KECK GEOLOGY CONSORTIUM

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

April 2011
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Students: *JESSE DAVENPORT*, College of Wooster, *KRISTINA DOYLE*, Amherst College, *B. PARKER HAYNES*, University of North Carolina - Chapel Hill, *DANIELLE LERNER*, Mount Holyoke College, *CALEB O. LUCY*, Williams College, *ALIANORA WALKER*, Smith College.

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Students: *ERIN CAMP*, Amherst College, *EVAN N. DETHIER*, Williams College, *HAYLEY CORSON-RIKERT*, Wesleyan University, *KEITH M. KANTACK*, Williams College, *ELLEN M. MALEY*, Smith College, *JAMES A. MCCARTHY*, Williams College, *COREY SHIRCLIFF*, Beloit College, *KATHLEEN WARRELL*, Georgia Tech University, *CIANNA E. WYSHNYSZKY*, Amherst College.

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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.

GEOLOGIC, GEOMORPHIC, AND ENVIRONMENTAL CHANGE AT THE NORTHERN TERMINATION OF THE LAKE HÖVSGÖL RIFT, MONGOLIA
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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Keck Geology Consortium: Projects 2010-2011
Short Contributions— Hövsgöl Rift, Mongolia

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

ANDREW ZUZA, Cornell University
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INTRODUCTION

Late-Cenozoic intraplate volcanism is prevalent throughout Mongolia. Though relatively widespread, volcanic fields are small in volume. The general proximity of these lavas to the Baikal rift zone (BRZ) has led many researchers to regard these as rift-related volcanic rocks, which leads to an important question: what is the relationship between the volcanic rocks and rifting? This question has important implications for the nature of the BRZ itself. Is it an active rift (see Logatchev and Zorin, 1992; Gao et al., 1994; Zorin et al., 2006), a passive rift (see Zonenshain and Savostin, 1981; Petit et al., 1997; Nielsen and Thybo, 2009), or some combination of the two (see Petit et al., 1996; Delvaux et al., 1997; Zorin et al., 2003)? A key test to these various hypotheses is the geochemical signature of the volcanic rocks.

Lake Hövsgöl, which sits in a north-south trending rift basin on the southwestern leg of the BRZ, has numerous exposures of volcanic rocks. This region is a great laboratory for examining the different hypotheses because it is the youngest and most recently active rift basin in the BRZ (Devyatkin and Smelov, 1980). Volcanism in the Hövsgöl area (21.4 Ma to 6.17 Ma: Rasskazov et al., 2000) predates extension and crustal rifting (Late-Miocene: Logatchev, 1992) by more than 15 Myr. This fact may argue against active rifting, but further study is necessary.

Regardless of the origins of volcanism and rifting, this study aims to examine the geochemical characteristics of these volcanic rocks to better understand their source, genesis, and evolution. The relationship of these volcanic rocks to rifting and the extent to which these lavas are involved in, or derived from, rifting has important implications for lithospheric development of Mongolia and Central Asia.

METHODS

The ~400 km2 field area was mapped at a scale of 1:200,000. Twenty-eight basalt samples were collected and were made into singly polished thin sections. Twenty-two samples were prepared for geochemical work. Major element analysis was conducted on all of these samples using a microprobe on glasses made from fused whole-rock powders, and NAA was utilized to examine the trace elements of 16 representative samples. Sr isotope ratios were analyzed for 11 samples using TIMS.

FIELD RELATIONS

Lava flows crop out extensively in the northern region of Lake Hövsgöl (Fig. 1), ranging from highly eroded relicts to well preserved flows that can be examined in cross-section (Fig. 2a, b). In these sections, rubbly aa flow tops are visible, with massive lava deposits underneath, often with sheared vesicles (Fig. 2a). Brecciated bottoms or the presence of paleosols demarcate the bottom of individual flows (Fig. 2b). Flow thickness generally ranges from 1 to 5 m, and the largest vertical section had at least 6 stacked lava flows. The lava flows lie unconformably on top of the Neoproterozoic Gargan and the Paleozoic Tunka terrane (Kuzmichev, 2001). Basement rock structures and fabrics generally trend NNE-SSW, perpendicular to regional extension. Quaternary fluvial, lacustrine, and glacial sediments cover much of the area around Lake Hövsgöl.

