Heterogeneous sources for Pleistocene lavas of Marie Byrd Land, Antarctica: new data from the SW Pacific diffuse alkaline magmatic province

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Summary Here we report new major and trace element and Sr-Nd-Pb isotope data for Pleistocene basaltic lavas from the Fosdick Mountains, Ford Ranges in west Marie Byrd Land. The studied lavas erupted from three volcanic centers: Mt. Avers (basanites), Mt. Perkins (basalts) and Recess Nunatak (basanites). The lavas are geochemically homogeneous within each volcanic center, but vary in composition among the centers. Although the studied lavas have incompatible element enrichment patterns that are similar to other lavas from central and east Marie Byrd Land volcanoes, they have isotopic compositions that are not represented by other Marie Byrd Land volcanoes. This indicates that the mantle source regions feeding Marie Byrd Land volcanism are more heterogeneous than previously indicated. The geochemistry of these magmas provide a means to evaluate competing hypotheses for the origin of these magmas: plume-related, rift-related, or related to sinking of subducted slabs.

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Introduction

Cenozoic volcanism in Marie Byrd Land defines a province that extends for nearly 1000 km along the northern edge of the West Antarctic Rift System. Volcanism in this province initiated at ~30 Ma and continued through Quaternary time. Several competing explanations have been proposed for the origin of this magmatism, including mantle plume(s) (e.g., Hole and LeMasurier, 1994), decompression melting due to rifting (e.g., Wörner, 1999), and melting triggered by detachment and sinking of subducted slabs (Finn et al., 2005). Geochemical studies of Marie Byrd Land (MBL) volcanism can define the chemical characteristics of its mantle source(s), which in turn can be used to help evaluate the multiple hypotheses for the origin of this volcanism. Here we present new geochemical data for basaltic lavas from the Fosdick Mountains in western MBL. These lavas represent the western-most volcanism in MBL, and our results will complement earlier studies that investigated volcanism in central and eastern MBL (Hart et al., 1997; Hole and LeMasurier, 1994; Panter et al., 1997; Panter et al., 2000), to provide a more complete picture of Cenozoic magmatism in Marie Byrd Land. Our study focuses on basaltic lavas erupted at three volcanic centers in the Fosdick Mountains: Mt. Avers (ca. 1.4 Ma; $^{40}Ar/^{39}Ar$ bulk rock age, unpublished), Recess Nunatak (not dated), and Mt. Perkins (ca. 1.4 Ma; $^{40}Ar/^{39}Ar$ bulk rock age, unpublished) (Fig. 1).

