Ocean island basalts and lithospheric melting: Constraints from the source mineralogy

C. Class
S.L. Goldstein
Max-Planck-Institut für Chemie, D-55020 Mainz, Germany.

Introduction

Mantle plumes constitute the primary mode of upwelling of material from the deep mantle (Morgan, 1971, Davies, 1990). Therefore, hotspot-related volcanics provide the only means available of examining compositional variations in the deep mantle. However, the deep mantle signature in hotspot-related volcanics might be obscured by entrainment of mantle material in the rising plume and interaction with the lithosphere, In an oceanic environment the contribution of lithospheric melts to hotspot volcanism has been generally considered minor based on isotopic and thermal arguments. However, it has been suggested that asthenospheric fluids and small degree melts continuously metasomatize the continental and the oceanic lithospheric mantle through time (e.g. McKenzie, 1989). Due to the lower temperature of the volatile-bearing solidus relative to the volatile-free solidus, metasomatized lithospheric mantle will more easily melt. Evidence for metasomatism comes mainly from mantle xenoliths showing, for example, volatile-bearing phases such as amphibole and phlogopite.

Here we present a simple trace element approach that makes it possible to identify minor phases in the solid residue during partial melting. Because amphibole and/or phlogopite are not stable in asthenospheric conditions, identification of their presence in the solid residue during partial melting provides evidence of a lithospheric magma source.

Method

We propose a simple approach to constrain the bulk partition coefficients of trace elements during partial melting. This approach can be applied to cogenetic volcanic suites derived from a chemically and isotopic homogeneous source by variable degrees of partial melting.

One highly incompatible element is chosen as an index for the degree of partial melting. The highest and the lowest concentration of this element in the volcanic suite represent the lowest (F_1) and highest degree (F_2) of partial melting observed. Linear regression lines are calculated for all other incompatible elements versus this 'index' element, and the concentrations of each element for F_1 and F_2 are estimated. The ratios of the two concentrations for each element ($f_{enrichment}$ will simply reflect its enrichment during partial melting for F_1 relative to F_2, independent of the relative concentrations of these elements in the source. It is important to emphasize that the $f_{enrichment}$ is independent of any melting model.

In order to illustrate the method, we use batch partial melting, although we could just as well use fractional melting (Shaw, 1970). Combination of the partial melting equations for one element and the two extreme degrees of partial melting F_1 and F_2 gives:

$$f_{enrichment} = \frac{C_{L1}}{C_{L2}} = \frac{D + F_2 * (1 - P)}{D + F_1 * (1 - P)}$$

batch melting

This illustrates that the $f_{enrichment}$ only depends on the bulk partition coefficient D, the hypothetical bulk partition coefficient of the melt P and the two degrees of melting F_1 and F_2. It can be shown that the $f_{enrichment}$ provides information on the relative partition coefficients for different elements even if there are uncertainties in the P-values and the degrees of melting. A major advantage of this approach is that it is independent of the composition of the mantle source.

Results

$f_{enrichment}$-values were calculated for incompatible elements measured on a basanite suite from La Grille volcano, Grande Comore Island, in the Indian Ocean. This volcanic suite is composed of near primary melts, which show a large range in trace element contents and are characterized by nearly homogeneous isotopic compositions. Fig. 1 shows the $f_{enrichment}$ obtained from these rocks.

The sequence of incompatible trace elements shown in this plot is consistent with increasing compatibility during partial melting of a 'normal' mantle mineralogy (i.e. olivine (ol), orthopyroxene

