Origin and evolution of a high-Ti ocean island basalt suite: The Laurens Peninsula Series, Heard Island, Indian Ocean

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Summary. The Laurens Peninsula Series (LPS) lavas of Heard Island are unique among ocean island suites in having extremely high TiO_2 (>4.5%) and high P_2O_5 (>1%) abundances in basanitic compositions. These chemical features are reflected in both their petrography and in the composition of calculated primary magmas, and lead to a suggested origin for the LPS source either as 'fossil' plume melt frozen within the lithospheric mantle or as continental lithospheric mantle detached during the break-up of Australia and Antarctica and incorporated into the Kerguelen Plateau.

Introduction. Heard Island (53°06'S, 73°30'E) is located 440km south-east of Kerguelen on the Kerguelen Plateau which rises 3700m above the adjacent ocean floor. The plateau is composed of 114-Ma isotopically enriched oceanic lithosphere (e.g. Weis *et al.*, 1989). There are two main volcanic cones on Heard Island: Big Ben (2745m) and Mt. Dixon (706m). LPS lavas are associated with the latter and can be divided into pre-Dixon and Mt. Dixon sequences. Topographic and stratigraphic relationships suggest that Pre-Dixon lavas range in composition from trachyandesite to trachyte whilst Mt. Dixon lavas range from basanite to trachyandesite (Barling, 1990).

Petrography. LPS basanites (7.5–5% MgO) have uniform petrographic features. Their phenocryst assemblage comprises titanaugite (52.5–60% of phenocryst assemblage; Mg# 80–75), Fe-Ti oxides (17.5–20%), olivine (10–12.5%; Fo_{83-79}), plagioclase (7.5–10%; An_{82}), apatite (minor) and very occasionally a small amount of kaersutite. Trachytes (<2% MgO) are also fairly uniform petrographically. They are characterised by titaniferous (~10% TiO_2) biotite and sanidine (Or_{36-44}) mantles on plagioclase (An_{48}). Their phenocryst assemblage is: plagioclase + sanidine (70% of phenocryst assemblage), biotite (10%), clinopyroxene (10%), Fe-Ti oxides (7.5%), kaersutite (2.5%), apatite (minor). The trachyandesites are petrographically diverse. They are distinguished from basanites by the presence (in most samples) of rare green-cored pyroxenes and kaersutite and from trachytes by the absence of sanidine and biotite.

Geochemistry. LPS lavas have olivine-nepheline normative compositions and are potassic (i.e. Na_2O-1.5 < K_2O). They have well-correlated major element variations. With respect to decreasing MgO content (7–0% MgO), SiO_2, Al_2O_3, Na_2O and K_2O increase, whereas FeO, CaO, TiO_2 and P_2O_5 decrease sharply. Of particular note are TiO_2 and P_2O_5 which have exceptionally high concentrations for OIBs; a feature reflected in the early appearence and unusually high proportions of Fe-Ti oxides and apatite in the phenocryst assemblage of basanites.

Rb, Nb, Zr, La, Ce, Th and Y behave incompatibly in LPS lavas. Initially Ba is also incompatible, but in some highly evolved compositions Ba is not detected. This is attributed to the presence of sanidine and biotite in the fractionating assemblages of evolved magmas. Sr and V behave similarly to TiO_2 and P_2O_5, decreasing rapidly with falling MgO. This behaviour is likewise attributed to the relative importance of apatite and Fe-Ti oxides in LPS lavas. Sc decreases with decreasing MgO, reflecting the abundance of pyroxene (50–60%) in the phenocryst assemblage.

LPS lavas are isotopically distinct from other Heard Island lavas. They have homogeneous isotope ratios: $^{87}Sr/^{86}Sr$ = 0.704728–0.704879, $^{143}Nd/^{144}Nd$ = 0.512684–0.512737, and $^{206}Pb/^{204}Pb$ = 18.527–18.794, $^{207}Pb/^{204}Pb$ = 15.558–15.586 and $^{208}Pb/^{204}Pb$ = 38.936–39.161 (Barling *et al.* 1994).

