Bayasgalan, A., Carson, R., Jordan, B., Wegmann, K., 2007. 20th Annual Keck Symposium; http://keck.wooster.edu/publications

GEOLOGY OF THE HANGAY NURUU, CENTRAL MONGOLIA

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INTRODUCTION

Two of the authors made reconnaissance visits to the Hangay Nuruu (mountains) of west-central Mongolia (Fig. 1).

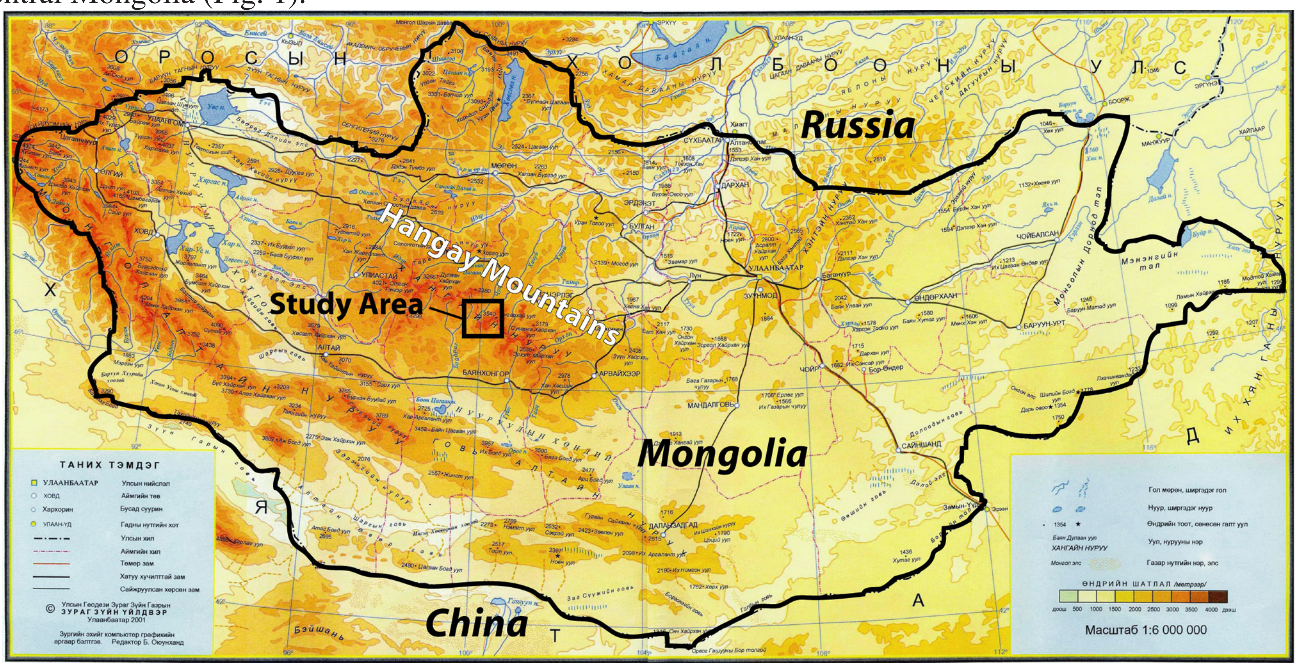

Figure 1. Map of Mongolia showing the Hangay Mountains (Nuruu) and the location of the study area. Topography depicted by color shading with gradation from light yellow (<500 m) to brown (>4,000 m).

They noted a wide variety of geologic features in and near these mountains including: Tertiary and Quaternary basalts (Whitford-Stark, 1987); active faults, notably the Bulnay strike-slip fault which generated two M>8 earthquakes in 1905 (Baljinnyam et al., 1993); widespread glaciation (Lehmkuhl, 1998); and local periglacial features such as cryoplanation terraces. Based on this reconnaissance and the success of Keck Geology Consortium projects to the Gobi in 2003 (Carson et al., 2004) and the Mongolian Altai in 2004 (Carson et al., 2005), a project was proposed for the Hangay Nuruu. The goals were to study Paleozoic and Mesozoic granites, the Cenozoic basalts, Quaternary tectonism, glacial and periglacial landforms and processes, and the late Quaternary paleoclimate and paleoecology.

