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Tracking the evolution of mantle sources with incompatible element ratios in stagnant-lid and plate-tectonic planets

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Abstract

The distribution of high field strength incompatible element ratios Zr/Nb, Nb/Th, Th/Yb and Nb/Yb in terrestrial oceanic basalts prior to 2.7 Ga suggests the absence or near-absence of an enriched mantle reservoir. Instead, most oceanic basalts reflect a variably depleted mantle source similar in composition to primitive mantle. In contrast, basalts from hydrated mantle sources (like those associated with subduction) exist from 4 Ga onwards. The gradual appearance of enriched mantle between 2 and 3 Ga may reflect the onset and propagation of plate tectonics around the globe. Prior to 3 Ga, Earth may have been in a stagnant-lid regime with most basaltic magmas coming from a rather uniform, variably depleted mantle source or from a non-subduction hydrated mantle source. It was not until the extraction of continental crust and accompanying propagation of plate tectonics that "modern type" enriched and depleted mantle reservoirs developed. Consistent with the absence of plate tectonics on the Moon is the near absence of basalts derived from depleted (DM) and enriched (EM) mantle reservoirs as defined by the four incompatible element ratios of this study. An exception are Apollo 17 basalts, which may come from a mixed source with a composition similar to primitive mantle as one end member and a high-Nb component as the other end member. With exception of Th, which requires selective enrichment in at least parts of the martian mantle, most martian meteorites can be derived from sources similar to terrestrial primitive mantle or by mixing of enriched and depleted mantle end members produced during magma ocean crystallization. Earth, Mars and the Moon exhibit three very different planetary evolution paths. The mantle source regions for Mars and the Moon are ancient and have HFS element signatures of magma ocean crystallization well-preserved, and differences in these signatures reflect magma ocean crystallization under two distinct pressure regimes. In contrast, plate tectonics on Earth has destroyed most or all of the magma ocean crystallization geochemical record, or less likely, the terrestrial magma ocean may not have been strongly fractionated during crystallization. The rather uniform incompatible element ratio record in pre-2 Ga oceanic terrestrial basalts requires vigorous mixing of most of the mantle between magma ocean crystallization and about 4 Ga, the onset of the preserved greenstone record.

Keywords: Plate tectonics; Stagnant-lid tectonics; Mantle evolution; Martian meteorites; Lunar basalts; Oceanic basalts; Archean greenstones

1. INTRODUCTION

An outstanding question in planetary evolution is what the changes in mantle composition are as a planet evolves from a stagnant-lid to a plate-tectonics thermal regime.

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Do the same types of geochemical reservoirs exist in both thermal regimes and what geochemical indices can be used to track these reservoirs as they evolve as planets cool? Incompatible trace element ratios in basalts have been useful in characterizing mantle domains in the Earth (Hofmann, 2004; Willbold and Stracke, 2010), although they should be used with caution in constraining ancient tectonic settings (Condie, 2015). Because the incompatibilities of Th and Nb in the terrestrial mantle are similar, the Nb/Th ratio of oceanic basalts is particularly useful in characterizing mantle sources of basaltic magma (Jochum et al., 1991; Hofmann, 1997, 2004), whereas elements with differing incompatibilities record both source composition and degree of melting. Only when Th is mobilized in a fluid phase is it fractionated from Nb (thus the low Nb/Th in arc basalts). Because Mars and the Moon seem to have bulk compositions similar to Earth (Newsom, 1995), incompatible element ratios in lunar and martian basalts may also be useful in characterizing mantle compositional domains in these bodies and in comparing them to Earth (Ruzicka et al., 2001). Although Earth was the only planet to acquire plate tectonics, incompatible element ratios should be useful to constrain the composition of basaltic mantle sources in any planet since degree of melting and fractional crystallization have very little effect on these element ratios.

