KECK GEOLOGY CONSORTIUM

PROCEEDINGS OF THE TWENTY-FOURTH ANNUAL KECK RESEARCH SYMPOSIUM IN GEOLOGY

April 2011
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Students: *HANNAH BOURNE*, Wesleyan University, *JONATHAN GRIFFITH*, Union College, *JACQUELINE KUTVIRT*, Macalester College, *EMMA LOCATELLI*, Macalester College, *SARAH MATTESON*, Bryn Mawr College, *PERRY ODDO*, Franklin and Marshall College, *CLARK BRUNSON SIMCOE*, Washington and Lee University.

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Faculty: *KARL W. WEGMANN*, North Carolina State University, *TSALMAN AMGAA*, Mongolian University of Science and Technology, *KURT L. FRANKEL*, Georgia Institute of Technology, *ANDREW P. deWET*, Franklin & Marshall College, *AMGALAN BAYASAGALN*, Mongolian University of Science and Technology.
Students: *BRIANA BERKOWITZ*, Beloit College, *DAENA CHARLES*, Union College, *MELLISSA CROSS*, Colgate University, *JOHN MICHAELS*, North Carolina State University, *ERDENEBAYAR TSAGAANNARAN*, Mongolian University of Science and Technology, *BATTOGTOH DAMDINSUREN*, Mongolian University of Science and Technology, *DANIEL ROTHBERG*, Colorado College, *ESUGEI GANBOLD, ARANZAL ERDENE*, Mongolian University of Science and Technology, *AFSHAN SHAIKH*, Georgia Institute of Technology, *KRISTIN TADDEI*, Franklin and Marshall College, *GABRIELLE VANCE*, Whitman College, *ANDREW ZUZA*, Cornell University.

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Students: *JESSE GEARY*, Macalester College, *KATHERINE KRAVITZ*, Smith College, *RAY MCGAUGHEY*, Carleton College.

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Keck Geology Consortium: Projects 2010-2011
Short Contributions— Hövsgöl Rift, Mongolia

LATE-CENOZOIC VOLCANISM IN THE HÖVSGÖL RIFT BASIN: SOURCE, GENESIS, AND EVOLUTION OF INTRAPLATE VOLCANISM IN MONGOLIA

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ARANZAL BAT-ERDENE, Mongolian University of Science and Technology
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GEOLOGIC, GEOMORPHIC, AND ENVIRONMENTAL CHANGE AT THE NORTHERN TERMINATION OF THE LAKE HÖVSGÖL RIFT, MONGOLIA

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AMGALAN BAYASAGALN, Mongolian University of Science and Technology

INTRODUCTION

Lake Hövsgöl, the 16th largest lake by volume in the world, is located in northern Mongolia south of the Vostoch Mountains that form the Mongolian-Russian boarder (Fig. 1). Its basin represents the southern boundary of the intracontinental Baikal Rift System, and though not as old, similarly owes its origin to tectonic activity related to the far-field effects of the Indo-Asia collision. Due to the remote location of the northern Hövsgöl basin, the geology and terrestrial paleoenvironmental history is poorly documented. Beginning in 2004, participants of Keck – Mongolia projects have been studying the variability in timing and extent of late Quaternary glacial systems at several other sites in northern and western Mongolia. This prior research is supportive of the hypothesis that variability in local down-valley extent of Pleistocene glaciers may reflect ongoing uplift of individual fault-bounded mountain ranges. Based upon satellite remote sensing data, the PIs noted that at the northwest corner of the Lake Hövsgöl basin there was apparent evidence for diachroneity between the down-valley extent of last glacial maximum (LGM) and older terminal moraines between parallel valleys less than 30 km apart. We hypothesized that this could be due to along-strike differential surface uplift of the western fault-bounded range. In addition, recent high-resolution Quaternary paleoclimate proxy records obtained from deep-water sediment cores from the lake basin as part of the International Continental Drilling Program provide an excellent framework from which to develop a detailed late Pleistocene-to-present glacial, fluvial, and shallow lacustrine chronostratigraphy for the northern Lake Hövsgöl rift that is anchored by high-precision radiometric age control. The