Samples are grouped into three spatial regions—west, northeast, and east—for analysis and discussion.

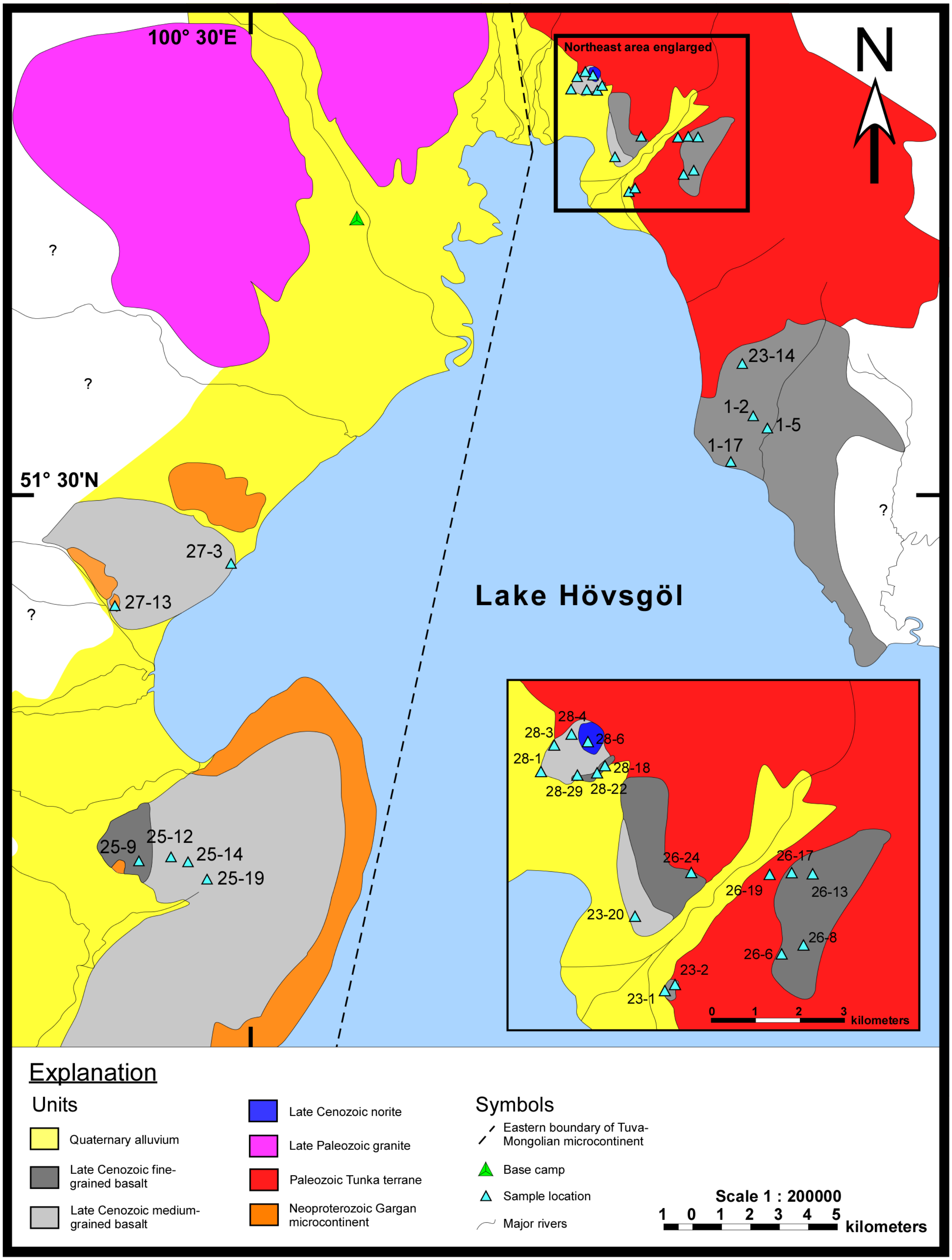

Figure 1. Geologic map of the northern region of Lake Hövsgöl. Terrane boundary from Zorin et al. (2003).

