

Partial melting of metabasalts at 2–7 GPa: Experimental results and implications for lower crustal and subduction zone processes

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Introduction

Rocks of basaltic composition have played a pivotal role in the geochemical evolution of the Earth's crust and upper mantle (e.g. Ringwood, 1990), and in the continued recycling of material between these two domains (Kay and Kay, 1990). The distinctive geochemical signature of basaltic ocean crust is apparent not only in subduction-related arc magmas (e.g. McDonough, 1991), but intraplate magmas as well (Hofmann and White, 1982), and the lower crust of the continents appears to be dominated by mafic granulites and eclogites of basaltic composition (e.g. Rudnick and Taylor, 1987). If ultra-metamorphism of basalt in these environments also involves partial melting, then the geochemical characteristics of subducted or otherwise foundered mafic crust, including Ringwood's megalith, may be profoundly affected (i.e., by loss of a melt component). Of course, where and if melting of metabasalt takes place will be critically dependent upon the availability of water and the pressure-temperature trajectory of the rock; simple devolatilization below the solidus should expel a water-rich fluid with much different trace element characteristics than a hydrous melt produced above the solidus. A variety of evidence garnered from experimental studies can be brought to bear on the question of whether or not partial melting of metabasalts in the mantle is an important element of these rocks' history. In general, this involves comparison of: (1) the experimental products of melting with arc magmas produced along convergent plate boundaries, and (2) the residues of melting with lower crustal (granulitic-eclogitic) and upper mantle (eclogitic) xenoliths.

Experimental method

Fine-grained (< 5–10 μm) powders of alkali basalt and low-K olivine tholeiite composition amphibolites were packed in graphite cups and enclosed in platinum capsules, which were then welded shut. Partial melting experiments of 5–15 days duration

were conducted in the piston-cylinder at 2.2 and 3.2 GPa and 1050–1150°C, and in the multi-anvil apparatus at 7 GPa and 1100–1200°C for run durations of 1–3 days. Several multi-anvil experiments utilized a thin diamond aggregate layer, sandwiched between thicker layers of rock powder, to collect small melt fractions and minimize problems related to quench crystallization. Major, minor, and trace element analysis of the liquids and residues from melting, by electron and ion microprobe, provide the basis for comparison of the experimental assemblages with orogenic magmas and lower crustal-upper mantle xenoliths.

Results

Phase assemblages are dominated by eclogitic residues (garnet + clinopyroxene) coexisting with SiO₂-rich melts. These liquids are water-under-saturated high-Al₂O₃, low-MgO, low-K₂O tonalites and trondhjemites at 3.2 GPa and at 2.2 GPa at temperatures ~ 1050°C, and comprise 15–30% of the assemblage by volume. In contrast, low-degree partial melts at 7 GPa and 1100–1150°C appear to be water-saturated, and exist as quenched 'crusts' within the diamond aggregate layer or in fluid-maintained interstitial pores; even without the diamond sponge present, these 'melts' (or, more generally, hydrous fluids) seem to be highly mobile, segregating to the lower ('cold') end of the experimental charge. Although difficult to analyze, this fluid phase is composed predominantly of (in descending order) SiO₂, Al₂O₃, K₂O, and TiO₂. Trace element analyses of the trondhjemitic-tonalitic melts at 3.2 GPa by ion microprobe indicate that their rare-earth patterns are strongly fractionated, and HREE-depleted (e.g. La/Yb = 15–40, Yb = 4–7 \times chondrite), with high Sr/Y ratios (40–110), low Cr/Y ratios (~ 1–2) and low Y-contents (5–8 ppm).

Relative proportions of the jadeite (Jd) and Tschermaks (Ts) molecules in residual clinopyroxenes in both sets of experiments have ratios of Jd:Ts ~ 1:2, criterion used by White (1964) to

delineate pyroxenes equilibrated under granulite facies conditions from those of the eclogite facies. Clinopyroxenes at 2.2–3.2 GPa contain 4–7 wt% Na₂O and 9–12 wt% Al₂O₃ and therefore can be classified as omphacite pyroxene, whereas at 7 GPa they contain 7–10 wt% Na₂O and 16–20 wt% Al₂O₃ and classify as jadeite. Rare earth patterns in clinopyroxenes at 3.2 GPa range from slightly *LREE*-depleted, concave-down at 4–8 × chondrite in the alkali basalt at 1100°C, to slightly *HREE*- and *LREE*-depleted, concave-down patterns at 3–10X chondrite in the low-K olivine tholeiite at 1100°C, and *LREE*-depleted, slightly concave-down patterns at 3–15 × chondrite in the low-K tholeiite at 1150°C. The following mineral–melt K_d 's for coexisting clinopyroxene and tonalitic melt at 3.2 GPa and 1100–1150°C are estimated from the ion probe measurements: $K_d^{Sr} \sim 0.1-0.2$; $K_d^Y \sim 1.0-1.5$; $K_d^{Cr} \sim 20-35$.