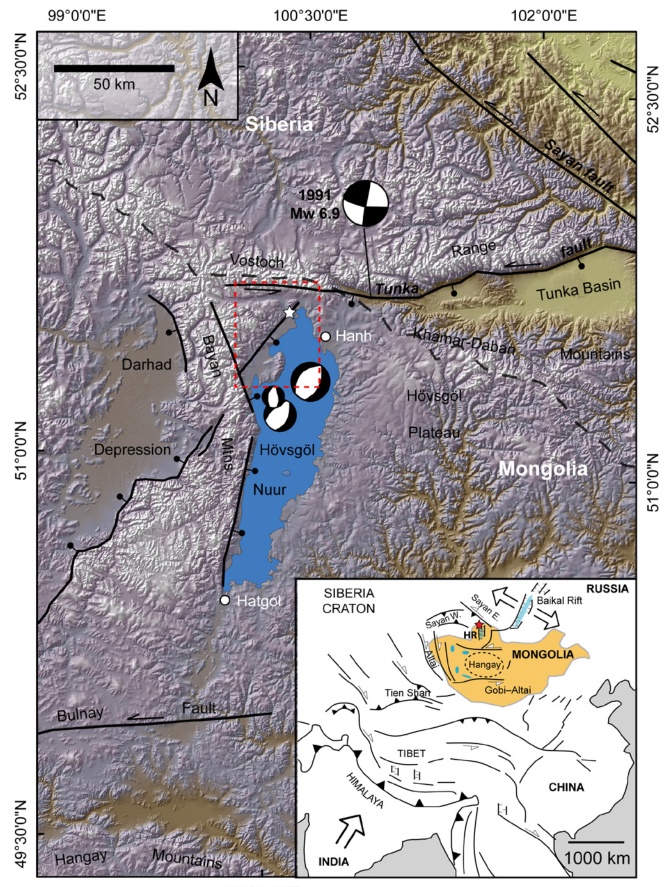

Figure 1. Inset: Tectonic setting of Central Asia. The red star denotes the project area at the north end of the Hövsgöl rift (HR). Main Image: Shaded digital topography of the Hövsgöl rift and surrounding areas, derived from 90 m SRTM dataset. Our base camp in the lower Horoo Gol valley is marked by the white star. Post-1950 > 4.0 magnitude focal mechanisms (Delouis et al., 2002) for the northern Hövsgöl rift. Dashed-line denotes location of 2010 Keck project area.

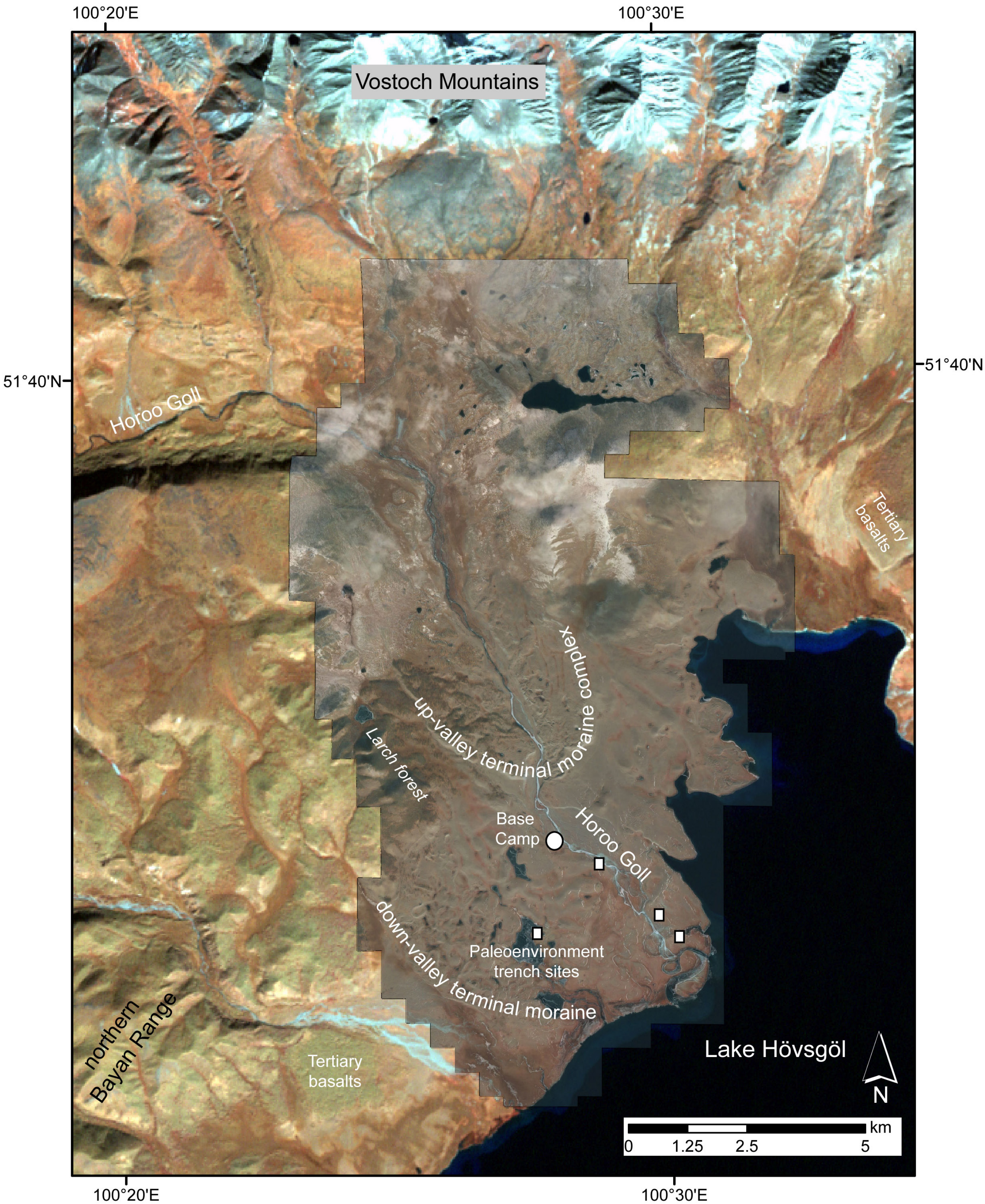

Figure 2. Satellite image mosaic of the study area at the northwest end of Lake Hövsgöl. The base Landsat image combines bands 2, 3, and 4. The detailed imagery covering the lower part of the Horoo Gol valley, delta plain, and Lake Hövsgöl shoreline is a 50-cm pixel resolution GeoEye scene acquired in November, 2010. Generalized student project areas are labeled.

underlying premise of this research project was that the high-latitude (51.5° N), elevation (1650 m) and continentality of the northern Hövsgöl rift provides a terrestrial setting that is sensitive to past tectonic and climate variability.