Crystal fractionation. The well-defined chemical trends of LPS lavas suggest a relatively constant parental magma composition and little variation in the processes involved in the evolution of the series. Incompatible trace element ratios in mafic-intermediate compositions show only slight variation, and the entire suite is isotopically homogeneous. These features suggest that either primary magmas for the series were derived by similar degrees of partial melting of an isotopically and chemically homogeneous source, or that they were derived from a single batch of magma. The occurence of
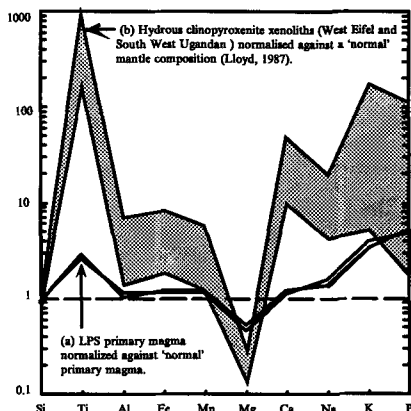
FIG. 1: Comparison of normalised major element compositions of LPS primary magmas and hydrous clinopyroxenite xenoliths.

trachytes early in the stratigraphic sequence indicates that the former is probably the case. A crystal fractionation model for the evolution of LPS lava compositions is therefore proposed.

The evolution of LPS magmas requires a two stage crystal fractionation model. The extract assemblage for the first stage of fractionation (cpx = 50%, Fe-Ti oxides = 20%, ol = 15%, pl = 10%, apt = 5%) agrees well with the observed phenocryst assemblage in basanites (see above). However, the extract assemblage for the second stage of fractionation has kaersutite as the major fractionating phase (48%) whereas in fact plagioclase is the most abundant phenocryst in trachytes (70%). A kaersutite-rich xenolith found in a LPS trachyandesite leads me to propose that kaersutite was preferentially retained in the magma chamber.

A variation of the method of Allègre et al. (1977) was used to derive bulk D values for trace elements. This method uses the Rayleigh fractionation law ($C_{liq} = C_{init} f^{(D-1)}$). With log f (fraction of residual liquid; estimated independently from the major element crystal fractionation model) plotted against log Cliq (trace element concentration in lava) the slope of linear data arrays equals D−1. The calculated D values are unusually high for incompatible trace elements (e.g. $D_{Th} = 0.17$–0.19). This is partly due to the high proportions of Fe-Ti oxides, apatite and clinopyroxene and the minor role played by olivine, but even so reconciling these coefficients with the calculated fractionating assemblage requires relatively high mineral/melt partition coefficients for all incompatible trace elements.

Primary magma and source compositions. Primary magma compositions were estimated by extrapolating the observed trace element trend for Ni, back to values appropriate to a primary magma (i.e. 200–450 ppm). The corresponding range of

log f was then used to determine (a) concentration ranges for other trace elements and (b) the amount of stage one fractionating assemblage to add to the most mafic LPS lava to estimate the major element composition of the primary magma. Calculated primary magmas have Mg-numbers in the range 56–58 and are not typical of primary magmas derived from normal mantle compositions.

Graphical comparison of the LPS primary magma compositions with 'normal' alkali basalt primary magma compositions (Basaltic Volcanism Study Project, 1981) shows that they are characterised by enrichment in TiO_2, Na_2O, K_2O and P_2O_5 (Fig. 1a). The pattern of enrichment in major (and trace) elements is reminiscent of the enrichment of clinopyroxene-amphibole-apatite ± mica mantle xenoliths relative to 'normal' mantle xenoliths (Fig. 1b). Xenoliths containing various combinations of biotite, kaersutite, clinopyroxene, sodic K-feldspar, Fe-Ti oxides, apatite, sphene (often occurring as dykes in isotopically enriched dunites) have been reported from Kerguelen (Grégoire, 1994) and may represent a suitable source material for the LPS magmas.

Two origins are proposed for the LPS source, both relate to the location of Heard Island on an oceanic plateau. A: The LPS source is 'fossil' plume melt frozen within the lithospheric mantle since the formation of the Kerguelen Plateau as a hotspot trace 114 Ma ago. B: The LPS source is a pocket of continental lithospheric mantle detached during the early phase of ocean basin development following the break-up of Australia and Antarctica and trapped within the lithospheric mantle beneath the developing Kerguelen Plateau.

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