The Americans flew to Mongolia's capital Ulaanbaatar. There we met the Mongolian professor, students, cooks, and drivers, and drove west toward our field area. We overnighted near Karakorum, the ancient capital of the Mongol Empire (2006 was the 800th anniversary of the founding of the Mongol Empire, and therefore a year of great celebration, including the festival of Naadam).

Passing through Tsetserleg, the aimag capital of Arkhangay, we set up base camp near Chuluut Gol (river) at latitude 47°16'N, longitude 100° 02'E, elevation 2,295 m (Figs. 2 and 3).

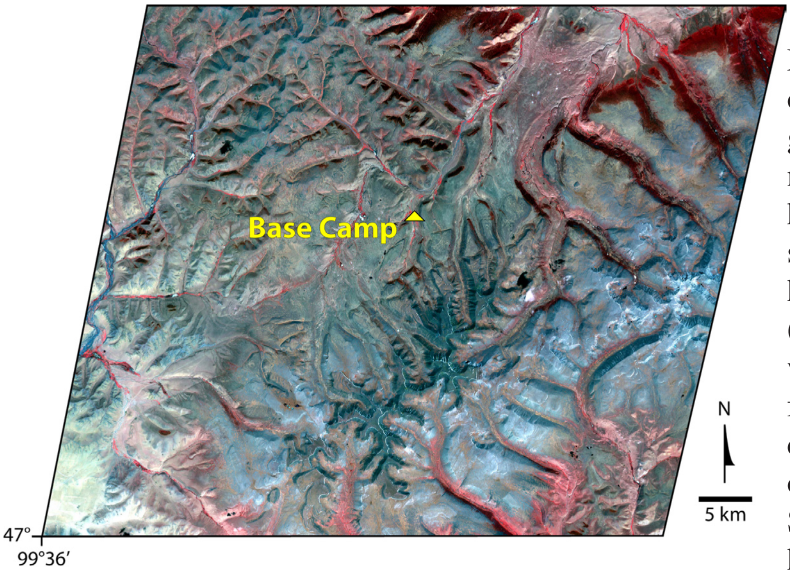

Figure 2. False-colored ASTER image of the study area, showing the location of base camp. The Egiin Davaa fault can be traced from south of camp to the southwestern corner of the image. Dark upper portions of the northeast-trending belt of mountains south of camp are Tertiary plateau lavas. These mountains are deeply incised by glacial troughs. Moraine complexes extend beyond the mountain front.

Figure 3. Base camp at 2,295 m below forested (Siberian larch) slopes in the central Hangay. Tertiary plateau lavas crop out in the upper slopes on the right.

The two visiting geologists from Great Britain joined us at base camp. Just upvalley from the base camp are Tertiary basalt flows; just downvalley are late Pleistocene terminal moraines. On the first of a few days of reconnaissance we drove southwest along the active Egiin Davaa normal fault, crossing the drainage divide of the Hangay Nuruu en route to Jargalant (Bayankhongor aimag), the nearest town to our camp.

Mongolia is the most sparsely populated country on Earth. The Hangay Nuruu have abundant grasslands so that almost daily we encountered nomadic families with their gers (yurts) and herds of horses, cows, yaks, yak-cow hybrids, sheep, and goats. Some north-facing slopes have forests of Siberian larch (*Larix sibirica*) (Fig. 3). The only other "trees" are dwarf willow (*Salix* sp.) and birch (*Betula* sp.). Being far from any ocean, Mongolia has a cold dry continental climate, with most precipitation occurring during the summer monsoon. Summer-time weather can be intense, with high wind, thunder and lightning, heavy rain, large hailstones, and snow above 3,000 m. The weather was usually ideal for field work, with sunny skies and light breezes. Getting around in the field included shuttles by four-wheel-drive vehicles, wading across streams, and long hikes.