The U.S.-based group flew to Ulaanbaatar, where we met our Mongolian faculty, student, and camp logistical counterparts. Thirty-two of us departed by vehicle caravan the following afternoon for the northern end of Lake Hövsgöl, a straight-line distance of 620 km, via the city of Moron and the Hövsgöl lakeside towns of Hatgol and Hanh. The journey took four days. We established our base camp (51.58587° N, 100.45931° E) along the upper delta plain of the Horoo Gol (river), which drains into the northwest corner of Lake Hövsgöl (Figures 2, 3).

Figure 3. Base camp, located along the lower Horoo Gol. The up-valley (likely LGM) terminal moraine complex is in the middle-ground. The south slope of the Vostoch Range is in the background.

Our initial intent was to have several students conduct research on active rift-bounding faults. However, upon our arrival at the field site, the local Mongolian boarder unit commander required that we travel no closer than 10 km from the Russian boarder, and this included the trace of the Tunka fault along the southern piedmont of the Vostoch range. This necessitated modification of the original student research plan submitted to the Keck Geology Consortium. We spent two days following our arrival conducting regional reconnaissance of the glacial and fluvial geomorphology, extrusive volcanic stratigraphy, and paleoenvironmental proxy record potential preserved in bog and lacustrine sedimentary sections as well as the dendroclimatology of surrounding Siberian larch (Larix sibirica) forests. In total we had nine student research projects: one focused on Neogene basalt geochemistry, three on Late Pleistocene glacial geomorphology, one on terrestrial cosmogenic nuclide (TCN) geochronology of glacial deposits, three on Holocene paleoenvironmental reconstructions of shallow lake and river terrace deposits, and one focused upon reconstructing past climate and temperature trends from dendrochronology of L. sibirica.

Students were responsible for their own research projects, but often they worked together in teams that included both U.S. and Mongolian participants (e.g., glacial or lake sediment groups). On a typical day, students working at remote sites were driven to their project areas, while those conducting research closer to base camp hiked. Faculty members accompanied student groups on a rotating basis. Mongolia is the most sparsely-populated nation in the world; however the pastoral resources of the Horoo Gol delta plain meant that seldom a day would pass without student interaction with local semi-nomadic families. After 14 days of field work, we drove for 4 ½ days back to Ulaanbaatar, where we spent a day exploring the city and attending cultural events before returning to our home institutions.

GEOLOGIC SETTING

Geodynamic Framework

Mongolia is situated in Asia at the transition between a N-S convergent province to the south in the Tien Shan and an E-W to NW-SE extensional province to the north in the Baikal rift zone (e.g., Baljinnyam et al., 1993; Cunningham et al., 1996; Bayasgalan et al., 1999). Molnar and Tapponnier (1975) first suggested that post-collisional "rigid" indentation of India into Asia since ~50 Ma is responsible for Cenozoic deformation throughout the whole of Central Asia, including crustal extension in the Baikal-Hövsgöl system of rifts (Fig. 1). Relative to stable Eurasia, western Mongolia and adjacent parts of central Asia (west of 100° E) currently accommodate ~10 mm/yr of northward-directed shortening related to the India-

Asia collision, while the ~2000 km long Baikal rift system is presently extending at ~4 mm/yr (Calais et al., 2003). The Hövsgöl rift demarcates a kinematic transition between predominantly transpressional deformation to the south and transtensional deformation to the north (Fig. 1; Baljinnyam et al., 1993). At long wavelengths, the Hövsgöl rift is a broad dome of elevated topography, with the rift lake at the center. Late Miocene to Pliocene lavas and moderate heat flow are present in the Hövsgöl rift (Windley and Allen, 1993). The Hövsgöl rift and Hangay Mountains demarcate a kinematic transition between predominantly transpressional deformation to the south and transtensional deformation to the north. The northern end of the rift basin is structurally bound between active faults uplifting the east-west trending Vostoch Range and the north-south trending Bayan Range. These faults accommodate and link extension between the Hövsgöl and Baikal rifts (Figures 1, 2).

Geologic Framework

The country is an important link between the amalgamated Neoproterozoic through lower Paleozoic terranes of the Siberian Craton in the north and complex Middle Paleozoic-Tertiary suturing and tectonics of northern China to the south (Sengör et al., 1993; Zorin, 1999). Mongolia is composed of a number of terrains or micro-plates – collections of smaller terranes which formed as continental fragments collided with the much larger Siberian Craton during the Early and Late Paleozoic (Tomurtogoo, 2003). The structures that formed during these terrane accretion episodes were repeatedly reactivated during the Mesozoic and Tertiary in response to accretion further south in western and central China.

