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AN IMPORTANT ROLE FOR AMPHIBOLE IN ARC MAGMAS – A CRUSTAL SPONGE?

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INTRODUCTION

It is widely acknowledged that arc magmas, whether erupted or emplaced in the crust are commonly differentiated relative to primary magma compositions. In fact there is much debate about the actual compositions of primary magmas at arcs – and the degree to which sediment, fluid and slab melts may contribute.

Basalts and andesites from subduction zones are typically porphyritic, containing a nominally gabbroic assemblage of plagioclase and pyroxene. In contrast, cumulate inclusions and plutonic rocks from arcs are more commonly amphibole-bearing.

In order to assess whether amphibole plays an important role in controlling the geochemical characteristics of arc magma suites, we have compiled REE data, and examined the behaviour of REE ratios with differentiation.

The test of differentiation controls is quite simple; using SiO_2 as an index of differentiation, we would expect i) gabbro fractionation to have a negligible effect on La/Yb and Dy/Yb ratios, ii) garnet fractionation to cause La/Yb and Dy/Yb to increase with differentiation, because $D_{La}<D_{Dy}<D_{Yb}$, and iii) amphibole fractionation to cause La/Yb to increase and Dy/Yb to decrease, because $D_{La} < D_{Dy} > D_{Yb}$.

We have restricted our attention to suites from a single volcanic edifice, on the basis that the characteristics of magma aliquots from a fixed location over a short time period are likely to reflect control by differentiation processes in the sub-volcanic plumbing system. Magmas from different volcanoes may, in contrast, reflect additional variable source effects (slab/fluid contributions). There are a limited number of cogenetic suites for which several analyses with high quality REE data (including Dy – hence INAA studies cannot be used) are available.

A SIGNIFICANT ROLE FOR AMPHIBOLE?

The results are shown in Figure 1. Most suites show differentiation trends consistent with significant amphibole fractionation – although there are exceptions to prove the rule (Surigao in the Philippines shows a garnet-dominated trend and Antahan in the Marianas appears to be gabbro). Amphibole control is consistent with the observation that amphibole-bearing cumulate inclusions are common in arc volcanic rocks, but is it consistent with phase equilibria?

The large variations in amphibole chemistry and the important control by H_2O content, mean that we must concede that amphibole stability is not well constrained. Nevertheless experimental studies place the upper thermal stability limit at ~1050°C. This may seem cool relative to eruption temperatures, although we must remember that i) recent work has shown that decompression – driven crystallization releases latent heat that increases magma eruption temperatures (Blundy et al., 2006), and ii) petrographic and micro-isotopic studies have shown that the crystals in many lavas represent a recycled cargo (Davidson et al., 2005; Turner et al., 2003) – implying that cumulate solids or mushes have been produced and subsequently entrained in hotter magmas.

The widespread occurrence of significant amphibole fractionation in arc magmas has a number of important implications;

i) The chemistry of arc magma suites is typically not controlled by the phase assemblage observed in the rocks, but rather by cryptic fractionation occurring at earlier (deeper) stages

ii) The implication of amphibole fractionation requires conditions in which amphibole is a stable phase. Although these cannot be precisely prescribed within the experimental framework currently available, conditions certainly need to be mid-deep crust and magmas need to be water-bearing, although not necessarily saturated (e.g. Allen and Boettcher, 1983).

iii) Mass balance considerations require that significant amphibole-bearing cumulates reside in the crust, which are likely relatively fertile and can be remelted to produce LREE-rich magmas (c.f. Annen et al., 2006, Petford and Gallagher, 2001).

iv) The occurrence of widespread amphibole cumulates represents an effective water filter between mantle and atmosphere (up to 30% of the H_2O leaving the mantle in magmas could be sequestered in amphibole in the crust).

v) If arc magmatism is an important process in the growth of the continental crust then a complementary process of cumulate recycling into the mantle is required (since arc magmas are fundamentally basaltic, and the continental crust is andesitic). Recycling of amphibole-bearing cumulates can transfer water and some incompatible elements (Rb, K) from the crust back into the mantle.