Ten research projects took place in July and August. Each of the ten American students had one or two Mongolian students working with him or her. On a typical day each team of one faculty member, one or two American students, and two or three Mongolian students would do field work. The samples we collected were held up at customs as we left Ulaanbaatar and/or as we arrived in the United States; most samples eventually reached the home campuses of the American students.

GEOLOGIC SETTING

The geology of Mongolia is complex: geological maps reveal the variety and complexity of rock types and structures, with representatives of all geological ages from Precambrian to Quaternary. Geologically, Mongolia is an important link between the Siberian craton, essentially an amalgamation of lower Paleozoic terranes, and northern China, an area of complex middle Paleozoic-Tertiary suturing and tectonics. The rocks record successive episodes of terrane accretions and consequent deformation. These tectonic boundaries encompass 'plates': collections of smaller terranes which formed as continental fragments were successively plastered against, and welded to, the much larger Siberian craton during the early and late Paleozoic. The structures that formed during these terrane accretion episodes were repeatedly reactivated during the Mesozoic and Tertiary, in response to further accretion south of Mongolia in western and central China.

The pre-Tertiary bedrock of the study area consists of a sequence of intensely deformed Carboniferous and Devonian sedimentary rocks intruded by late Paleozoic and Mesozoic granitoid plutons. The plutonic rocks are part of a belt of Paleozoic and Mesozoic granitoids that extends to the Sea of Okhotsk, the largest granitoid province in Asia (Jahn et al., 2004). In the study area these granitoids are represented by the Hangay batholith and associated outlying plutons. The two main units of the Hangay batholith in the study area have been ascribed to the Permian Hangay complex and the Triassic-Jurassic Egiin Davaa complex (Takahashi et al., 1999; Jahn et al., 2004). These units are predominantly granite and granodiorite with subordinate pegmatite, aplite, and other lithologies.

Across much of the study area pre-Tertiary bedrock is overlain by Cenozoic basaltic lavas. Cenozoic volcanism in Mongolia is part of a diffuse volcanic province in central Asia including northern China and Siberia, south of the Baikal Rift (Whitford-Stark, 1987; Barry and Kent, 1998). This province is predominantly basaltic and commonly alkaline including trachybasalts, basanites, tephrites, and hawaiites. The origin of this diffuse volcanic province is equivocal: Windley and Allen (1993) propose a mantle plume; alternatively, Barry et al. (2003), argue against a plume and propose a model of magmatism driven by a shallow thermal anomaly heating metasomatized lithosphere. In the study area Cenozoic volcanic rocks occur in two distinct modes of field occurrence. Tertiary lavas occur in sequences exceeding 500 m in thickness that constitute plateaus making up much of the high Hangay southeast of Chuluut Gol. Quaternary lavas are found as isolated lava fields in topographic lows, confined by valleys carved into the pre-Tertiary bedrock. Both the Tertiary and Quaternary lavas are lithologically and chemically diverse, ranging in composition from basalt to phono-tephrite.

Some of the world's largest recorded intracontinental earthquakes have occurred in this part of Mongolia, including four with magnitudes >8 during the twentieth century (Baljinnyam et al., 1993). These very large events occurred on strike slip and thrust faults north, west, and south of the Hangay. Mapped faults in the Hangay predominantly display normal-style displacements (Tomurtogoo, 1999). Unlike fault systems further north, those in the Hangay appear to be relatively young, with offset Neogene basalt flows constraining total movement to several hundred meters or less. Similarly, the depth of Quaternary fluvial sediments (~150 m) filling half grabens formed by normal faults in the Hangay Nuruu are consistent with the offsets measured on basalt flows. The young normal fault systems in the Hangay are perhaps a response to crustal uplift and doming in the range. In addition, the faults with the clearest evidence for Holocene activity within the Hangay occur at relatively high elevations suggesting that these areas are most actively extending (Cunningham, 2001).