The northern margin of the Mongolian plateau and adjacent parts of the Siberian Craton are dominated by the active Baikal and Hövsgöl intracontinental rifts (Fig. 1). Sedimentation in the Baikal rift began in the Oligocene (30 to 35 Ma; e.g., Logatchev and Zorin, 1987), while Hövsgöl extension initiated more recently at about 5 Ma (Fedotov et al., 2006). Geological and geomorphic evidence document relatively recent uplift, faulting, and volcanism in the region, although when these processes initiated or how they relate in space and time are poorly understood. The Pliocene-Quaternary Hövsgöl rift is a north-south-trending half-graben situated ~100 km to the southwest of Lake Baikal. Lake Hövsgöl presently exceeds 200 m in water depth and more than 1 km of sediment has accumulated in the rift axis since extension initiated (Hövsgöl Drilling Program Members, 2009).

The basement geology of the northern Hövsgöl rift region consists of Precambrian crystalline rocks and a Neoproterozoic passive-margin sedimentary cover known as the Tuva-Mongolian Massif of the Gargan microcontinent. Following collision of the Gargan microcontinent with the Siberian platform, establishment of a new subduction zone outboard of the Gargan terrane resulted in the intrusion of arc magmas into the overlying Gargan sequence at 785 ± 11 Ma (Kuzmichev et al., 2001). These intrusions crop out in the study area. Miocene to Quaternary basalts unconformably overlie the Neoproterozoic basement rocks along the flanks of the Hövsgöl rift and are the remnants of a single volcanic plateau surrounding Lake Hövsgöl (Fig. 3; Whitford-Stark, 1987). The flows are multi-layered with 6 to 10 individual units totaling 100 to 150 m in thickness. Although the largest volume of these basalt flows exists on the eastern side of the rift, lesser areas of basalt crop out across the 2010 study area.

Geomorphic Framework

Both of the Hövsgöl rift-bounding ranges, the Vostoch and Bayan Mountains, had significant cirque and valley glaciers during the late Pleistocene. Discernible on satellite imagery, the largest and furthest down-valley ice extent was interpreted as occurring during Marine Isotope Stage (MIS) 6 to 4 glaciations, with the younger inset terminal moraine complex deposited during MIS 2 glaciation (Figure 2; Kulakov, 1981; Krivonogov et al., 2003). However, until now, publications with numerical dates for Pleistocene glacial systems of the Hövsgöl rift are lacking (see below).

Since 2004, Keck - Mongolia groups have been working to understand the variability in timing and extent of glacial systems in western and northern Mongolia. The consensus view that is emerging from our and others' work (e.g., Lehmkuhl, 1998; Gillespie et al., 2008; Bader et al., 2009; Wegmann et al., 2009) is that the timing of maximum glacier advance across western Mongolia is approximately synchronous, but differs from Siberia and western Central Asia, supporting the inference that paleoclimatic conditions in Central Asia exhibit strong regional trends. Furthermore, we hypothesize that the rate of tectonically-induced topographic uplift of individual ranges appears to be a locally important control on the timing and down-valley extent of maximum glacial advance (e.g., Wegmann et al., 2009), adding complexity to paleoclimate interpretations from glacial landforms lacking geochronologic age control.

Fluvial, littoral, and periglacial landforms, such as river terraces, beach ridges, pals and perhaps pingos exposing post-glacial lake sediments are preserved in the Horoo Gol valley and delta plain (Fig. 2). There are no previously published ages for these features along the northwest shore of the lake.

The Lake Hövsgöl region has a harsh continental climate characterized by very cold, dry winters and mild summers with most of the annual precipitation occurring during July and August. Nearly fifty years of climate records from the rift basin indicates that the mean annual temperature is increasing at a rate of about 0.05° C yr-1 and precipitation is increasing at 1 to 2 mm yr-1 in parallel with temperature (Namkhijanstan, 2006; Nandintsetseg et al., 2007); both consistent with model results suggesting that northern Mongolia and the Siberia taiga will warm considerably in coming decades (IPCC, 2007).

STUDENT PROJECTS

Late Cenozoic Volcanism

Andrew Zuza and Aranzal Bat-Erdene examined late Cenozoic basalts from a 400 km2 area at the northern end of the Hövsgöl Rift basin. They collected a total of 28 lava samples from at least two distinct volcanic deposits that range in age from 9.5 Ma to 16.44 Ma (Rasskazov et al., 2000). Andrew and Aranzal performed petrographic and geochemical studies on the collected samples. Thin sections, major and minor element concentrations, and isotopic ratios were analyzed to determine magma source, genesis, and evolution in order to improve our understanding of the relationship between volcanism and rifting in the southern Baikal Rift zone.