Although models for planetary evolution suggest that Earth evolved from a stagnant-lid state into a plate-tectonic state, the timing of this evolution is poorly constrained (O'Neill et al., 2007; Moore and Webb, 2013; Korenaga, 2013; Harris and Bedard, 2014). In principle, it should be possible to better constrain this timing by comparing the evolution of Earth's mantle with the mantles of Mars and the Moon using incompatible element ratios in basalts, assuming that Earth at one time was in a stagnant lid regime. However, there are limiting factors to such a study. The effects of alteration and metamorphism need to be minimized by careful selection of samples and use of geochemical filters. For the lunar and martian samples there are also questions about sample representativeness due to small sample size, analytical uncertainties and sample variability (Treiman, 2003; Greenough and Ya'coby, 2013). Also there are questions about whether these samples can be treated as true "melt" compositions and how to correct for the effects of degree of melting, fractional crystallization, magma mixing and crustal assimilation.

In this study we have selected four incompatible element ratios of high field strength (HFS) elements to minimize the effects of secondary processes such as alteration and metamorphism (both terrestrial and extraterrestrial): Zr/Nb, Nb/Th, Th/Yb, and Nb/Yb. All four ratios are widely used to characterize mantle sources for modern oceanic basalts (Pearce, 2008; Condie, 2015; Li et al., 2015). Although other incompatible element ratios have similar characteristics, we have a large database for terrestrial basalts for these four ratios, and thus they have been selected for comparisons with lunar and martian basalts. All four ratios are controlled to some degree by both the source composition and the amount of melting of mantle sources (Arculus, 1987; Greenough and Ya'coby, 2013). Because of the similarity of bulk distribution coefficients of Th and Nb, the Nb/Th ratio is not greatly affected by the degree of melting unless the mantle source retains ilmenite. In particular, Nb is compatible in ilmenite, whereas Th is incompatible, and this will result in the retention of Nb in the restite. In addition, Th/Yb and Nb/Yb record the presence of garnet in the restite since heavy REE are retained by garnet (high-Ca pyroxene also has a minor effect). Using Nb/Th, Zr/Nb, Th/Yb and Nb/Yb ratios in young oceanic basalts, three mantle domains can be identified (Condie, 2005; Pearce, 2008): enriched mantle (EM), depleted mantle (DM), and hydrated mantle (HM) (Figs. 1 and 2). DM is characterized by high values of Nb/Th and Zr/Nb due to Th depletion relative to Nb, and to Nb depletion relative to Zr. EM retains high Nb/Th ratios but typically has Zr/Nb ratios < 20. In contrast, HM has very low Nb/Th (<8) and variable Zr/Nb ratios. DM is most widespread in the asthenosphere tapped at ocean ridges, but also may appear in mantle wedges associated with subduction. EM is a common mantle source for basalts erupted in oceanic plateaus and islands, where it is thought to occur in mantle plumes and as inhomogeneities in the asthenosphere (Hofmann, 1997). Because small degrees of melting can also produce basaltic magma with an EM signature, only tholeiites (with degree of melting of 10–30%) are included in our study. Today HM is characteristic of basalts derived from subduction-related mantle. Many modern oceanic basalts also plot between the DM and EM fields and these are mostly from oceanic plateaus or ocean ridges contaminated with plume sources (EMORB). In this study, these intermediate oceanic basalts are grouped with EM basalts.

Pearce (2008) introduced the Th/Yb and Nb/Yb indices to better understand the relationships between oceanic basalts and their sources (Fig. 2). Both ratios are sensitive to degree of melting and restitic garnet in the mantle and the Th/Yb ratio can be used to distinguish subduction-related basalts due to the enrichment of Th in the mantle wedge by fluids released from descending plates. As pointed out by Condie (2005, 2015), geochemical criteria should be used in association with geologic, stratigraphic and petrologic data when characterizing basalts by source and tectonic setting. Appendix A1 summarizes the rock types, metamorphic characteristics, stratigraphic relations and associated sedimentary rocks in basalts from the EM, DM and HM sources. However, as pointed out by Pearce (2008), Condie (2015) and Li et al. (2015), yet often neglected in the literature, geochemical discriminant indices should not be used by themselves to identify ancient tectonic settings. Zr/Nb, Th/Yb, and Nb/Yb are sensitive to enrichment and depletion of mantle sources and degree of melting, whereas Nb/Th is particularly sensitive to fluid mobilization of Th during subduction and extraction of continental crust (Hofmann, 1997; Pearce, 2008; Condie, 2005, 2015) (Figs. 1a and 2a). Our results suggest that these four incompatible element ratios are useful in contrasting and comparing the evolution of stagnant-lid and plate-tectonic planets.