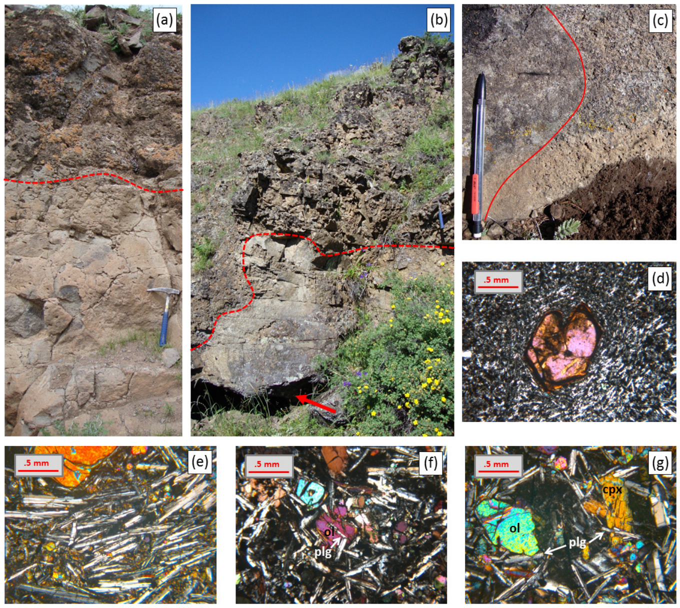

Figure 2. Typical flows (a, b) in cross section, showing rubbly aa top flow and more massively bedded flow interior, separated by red dashed line. Hammer for scale. Sheared vesicles are present (a) in massive beds. Eroded paleosols (b), indicated by red arrow, are often present at the base of individual flows; (c) Contact between medium-grained and coarse-grained basalts; Photomicrographs showing (d) euhedral olivine weathering to iddingsite, (e) trachytic texture of plagioclase, (f) olivine growing around plagioclase, and (g) clinopyroxene growing around plagioclase, with plagioclase growing around olivine.

The flows were also compared with similar volcanic deposits 10 km east of the lake (i.e. Heven Plateau: Perepelov et al., 2010).

Dating of the flows by Rasskazov et al. (2000) show that the west and north east flows are 9.5 + .3 Ma (K-Ar) and 10.2 + .5 Ma (K-Ar), respectively. The eastern flows are 16.44 + .08 Ma ($^{40}Ar/^{39}Ar$) and the Heven Plateau flows are 17.1 + .4 Ma ($^{40}Ar/^{39}Ar$: Perepelov et al., 2010).

PETROGRAPHY

The samples are silica undersaturated, alkali basalts. Olivine phenocrysts are abundant in all but one sample. Olivine composition is generally 85-90% forsterite (+ optic sign and 2V ≈ 90°). Olivine often exhibits normal zoning (i.e Mg-rich cores with more Fe-rich rims). Clinopyroxene and plagioclase are