The Hangay Nuruu are one of four ranges in Mongolia that experienced Quaternary glaciation. Lehmkuhl (1998) calculated the modern equilibrium line altitude (ELA) in the Hangay Nuruu to be just below the elevation of the highest peaks, allowing for limited year-round snow fields. The Pleistocene ELA was more than 1,000 m below today's, so that there are extensive cirques and glacial troughs. The source area for the glaciers in our part of the Hangay Nuruu was cirques with headwall elevations of about 3,400 m. The ice cut glacial troughs extending north as much as 30 km, eventually coalescing into piedmont glaciers in the vicinity of Egiin Davaa and the valleys of the Chuluut Gol and the Davaatiin Gol.

Much of the area of the Hangay Nuruu is covered with quite a variety of periglacial landforms because of extremely low winter temperatures and many annual freeze-thaw cycles. In high places where there was not late Pleistocene glaciation, cryoplanation terraces are widespread. Slopes are experiencing solifluction, with prominent lobes in places. Block fields and sorted polygons with boulder and cobble rims are located on cryoplanation terraces and elsewhere. Some valleys have palsa fields associated with the permafrost.

Student Projects

American students worked closely with Mongolian students in the field. In the paragraphs that follow Mongolian students who were specifically linked with an American student, or team, are listed with them. Other Mongolian students played a critical role in the project but contributed to several different projects.

Rachel Landman, assisted by Davaadulam Tumenjargal, studied granitoids of central Hangay (Fig. 4) in five localities, sampling granitoids from both the Permian Hangay and Triassic-Jurassic Egiin Davaa complexes as well as adjacent metamorphic rocks. Rachel studied these rocks with several different techniques. She has conducted petrographic and geochemical studies to evaluate the petrogenesis of the magmas. She investigated the possibility of pressure constraining assemblages in both the granitoids and metamorphic rocks in their contact aureole. Rachel also collaborated with Karl Wegmann to conduct a U-Th/He thermochronologic study of the granitoids to try to constrain the low-temperature exhumation history of these rocks. The thermochronologic study is a work in-progress, not completed at the time of publication of this volume.

Figure 4. Petrology students look south into the upper Botgon Gol valley. Tertiary volcanic rocks are well exposed in the glacial trough and the small hanging valleys joining it from the west (right). Light outcrops below the saddle are Mesozoic granitoids that nonconformably underlie the Tertiary volcanic rocks.

Brian Kastl and **Jacob Tielke**, working with Javkhlan Otgonkhuu, investigated the Tertiary plateau lavas exposed in the Botgon River valley (Fig. 4), the next valley east of base camp. This area was selected because the thickest continuous exposure of Tertiary lavas in the study area crops out here and includes a basal contact with underlying granites. They mapped, and characterized the physical volcanology of units spectacularly exposed in the cirque at the southern end of the valley. The principal focus of their study was a 709-m measured section through the Tertiary lavas. They characterized 63 lavas and four dikes in the section, and collected a representative sample suite. They followed-up the field investigation with petrographic and geochemical study of the lavas to constrain the conditions of melting and processes of magmatic differentiation. An Ar/Ar geochronology study of the section is being conducted in collaboration with Karl Wegmann.

Angela Ekstrand, assisted by Tamir Enkhbaatar and others, studied the Quaternary basaltic lavas of the south-central Hangay Nuruu. The study area was over two hours south of base camp so a temporary second base camp was established to serve this project and the Egiin Davaa fault group. Angela and her team investigated Quaternary lavas at seven sites, characterizing and measuring a section of the lavas at three of these sites, and obtaining a representative sample suite from these sections as well as from the other sites. Angela conducted petrographic and geochemical studies on these samples including SEM analyses of minerals. Angela, Brian, and Jake are able to compare their results to those reported by Barry et al. (2003) for Quaternary basalts in the northern Hangay as well as their own lavas of different ages. Changes, or constancy, in time and space may be manifestations of variations in tectonic processes of magma genesis.