Compositions of residual garnets show a (limited) range in Fe/Mg, reflecting bulk composition variations as well as temperature, but they are generally almandine-rich, with grossular contents of 15–25 mol%; average composition is Fe₄₆Mg₃₄Ca₂₀. More magnesium-rich garnets (Fe₂₆Mg₅₇Ca₁₇) are stable only at near-liquidus conditions at 7 GPa and 1200°C. MnO contents are nearly constant over the P-T range covered by the experiments (MnO in garnet $\sim 0.4-0.6$ wt%), while garnets in the 7 GPa experiments are high in P₂O₅ ($\sim 0.2-0.3$ wt%). In contrast, TiO₂ content in garnets appears to be quite sensitive to temperature and melt composition; at 2.2 and 3.2 GPa, garnet coexisting with trondhjemitic-tonalitic melts has 1–2 wt% TiO₂. Garnets at 7 GPa and 1100–1150°C also contain approximately 1 wt% TiO₂, an amount which quickly drops to below 0.5 wt% by 1200°C. In the more Ti-rich low-K tholeiite bulk composition, residual rutile is stable up to 1150°C at 3.2 GPa and coexists with SiO₂-rich melts containing up to 2 wt% TiO₂; rutile is also stable in both bulk compositions at 7 GPa and temperatures up to 1150°C. Rare earth patterns for garnet coexisting with trondhjemitic-tonalitic melts are nearly constant at 50–70X chondrite from Sm through Lu, and relatively *LREE*-depleted (e.g. La $\sim 2-10 \times$ chondrite). The following mineral–melt K_d 's for coexisting garnet and tonalitic melt at 3.2 GPa and 1100–1150°C are estimated from the ion probe measurements: $K_d^{Sr} \sim 0.02-0.2$; $K_d^Y \sim 8-18$; $K_d^{Cr} \sim 15-50$.

Discussion

The prevailing opinion of those studying subduction-related arc magmatism is that primitive high-Mg basalts, parental to the dominant andesite

magmas erupted along convergent plate boundaries, are derived from partial melting of the underlying mantle wedge fluxed by a hydrous fluid component derived from the subducted slab. In this view, direct melting of oceanic crust during subduction to produce andesitic liquids is a rare occurrence. However, there is geochemical evidence to suggest that, in the recent geologic past, it does occur under certain extreme conditions (e.g. Defant and Drummond, 1990), and that it may have been very important in the growth of the early continental crust in the Archaean (Martin, 1986). High-Al₂O₃ trondhjemites and tonalites from the Archaean (TTG), and comparable rocks of much younger age (albeit rare), share many of the geochemical features of the experimental liquids produced by partial melting of basalt in the eclogite stability field. These include, besides the major-element similarities, rare-earth element patterns that are highly fractionated and *HREE*-depleted, high Sr/Y ratios, low Cr/Y ratios, and low Y-contents, features which combined distinguish these rocks from demonstrably mantle-derived arc magmas (e.g. high-Mg andesites and boninites). Partial melting of underplated, mantle-derived metabasalts in overthickened lower crust beneath the southern Andes (Atherton and Petford, 1992) results in magmas with characteristics similar to the TTG suite.

Garnet in residual eclogite assemblages from these experiments is similar in composition to garnets in Group II eclogites and Ca-rich garnets in Group I eclogites that occur as xenoliths in the Roberts Victor and Schuller kimberlites (MacGregor and Manton, 1986; de Bruin, 1989), in terms of Fe–Mg–Ca, but has considerably higher TiO₂ contents (> 1.0 wt% vs. $< 0.5-0.6$ wt%). The range of clinopyroxene compositions in the eclogite xenoliths is virtually the same as that in the lower pressure (2.2 and 3.2 GPa) melting experiments (i.e., Na₂O = 3–6 wt%, Al₂O₃ = 8–14%). Thus the interpretation of some eclogite xenoliths as representing remnants of subducted oceanic crust (e.g. Helmstaedt and Schulze, 1986; MacGregor and Manton, 1986) is consistent with the experimental data only if they originate from depths corresponding to pressures (considerably) less than 7 GPa. The low TiO₂ contents of garnets in eclogite xenoliths can be explained if temperatures greater than approximately 1150°C are considered, which in turn implies that (1) if a small amount of water were present, melting took place, and (2) residual rutile would have been consumed because of its relatively high solubility in liquids of intermediate composition (Ryerson and Watson, 1988).