Late Pleistocene Glacial Geomorphology

Briana Berkowitz, with the assistance of Esugei Danbold and Zolzaya Samandbadir, investigated the moraines in the Horoo Gol valley for the purpose of relative age dating, which they accomplished through field mapping and the collection of frequency, height, volume, and rebound strength data on boulders located along the crest of 10 distinct terminal and recessional moraines, and from vertical cross-moraine topographic profiles using differential GPS (DGPS). Results of statistical testing of average frequency, volume, height, and rebound strength for moraine crest boulders are supportive of the outer 9 moraines ("Piedmont" moraine complex) having been deposited during a single glacial interval. Boulders from the morphologically-distinct 10th moraine ("Valley" moraine complex) exhibit slightly higher mean rebound strength, suggesting that it belongs to a younger glacial advance than the downvalley Piedmont moraines; however, statistical tests between moraine populations were inconclusive, suggesting that the two morphologically distinct moraine complexes may be close in age (Fig. 4).

Gabrielle Vance and Esukhei Ganbold focused on the presumed Last Glacial Maximum (LGM) moraine of the Horoo Gol Valley moraine complex (Fig. 2). Together with Afshan Shaikh, Briana Berkowitz, and

Figure 4. Students collecting rock weathering data and a TCN-exposure age sample from a large boulder preserved along the crest of the up-valley terminal moraine. Lake Hövsgöl is visible in the background.

Daniel Rothberg, they sought to establish a glacial chronology for the Horoo Gol valley via field mapping, DGPS surveys, boulder counts, and sampling for cosmogenic dating. Gabrielle, Esu, and Dan worked to map the upper valley and the prominent moraine complex at its mouth. Gabrielle analyzed boulder count and DGPS data to aid in relative dating of the moraines and used GIS to map LGM ice extents and reconstruct equilibrium line altitudes (ELAs) of the Horoo Gol valley glacier. Such reconstructions will be useful for regional comparisons with other ranges in Central Asia.

Daniel Rothberg and Esukhei Ganbold focused on testing the hypothesis that late Quaternary surface uplift of the Bayan Range along the fault bounding the western Hövsgöl rift has resulted in diachronous glacial sequences from adjacent valleys. Their research is collaborative with the students assessing the timing of glacial advances in the Horoo Gol valley. They utilized glacial equilibrium line altitude estimates using the Toe-To-Headwall-Altitude (THAR) method as well as morphometric analysis of fault-produced triangular facets along the range front in their investigation.

Sample	Latitude (°N)	Longitude (°E)	Elevation (m)	Age [a,b] (ka)
Piedmont moraine complex				
HG-0710-1	51.54531	100.44350	1661	32 ± 3
HG-0710-2	51.54517	100.44353	1665	22 ± 2
HG-0710-3	51.54982	100.44181	1675	9 ± 1 [c]
HG-0710-4	51.55138	100.43839	1680	25 ± 2
HG-0710-5	51.55001	100.44070	1680	12 ± 1 [c]
HG-0710-6	51.55000	100.44081	1680	20 ± 2
Valley moraine complex				
HG-0710-7	51.59144	100.45055	1747	23 ± 2 [d]
HG-0710-8	51.59438	100.43893	1767	15 ± 1
HG-0710-9	51.59555	100.47244	1731	15 ± 1
HG-0710-10	51.59552	100.47255	1732	28 ± 3 [d]
HG-0710-11	51.59696	100.47472	1740	14 ± 1
HG-0710-12	51.58976	100.46648	1696	16 ± 1

[a] Ages calculated following Balco et al. (2008).

[b] Uncertainties are reported at the 1σ confidence level.

[c] Sample age interpreted as anomalously young based upon mean ages obtained from the inset and younger valley moraine complex; excluded from the calculated mean age of the terminal Piedmont moraine.

[d] Sample age interpreted as anomalously old due to nuclide inheritance.

Table 1. Preliminary ^{10}Be ages from Lake Hovsgol moraines.

Late Pleistocene Glacial Geochronology

Afshan Shaikh, Briana Burkowitz, Zolzaya Samandbadir and Esukhei Ganbold focused on mapping the moraines of the Horoo Gol valley and collecting ^{10}Be terrestrial cosmogenic nuclide (TCN) samples from in-situ boulders deposited on moraine crests (Fig. 4; Table 1). They collected 6 samples each for the presumed pre-LGM outermost Piedmont moraine complex (e.g., Krivonogov et al., 2003) and younger Valley moraine complex, respectively. Afshan extracted ^{10}Be from TCN samples at the Georgia Institute of Technology's TCN geochronology laboratory. These surface exposure dates will help validate predictions of past glacial advances both in the Horoo Gol valley and in regional comparisons with other numerically

Figure 5. A portion of a trench dug into hillside exposing Holocene lake deposits at the "Pickle Lake" site. White marl-rich layers alternate with darker sediment and organic rich sediments.