Figure 5. Scarp of the active Egiin Davaa fault near Jargalant (two people on the upthrown block and two people on the downthrown block).

Emily Parker and **Juliana Williams**, working with Uyanga Bold and Erdenebayar Oyun, studied the Egiin Davaa fault between base camp and ~15 km southwest of Jargalant (Fig. 5). This northeast-striking fault, at least 80 km long, is upthrown on the southeast. Near camp the post-glacial fault scarp is as much as 10 m high. The fault appears to have more throw northeast of camp, but has been more recently active toward Jargalant. The throw along the 51-km-long recent scarp ranges from approximately 1 to 6 m. Radiocarbon dating of organic material found in trenches suggests that the a large earthquake occurred here during the middle Holocene. They evaluated scarp profiles to determine the magnitude and amount of lateral slip associated with the scarp-producing earthquake.

Adam Pearson, with assistance from Demberelsuren Batbold and Khurelbaatar Ariunzaya, mapped the extent of the glaciers originating about 10 km south and east of Egiin Davaa. As these glaciers joined, some ice overwhelmed the drainage divide at Egiin Davaa and flowed almost 10 km southwest. Most of the ice flowed north to occupy the valley of the Chuluut Gol near camp (Fig. 6), more than 20 km from the cirques. Adam used a large variety of weathering parameters to determine relative ages of moraines. Beyond terminal moraines of the Late Glacial Maximum (LGM), glaciers left moraines with weathering characteristics suggesting an age of oxygen isotope stage 4 (Lehmkuhl, 1998) or perhaps more likely 6.

Brian Coggan, with the help of Ulziiburen Burenjargal, investigated glaciers farther east which filled the valleys of the large tributaries to the Davaatiin Gol. Like Adam, he mapped glacial limits and measured weathering parameters of boulders on different ages of moraines. In this area the ice advanced north over a plateau between the Davaatiin Gol and the Chuluut Gol, filling the valley of the Chuluut Gol, and most likely damming this river to form a lake which may have released jökulhlaups. This glacier complex stagnated to leave very hummocky moraines in the valley of the Chuluut Gol and widespread kettles on the plateau to the southeast. Brian reconstructed former equilibrium line altitudes, and glacier and ice-dammed lake areas and volumes.

Emilee Skyles, assisted by Ganzorig Vanchig and Jargal Otgonhuu, studied periglacial landforms, surveying cryoplanation terraces (Fig. 6) and palsas, and excavating trenches in patterned ground and solifluction lobes. Emilee focused on different stages of palsa development. One palsa had dramatic changes in morphology while the almost one-meter-thick cap of peat collapsed as the underlying ice core melted.

Figure 6. View north of the upper Chuluut Gol valley with a terminal moraine complex at the "big bend". Devonian metasedimentary and metavolcanic rocks crop out on the lower slopes of the mountains in the distance, with well developed cryoplanation terraces near their summits.

Laurel Stratton concentrated on late Quaternary paleoclimate. Glacial and periglacial landforms, together with radiometric dates, give indications of climate change over tens or hundred of thousands of years. For the more recent climate history, we cored and excavated through the organic-rich active layer in valleys and elsewhere, never getting as much as a meter deep because of the shallow permafrost. However, at one site peat from the base of the active layer has a radiocarbon age of 4,970 ± 20 yBP. Time and logistics did not allow Laurel to complete her research on past climate based on the pollen in the peat. We also cored the largest Siberian larches we could find in many small forests. Laurel is studying the climate information preserved in tree rings of larch trees as much as 600 years old.