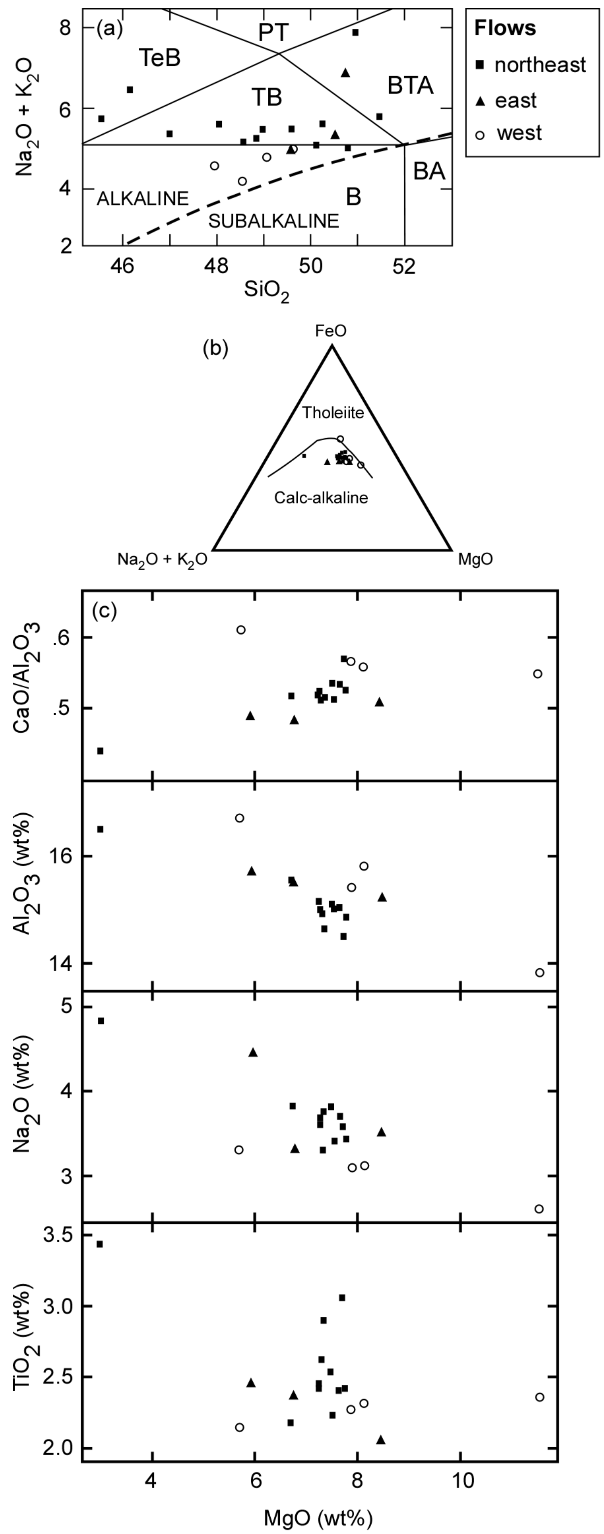

Figure 3. (a) Total alkalis ($Na_2O + K_2O$) vs SiO_2 relative to the TAS classification scheme of Le Bas et al. (1986), where B—basalt, TB—trachybasalt, TeB—tephrite basanite, PT—phonotephrite, BTA—basaltic trachyandesite, and BA—basaltic andesite. (b) AFM plot ($Na_2O + K_2O$ – FeO – MgO tertiary) following Irvine and Baragar (1971). (c) Variation diagrams of MgO vs CaO/Al_2O_3, Al_2O_3, Na_2O, and TiO_2.

also sometimes zoned. Minor alteration is present in many of the samples, with small amounts of olivine weathering to iddingsite (Fig. 2d). Some olivine is also rimmed by pyroxene. Generally, textural growth patterns reveal expected mineralization sequences, with olivine and calcium-rich plagioclase crystalizing before the pyroxenes and less calcic plagioclase.

Northeast flows

Samples from the northeast have the most diverse range of textures. A portion of these samples represent an extrusive lava flow. They are finer-grained and porphorytic, dominated by euhedral olivine phenocrysts. These samples have an aphanitic ground mass populated by plagioclase microlites, which sometimes have a preferred orientation, presumably controlled by flow direction. Some samples have larger plagioclase phenocrysts, indicating slower cooling rates. Some clinopyroxene (modal 5-15) and orthopyroxene (modal 5-10) phenocrysts exist.

Other samples have undergone slower cooling, and are medium-grained, with a phaneritic texture. They are made up of predominately euhedral to subhedral olivine, plagioclase, and clinopyroxene, with lesser amounts of orthopyroxene. Plagioclase often exhibits trachytic textures (Fig. 2e). Textural growth patterns reveal that Ca-rich plagioclase crystallized first (Fig. 2f), followed by olivine and intermediate plagioclase, and then clinopyroxene (Fig. 2g).

The last dominant lithology in this region is phaneritic with large grains (>5mm). This lithology has a relatively sharp contact with the medium-grained deposits that were discussed above (Fig. 2c). There is no olivine present in these samples, but clinopyroxene, orthopyroxene, and plagioclase feldspar dominate. There are also long (~5mm), preferentially oriented ilmenite crystals. The plagioclase feldspar is the intermediate to calcic labradorite (%An ~55%). The labrodorite commonly grows around the clino- and orthopyroxenes, although some synchronous growth is evident.

These three dominant lithologies are likely part of the same flow or dyke (Fig. 1), with the fine grained rocks representing the chilled margin of the flow or dyke.