Lab Code	Sample name	Material	Depth beneath surface (cm)	Fraction modern	1σ error	$\delta^{14}C$ (‰)	1σ error	^{14}C age (BP)	Calendar age (BP)
Horoo Gol Holocene River Terrace Site 1 (51.57701° N, 100.46730° E)									
UCI-88854	HS1-20-23	charcoal	20 to 23	0.8353	0.0024	-164.7	2.4	1445 ± 25	1330 ± 25
UCI-86075	HS1-88-90	fish bones	88 to 90	0.7686	0.0013	-231.4	1.3	2115 ± 15	2090 ± 35
Horoo Gol Holocene River Terrace Site 2 (51.56533° N, 100.49772° E)									
UCI-86063	HS2-172-175	plant matter	172 to 175	0.3620	0.0008	-638.0	0.8	8165 ± 20	9080 ± 50
Horoo Gol Holocene River Terrace Site 3 (51.55941° N, 100.50169° E)									
UCI-88855	HS3-0-14	plant matter	0 to 14	0.9595	0.0027	-40.5	2.7	330 ± 25	385 ± 70
UCI-86064	HS3-110-130	charcoal	110 to 130	0.7577	0.0013	-242.3	1.3	2230 ± 15	2250 ± 70
Pickle Lake Trench (51.560853° N, 100.461488° E)									
UCI-86065	PLT2-88-90	plant matter	88 to 90	0.6880	0.0015	-312.0	1.5	3005 ± 20	3210 ± 50
UCI-88857	PLT2-155-157	plant matter	155 to 157	0.6486	0.0021	-351.4	2.1	3480 ± 30	3765 ± 65
UCI-88858	PLT2-283-285	plant matter	283-285	0.5698	0.0017	-430.2	1.7	4520 ± 25	5185 ± 120
UCI-88859	PLT2-305-307	plant matter	305-307	0.5596	0.0017	-440.4	1.7	4665 ± 25	5390 ± 70
Pickle Lake Trench - shore face riser (51.560912° N, 100.461201° E)									
UCI-86066	PLT2C-33	plant matter	33	0.7295	0.0014	-270.5	1.4	2535 ± 15	2645 ± 95
UCI-88860	PLT2C-250	plant matter	250	0.7115	0.0021	-288.5	2.1	2735 ± 25	2820 ± 35

Radiocarbon concentrations are given as fractions of the modern standard, $D^{14}C$, and conventional radiocarbon age, following the conventions of Stuiver and Polach (1977). Sample preparation backgrounds have been subtracted, based on measurements of ^{14}C-free wood (organics), calcite (carbonates), and whalebone. All results have been corrected for isotopic fractionation according to the conventions of Stuiver and Polach (1977), with $\delta^{13}C$ values measured on prepared graphite using the AMS spectrometer. These can differ from $\delta^{13}C$ of the original material, if fractionation occurred during sample graphitization or the AMS measurement, and are not shown. Samples ages were converted to calendar years BP with the OxCal v. 4.1.7 software using the INTCAL09 calibration curve. Reported ages are rounded to the nearest 5 year increment.

Table 2. Radiocarbon results for Holocene fluvial and lacustrine sediments.

dated glacial deposits throughout Central Asia.

Holocene Paleoecology

Kristin Taddei, Mellissa Cross, Daena Charles, Bilguunbayar Bayanmunkh, Tsendjav Erdene, and Delgertsetseg Burendelgar studied Holocene lake and fluvial terrace deposits on the Horoo Gol delta plain, northwest of Lake Hövsgöl. They excavated two large trenches to a depth of 3 m on the uplifted bank of a small lake, informally named “Pickle Lake” (51.560815° N, 100.461636° E, 1643 m elev.) that exhibited alternating silty organic and marl-rich sediments (Fig. 5). The team also trenched three Holocene fluvial terrace (HS1-3) sites adjacent to Il Horoo Gol. These localities exhibited mostly sandy sediment. Each U.S. student took on one of these fluvial trenches for their own independent research. The goal of this suite of student projects is to contribute to the terrestrial paleoclimate and paleoenvironment records of Lake Hövsgöl and surrounding areas during the Holocene and to compare to published deep-lake records covering the same period. The students working on the Holocene paleoecology project collected proxy data sets including radiocarbon, grain size, mineralogy, weight percent organic and inorganic carbon, microfossils (diatoms and pollen), magnetic susceptibility, and stable isotope ratios of carbon, nitrogen, and oxygen.

Late Holocene Dendroclimatology

L. John Michaels, Tsagaannaran Erdenebayar, and Battogtoh Damdinsuren collected over 30 dendrochronologic cores and cross sections from living and recently harvested Siberian larch (Larix sibirica) across elevation and environmental gradients in and surrounding the Horoo Gol valley. They constructed a several-hundred year tree ring chronology and ring-width indices and performed stable isotope (O,

H) analyses of extractable alpha-cellulose in order to characterize decadal-to-centennial variability of temperature and precipitation change in the context instrumental evidence for ongoing climate change. Analysis from local meteorological stations indicates that the average annual temperature of the area has increased by nearly 2° C since the early 1960's. Longer-term proxy records for temperature, precipitation, and length of growing season will be important for future predictions of the impacts of climate change on both ecosystem dynamics and the semi-nomadic herders living in the northern Hövsgöl rift.

MAJOR SCIENTIFIC ACCOMPLISHMENTS

Cenozoic Basalt Geochemistry

Geochemical results indicate that basalts erupted at the northern end of Lake Hövsgöl contain minimal crustal contamination and likely originated from an asthenospheric source that interacted with metasomatized lithospheric mantle. Importantly, lava chemistry has changed little over 20 Ma, suggesting that volcanism is decoupled from crustal extension of the Hövsgöl rift; rifting is likely a passive response to far-field tectonic stresses, rather than localized by upwelling related to a mantle plume.