MAJOR SCIENTIFIC ACCOMPLISHMENTS

Cenozoic Volcanism

The Quaternary lavas differ little from the Tertiary lavas, and the geochemistry of the lavas studied in the central and southern Hangay differ little from published analyses of Quaternary lavas of the Tariat Depression to the north (Barry et al., 2003).

The lack of variation in time and space argues against the involvement of a mantle plume. These lavas were modeled to be the result of 3-7% partial melting of metasomatized garnet lherzolite mantle at depths of >70 km. Fluid flux associated with metasomatism may have driven volcanism or preconditioned the upper mantle for subsequent melting.

Lavas evolved primarily through fractionation in lower crustal magma chambers. In contrast with previous studies of Cenozoic volcanism in central Mongolia (Barry and Kent, 1998; Barry et al., 2003), we find evidence that plagioclase feldspar was a significant fractionating phase, and that magma mixing and assimilation play a role in the evolution of some central Mongolian lavas. The differences in interpretation are probably the result of detailed study of closely related sequences in our work versus regional studies.

Tectonism

Late Paleozoic and early Mesozoic granitoids show striking geochemical similarities. Plotted on trace element tectonic discrimination diagrams, most samples of both units plot in the field for an intraplate setting. This favors the interpretation that this magmatism was driven by post-orogenic processes in the wake of Paleozoic orogeny rather than contemporaneous subduction zone processes.

Possible magmatic epidote found in the Paleozoic granitoids suggests high-pressure emplacement, and exhumation to shallower depths before emplacement of the Mesozoic granitoids.

Although the Egiin Davaa normal fault has more displacement to the northeast, the most recent offset has been to the southwest. Based on radiocarbon dating of organics recovered from trenches, rupture occurred between 7,369 and 4,916 years ago.

Glaciation

Unlike at least one part of the western Hangay Nuruu, where the outermost moraine is believed to be late Pleistocene (oxygen isotope stage 2) (Carson and Carson, 2004), we found a record of at least two glaciations, with outer moraines likely to be oxygen isotope stage 4 or 6. Some ice-transported boulders beyond all moraines indicate an even earlier glaciation.

Recessional moraines upvalley of terminal moraine complexes indicate pauses in the retreat of late Pleistocene glaciers, one of which was radiocarbon dated to 11,250 radiocarbon years before present, possibly correlating to the initiation of the Younger Dryas climatic interval.

The presence of rare facets, polish, and striations indicate that at least parts of the glaciers were warm-based and sliding at least some of the time. Considering that temperatures during glaciation were much lower than those of today, it is expected that much of the ice was cold-based.

The topography of the area caused the glacier originating in the Davaatiin Gol drainage system to leave ice-stagnation topography.

The Davaatiin Gol glacier complex filled the valley of the Chuluut Gol, almost certainly creating an ice-dammed lake which released jökulhlaups.

Periglacial Processes

The Hangay Nuruu exhibit widespread and prominent cryoplanation terraces. Some have ice-transported erratic boulders on them; these glaciers were most likely cold-based or they would have eroded the terraces.

We were able to document the decay of a palsa as its ice core melted.

Paleoclimate

We cored Siberian larch to obtain a greater than 600-year (back to A.D.1388) dendrochronologic record of climate change in the Hangay Nuruu. The oldest published tree-ring records from living trees in Mongolia go back to the year A.D.1340 (Davi et al., 2006) and A.D.1465 (Jacoby et al., 1996).

ACKNOWLEDGMENTS

For the third Keck Mongolia project, Ben Meadows Company generously donated field equipment for the Mongolian students.

John Wegmann, a doctor from Port Angeles, Washington, joined his third Keck project in Mongolia, prepared to help us in case of illness or accident.

We are deeply appreciative for all the safe travel, including fording streams, by the drivers, and for all the excellent food, including bread baked daily, prepared by the cooks.

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