

Compositional variations in the sub-continental lithospheric mantle and implications for its role in basalt petrogenesis

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Introduction

The role of the sub-continental lithospheric mantle (SCLM) as a source for continental basalts has been strenuously debated. On the one hand, the SCLM provides a convenient and compositionally distinct alternative to the continental crust as a reservoir in which to store the light rare earth element rich materials that will evolve low $^{143}\text{Nd}/^{144}\text{Nd}$. On the other hand, major element, Re/Os isotope and density considerations suggest that the bulk of the lithospheric mantle is depleted in basaltic components calling into question its ability to generate large volume tholeiitic provinces. Coupled variations in initial $^{143}\text{Nd}/^{144}\text{Nd}$ and $^{187}\text{Os}/^{188}\text{Os}$ for Karoo picrite basalts (Ellam *et al.*, 1992) indicated the involvement of a low Sm/Nd, low Re/Os source - that has thus far only been encountered elsewhere in lithospheric mantle xenoliths (e.g., Walker *et al.*, 1989) and lamproite (Lambert *et al.*, 1991) - apparently confirming SCLM involvement. However, these data also suggested the involvement of asthenospheric or plume material with relatively high initial $^{143}\text{Nd}/^{144}\text{Nd}$ and $^{187}\text{Os}/^{188}\text{Os}$. A model in which small volume melts derived from the SCLM mix with sub-lithospheric magmas (McKenzie, 1989; Ellam & Cox, 1991) is consistent with these conclusions. Here we investigate the validity of such a model for flood basalts elsewhere. At issue are two main points; firstly, is the lithospheric component typically a small volume melt or are some flood basalts derived from predominantly or wholly lithospheric sources; secondly, how typical is the well-studied Karoo example in which lithospheric involvement is now most clearly demonstrated?

New experimental constraints

Recent advances in experimental petrology techniques (Hirose & Kushiro, 1993; Baker &

Stolper, 1994) have provided new constraints on mantle melting with which to compare the data available from continental flood basalts and lithospheric mantle xenoliths. Baker & Stolper (*op. cit.*) propose a melting equation relating the proportions of solid and melt phases based upon their 10 kb experiments. Applying their expression to a depletion processes such as might be responsible for lithosphere stabilisation yields substantial agreement with average major element compositions (Hawkesworth *et al.*, 1990) of mantle xenoliths and ultra-mafic massifs.

Based upon CaO and Al_2O_3 contents, the melting equation implies that the average of garnet lherzolite xenoliths lies close to the point where clinopyroxene and spinel are removed from the residual assemblage. Further melting of such a residue will be dominated by orthopyroxene. In this case, any such melts would have clearly defined characteristics (e.g., low Ca, Al) and the ability of the SCLM to generate large volumes of basalt would be severely limited. Moreover, such a SCLM would be highly sensitive to the introduction of metasomatic components which could be selectively sampled by subsequent magmatism. Indeed, both the major and trace element characteristics of the lithospheric melt would be dominated by the metasomatic component.

By contrast, the average spinel lherzolite is more fertile and could yield significant amounts of basalt before the available clinopyroxene and spinel were exhausted. In this case the ability of the depleted SCLM to generate magmas would be enhanced and the melts would be less extreme in composition. Subsequent generation of incompatible element rich magmas would again need the operation of a trace element enrichment process but does not necessarily require that enrichment to provide basalt-forming major element constituents. However, this more fertile lithospheric mantle is more dense and its preservation potential as lithosphere may be reduced.

Application of experimental data to basalts

Comparison between MgO, CaO and Al₂O₃ contents of continental basalts and the products of recent low degree melting experiments reveals very little overlap. From a large data base of flood basalts only a handful plot within the fields defined by the experimental data. In large part this reflects the fact that most flood basalts have evolved by fractional crystallisation and have MgO contents lower than the experimental primary melts.

Mafic samples from the Karoo Province have MgO within the range expected for primary melts (10–17%) but show much lower CaO and Al₂O₃ contents. While low CaO might reflect crustal involvement, it seems unlikely that a crustal contaminant would be characterised by low Al₂O₃. Moreover, there is abundant evidence to suggest that the majority of the Karoo mafic samples have not undergone significant crustal contamination (Ellam & Cox, 1989; 1991). Rather, the low CaO, low Al₂O₃ signature is more readily attributed to a basalt depleted lithospheric mantle source in accordance with the Nd and Os isotope data. Interestingly, several mafic samples from the Siberian Province (Wooden *et al.*, 1993; Mitchell, unpublished data) mimic the Karoo trend raising the possibility of a similar origin. In contrast, picritic flood basalts from the Tertiary N. Atlantic province (e.g., Francis, 1985) are much richer in Ca and Al so that they overlap the experimental fields and thus suggest a fertile, presumably sub-lithospheric, mantle source.

Evolved flood basalts reveal CaO-Al₂O₃-MgO relationships that are consistent with protracted fractional crystallisation. Most, however, are multiply saturated and have crystallised a mixture of olivine ± clinopyroxene ± plagioclase making unequivocal reconstruction of primary compositions problematic. For elements such as CaO and Al₂O₃, the evolved basalts show a similar range to that seen for picritic samples. However, the bimodal distribution recorded by the picrites is not apparent in the basalt data set. It is particularly clear that basalts derived from Ca- and Al-poor lithospheric sources that evolve through fractionation of olivine would lose their characteristic SCLM low CaO, low Al₂O₃ major element signature during the fractionation process.

Conclusions

Comparison of recent experimental results and data from mantle xenoliths suggests that compositional variations in the sub-continental mantle lithosphere are sufficient to radically affect its capacity to generate basaltic melts. The nature of any mantle lithosphere contribution to continental magmatism will vary markedly dependent on the degree of melt extraction required to stabilise the lithospheric mantle. Under appropriate thermal conditions basalts may be generated from wholly lithospheric source regions. Nonetheless, the most compelling examples of mantle lithospheric involvement in basaltic magmatism remain those that entail the incorporation of small degree melts into asthenospheric magmas. Elemental characteristics that appear diagnostic of this process are found in other flood basalt provinces suggesting widespread applicability.

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