Alkalic magmas generated by partial melting of garnet pyroxenite

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ABSTRACT

Many oceanic-island basalts (OIBs) with isotopic signatures of recycled crustal components are silica poor and strongly nepheline (*ne*) normative and therefore unlike the silicic liquids generated from partial melting of recycled mid-oceanic-ridge basalt (MORB). High-pressure partial-melting experiments on a garnet pyroxenite (MIX1G) at 2.0 and 2.5 GPa produce strongly *ne*-normative and silica-poor partial melts. The MIX1G solidus is located below 1350 and 1400 °C at 2 and 2.5 GPa, respectively, slightly cooler than the solidus of dry peridotite. Chemographic analysis suggests that natural garnet pyroxenite compositions straddle a thermal divide. Whereas partial melts of compositions on the silica-excess side of the divide (such as recycled MORB) are silica saturated, those from silica-deficient garnet pyroxenites can be alkalic and have similarities to low-silica OIB. Although the experimental partial melts are too rich in Al_2O_3 to be parental to highly undersaturated OIB suites, higher-pressure (4–5 GPa) partial melting of garnet pyroxenite is expected to yield more appropriate parental liquids for OIB lavas. Silica-deficient garnet pyroxenite, which may originate by mixing of MORB with peridotite, or by recycling of other mafic lithologies, represents a plausible source of OIB that may resolve the apparent contradiction of strongly alkalic composition with isotopic ratios characteristic of a recycled component.

Keywords: pyroxenite, alkali basalt, basanite, partial melting, recycled crust.

INTRODUCTION

There is considerable evidence that the source regions of some oceanic-island basalts (OIBs) contain a component derived from recycled oceanic crust (e.g., Hofmann, 1997). However, partial melts of oceanic-crust lithologies (particularly pyroxene-rich rocks such as quartz and coesite eclogites that correspond to average oceanic crust) are silica saturated (Green et al., 1967), whereas many oceanic islands are characterized by low-silica, alkalic (i.e., *ne*-normative) lavas. This is particularly true of OIB localities with isotopic signatures most clearly associated with recycled crustal materials (i.e., those with enriched mantle "EM1, EM2" and "HIMU" [high $^{238}U/^{204}Pb$] signatures; e.g., Hofmann, 1997), which are typically composed of alkali basalts, basanites, and nephelinites (Fig. 1). The formation of these highly undersaturated magmas thus presents a challenge for models that require recycled, pyroxene-rich oceanic crust to constitute a major component of the source regions of OIBs.

Small-degree partial melts of peridotite at high pressure can be strongly alkalic (Takahashi and Kushiro, 1983), particularly when generated in the presence of carbonate (Hirose, 1997). Peridotites are thus potential sources for some alkalic OIB magmas, but experimentally produced partial melts of peridotite are generally too aluminous at a given MgO concentration to be parental to typical OIB suites (Fig. 1),

and geochemical evidence favors production of some OIB magmas partly from partial fusion of pyroxene-rich lithologies (Hauri, 2002). Alkalic glasses also result from partial melting of a mixture of subducted crust and peridotite at pressures of 2–3.5 GPa (Kogiso et al., 1998; Yaxley and Green, 1998), and thus melting of such mixtures might explain both the involvement of oceanic crust and the alkalic character of OIBs with crustal geochemical signatures. Such mixtures could be produced by mechanical disaggregation of subducted eclogite (Tabit et al., 1997) or by hybridization of peridotite by partial melts of eclogite (Yaxley and Green, 1998). However, partial melts of such hybridized peridotite have low CaO and high Al_2O_3 relative to probable OIB parental lavas (Fig. 1) (Kogiso et al., 1998). Also, linear mixing trends between incompatible (Pb, He, Sr) and compatible (Os) isotope ratios are difficult to reconcile with a source composed of peridotite with small proportions of admixed subducted crust (Hauri, 1997; Becker, 2000). It is therefore important to investigate experimentally whether pyroxenite (a term we use to encompass all pyroxene-dominated rocks, including garnet pyroxenite, websterite, eclogite, etc.) can produce highly undersaturated partial melts from which oceanic-island lavas might be plausibly derived.

