Crustal assimilation during turbulent magma ascent (ATA); new isotopic evidence from the Mull Tertiary lava succession, N. W. Scotland

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Abstract Assimilation of crustal rocks with concomitant fractional crystallisation (AFC) is a well documented phenomenon in many igneous suites, but geochemical evidence from the Tertiary Mull lava succession suggests that in these magmas crustal contamination occurred by a distinctly different mechanism. Lavas from the lower half of the Mull Plateau group (MPG) can be divided into two broad sub-types; high (> 8%) MgO basalts with elevated Ba and K; and lower MgO (< 8%) basaltic-hawaiites with lower Ba and K. The lower crust and most of the upper crust beneath Mull is probably of Lewisian age. The Sr-, Nd- and Pb-isotope compositions of local Lewisian crustal samples yield the following ranges: $^{87}$Sr/$^{86}$Sr = 0.71002–0.72348, $^{143}$Nd/$^{144}$Nd = 0.51045–0.51058 and $^{206}$Pb/$^{204}$Pb = 14.0–14.6. Ten lavas have also been analysed and yield the following ranges: $^{87}$Sr/$^{86}$Sr = 0.7028–0.7042, $^{143}$Nd/$^{144}$Nd = 0.51214–0.51230 and $^{206}$Pb/$^{204}$Pb = 15.1–17.9. However, within this range, it is predominantly the more primitive mafic compositions, with elevated Mg, Ba and K, that show the lowest Nd- and Pb-, and the highest Sr-isotope values. Modelling of these isotopic results, in conjunction with major and trace element data, show that: (1) contamination by Lewisian lower crustal material does occur; (2) that the process involved was not one of assimilation with concomitant fractional crystallisation (AFC). The proposed contamination process is one whereby the hottest (most MgO rich) magmas have assimilated acidic partial melts of Lewisian lower crust during turbulent ascent (ATA) through thin, poorly connected dyke- and sill-like magma chambers. The chemical composition of the contaminated lavas can be modelled successfully through addition of ~ 5% acidic Lewisian crust to an uncontaminated lava. In contrast, the more evolved magmas - which probably fractionated at sub-crustal levels - were either not hot enough to melt significant amounts of crust, or did not ascend turbulently because of their higher viscosity, and so are less contaminated with crust.

Introduction

Crustal contamination of hot basaltic magmas erupted through thick continental crust, whether by partial or bulk assimilation, is an intuitively reasonable and thermodynamically possible process, for lavas which contain few phenocrysts. This process has been demonstrated geochemically in many different igneous provinces (e.g. Deccan Traps - Cox and Hawkesworth 1985, Devey and Cox 1987; Karoo - Cox 1988; Parana - Mantovani et al. 1985; British Tertiary Igneous Province (BTIP) - Thompson 1982, Dickin et al. 1984, Thompson et al. 1986, Wallace et al. 1994; East Greenland - Larsen et al. 1989, Blichert-Toft et al. 1992). Furthermore, field evidence in support of crustal melting caused by the heat of minor intrusions is also widespread, e.g. East Greenland, (Blichert-Toft et al. 1992) and the BTIP (Kille et al. 1986; Wyllie 1961).

Crustal contamination of BTIP magmas has long been postulated. Bailey et al. (1924) suggested that assimilation of acidic crust by the alkaline "Hebridean...
plateau magma type” generated the tholeitic (“non-porphyritic central”) magma type with its tendency towards silica oversaturation. The Sr-, Nd-, Ce- and Pb- isotope studies on Tertiary igneous rocks from western Scotland (Moorbath and Bell 1965; Moorbath and Welke 1969; Carter et al. 1978; Dickin et al. 1987) confirmed a significant Lewisian crustal component in many Hebridean magmas. Despite the massive weight of evidence for crustal contamination in Hebridean magmas, Beckinsale et al. (1978) proposed that partial melting of a vertically heterogeneous mantle could explain the geochemistry of the Mull Plateau group (MPG) lavas. Their data produced pseudoisochrons on isotope variation diagrams, which they believed dated a mantle differentiation event. They noted a whole rock isochron age for the MPG lavas (17 samples) of 128 ± 15 Ma. This age was interpreted as “a younger limit for an isotopic homogenisation event in the plagioclase lherzolite source region”.

Moorbath and Thompson (1980) studied the Sr-isotope systematics of various Hebridean lavas and intrusions and pointed out that, since Sr is more compatible than Rb in plagioclase, if magmas which had fractionated feldspar were excluded from consideration, then no correlation was observed between 87Sr/86Sr and Rb/Sr.

This paper focuses attention on the geochemical evidence for the mechanisms of crustal contamination during the petrogenesis of the MPG. It will be shown that assimilation with concomitant fractional crystallisation (AFC) – the most commonly invoked mechanism of crustal contamination – cannot explain the geochemical signatures of the MPG lavas. An alternative model will be proposed, in which the hottest magmas become the most contaminated with continental crust.

**Geological setting**

The Tertiary lavas

Tertiary magmatism in western Britain is believed to have been caused by the arrival of a mantle plume below the North Atlantic region (White 1988; Bott 1988). Most of the early volcanism occurred predominantly in regions such as western Britain, where the lithosphere had already substantially been thinned in pre-Tertiary times (Thompson and Gibson 1991). The volcanism associated with these pre-existing, lithospheric thinspots ultimately led to a series of igneous centres along the west coast of Britain (Fig. 1a).

The Isle of Mull (Fig. 1b) represents the eroded basal remnant of one of these BTIP volcanoes. Today the lava flows from the earliest period of igneous activity cover an area of over 900 km², and attain a maximum thickness of approximately 1000 m on the highest peak on the island, Ben More. Intruded into these lava flows is a central complex comprising a wide variety of igneous rocks.

The excellent exposure on Mull has enabled extensive flow-by-flow sampling of this lava succession. The hydrothermal alteration of lava flows associated with central intrusive complexes is a well known phenomenon, and Mull is no exception. A study of the amygdales by Walker (1970) revealed the presence of alteration zones grading outwards with decreasing intensity; from greenschist-facies alteration close to the central complex (Fig. 1), to lower grade zeolite-facies alteration in the western coastal regions of the island. A further study on the Mull basalt flows (Morrison 1978, 1979) focused attention on the mobility of elements, both at lower and higher grades of alteration. The chief conclusions of this study were that most elements were relatively “immobile” at low zeolite-facies grades, but at higher grades of alteration only Ti, Zr, Y, P, Nb and the REE were effectively “inamobile”. In accordance with the suggestions of Morrison (1979) samples have been collected, where possible from the solid centres of flows and not the more altered vesicular margins. The lavas used in this study were all collected from sections showing minimal hydrothermal alteration.

The lava succession has been divided into three different magma types (Kerr 1993a); the earliest flows (which cover most of the lava field) are transitional-alkalic lavas and known as the (MPG) Mull Plateau group (Morrison 1979). These are followed by the more tholeiitic Coire Gorm (CG) magma type and the youngest Central Mull Tholeiites (CMT), using the terminology of Kerr (1993a).