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Research paper

Melt inclusion Pb-isotope analysis by LA–MC-ICPMS: Assessment of analytical performance and application to OIB genesis

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ABSTRACT

It is widely acknowledged that olivine-hosted melt inclusions retain compositional information unavailable from the study of bulk-rock samples alone. Whether or not the compositions of melt inclusions are truly representative of geologically significant melt bodies has, however, been called into question; isotopic data are critical to resolving this debate but the rare existing data are contradictory. Previous studies of Pb isotope ratios suggest that large compositional variations are preserved by melt inclusions whereas Sr isotope data apparently do not. A new and extensive laser ablation Pb-isotope database is presented here and displays a degree of isotopic heterogeneity in key samples from Mangaia and the Pitcairn seamounts significantly less than previously reported. More than 95% of the inclusions analysed, including results for the low abundance Pb-isotope, ^{204}Pb, which has previously proven difficult to measure, are within error of bulk-rock analyses from these locations. Trace element measurements on two inclusions of different isotopic character from the Pitcairn Seamounts are closely similar to each other, and do not easily support models in which melt inclusions from this locality represent mixing between the Pitcairn mantle plume and the local MORB magmas or lithosphere. Instead, a second component, likely derived from within the plume, is required to explain the isotope and trace element variations observed. In terms of isotopic compositions then, melt inclusions may in most cases be representative of geochemical conditions prevailing within the magmatic plumbing system. The range of isotopic compositions found in a single sample likely includes the composition of the transporting melt (groundmass of the rock) and compositions previously trapped in crystals in the magmatic plumbing system.

1. Introduction

Silicate melt inclusions (hereafter 'melt inclusions') are small portions of melt, trapped by crystals growing within magmas (Roedder, 1979). It is commonly accepted that once trapped, the incompatible trace element signature of the melt is effectively preserved, being isolated from subsequent chemical evolution, and thus provides a detailed record of early magmatic history that may not always be evident from bulk-rock studies. As a result, melt inclusions may have great significance in the interpretation of magmatic processes and magma evolution.

It has also been suggested that melt inclusions in high-magnesian olivine phenocrysts which show distinctly different major and trace element concentrations to their host rocks may actually reflect grain-scale phenomena (Danyushevsky et al., 2004), where hot, primitive melts react within the magmatic system with more evolved crystal phases, resulting in the trapping of a melt which would not necessarily be representative of the macro system. This then raises the critical question as to whether those melt inclusions in olivine phenocrysts, which are characterised by a significant range of compositions, extending well outside the range observed in host lavas, are truly representative of geologically significant magma bodies, or are simply artefacts of localised grain-scale phenomena.

The ability to determine isotopic compositions in melt inclusions offers the prospect of some resolution to this debate since isotope ratios may be insensitive to many of the localised melting reactions that would otherwise affect major and/or trace element concentrations. The limited research in this area to date, however, has produced conflicting observations. Published Pb isotope ratios (Saal et al., 1998; Yurimoto et al., 2004; Saal et al., 2005) measured in olivine-hosted melt inclusions employing secondary ion mass spectrometry (SIMS) analytical techniques suggest that they do in fact record large compositional variations not seen in their hosts. For example, nearly 50% of the Mangaia (Cook Islands, S. Pacific) melt inclusions reported by Saal et al. (2005) exhibit compositions that are not observed in erupted lavas (Fig. 1). In contrast, however, Sr isotope measurements of melt inclusions from Samoa in the S. Pacific (Jackson and Hart, 2006) and a limited number (n = 8) of more