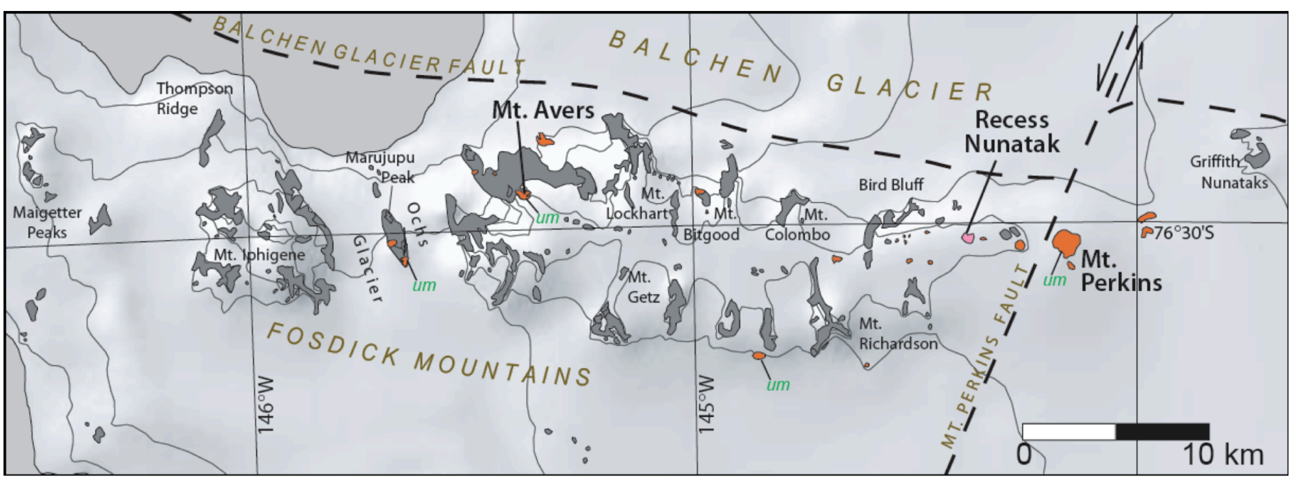

Figure 1. Map of the study area with volcanic rock exposures indicated in orange. Sites with abundant ultramafic xenoliths are labeled "um." Volcanic vent bearing crustal xenoliths is indicated in pink. Base map by G. Balco, with data from the Antarctic Digital Database and the Radarsat Antarctic Mapping Project (RAMP) Digital Elevation Model.

Field relationships and sample descriptions

Crystalline bedrock of the Fosdick range consists of migmatite gneiss and plutonic rocks of Paleozoic and Mesozoic age (Siddoway et al., 2004). Basaltic volcanic centers and flows conform to glaciated topography in the Fosdick Mountains, resting depositionally upon frost-heaved periglacial surfaces and upon angular glacial boulders that mantle bedrock surfaces at low elevations. Many volcanic exposures consist of delicate tephra, cinder, and splatter forms, not evidently modified by wet-based glacial ice. In addition, a few necks and irregular conduits cut through bedrock near a north-south-striking vertical fault in the Ochs Glacier area. Ultramafic xenoliths, 0.2 to 25 cm across, occur in abundance at several sites (Fig. 1). Crustal xenoliths are only rarely present.

At Mt. Avers (76º29´S,145º21´W), glassy, vesiculated basanites with ropy surface textures form thin flows upon glaciated summit topography, descending from 1050 to 900 m elevation. The sampled rocks contain small olivine-pyroxene aggregates (< 8mm) in an aphanitic groundmass. An array of subvertical dikes of olivine-pyroxene-plagioclase basalt, 0.3 to 1.5 m in width, intrudes the bedrock of migmatite gneiss beneath the summit flows. The dikes have azimuth strikes of 175-355 and vertical extent of >500 m. The mineralogy and spatial association of the dikes suggest that they are feeders to the summit flows.

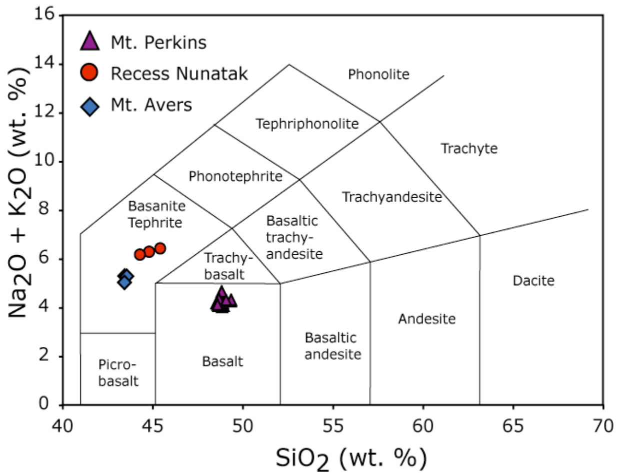

Figure 2. Classification of lavas based on SiO_2-(Na_2O+K_2O) variation.

The Mt. Perkins center (76º32´S 144º08´W) is situated on the crest of the eastern Fosdick range, where contacts with underlying gneissic bedrock are not exposed. Glacial erosion has incised a ~200 m sequence of 2 to 4 m thick flows of gray, vesicle-free, pyroxene-olivine-plagioclase basanite. These pass upward into basaltic breccia, which is unconformably overlain by golden-tan-colored tephra layers that dip inward to a summit depression (Luyendyk et al., 1992).