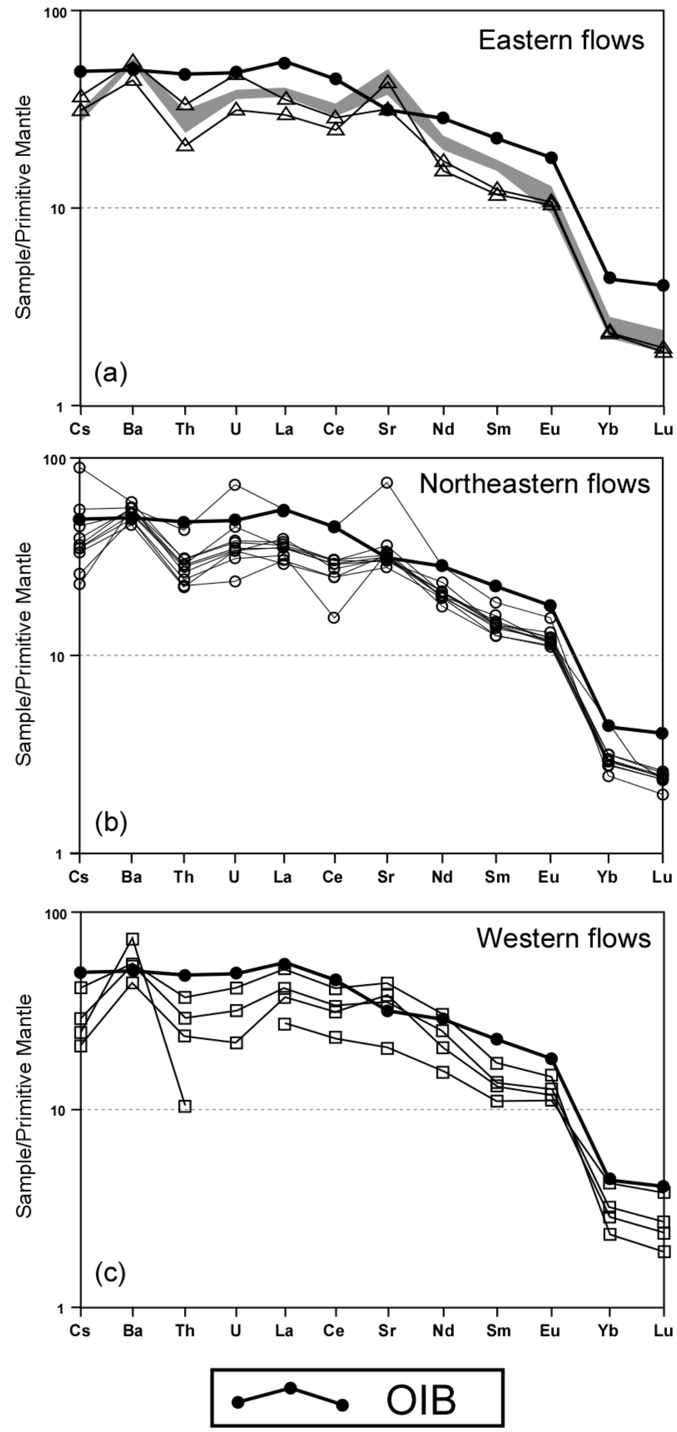

Figure 4. Primitive mantle-normalized trace element patterns for (a) eastern, (b) northeastern, and (c) western field locations. Shaded line represents lavas from the Heven Plateau. Heven Plateau data from Perepelov et al. (2010). OIB and primitive mantle compositions from Sun and McDonough (1989).

West flows

Samples from the western region display less variety than those in the northeast. Some have a fine-grained to glassy plagioclase matrix, with mostly olivine phenocrysts. Other medium-grained samples contain euhedral plagioclase and olivine, often with olivine growing around existing plagioclase (Fig. 2f). Clinopyroxenes and orthopyrxenes are also present, but are subhedral to anhedral, and exist in lesser amounts.
East flows

These flows are glassier, with more groundmass by volume. Overall, these flows appear different from the other two regions, dominated solely by olivine phenocrysts. Rare clinopyroxene phenocrysts exist.

