtherest downvalley moraines appear quite young, suggesting that the elevation of the glaciated valleys has increased during this time. Second, the Buyant Gol (river) cuts directly across the axis of the mountains and appears to be an antecedent stream. Finally, there is evidence of Holocene movement along the HSF from offset landforms, suggesting that this uplift may be ongoing. Based on this evidence a project was proposed to study the Quaternary glacial and tectonic geomorphology and climate along the western flank of the Höh Serh Range.

The American group flew to Ulaanbaatar, Mongolia, where we spent the night before flying to the provincial capital of Khovd in western Mongolia. In Khovd we met A. Bayasgalan and the Mongolian students who had driven from Ulaanbaatar with vehicles and equipment. We also met Richard Walker of Oxford University, Aamga Tsolmon of the Mongolian University of Science and Technology, and two students, Steve Boettcher and Laura Gregory, who were exploring tectonic geomorphology near our study area. Together we
drove west to the Deliün Valley on the west side of the Höh Serh Range in the Mongolian Altai. We made base camp at the mouth of the Yamaat Valley at 47.905° N, 90.724° E (Fig. 2) 

We spent several days conducting reconnaissance south along the Buyant Gol and north along the HSF and nearby Tsagaan Salaa fault. Richard Walker’s group accompanied us during this period before returning to their field area to the north. Our investigations revealed several promising locations to situate research projects on fault expression and glaciation. In total there were eleven student research projects: five focused on glacial geomorphology, four on tectonic geomorphology, one focused on a huge debris-flow deposit, and one focused on late Holocene climate.

Each project included one American student and one Mongolian student. On a typical day, students at remote sites were driven to their project areas while others hiked in. Professors accompanied student groups on a rotating basis. Mongolia is the most sparsely-populated nation on Earth, but many students met Kazakh nomads during the course of their research. We were also able to attend the festival of Naadam just across the Yamaat River from our base camp and witness a total eclipse of the sun that coincided with our visit (Fig. 3). After three weeks in the field we flew back to Ulaanbaatar, where we spent a day exploring the city and attending cultural events before returning to our home institutions.
**GEOLOGIC SETTING**

Mongolia’s geology is complex. The Mongolian Altai generally consists of Paleozoic metasedimentary rocks intruded by primarily Paleozoic plutonic complexes. The bedrock geology of the Mongolian Altai can be interpreted as a complex orogenic collage of large Paleozoic subduction-accretion complexes accreted against a Precambrian continental terrane in what is today north-central Mongolia (Sengör et al., 1993). Beginning in the late Cenozoic, the collision of India with Eurasia has produced intraplate stress leading to the reactivation of motion exploiting these Paleozoic fabrics (Cunningham, 1998).

In the Mongolian Altai, transpressional deformation along these NNW-SSE-trending structures has uplifted a number of fault-bounded ranges, which probably exhibited little regional relief prior to the Cenozoic (Cunningham et al., 2003). Movement along these faults continues today. GPS velocities suggest that up to 7 mm y\(^{-1}\) of crustal shortening between Siberia and western China (roughly 15% of the total shortening resulting from the Indo-Eurasian collision) is accommodated along the Mongolian Altai (Calais et al., 2005). Not surprisingly, large earthquakes have been recorded in this region, including the Ms 8.0 Fu Yun earthquake in the Chinese Altai in 1931 (Baljinnyam et al., 1993) and a 2003 Mw 7.2 earthquake in the Russian Altai (Rogozhin et al., 2004).

Transpressional stress in the Höh Serh Range is accommodated along the HSF, which runs NNW-SSE along the western edge of the range, and is responsible for uplift along the western side of the east-dipping fault block composing the Höh Serh Range; this block is actively overriding the Buyant Gol half-ramp basin to the west (Baljinnyam et al., 1993). North of our base camp the HSF bifurcates into two strands, with predominantly right-lateral motion along the eastern strand (the continuation of the HSF) and predominantly thrust motion along the western strand (the Tsagaan Tsalaa fault) (Cunningham et al., 2003).

The Mongolian Altai is the largest of at least four ranges in Mongolia where glaciation in the recent past and in the Pleistocene has shaped mountain geomorphology. The distribution of periglacial landforms such as moraines, cirques, and erratics suggests that the regional equilibrium-line altitude (ELA) has risen about 500 m since the Pleistocene (compared to about 1000 m in the western Russian Altai and Hangay ranges); this disparity may result from aridity in the Mongolian Altai limiting Pleistocene ice volume (Lehmkuhl et al., 2004). Based on paleoenvironmental studies in the nearby Uvs Nuur basin, climate in western Mongolia changed from cold and dry during the last glacial maximum (LGM) to warmer and more humid during the Holocene (Grunert et al., 2000) with at least one arid period occurring during the Holocene (An et al., 2008). Currently in the Höh Serh Range, the ice cap atop Praying Mountain (Fig. 4) is the only remnant of the once-extensive Pleistocene glaciers.