IMPLICATIONS FOR MAGMA SOURCES

The differentiation trends shown in Figure 1 do not back project to a common parent – even when only volcanoes from the same arc are considered. This could mean either;

i) There is an unseen very early/ deep stage of differentiation responsible for the dispersion in La/Yb and Dy/Yb among the most primitive magmas at a given arc, or

ii) Variations in parent magma chemistry reflect primary magmas – i.e. are inherited from the mantle source

In the case of (i) deep fractionation involving garnet could be responsible for elevating La/Yb (and Dy/Yb). In this case we might expect a correlation between La/Yb projected to 50% SiO_2 (a nominal parental basalt composition) and crustal thickness. That is, the thicker the crust, the more deep garnet fractionation is promoted. No such correlation can be discerned with the available data – but it should be noted that we do not have reliable crustal thickness data at each volcanic centre.

In the case of (ii) greater LREE enrichment might reflect a greater slab-derived sediment component added to the mantle source. In this case we might expect higher La/Yb to correlate with lower $^{143}Nd/^{144}Nd$. No convincing correlation exists (Figure 2), although given the broad ranges in $^{143}Nd/^{144}Nd$ and La/Yb represented by sediments worldwide, it is not inconceivable that at least the primitive magmas from each suite reflect sediment-modified mantle wedge. Notwithstanding the lack of correlation with crustal thickness however, the data in Figure 2 might also reflect deep crustal contamination. Given that there is no independent evidence for old (low $^{143}Nd/^{144}Nd$) crust in the basements of many of the arcs considered, we favour the second possibility.

REFERENCES CITED

Allen, J.C., and Boettcher, A.L., 1983, The stability of amphibole in andesite and basalt at high pressures: American Mineralogist v. 68, p. 307-314.

Annen C., Blundy J.D., and Sparks, R.S.J., 2006. The Genesis of Intermediate and Silicic Magmas in Deep Crustal Hot Zones: Journal of Petrology, v.47, p. 505-539.

Blundy, J., Cashman, K. and Humphreys, M., 2006, Magma heating by decompression-driven crystallisation beneath andesite volcanoes: Nature, v. 443, p. 76-80.

Davidson, J.P., Hora, J.M., Garrison, J.M. and Dungan, M.A., 2005, Crustal Forensics in Arc Magmas: Journal of Volcanology and Geothermal Research, v. 140, p. 157-170.

Finney, B.M., 2004, Magmatic differentiation at an island-arc caldera: a stratigraphically constrained multi-isotope study of Okmok Volcano, Aleutian Islands, Alaska: [PhD thesis]: University of Bristol, 296 p.

George, R., Turner, S., Hawkesworth, C., Nye, C., Bacon, C., Stelling, P., and Dreher, S., 2004, Chemical versus temporal controls on the evolution of tholeiitic and calc-alkaline magmas at two volcanoes in the Aleutian arc: Journal of Petrology, v.45, p. 203-219.

Handley, H., 2006, Geochemical and Sr-Nd-Hf-O isotopic constraints on volcanic petrogenesis at the Sunda Arc, Indonesia: [PhD thesis]: University of Durham.

Macpherson, C.G., Dreher, S.T. and Thirlwall, M.F., 2006, Adakites without slab melting: High pressure differentiation of island arc magma, the Philippines: Earth and Planetary Science Letters, v. 243, p. 581-593.

Petford N, Gallagher K. 2001, Partial melting of mafic (amphibolitic) lower crust by periodic influx of basaltic magma: Earth and Planetary Science Letters, v. 193, p. 483–89.

Turner, S., George, R., Jerram, D.A., Carpenter, N., and Hawkesworth, C.J., 2003, Case studies of plagioclase growth and residence times in island arc lavas from Tonga and the Lesser Antilles, and a model to reconcile discordant age information: Earth and Planetary Science Letters, v. 214, p. 279-294.