GEOCHEMISTRY

Major and minor elements

Major element analysis reveals that a majority of the lavas in this region are basalt or trachy-basalt, with lesser amounts of basaltic trachyandesite and tephrite basanite (Fig. 3a). All of the samples are alkaline (Fig. 3a). They are basic (45.6-51.0 wt % SiO_2), generally with high MgO (5.7-11.5 wt %). The lavas follow a calc-alkaline trend on an AFM plot (Fig. 3b).

Plots of SiO_2, K_2O, and FeO versus MgO show substantial scatter (not shown), and limited trends exists in plots between CaO/Al_2O_3, Al_2O_3, Na_2O, and TiO_2 versus MgO (Fig. 3c). With decreasing MgO, CaO/Al_2O_3 also decreases, whereas Al_2O_3 increases. This suggests that the fractionation of clinopyroxene, which incorporates more CaO than Al_2O_3, is important for the evolution of these magmas. Na_2O and TiO_2 generally increase with decreasing MgO, although the correlation is faint. The sample with the largest-grain size is most evolved (~3 wt % MgO) and has the highest TiO_2 (3.44 wt %), consistent with occurrence of ilmenite crystals.

Trace elements

These lavas, as well as those at Heven Plateau (Perepelov et al., 2010), have similar primitive mantle-normalized trace element patterns (Fig. 4), and are

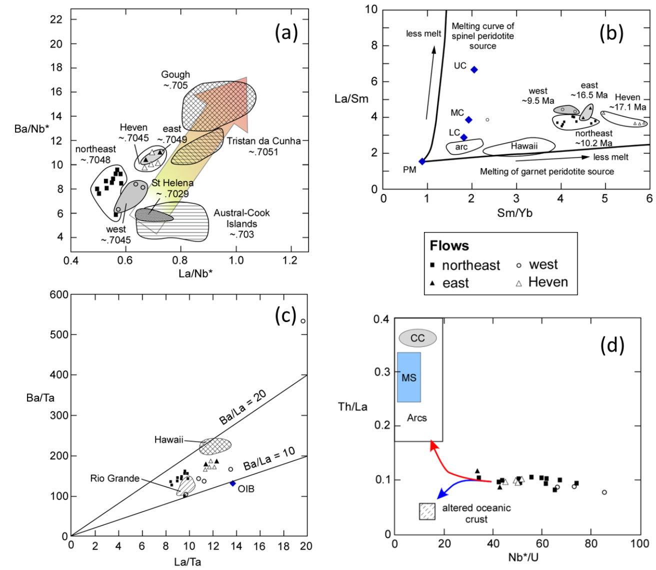

Figure 5. (a) La/Nb vs Ba/Nb* for Hövsgöl and Heven Plateau samples (Perepelov et al., 2010), where Nb* = 17 × Ta (Sun and McDonough, 1989). Arrow represents typical positive correlation between the linear relationship of Ba/Nb and La/Nb ratios and increasing 87Sr/86Sr ratios of OIB, as described by Sun and McDonough (1989). Numerical values represent 87Sr/86Sr ratios. Gradation in arrow depicts transition between the HIMU- type(white) and EM1-type (red) OIB sources. Ratios for St. Helena, Tristen de Cunha, and Gough are modified from Weaver et al. (1986) and data from Austal-Cook Islands from Panter et al. (2006). (b) Sm/Yb vs La/Sm for Hövsgöl and Heven Plateau samples (Perepelov et al., 2010). Shown for comparison are arc rocks (Kay et al., 1993) and Hawaiian basalts (Lassiter & DePaolo, 1997). Primitive mantle (PM) composition from Sun and McDonough (1989) and lower crustal (LC), middle crustal (MC), and upper crustal (UC) compositions from Rudnick and Fountain (1995). Batch melting curves show characteristics of magmas derived from smaller degrees of partial melting of spinel peridotite and garnet peridotite sources, based on Lassiter and DePaolo (1997). Dates are from Rasskazov et al. (2000). (c) La/Ta vs Ba/Ta for Hövsgöl and Heven Plateau samples (Perepelov et al., 2010). OIB composition from Sun and McDonough (1989), Hawaii compositions from Watson (2003) and Rio Grande compositions from Thompson et al. (2005). (d) Nb*/U vs Th/La for Hövsgöl and Heven Plateau samples (Perepelov et al., 2010), where Nb* = 17 × Ta (Sun and McDonough, 1989). Red arrows shows projected influence of continental crust, arcs, or marine sediments on melt, and blue arrow shows projected influence of altered oceanic sediments. Continental crust (CC) from Rudnick and Fountain (1995). Arcs, marine sediment (MS), and altered oceanic crust compositions are from Klein and Karsten (1995).*

enriched in incompatible trace elements. They have steep rare earth element (REE) patterns, enriched in light rare earth elements (LREE) relative to heavy rare earth elements (HREE), similar to ocean island basalts (OIB).