Recess Nuntak (76º31´S, 144º17´W) is a glacially eroded remnant of a vent complex. The black vesiculated glassy tephra exhibits vertical flow banding. This is the only one of the studied sites that contains crustal xenoliths. These abundant xenoliths are felsic gneiss and range in size up to 20 cm. Ultramafic crystalline aggregates and xenoliths were not found. No contacts with Fosdick gneisses were exposed when the nunatak was visited in 1990-91.

Major and trace element geochemistry

On the basis of their SiO_2 and alkali contents, the lavas from Mt. Perkins are classified as basalts, whereas the lavas from Mt. Avers and Recess Nunatak are basanites (Fig. 2). In the entire suite of lavas studied, SiO_2 content ranges from 43 to 49 wt. %, and the MgO content ranges from 7 to 12 wt. %. With a few exceptions, the lavas within each volcanic center are homogeneous in their major and trace element compositions, and may be related by only a small amount of olivine fractionation. The general homogeneity of the lavas within each volcanic center, as well as the strong, positive correlation of large ion lithophile elements (Rb, K, Ba) with Nb, suggest that the lavas have been affected by minimal or no contamination through assimilation of underlying continental crust.

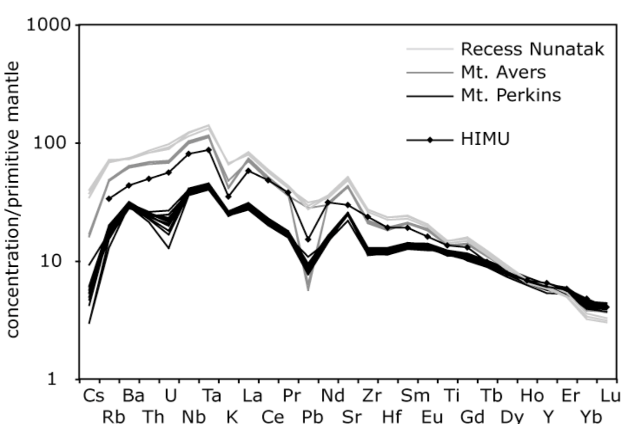

Figure 3. Primitive mantle-normalized (Sun and McDonough, 1989) spider-diagram of incompatible trace elements. HIMU composition from Willbold and Stracke (2006).

Although each volcanic center is chemically homogeneous, trace element concentrations vary among the three volcanic centers. All three centers show enrichments of light rare earth elements (REE) relative to heavy REE, with chondrite-normalized REE slopes ($[La/Lu]_n$) of 6.7-7.7 for Mt. Perkins, 18.8-20.1 for Mt. Avers and 25.3-26.4 for Recess Nunatak. These are consistent with residual garnet in the source of the magmas. The spider diagram of primitive mantle-normalized incompatible trace element concentrations (Fig. 3) shows depletions in some large ion lithophile elements (Cs, Rb) as well as slight depletions in Zr, Hf and Ti (Mt. Avers and Recess Nunatak, only), and enrichments in Nb and Ta. Recess Nunatak has the highest concentrations of incompatible elements, whereas Mt. Perkins has the lowest. The three volcanic centers show relatively similar patterns of overall incompatible element abundances, suggesting that the lavas from the three volcanoes are derived from sources with similar patterns of incompatible element abundances. This pattern is similar to that which characterizes HIMU-type ocean island basalts (Wilbold and Stracke, 2006).