Several lines of evidence suggest that partial melts of some pyroxenites can be silica undersaturated. Apparently endogenous *ne*-normative glass has been documented in pyroxenite xenoliths (Francis, 1991). Chemographic analysis of simple systems (O'Hara, 1968) and thermodynamic modeling in more complex systems (Hirschmann and Pertermann, 2000; Schiano et al., 2000) reveal that the aluminous pyroxene plane (e.g., the ternary $CaSiO_3$-$MgSiO_3$-Al_2O_3) is a thermal divide, so either silica-rich or silica-poor liquids can coexist with garnet and pyroxene. Finally, mildly alkalic liquids (≤ 4 wt% normative *ne*) result from melting experiments on eclogite (Ito and Kennedy, 1974), clinopyroxenite, and olivine clinopyroxenite (Kogiso and Hirschmann, 2001). Yet, relatively little is known about formation of alkalic liquids by partial melting of pyroxenite, and to our knowledge, there have been no reports of experimentally produced partial melts of pyroxenite that are comparable to the low-silica (<45 wt%) lavas commonly erupted at oceanic islands. Here we report strongly *ne*-normative liquids produced by partial melting of a garnet pyroxenite at 2 and 2.5 GPa.

EXPERIMENTAL METHODS

The starting material for the experiments is a mixture of two natural pyroxenites from the Balmuccia massif (Shervais and Mukasa, 1991); it approximates a typical mantle pyroxenite composition based on a survey of worldwide occurrences (Fig. 2). Experiments with a preliminary mixture produced large (400 μm) porphyroblasts of garnet with many inhomogeneous inclusions of pyroxene, so 1 wt% finely powdered pyrope was added as crystal seeds. The final mixture, MIX1G, was dried at 1000 °C for 1.5 h in a CO_2-H_2 gas stream near the fayalite-magnetite-quartz buffer and then ground in agate until it passed through a 15 μm screen. The bulk composition was determined by microprobe analysis of a glass fused at 1500 °C and 1 GPa (Table 1). Experiments were conducted in a piston-cylinder apparatus using the methods of Baker and Stolper (1994). For experiments in which the expected degree of partial melting was small, the diamond aggre-