There are notable negative Th anomalies in all of the samples, and slight positive Ba and Sr anomalies in many samples. Ba/La ratios are slightly higher than those found in OIB (Fig. 5c). Overall, the samples are slightly less enriched than OIB.

The volcanic deposits at Heven Plateau have similar LREE enrichment (La/Yb = 20.6-21.6) relative to the flows on the east (La/Yb = 17.9-21.0), suggesting a similarity between these deposits. The lavas from the northeast have slightly less LREE enrichment (La/Yb = 14.1-30.8), and the western flows have varied LREE enrichment (La/Yb = 9.1-31.9). The La/Yb ratios of the northeastern and western flows overlap, supporting similarity.

Strontium isotopes

All but one of the analyzed samples have $^{87}Sr/^{86}Sr$ ratios in the range of .7039 to .7050, and the outlier sample has a ratio of .7060. The average ratio values of around .7047 is most similar to an EM1-type OIB source, but the ratios fall between the two end-member OIB-source types—HIMU ($^{87}Sr/^{86}Sr$ = .7029) and EM1 ($^{87}Sr/^{86}Sr$ = .705)—suggesting a mixing of source types (Sun and McDonough, 1989). The occurrence of an anomalously high $^{87}Sr/^{86}Sr$ ratio (.7060) is discussed later.

DISCUSSION

Crustal contamination

Mantle-derived lavas should be analyzed to evaluate the extent of crustal contamination. The samples have low Th/La and $^{87}Sr/^{86}Sr$ ratios, which is evidence against upper crustal contamination. The samples are not depleted in Ta and they do not trend toward continental crust or marine sediment influence on a plot of Nb*/U vs Th/La (Fig. 5d).

Barry et al. (2003) showed that the lower and middle crust in the region has higher $^{87}Sr/^{86}Sr$ ratios (>.705) and Sr concentrations (Barry et al., 2003). Only one sample has values this high ($^{87}Sr/^{86}Sr$ ratio = .706 and Sr = 1576 ppm), which may indicate crustal contamination.

Fractional crystallization

The low MgO contents of these lavas indicate that they are not the product of primary melts, suggesting some shallow-level fractionation and differentiation of a parental melt. The compositional trends of these lavas can partly be explained by the fractional crystallization of observed olivine and clinopyroxene phenocrysts. Olivine phenocrysts are observed in all but one samples, with clinopyroxene present in most. The trend of decreasing CaO/Al_2O_3 with decreasing MgO (Fig. 3c) suggests that the fractionation of clinopyroxene plays a big role in differentiating the magma. The fractionation of plagioclase was less important, as plagioclase would have taken both CaO and Al_2O_3 out of the melt, which is not seen as MgO decreases (Fig. 3c). The lack of a negative Eu anomaly (Fig. 4) also supports this.

The considerable scatter with these trends suggests that fractionation of a single parental melt cannot be entirely responsible for the compositional differences of these samples. Magma mixing, high-pressure fractionation (see Barry et al., 2003), or a varied source may account for the observed compositional differences.

Melt source

Steep REE patterns (La/Yb ~ 15-30) suggest that melting occurred within the garnet lherzolite stability field (Fig. 4, 5b). The spinel-garnet transition zone in the region is located at ~65 km depth (Ionov et al. 1998), providing a minimum depth for melt production. Other investigations on Mongolian basalts have shown magma generation depths greater than 70 km (Barry et al., 2003; Perepelov et al., 2010). Geochemical evidence (Fig. 5b), pressure/temperature constraints at > 65 km depth, and other studies (e.g. Barry et al., 2003) suggest that a low degree of partial melting produced these magmas. Anhydrous melting at these depths would require extremely elevated asthenospheric mantle temperatures, which are not observed in geophysical surveys (Poort and Klerkx, 2004). Xenolith studies also indicate that the lower lithosphere does not have temperatures greater than 1100°C (Ionov et al., 1998).