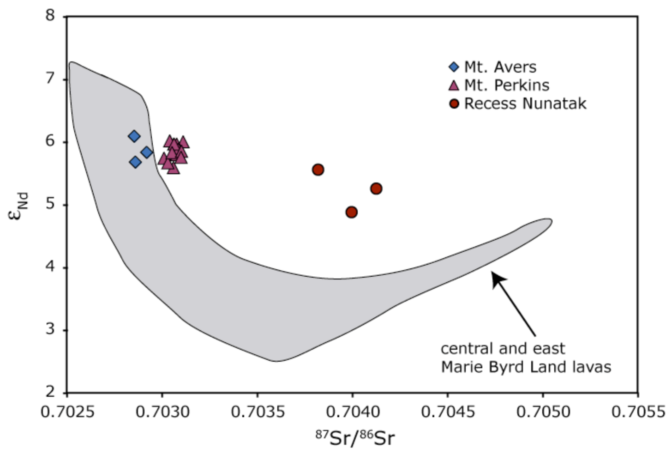

Figure 4. Sr-Nd isotope variation of Marie Byrd Land lavas. Field for central and east MBL lavas from Hole and LeMasurier (1994), Hart et al. (1997), Panter et al. (1997) and Panter et al. (2000).

Isotope geochemistry

The compositional homogeneity of the lavas within each volcanic center that is evident in their major and trace element compositions is also reflected in their Sr, Nd and Pb isotope compositions (Figs. 4 and 5). The lavas from the three volcanic centers have overlapping ranges of Nd isotope compositions; together, the three centers define an ε_{Nd} range of 4.9 to 6.9. In contrast, each center defines a distinct range in Sr isotope compositions: $^{87}Sr/^{86}Sr$ = 0.70286-0.70292 in Mt. Avers, 0.70301-0.70310 in Mt. Perkins, and 0.70382-0.070413 in Recess Nunatak. Only Mt. Avers falls within the field of Sr-Nd isotope compositions defined by other lavas from Marie Byrd Land (Fig. 4). Both Mt. Perkins and Recess Nunatak have ε_{Nd} values that are higher at a given $^{87}Sr/^{86}Sr$ than the field defined by other Marie Byrd Land lavas.

Each volcanic center also defines a separate field in $^{206}Pb/^{204}Pb$ - $^{207}Pb/^{204}Pb$ compositional space. Recess Nunatak has the least radiogenic $^{206}Pb/^{204}Pb$ (19.043-19.163), Mt. Perkins has intermediate $^{206}Pb/^{204}Pb$ (19.222-19.268) and Mt. Avers has the most radiogenic $^{206}Pb/^{204}Pb$ (19.458-19.613). However, $^{206}Pb/^{204}Pb$ in both Mt. Perkins and Recess Nunatak is less radiogenic than other Marie Byrd Land lavas (Fig. 5). Furthermore, although the lavas have trace element characteristics of the HIMU mantle component, their Pb isotope compositions are not radiogenic enough to be considered a direct representation of the HIMU mantle source in the strictest definition (e.g., Willbold and Stracke, 2006).

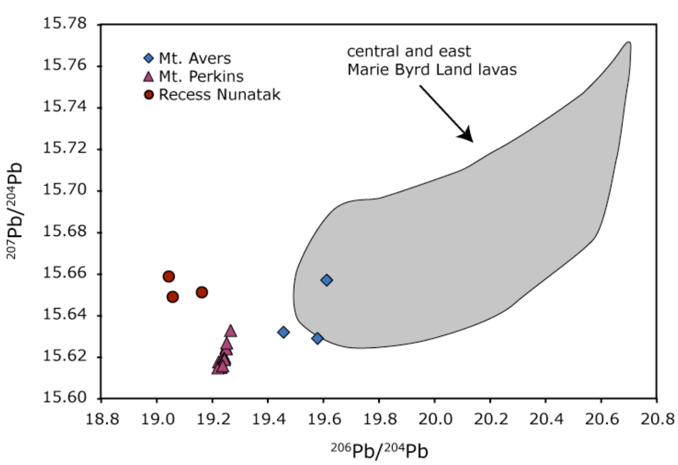

Figure 5. $^{206}Pb/^{204}Pb$-$^{207}Pb/^{204}Pb$ variation of Marie Byrd Land lavas. Field of central and east MBL lavas from Hart et al. (1997) and Panter et al. (2000).