**STUDENT PROJECTS**

Elizabeth Brown, working with Ragchaasuren Ganbayar, collected 12 samples of granite and gneiss for apatite fission track analysis in order to constrain the low-temperature exhumation history of the Höh Serh Range. While a similar study (Vassallo et al., 2007) was done in the Gobi-Altai,
~1000 km southeast, no fission track data exists in the Mongolian Altai. Widespread distribution of granite allowed Elizabeth to collect samples with a total vertical relief of ~1.5 km, covering a distance of about 30 km along the Höh Serh Fault.

Kristin Sweeney, working with Tsolmon Adiya, investigated the northernmost segment of the HSF in our project area. Their study focused both on the main fault strand and on the Tsagaan Salaa Fault, a small thrust splay to the west. They characterized the geomorphic expression of the fault, recording the orientation of tension gashes and mole tracks, as well as measuring the offset of major drainages via satellite imagery. Using differential GPS, they surveyed a fault scarp resulting from the motion of the Tsagaan Salaa Fault, measuring a vertical offset of 5.5 ± 0.5 m. Based on the survey of fluvial strath terraces along the same fault, this offset may record as many as two separate ruptures. Tsolmon and Kristin also collected six samples for cosmogenic dating that will be used to estimate a modern slip rate for the Tsagaan Salaa Fault.

Jodi Sprajcar, working with Bolor Erdenebat, studied the HSF between Ice Lake Valley and Naran Khondii Valley. In this area the HSF offsets two channels and one ridge. Jodi calculated a slip rate from the offset distances of these three features, using glacial history and bar and swale topography to estimate the timing. Gradual fault creep has probably affected this section of the fault since the LGM. Three landslides just north of these offsets suggest up to three major slip events.

Chelsea Durfey, working with Jargal Otgonkhuu, studied a 10-km segment of the HSF between Naran Khondii Valley and Debris Flow Valley. Chelsea and Jargal conducted a detailed reconnaissance survey in which they described the HSF’s geomorphic expression in 54 locations. They surveyed features and calculated offset by hand and with a differential GPS. Chelsea compiled offset locations, differential GPS profiles, and the fault into a GIS and used x-y graphs to vertical offset profiles. Right-lateral offsets average 33 ± 50 m and show no north-south trend; the thrust component averages 3 ± 9 m and is most pronounced between Naran Khondii Valley and Rhyolite Valley.

Andrea Seymour, working with Galbadrakh Sukhbaatar, studied the glacial history of Ice Lake Valley. This glacial trough contains five dominant moraines. Andrea mapped glacial features including moraines and highest granite erratics. From these data points Andrea constructed ice limits and ELAs for each moraine. Samples of granitic boulders were collected for cosmogenic dating to determine when the three largest moraines were deposited.

Kathryn Ladig, working with Munkh-Erdene Enkhbayar, studied the geomorphology of Naran Khondii Valley. The study site was to the north of base camp, between Ice Lake Valley and Rhyolite Valley. Detailed geomorphic descriptions of the valley were made and GPS points were taken to record the locations of landforms, such as river terraces and moraines. Upon return to the United States, the GPS points were mapped using ArcGIS, particularly in order to examine the retreat of a glacier located on the north headwall of Praying Mountain. The retreat of this glacier may be of concern to the local residents as they rely on its meltwater as a major water resource.

Kelly Dundon, working with Esukhei Ganbold, studied the glacial geomorphology of Rhyolite Valley, a glacial trough 3 km north of base camp. Kelly and Esukhei mapped ice marginal channels and the crests of moraines to determine the limit of glacial ice in Rhyolite Valley. Using ArcGIS and Russian topographic maps of the area, 3-D models of the former glacier were generated. ELAs were determined for the glacial ice that deposited each moraine complex in Rhyolite Valley, including the ELA during the LGM. At the LGM, the glacier in Rhyolite Valley occupied more than 0.8 km$^3$ and covered 7 km$^2$.

Gia Matzinger, working with Battogtokh Davaasambuu, studied the glacial history and geomorphology of Yamaat Valley, where our base camp was located. Gia located landforms, sediments and erratics with a GPS and topographic maps.
After returning to the United States, Gia used GIS to determine maximum ice extents, volume and ELA of Late Pleistocene glaciation of the valley. Gia also estimated paleodischarge of a possible jökulhlaup or moraine burst flood event that deposited anomalous boulders using topographic maps and the Manning equation.

Ryan Leary, working with Tamir Battogtokh, studied the glacial history of Debris Flow Valley, a system of glacial troughs roughly 20 km south of the project base camp. Ryan and Tamir mapped the extensive moraines in this area using GPS. Using the location of moraine complexes, topographic maps, and satellite data, it was possible to calculate the ELA for the most recent glaciation of the valley.

Gregory Mortka, working with Mergen Naranchimeg, studied the genesis of the Delüün Debris Flow Deposit at the mouth of Debris Flow Valley, approximately 20 km south of base camp. Greg mapped the deposit using GPS and DPGS, and measured its extents using ArcGIS and KaleidaGraph. Greg also built a flume model to characterize the debris flow event. The debris flow was probably produced by the catastrophic failure of a moraine that had impounded a glacial lake.