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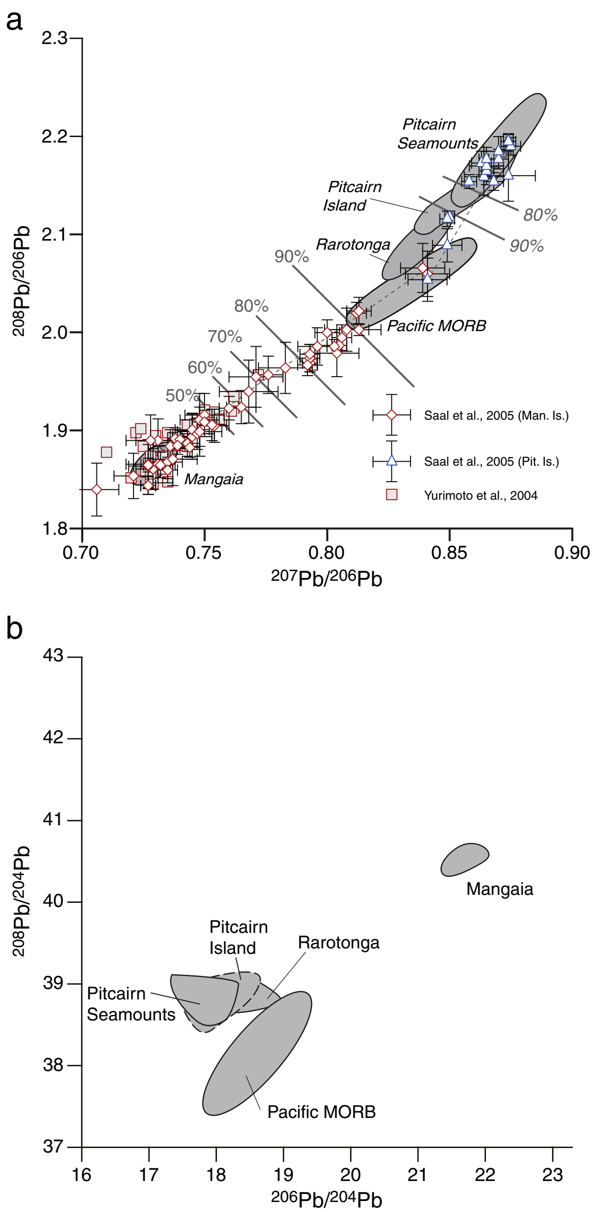

Fig. 1. (a) The $^{208}Pb/^{206}Pb$ vs. $^{207}Pb/^{206}Pb$ results of previous olivine-hosted melt inclusion Pb isotope studies from Mangaia and Pitcairn Island (Saal et al., 1998; Yurimoto et al., 2004; Saal et al., 2005), showing fields for Pacific MORB (White and Hofmann, 1982; Macdougall and Lugmair, 1986; Ito et al., 1987; White et al., 1987), Mangaia (Hauri and Hart, 1993; Woodhead, 1996; Schiano et al., 2001), Pitcairn Island (Woodhead and McCulloch, 1989), Pitcairn Seamounts (Woodhead and Devey, 1993) and Rarotonga (Hauri and Hart, 1993; Schiano et al., 2001) whole rock analyses. Percentage values (italicised for Pitcairn Seamounts) indicate degrees of mixing between typical OIB sources, and the most MORB-like inclusions of Saal et al. (2005). The Mangaian melt inclusion data are interpreted to reflect mixing values of up to 90% contamination. Plot (b) shows the more familiar $^{208}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ diagram for the same fields.

recent measurements of Pb isotope determinations in melt inclusions from Erebus volcano, Antarctica (Sims et al., 2008), appear to be entirely consistent with their hosts, leaving considerable ambiguity in the interpretation of melt inclusion isotope data.