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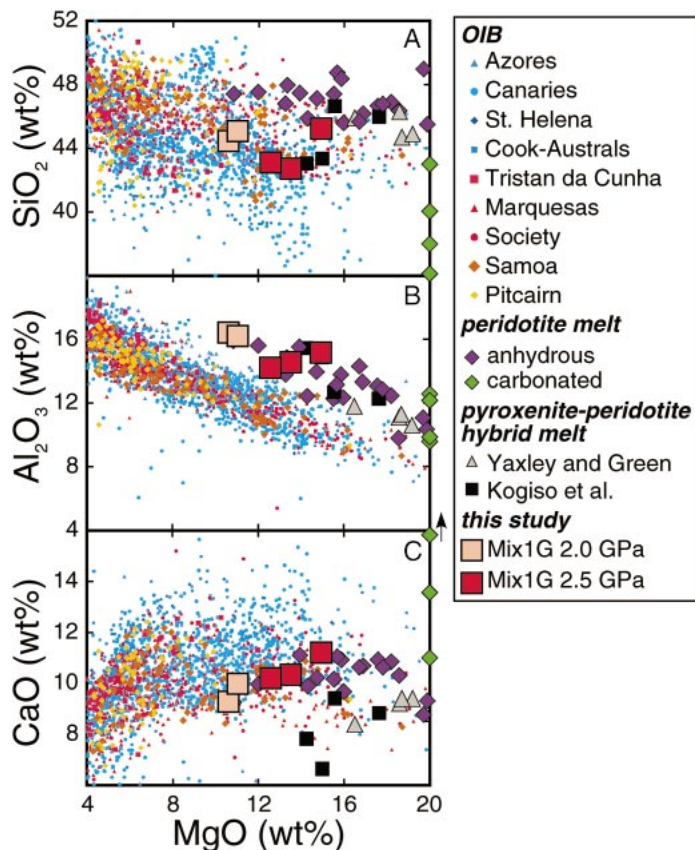
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Figure 1. Compositions of mafic lavas from representative oceanic-island chains associated with strong signatures of recycling (small color symbols) compared to glasses from partial-melting experiments, including partial melts of MIX1G garnet pyroxenite (red and orange squares), anhydrous peridotite (2–5 GPa) (Hirose and Kushiro, 1993; Walter, 1998), pyroxenite + peridotite hybrid experiments (3–3.5 GPa) (Kogiso et al., 1998; Yaxley and Green, 1998), and carbonated peridotite (3 GPa) (Hirose, 1997). Carbonated peridotite partial melts are highly magnesian (23–24.9 wt% MgO) and have been projected down to 20 wt% MgO along an olivine fractionation trend by assuming that $K^{Fe\text{-}Mg}_d = 0.35$. Oceanic-island basalt (OIB) data from Georoc database (http://georoc.mpch-mainz.gwdg.de/ [accessed August 2002]) from selected island chains with extreme isotopic signatures: EM1—Pitcairn; EM2—Samoa, Tristan da Cunha, Marquesas, Societies, Cook-Australs; HIMU—St. Helena, Canaries, Azores, Cook-Australs.
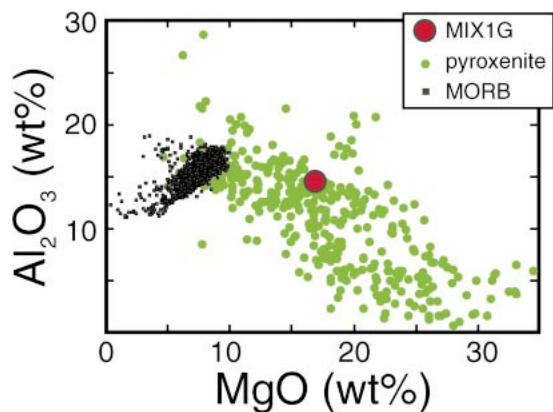

Figure 2. Comparison of MIX1G starting material to spectrum of mantle pyroxenite compositions from xenoliths and from orogenic massifs (Hirschmann and Stolper, 1996) and from mid-oceanic-ridge basalt (MORB) selected from Petdb database (http://petdb.ldeo.columbia.edu/petdb/ [accessed August 2002]).
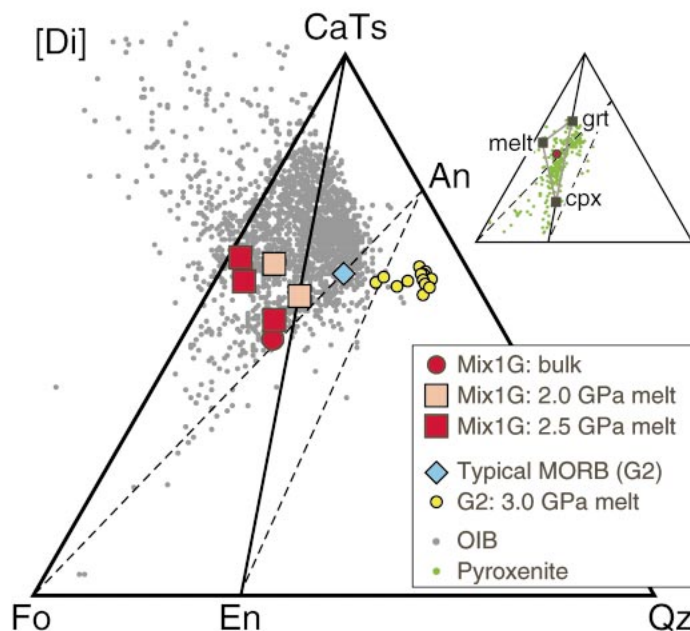