Late Quaternary Glacial Geomorphology & Geochronology

We report the first preliminary TCN surface exposure age estimates from moraines in the Hövsgöl rift basin, six each from the Piedmont and Valley moraine complexes (Fig2; Table 1). Four of the six TCN boulder samples from the Piedmont moraine complex provide geologically realistic ages (not younger than the age of the inset, younger Valley moraine complex) with a mean of 24.8 ± 4.5 ka. TCN results from the terminal crest of the Valley moraine complex, 5 km upvalley, yield a mean surface exposure age of 15 ± 0.7 ka, when two older outliers are excluded due to the probability that these two samples contain an inherited nuclide signal (Table 2). The TCN results indicate two closely timed phases of glacial equilibrium and terminal moraine deposition during MIS 2, contradictory to our own and others (e.g., Kulakov, 1981; Krivonogov et al., 2003) interpretations of moraine age based upon landscape position and morphology, alone. This finding is not congruous with our hypothesis that differential surface uplift of the Bayan rage resulted in diachronous glacial chronologies along the western shore of Lake Hövsgöl, but is consistent with our relative age dating results from the Horoo Gol moraines that indicate the elapse of only a short duration (c. 10 ka) between deposition of the Piedmont and Valley moraine complexes based up measures of boulder frequency, volume, height, and hardness. Reconstruction of glacier extents through time for the Horoo Gol valley indicates that glacial ELAs were about 1,100 m lower than at present for the western Vostoch and northern Bayan ranges, and only about 75 m different between peak MIS 2 (Piedmont moraine complex; ELA of 2,070 m) and late MIS 2 (Valley moraine complex; ELA of 2,145 to 2,170 m).

Holocene Paleoenvironmental Proxies

We report 11 new radiocarbon analyses from Holocene lacustrine and fluvial deposits of the Horoo Gol delta plain (Table 2), spanning the interval between 9,000 to 400 cal yr BP. The Pickle Lake trench shallow-water lacustrine section records environmental change between 5,400 to 2,650 cal yr BP. Sedimentology and environmental proxy records (pollen, diatoms, stable isotopes) from the Pickle Lake locality indicate that that effective moisture has fluctuated at the site, resulting in variable lake levels through time. The early Holocene of the Horoo Gol delta was wet, and characterized by pine-birch forests. The middle Holocene was drier, when grass pollen is dominate in the sedimentary record. A transition to generally more humid, boreal forest-like conditions occurred after about 4,500 ybp. These results are broadly consistent with regional Holocene paleoclimate studies (e.g., An et al., 2008).

CONCLUSIONS

During a two-week summer field season in 2010, participants of the Lake Hövsgöl Keck project conducted detailed field mapping and collection of Tertiary lavas, late Pleistocene glacial, and Holocene lacustrine, fluvial, and tree core samples. Preliminary results document climate and environmental change on millennial-to-centennial scales at the northern end of the Hövsgöl rift basin. Integration of results from individual student projects will guide future publications exploring the paleoclimate, paleoenvironmental, and active tectonic history of this remote and little studied region of northern Mongolia, which can be compared with similar records from other parts of Central Asia.

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REFERENCES

An, C., Chen, F., and Barton, L., 2008, Holocene Environmental Changes in Mongolia: A Review: Global and Planetary Change, v. 63, p. 283-289.

Bader, N. E., Bayasgalan, A., Carson, R. J., Frankel, K. L., and Wegmann, K. W., 2009, Geology of the Höh Serh Range, Mongolian Altai, in de Wet, A., ed., Proceedings of the Twenty-Second Annual Keck Research Symposium in Geology, Volume 22: Lancaster, Keck Geology Consortium, p. 219-225.

Balco, G., Stone, J.O., Lifton, N.A., and Dunai, T.J., 2008, A complete and easily accessible means of calculating surface exposure ages or erosion rates from 10Be and 26Al measurements: Quaternary Geochronology, v. 3, p. 174-195.

Baljinnyam, I., Bayasgalan, A., Borisov, B. A., Cisternas, A., Dem'yanovich, M. G., Ganbaatar, L., Kochetkov, V. M., Kurushin, R. A., Molnar, P., Philip, H., and Vashchilov, Y. Y., 1993, Ruptures of major earthquakes and active deformation in Mongolia and its surroundings: Geological Society of America Memoir 181, 62 p.

Bayasgalan, A., Jackson, J., Ritz, J.-F., and Carretier, S., 1999, Field examples of strike-slip fault terminations in Mongolia, and their tectonic significance: Tectonics, v. 18, no. 3, p. 394-411.

Calais, E., Vergnolle, M., San'kov, V., Lukhnev, A., Miroshnitchenko, A., Amarjargal, S., and Déverchere, J., 2003, GPS measurements of crustal deformation in the Baikal-Mongolia area (1994-2002): Implications for current kinematics of Asia: Journal of Geophysical Research, v. 108, no. B10, 2501.

Cunningham, D. W., Windley, B. F., Dorjnamjaa, D., and Badamgarav, Z., 1996, A structural transect across the Mongolian Western Altai: Active transpressional mountain building in central Asia: Tectonics, v. 15, no. 1, p. 142-156.