In this contribution, we provide the first laser ablation MC-ICPMS Pb isotope data for olivine-hosted melt inclusions, combined with an in-depth investigation of analytical performance based upon analyses of both glass reference materials and a sample from Tonga which, based upon previous studies, is assumed to contain a single population of melt inclusions. New measurements are then provided for the

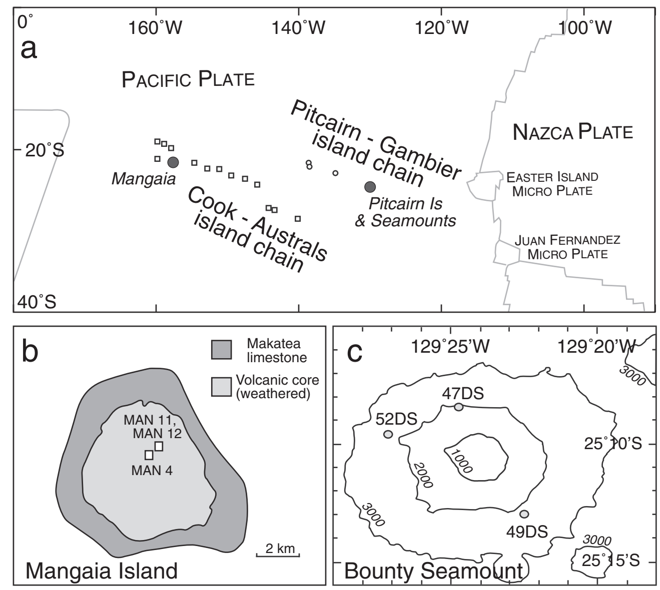

Fig. 2. The location of the Cook–Austral and Pitcairn–Gambier island chains on the Pacific plate (a) (adapted from Bonneville et al., 2006), and the locations of Mangaia (b) (adapted from Woodhead, 1996) and Pitcairn Seamount sampling locations (c) (adapted from Scholten et al., 2004). In (a), other islands in the Cook–Austral chain are shown by squares, and other islands in the Pitcairn–Gambier chain are shown by circles. (b) shows the surface geology of Mangaia Island, and (c) shows the bathymetric contours of the Bounty Seamount.

end-member OIB localities of Mangaia ('HIMU') and the Pitcairn Seamounts ('EM-I') (Fig. 2; Zindler and Hart, 1986) providing a method-independent evaluation of the published SIMS data, much of which is based on samples from these same locations. One of the advantages of laser ablation is that it is a relatively rapid technique requiring little sample preparation, and in this study we present 90 new melt inclusion Pb isotope analyses, representing roughly one third of the existing global database (Saal et al., 1998; Kobayashi et al., 2004; Yurimoto et al., 2004; Saal et al., 2005; Maclennan, 2008; Sims et al., 2008). Laser ablation techniques typically consume far more sample than SIMS-related techniques and thus sampling volumes may be more representative of whole inclusions. Furthermore, the larger analyte volume also permits measurement of the critical non-radiogenic isotope ^{204}Pb, allowing comparison with conventional Pb isotope bulk-rock data sets, in addition to the $^{207}Pb/^{206}Pb$ and $^{208}Pb/^{206}Pb$ ratios. Our new data are compared with existing literature values and the geological implications discussed.

2. Samples

2.1. North Tongan boninite

Our 'reference sample', used primarily to characterise the limitations of the analytical method, comes from the Tonga subduction system in the S.W. Pacific. Boninites from the northern termination of the Tofua Arc have been well studied in terms of their petrology, geochemistry and mineralogy, and are one of very few reported occurrences of boninites from an active arc setting (Sharaskin et al., 1983; Falloon and Green, 1986; Falloon et al., 1987, 1989; Sobolev and Danyushevsky, 1994; Danyushevsky et al., 1995; Falloon et al., 2007). Their genesis is explained in terms of mixing of a number of trace element enriched and depleted components derived from the Tongan slab and the adjacent Samoan plume (Danyushevsky et al., 1995; Falloon et al., 2007). Sample 16-26-2 is a moderately trace element enriched picrite with abundant olivine phenocrysts (Fo_x 0.86–0.92; Sobolev and Danyushevsky, 1994). The major and trace element and Pb isotopic composition of the whole rock sample is presented in