Figure 3. Partial-melting behavior of garnet pyroxenites in pseudo-ternary system Mg_2SiO_4 (Fo)–$CaAl_2Si_2O_6$ (CaTs)–SiO_2 (Qz) projected from diopside [Di], using projection methods of O'Hara (1968). *Ne*- and *hy*-normative compositions are separated by join between Fo and anorthite (An), as indicated by dashed line. All stoichiometric garnet and pyroxene plot along thermal divide defined by En (enstatite)–CaTs. Silica-excess pyroxenites, such as those with composition of mid-oceanic-ridge basalt (MORB), plot to silica-rich side of this join and produce *hy*- or *qz*-normative partial melts, as illustrated by G2 partial-melting experiments of Pertermann and Hirschmann (2003). Silica-deficient pyroxenites, such as MIX1G, plot to silica-poor side of join and produce Si-poor *ne*- or *hy*-normative partial melts. Compositions of oceanic-island basalt (OIB) from Figure 1 are plotted for comparison (gray circles). Inset shows schematic partial-melting relationships for MIX1G. Mass balance requires that melt coexisting with garnet and pyroxene plot strongly to silica-deficient side of thermal divide. Note that many natural pyroxenites (from compilation of Hirschmann and Stolper, 1996) are also silica-deficient.

gate method was used to inhibit quench modification of liquid compositions. However, compositions of glass shards collected from diamond aggregates from several experiments were highly variable, particularly in alkali concentrations. Their heterogeneity may result from quench crystallization of alkali feldspar, crystals of which were observed in grain mounts of diamond aggregate in run 95MMH27. Compositions of these glasses are not reported.

EXPERIMENTAL RESULTS

At 2.5 GPa between 1375 and 1500 °C, aluminous clinopyroxene (cpx) and garnet (gt) are stable phases in MIX1G pyroxenite (Table 1 and Table DR1[1]). Olivine (ol) and spinel are present in runs quenched at 1375 and 1400 °C. Glass was observed between 1400 and 1500 °C. At 1375 °C, glass is not present in the main charge and material between diamond aggregate grains was lost during polishing, so we cannot be sure whether partial melting occurred. We assume that the MIX1G solidus is between 1375 and 1400 °C at 2.5 GPa. At 2 GPa, cpx, spinel, and glass are present between 1350 and 1400 °C; garnet is present at 1350 and 1375 °C. Thus, it appears that the solidus of

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[1]GSA Data Repository item 2003072, Table DR1, mineral compositions and modes from experiments on MIX1G garnet pyroxenite, is available from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, editing@geosociety.org, or at www.geosociety.org/pubs/ft2003.htm.

Run	n^*	Mode†	SiO_2	TiO_2	Al_2O_3	Cr_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Total	Mg#§	$Ne^\#$
95MMH09 1 GPa, 1500 °C, 1 hour (glass gives MIX1G bulk composition)																
gl*	25		45.6(2)	0.90(6)	15.2(1)	0.11(2)	7.8(1)	0.15(2)	16.67(9)	11.48(2)	1.4(1)	0.04(1)	0.01(1)	99.32	79.3	
96MMH05 2 GPa, 1400 °C, 62.5 h, cpx + spn + gl																
gl	10	0.26	45.1(3)	2.0(1)	16.2(1)	0.03(4)	10.9(1)	0.16(3)	11.1(2)	9.98(8)	2.60(4)	0.08(1)	0.05(3)	98.13	64.4	2.2
96MMH07 2 GPa, 1375 °C, 63 h, diamonds, cpx + gt + spn + gl																
gl	8	0.14	44.4(4)	2.3(1)	16.4(2)	NA	12.81(4)	0.1(1)	10.6(1)	9.3(1)	3.78(1)	0.12(1)	0.03(1)	99.9	59.7	9.8
96MMH09 2 GPa, 1350 °C, 87 h, diamonds, cpx + gt + sp + gl																
95MMH23 2.5 GPa, 1500 °C, 34 h, cpx + gt + gl																
gl	16	0.67	45.2(1)	1.3(1)	15.2(1)	0.05(3)	9.1(2)	0.17(4)	15.0(1)	11.2(1)	1.91(7)	0.05(1)	0.02(2)	99.09	74.6	2.5
95MMH17 2.5 GPa, 1475 °C, 43 h, cpx + gt + gl																
gl	15	0.28	42.7(1)	1.87(6)	14.54(7)	NA	12.0(2)	0.17(3)	13.54(7)	10.3(1)	3.04(4)	0.09(1)	0.04(2)	98.37	66.7	10.7
95MMH15 2.5 GPa, 1455 °C, 46/30 h**, cpx + gt + gl																
gl	5	0.21	43.1(7)	2.58(9)	14.20(2)	NA	13.6(4)	0.15(3)	12.5(3)	10.2(1)	3.72(7)	0.08(2)	0.06(1)	100.2	62.3	13.7
96MMH03 2.5 GPa, 1435 °C, 60 h, diamonds, cpx + gt + gl																
95MMH27 2.5 GPa 1400 °C, 68.5 h, diamonds, cpx + gt + sp + ol + gl																
96MMH15 2.5 GPa 1375 °C, 65 h, diamonds, cpx + gt + sp + ol																