The existence of volatiles could produce melts at these lower temperatures.
Enrichment in fluid-mobile elements (e.g. positive Sr and Ba anomalies: Fig. 4) and low La concentrations (Fig. 5a) suggest that hydrous minerals may have contributed to the melt. As pointed out by Sun and McDonough (1989), lower La/Nb and $^{87}Sr/^{86}Sr$ ratios may show that the melting source interacted directly or indirectly with altered recycled oceanic crust (e.g. an old slab). The lavas have low values for these ratios, falling off the trend for typical OIB melts (Fig. 5a). The calc-alkaline trend (Fig. 3b) also suggests some influence of a subducted slab on the melt. A plot of Nb*/U vs Th/La (Fig. 5d) reveals that the melt source was not directly related to altered oceanic crust, as the they do not trend toward direct influence with altered oceanic crust (Klein and Karsten, 1995). Th concentrates in oceanic crust, and is relatively immobile, so its strong depletion in the Hövsgöl lavas (Fig. 4) also confirms that the magmas are not the product slab melting.

As previously suggested by Barry et al. (2003), this may suggest the presence of a metasomatized lithospheric mantle source. Sr enrichment is associated with the melting of amphibole and Ba enrichment can be associated with the melting of phlogopite (Fig. 4). Metasomatic enrichment of the lithosphere would provide such hydrous minerals. High Nb* (i.e. 17 × Ta: Sun and McDonough, 1989) enrichment (>35 ppm) also supports this idea, as high Nb concentrations may be derived from metasomatized lithospheric mantle (Stein and Kessel, 1997).

Magma genesis and evolution

Even with a volatile-rich metasomatized lithospheric mantle, a thermal source is still required to initiate melting. Shallow asthenospheric upwelling, seen as a slight thermal anomaly beneath Mongolia (Zhao, 2001), may trigger melting. $^{87}Sr/^{86}Sr$ ratios around ~.7047 support this, suggesting the mixing of EM1 (i.e. enriched asthenosphere) with HIMU (i.e. a metasomatized source) (Sun and McDonough, 1989).
The results of this study, as well as others (e.g. Barry et al., 2003; Perepelov et al., 2010), indicate that Late-Cenozoic volcanism in this region has been relatively continuous and similar for over 20 Myr. Incompatible element patterns and isotopic ratios for the flows analyzed in this study, which span ~8 Myr, show little variation (Fig. 4, 5). This fact, along with a gradual increase in the degrees of partial melting over time (Fig. 5b), may suggest that asthenospheric upwelling is related to thermal blanketing of the region by a thickened mantle lithosphere (see synthesis by Yin, 2010). Other models for asthenospheric upwelling (e.g. deep-rooted plume or delamination) would likely show more temporal and chemical variations.

CONCLUSIONS

Petrographic and geochemical analysis of Late-Cenozoic lavas from the Hövsgöl rift basin was conducted in order to determine magma source, genesis, and evolution. Crustal contamination was likely minimal. Trace elements and isotopic ratios reveal that low degrees of partial melting of garnet lherzolite occurred at depths greater than 65 km. An enriched asthenospheric source probably interacted with a volatile-rich, metasomatized lithospheric mantle, to produce melts without requiring significantly elevated temperatures.

The cause of asthenospheric upwelling is questionable, although consistent lava compositions over at least 20 Myr, and increasing degrees of partial melting with time, may support the model of thermal blanketing by a thickened lithosphere.

In terms of the debate between active and passive rifting, low-volume volcanism, lack of a deep-rooted low velocity zone (Zhao, 2001), and the temporal disconnect between volcanism and crustal rifting (> 15 Myr: Rasskazov et al., 2000; Logatchev, 1992) seem to rule out the possibly of a mantle plume driving extension. Minor upwelling is likely occurring to trigger melting of a volatile-rich metasomatized source, but it is unlikely that this is causing intra-continental extension. In this region, rifting is likely passive, with extension along preexisting structures (e.g. sutures, fabrics, etc.)

being controlled by far-field stress.

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