Wade, J.A. et al., 2005, The May 2003 eruption of Anatahan volcano, Mariana Islands: Geochemical evolution of a silicic island-arc volcano: Journal of Volcanology and Geothermal Research, v. 146, p. 139 – 170.

FIGURES

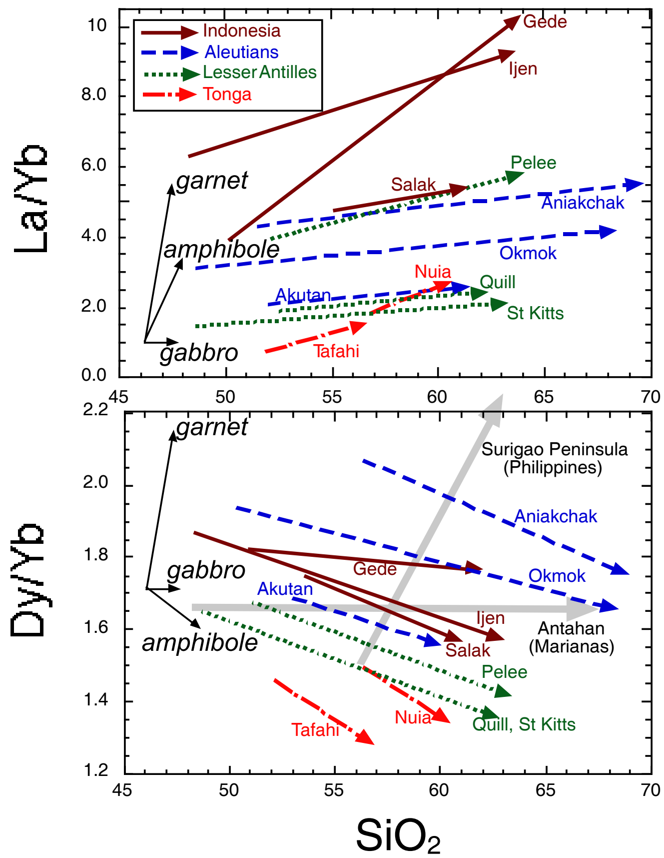

Figure 1. REE data compilation for arc volcanoes worldwide. Schematic fractionation trend control vectors are indicated. Data from Handley (2006), George et al. (2004), Finney (2004), Macpherson et al., 2006, Wade et al., 2005, and unpublished data (Turner, Davidson).

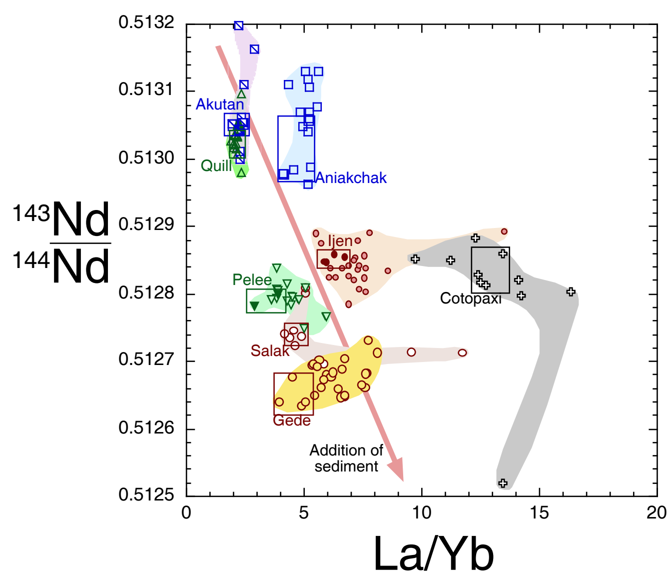

Figure 2. $^{143}Nd/^{144}Nd$ vs La/Yb showing that i) most intra-volcano trends are unsystematic, but ii) $^{143}Nd/^{144}Nd$ - La/Yb relations could reflect sediment addition to the mantle wedge, especially when the most mafic samples – boxed, highlighted as bold – of each suite are considered.