Note: Phase compositions determined by electron microprobe at California Institute of Technology and University of Minnesota with 15 kV and 20 nA (minerals) or 5 nA (glasses) beam conditions, ZAF data reduction, and natural mineral standards. Abbreviations: gl = glass, cpx = clinopyroxene, gt = garnet, spn = spinel, ol = olivine.
   $*n$ = number of probe analyses averaged.
   †Proportion of liquid present in experimental charge determined by least-squares mass balance.
   §Mg# = 100*molar Mg/(Mg + Fe).
   #Ne = nepheline weight percentage in CIPW norm.
   **Experimental charge was at T and P for 46 h, quenched, re-encapsulated, and run at T and P for 30 additional h.

MIX1G is just lower than that of fertile mantle peridotite, which is 1363 and 1418 °C ± 20 at 2 and 2.5 Gpa, respectively (Hirschmann, 2000). Glasses are low in SiO_2 (42.7–45.2 wt%), and compositions range from mildly *ne*-normative (2%) alkali picritic at high temperature to strongly *ne*-normative (9–14%) basanitic (Table 1). All glasses are rich in MgO (10.6–15.0 wt%) and CaO (9.3–11.2 wt%) (Fig. 1).

DISCUSSION

Comparison to Lavas from Oceanic Islands

The characteristics of source regions of oceanic islands have received relatively little attention from experimental petrologists. The exceptions are studies pertaining to Hawaii (e.g., Eggins, 1992; Wagner and Grove, 1998, and citations therein), but most Hawaiian lavas are tholeiitic, so such work is not directly applicable to the origins of silica-undersaturated lavas characteristic of many oceanic islands. The strongly alkalic, low-silica experimental glasses from this study are comparable to such OIB lavas in terms of their SiO_2 and CaO contents (Fig. 1) but are richer in Al_2O_3 than the lavas at comparable MgO contents (Fig. 1).

While the MIX1G glasses are not ideal matches to likely parental melts of alkalic OIB, at a given MgO concentration they are lower in SiO_2 than partial melts of anhydrous peridotite and their CaO concentrations are more similar to OIB than hybridized or carbonated peridotite (Fig. 1). Experimental partial melts of both pyroxenite and peridotite are more aluminous than the trend defined by OIB lavas. In the case of MIX1G, this is not directly a result of the Al_2O_3-rich bulk composition, since the Al_2O_3 in the melt is buffered by garnet saturation. Higher-pressure partial melts of MIX1G have less Al_2O_3 at garnet saturation and thus might be more similar to likely alkalic parental liquids (Kogiso et al., 2001).