Discussion

The relatively similar patterns of incompatible trace element abundances among the three volcanic centers contrasts with their distinctive Sr-Nd-Pb isotope characteristics. Whereas the incompatible trace element characteristics of the three centers can be related to a common mantle source by variable degrees of melting, the distinct isotope characteristics of each volcanic center preclude this relationship; the $^{206}Pb/^{204}Pb$-$^{207}Pb/^{204}Pb$ variation requires that at least three source components contribute to the west MBL lavas. Furthermore, Mt. Avers, which has incompatible trace element concentrations and ratios that are intermediate to those of Mt. Perkins and Recess Nunatak, has Sr-Nd-Pb isotope compositions that lie at the edge of the total range represented by the studied lavas (Figs. 3-5). Recess Nunatak has extreme compositions in both trace element and isotope compositional space; it has the highest concentrations of incompatible trace elements as well as the most radiogenic Sr and least radiogenic Nd and ^{206}Pb isotope ratios. Recess Nunatak is also the only site among the three studied that contains crustal xenoliths, and therefore these lavas may have experienced some degree of crustal contamination. However, incompatible trace element ratios that are typically diagnostic of crustal contamination (Nb/U, Ce/Pb, Zr/Hf, Nb/Ta) do not correlate with isotope composition (Sr, Nd or Pb) in Recess Nunatak lavas, or any of the other studied lavas, indicating that crustal contamination has not had an identifiable effect on the composition of these lavas. Rather, the incompatible trace element data indicate that some common process may be involved in the formation of the magmas or their mantle sources, whereas the isotope data reflect heterogeneities that are preserved through the various processes of magma generation and evolution.

The incompatible trace element patterns of all Marie Byrd Land lavas are similar to the pattern that characterizes the HIMU mantle source (Fig. 3; Hart et al., 1997; Panter et al., 2000). In contrast, the isotope compositions of Marie Byrd Land lavas define a very broad range, one end of which coincides with the HIMU mantle endmember. Of the new results presented here, only the lavas of Mt. Avers fall within the range of isotope compositions defined for Marie Byrd Land by previous studies, and none of the studied lavas show isotopic characteristics of the HIMU mantle source; in the west MBL lavas, Pb is too unradiogenic and both Sr and Nd are too radiogenic. Thus, although HIMU appears to be a common mantle component throughout the region, it is not the exclusive mantle source component that feeds volcanism in Marie Byrd Land. For example, the mantle sources that are sampled by Recess Nunatak and Mt. Perkins are apparently not sampled by other volcanoes in Marie Byrd Land. These two volcanoes, which are within 10 km of each other, may sample a local mantle source, possibly facilitated by the proximal location of these two volcanoes to the juncture of the Balchen Glacier and Mt. Perkins faults.

The HIMU mantle component was initially defined on the basis of its radiogenic Pb isotope compositions, reflecting high time-integrated U/Pb ratios (hence, 'high-μ', where $\mu = {}^{238}U/{}^{204}Pb$). This mantle component is also characterized by distinctive trace element and Nd-Sr-Hf isotope compositions which, taken together, reflect the origin of the HIMU component as ancient, subducted oceanic crust. The HIMU mantle source is primarily sampled by melting in the mantle plumes that feed ocean island volcanism. However, HIMU and similar mantle sources are also sampled in regions that are not affected by plume activity (e.g., Gaffney et al., 2007); magmatism in a variety of tectonic environments can access the HIMU mantle component. Whereas the incompatible trace element compositions of subducted oceanic crust do not change with aging during storage in the mantle, the isotopic characteristics do; the isotopic characteristics of subducted oceanic crust depend on its age. Subduction may also introduce heterogeneity into the sub-continental lithosphere via metasomatism by fluids released from slabs as they subduct beneath the continent. The compositional range of Marie Byrd Land lavas may reflect mixing between melts of dewatered, subducted oceanic crust and melts of metasomatized lithosphere. Such a scenario is consistent with the tectonic setting of MBL magmatism, yet does not require the involvement of a mantle plume in the region.

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