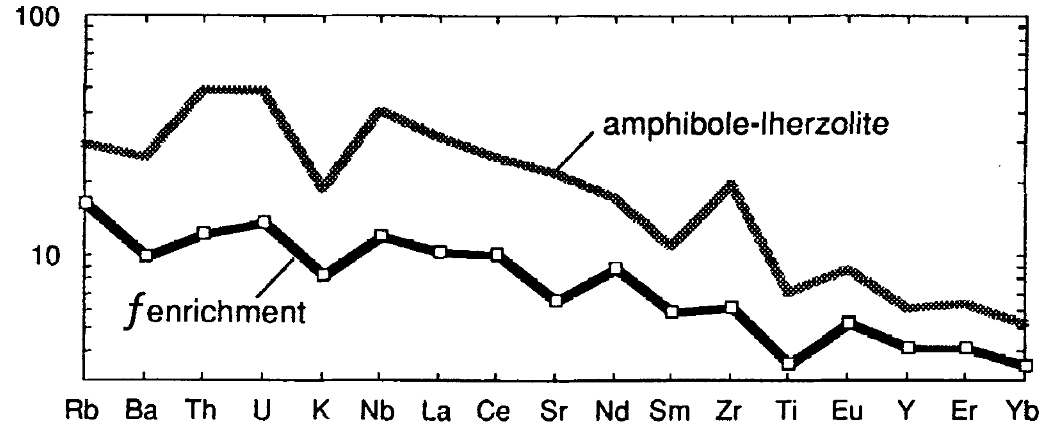

FIG. 1. $f_{enrichment}$-values for trace elements in the La Grille volcanic suite (squares). For comparison a non-modal batch melt of a model amphibole-lherzolithe is shown (absolute numbers are arbitrary).

(opx), clinopyroxene (cpx) and garnet (grt) ± spinel (sp)) and subsequent fractional crystallization of ol and cpx. It is striking that in La Grille, Ba, K, Sr and Ti have significant lower $f_{enrichment}$-values than the adjacent elements. Therefore these elements have relatively higher bulk partition coefficients than expected based on a 'normal' anhydrous mantle mineralogy. The more compatible behavior of these trace elements indicates that over the interval of partial melting an additional residual phase was present in the solid residue, which has higher mineral/melt partition coefficients for these elements than ol, opx, cpx and grt ± sp, and therefore results in a relative higher bulk partition coefficient for these elements.

To illustrate the effects of an additional residual phase, the composition of a melt in equilibrium with amphibole, ol, opx, cpx, and grt was calculated. The calculation is based on non-modal batch partial melting with amphibole/melt partition coefficients from Adam, Green and Sie (1993), Irving and Frey (1984), and Beattie (1993). The pattern of the amphibole-garnet-lherzolite is almost perfectly parallel with the $f_{enrichment}$ pattern, with the exception of Sr. This indicates that amphibole was present in the solid residue during the formation of the La Grille melts.

The presence of amphibole as a residual phase during partial melting is a clear evidence for melting in the lithosphere, because at asthenospheric conditions amphibole and phlogopite are not stable. Grande Comore Island is formed by two volcanoes, Karthala and La Grille. The presence of amphibole in the source region of the La Grille volcanic suite implies that this volcano is mainly composed of lithospheric melts. In contrast, Karthala lavas are derived mainly from the plume. The example of Grande Comore shows that lithospheric melts can play a major role in the formation of hotspot-related volcanics, even in an oceanic intraplate environment. This is further supported by the data from the Honolulu Volcanics, Oahu, which show the presence of phlogopite and a Ti-rich phase in the solid residue indicating lithospheric melting (Clague and Frey, 1982). Although we have applied the $f_{enrichment}$-approach to an oceanic island basaltic suite, it is completely general and can be applied to basaltic suites in any tectonic environment as long as they fulfill the correct prerequisites.

References

Adam. J., Green. T.H. and Sie, S.H. (1993) *Chem. Geol.*, **109**, 29–49.

Beattie, P. (1993) *Nature*, **363**, 63–5.

Clague, D.A. and Frey, F.A. (1982) *J. Petrol.*, **23**, 447–504.

Davies, G.F. (1990) *Earth planet. Sci. Lett.*, **99**, 94–109.

Irving, A.J. and Frey, F.A. (1984) *Geochim. Cosmochim. Acta*, **48**, 1201–21.

McKenzie, D. (1989) *Earth planet. Sci. Lett.*, **95**, 53–72.

Morgan, W.J. (1971) *Nature*, **230**, 42–3.

Shaw, D.M. (1970) *Geochim. Cosmochim. Acta*, **34**, 237.