Brittany Gaudette, working with Delgertsetseg Burendelger, collected dendochronological data from 23 Siberian larch (Larix siberica) trees from two stands in the Mongolian Altai. Because larch forests are uncommon in the Mongolian Altai, the stands that do exist are likely to be at their environmental extent and sensitive to changes in climate. Sample cores were collected from larch stands are on north-facing slopes between 2400 to 2900 m. Brittany assembled six chronologies, the longest beginning at ca. A.D. 1600. This study aims at extending paleoclimate proxy records beyond geographically and temporally-limited instrumental climate data for the Mongolian Altai.

MAJOR SCIENTIFIC ACCOMPLISHMENTS

Tectonic geomorphology

Both perennial and ephemeral stream channels are dextrally offset along the trace of the Höh Serh Fault. Measured strike-slip drainage offsets range from 10 to 1500 m. Prominent shutter ridges are common along the trace of the fault; several alluvial fans and an LGM terminal moraine preserve evidence of recent fault rupture with scarps, left-stepping en echelon “mole tracks”, and tension gashes.

Preliminary slip rates based on surveyed offsets and estimated landform ages (from fan morphology and soil development) suggest about 1 to 2 mm y\(^{-1}\) of strike-slip and 0.5 mm y\(^{-1}\) of vertical offset along the Höh Serh Fault. over latest Pleistocene to early Holocene timescales. This may account for between 15 and 30% of the total shortening accommodated across the Mongolian Altai.

Post-glacial strath terraces are preserved along two streams oriented perpendicular to the Tsagaan Tsalaa fault strand. Three mappable straths extend about 1 km upvalley from the mountain front along each stream. Individual terraces are vertically separated by 2 ± 0.5 m, and each projects into a small knickpoint in the modern channel. These straths may represent stream channel response to instantaneous base-level fall resulting from individual surface rupture events along the fault.

Glacial geomorphology

Tectonic and glacial geomorphology in the Höh Serh Range are tightly linked: for example, we observed no pre-LGM glacial deposits in the valleys along the east side of the Delüün Valley. In contrast, in the Altai mountains west of the Delüün Valley an older moraine complex (presumably Oxygen Isotope Stage 6) extends about 8 km further downvalley. This difference may be due to recent movement along the HSF, since rapid uplift may have increased the land area above the ELA, enabling recent glaciers to extend further than might be expected.
We estimate that the putative LGM ELA in the western flank of the Höh Serh Range was at approximately 3200 m. Between the LGM and 1963, the ELA rose from about 3200 m to at least 3600 m; currently the ELA is probably above 4000 m, because (1) the summit ice elevation has dropped about 35 m since 1963, and (2) the area of the glacier has been reduced by about a third since 1963. The ELA is sensitive to both temperature and precipitation (Steiner et al., 2008), so the increased ELA that we observe could be the result of either increased temperature or decreased precipitation. Temperature records from Delüün and Khovd suggest reduced precipitation since 1990 and increased mean annual temperature since the mid-1980s.

Areal extent of the glaciers west of the Höh Serh drainage divide decreased from approximately 104 km² during the LGM to about 6 km² in 1963 to about 4 km² today. If the present rate of loss continues, these glaciers will have disappeared by about 2080. In Delüün, where precipitation between 1996 and 2007 averaged only about 90 mm y⁻¹, the loss of mountain glaciers will impact local nomadic communities.

**Cosmogenic Dates**

We obtained 28 ¹⁰Be cosmogenic surface exposure dates, 11 on alluvial fans and 17 on moraines. Samples were processed at the Georgia Tech Cosmogenic Nuclide Geochronology Laboratory and analyzed at the Lawrence Livermore National Laboratory Center for Accelerator Mass Spectrometry. Five dates on an alluvial fan near the middle of the Höh Serh fault have a mean age of 15+/- 2 ka, which is likely the maximum age of the most recent oblique-slip movement in the central part of our study area. Six dates on an alluvial fan cut by the Tsagaan Salaa fault, an associated thrust splay of the Höh Serh fault, have a mean age of 35+/- 5 ka. Combined with the measured offset of 5.5 +/- 0.5 m and the fault's dip, these ages yield a shortening rate of 0.23 mm/yr over the late Pleistocene.

Along Chigerty Gol west of the Delüün Valley, boulders on an old moraine have cosmogenic dates of 58, 84, and 115 ka, whereas four boulders on a young moraine yiled dates with a mean of 13 +/- 1 ka. Boulders on the outermost (and likely LGM) moraines at the base of the Höh Serh Range have ages of 31, 33, and 44 ka (Yamaat Valley), and 35, 40, 60, and 70 ka (Ice Lake Valley). These dates suggest that the LGM in this area was about 31 to 44 ka. Finally, three boulders on a recessional moraine in Debris Flow Valley have exposure ages of 13, 63, and 120 ka, suggesting that the large debris flow sourced from the dated recessional moraine may have occurred during the latest Pleistocene.

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