Delouis, B., Déverchère, J., Melnikova, V., Radziminovitch N., Loncke, L., Larroque C., Ritz F. J., San'kov, V., 2002, A reappraisal of the 1950 (Mw 6.9) Mondy earthquake, Siberia, and its relationship to the strain pattern at the southwestern end of the Baikal rift zone: Terra Nova, v. 14, no. 6, p. 491-500.

Fedotov, A., San'kov, V., De Batist, M., Kazansky, A., Parfeevets, A., and Miroshnitchenko, A., 2006, Chronology of Baikal rift system: EOS Trans. AGU, v. 87, no. 25, p. 246.

Gillespie, A. R., Burke, R. M., Komatsu, G., and Bayasgalan, A., 2008, Late Pleistocene glaciers in Darhad Basin, northern Mongolia: Quaternary Research, v. 69, no. 2, p. 169-187.

Hövsgöl Drilling Program Members, 2009, Lacustrine sediment record from Lake Hövsgöl, NW Mongolia: results from the HDP-04 and HDP-06 drill cores: Quaternary International, doi: 10.1016/j.quaint.2009.02.008.

IPCC, 2007, Climate Change 2007 – the physical science basis: Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, in Solomon, S., et al., eds.: Cambridge, Cambridge University Press, 996 p.

Krivonogov, S. K., Bezrukova, E. V., Takahara, H., and Riedel, F., 2003, Lake Hövsgöl in the Lake Pleistocene and Holocene: On-Land Geological Evidence for a Change in its Level, in Kashiwaya, K., ed., Long Continental Records from Lake Baikal: Tokyo, Springer, p. 187-206.

Kulakov, V. S., 1981, Ancient and modern glaciations of the north Mongolia (trans-Khubsugulia). In: Transactions of the Soviet-Mongolian complex Khubsugul expedition (in Russian). Irkutsk, p. 10-19.

Kuzmichev, A. B., Bibikova, E. V., and Zhuravlev, D. Z., 2001, Neoproterozoic (~800 Ma) orogeny in the Tuva-Mongolia Massif (Siberia): island arc–continent collision at the northeast Rodinia margin: Precambrian Research, v. 110, p. 109-126.

Lehmkuhl, F., 1998, Quaternary glaciations in Central and Western Mongolia, in Owen, L. A., ed., Mountain Glaciation: Chichester, John Wiley & Sons Ltd, p. 153-167.

Logatchev, N. A., and Zorin, Y. A., 1987, Evidence and causes of the two-stage evolution of the Baikal rift: Tectonophysics, v. 143, p. 225-234.

Molnar, P., and Tapponnier, P., 1975, Tectonics of Asia: Consequences and implications of a continental collision: Science, v. 189, p. 419-426.

Namkhijantsan, G., 2006, Climate of the Hövsgöl Lake Region, in Goulden, C. E., Sitnikova, T., Gelhaus, J., and Boldgiv, B., eds., The Geology, Biodiversity and Ecology of Lake Hövsgöl (Mongolia): Leiden, The Netherlands, Backhuys, p. 63-76.

Nandintsetseg, B., Greene, J. S., and Goulden, C. E., 2007, Trends in extreme daily precipitation and temperature near lake Hövsgöl, Mongolia: International Journal of Climatology, v. 27, no. 3, p. 341-347.

Rasskazov, S. V., Logachev, N. A., Brandt, I. S., Brandt, S. B., and Ivanov, A. V., 2000, Geochronology and geodynamics of the Late Cenozoic in southern Siberia, southern and eastern Asia, Moscow, Nauka Publications, 288 p.

Sengör, A. M. C., Natal'in, B. A., and Burtman, V. S., 1993, Evolution of the Altaid tectonic collage and Palaeozoic crustal growth in Eurasia: Nature, v. 364, p. 299-307.

Stuiver, M., and Polach, H. A., 1977, Discussion: Reporting of 14C data: Radiocarbon, v. 19, p. 355-363.

Tomurtogoo, O., ed., 2003, Tectonic map of Mongolia: Mongolian Academy of Sciences, scale 1:1,000,000.

Wegmann, K. W., Frankel, K. L., Carson, R. J., Bader, N. E., Bayasgalan, A., Dundon, K., Ladig, K., Leary, R., Matzinger, G., Mortka, G. E., Seymour, A., and Colbert, T., 2009, Timing and extent of late Pleistocene glaciation in the central Mongolia Altai: Geological Society of America Abstracts with Programs, v. 41, no. 7, p. 35.

Whitford-Stark, J. L., 1987, A survey of Cenozoic volcanism on mainland Asia: Geological Society of America Special Paper 213, 74 p.

Windley, B. F., and Allen, M. B., 1993, Mongolian plateau: Evidence for a late Cenozoic mantle plume under central Asia: Geology, v. 21, no. 4, p. 295-298.

Zorin, Y. A., 1999, Geodynamics of the western part of the Mongolia-Okhotsk collisional belt, Trans-Baikal region (Russia) and Mongolia: Tectonophysics, v. 306, no. 1, p. 33.