Producing Alkalic Liquids from Pyroxenites

Production of alkalic liquids by partial melting of garnet pyroxenite can be understood by considering the pseudoternary system forsterite (Fo, Mg_2SiO_4)–Ca-Tschermak pyroxene (CaTs, $CaAl_2SiO_6$)–quartz (Qz, SiO_2) projected from diopside [Di, $CaMgSi_2O_6$] (Fig. 3), using the projection scheme of O'Hara (1968). In this projection, all stoichiometric garnet and pyroxene plot along the join between enstatite (En) and CaTs, so this join is a thermal divide when cpx and garnet are the sole minerals in the residue (O'Hara, 1968). Thus, silica-excess

garnet pyroxenites have bulk compositions on the Si-rich side of the divide and generate silicic partial melts (Fig. 3), and silica-deficient garnet pyroxenites, such as the one studied here, plot on the Si-poor side of the divide and generate low-silica partial melts. Accessory minerals characteristic of silica-excess garnet pyroxenites are quartz, coesite, feldspar, and/or kyanite, whereas silica-deficient compositions have small amounts of olivine, spinel, and/or Fe-Ti oxide. Mid-oceanic-ridge basalt (MORB) compositions form silica-excess garnet pyroxenite at high pressure, and partially melt to form *hy*- or *qz*-normative liquids. In contrast, MIX1G has accessory olivine and spinel under near-solidus conditions, and therefore can generate strongly *ne*-normative liquids (Fig. 2).

If typical oceanic basalt is not silica-deficient, are there plausible processes that might convert MORB protoliths to silica-deficient pyroxenite prior to delivery to OIB source regions? Extraction of partial melt or fluid from eclogite in subduction zones cannot generate silica-deficient residues, though it can generate bimineralic compositions, i.e., those consisting solely of garnet and cpx and falling on the thermal divide. Partial melts of bimineralic garnet pyroxenite can be alkalic (Ito and Kennedy, 1974), and further investigation is required to determine if they can have compositions plausibly parental to OIB. Conversion of silica-excess or bimineralic pyroxenite to silica-deficient pyroxenite (as has been invoked by Lundstrom et al., 2000) requires either (1) hybridization with peridotite; (2) metasomatism by a silica-deficient fluid such as carbonatite; or (3) removal of low-pressure partial melts or fluids in the presence of olivine or spinel.

Many natural pyroxenites from xenolith and peridotite massifs are silica deficient (Fig. 3), and silica-deficient pyroxenites in OIB source regions may originate from protoliths other than MORB. Cumulate oceanic gabbros with more olivine than feldspar (on a molar basis) are silica deficient, and the same may be true for olivine-bearing cpx- or garnet-rich delaminated lower crust of continents or arcs (Jull and Kelemen, 2001) and for veins formed in the oceanic lithosphere (Halliday et al., 1995). For example, the silica-deficient ilmenite eclogites from Koidu, Sierra Leone, are thought to originate either from subducted lower oceanic crust or from fragments of delaminated lower continental crust (Barth et al., 2002).

Fate of Low-Silica Partial Melts of Pyroxenite

An important question is whether alkalic partial melts of pyroxenite can maintain their petrologic character after they segregate from

their sources. Strongly undersaturated liquids might react incongruently with orthopyroxene (opx) in peridotite, precipitate olivine, and thereby become similar in composition to partial melts of peridotite or hybridized peridotite. Lundstrom et al. (2000) argued that such reactions promote formation of dunite channels. If pyroxenite bodies have relatively large spatial dimensions, their partial melts could segregate into conduits that allow transport without significant interaction with peridotite (Kogiso et al., 2000). Such conduits must exist in the shallow mantle—otherwise, highly undersaturated magmas could not traverse the lithosphere—but it is less clear whether they exist at greater depths. On the other hand, opx may be absent from near-solidus peridotite above 3.5 GPa (Walter, 1998), so partial melts of garnet pyroxenite formed at great depths may not be much-affected by melt-rock reactions at high pressure.

CONCLUSIONS

Oceanic-island basalts with strong signatures of crustal recycling are silica-poor and unlike high-pressure partial melts of typical oceanic crust, which are silica-rich. But a wide class of mantle pyroxenites are silica-deficient, and experiments on a silica-deficient pyroxenite at 2–2.5 GPa show that partial melts are low in silica and have similarities to alkalic OIB with strong recycling signatures. Partial melt compositions are more aluminous than such OIB, but this difference may diminish at higher pressure.

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