



# Magnesium isotopic compositions of altered oceanic basalts and gabbros from IODP site 1256 at the East Pacific Rise



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## ABSTRACT

To investigate the behaviour of Mg isotopes during alteration of oceanic crust and constrain the Mg isotopic compositions of the altered oceanic crust (AOC), high-precision Mg isotope analyses have been conducted on forty-four altered basalts and gabbros recovered from IODP site 1256, which represent the carbonate-barren AOC formed at the East Pacific Rise (EPR). These samples were altered by interaction of seawater-derived fluids with oceanic crust at different temperatures and water/rock ratios. With the exception of one sample that has a slightly heavier Mg isotopic composition ( $\delta^{26}\text{Mg} = 0.01 \pm 0.08\text{‰}$ ), all the other samples have relatively homogeneous and mantle-like Mg isotopic compositions, with  $\delta^{26}\text{Mg}$  ranging from  $-0.36$  to  $-0.14\text{‰}$  (an average value of  $-0.25 \pm 0.11\text{‰}$ , 2SD,  $n = 43$ ). This suggests that limited Mg isotope fractionation occurred during alteration of oceanic crust at the EPR at bulk rock scale, irrespective of highly variable alteration temperatures and variable water/rock ratios. Thus, our study suggests that the offset of  $\delta^{26}\text{Mg}$  values between seawater and global runoff dominantly results from the formation of marine dolomite as a sink for Mg. The mantle-like Mg isotopic composition further indicates that recycling of carbonate-barren AOC would not result in Mg isotope heterogeneity of the mantle at global scale. Consequently, the light Mg isotopic compositions of the mantle at local scale must result from incorporation of recycled Mg isotopically light carbonates.

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## 1. Introduction

Magnesium is a fluid-mobile, major element in Earth's hydrosphere and lithosphere. It has three isotopes ( $^{24}\text{Mg}$ ,  $^{25}\text{Mg}$ , and  $^{26}\text{Mg}$ ) with a  $>8\%$  mass difference between  $^{26}\text{Mg}$  and  $^{24}\text{Mg}$  that is large enough to result in detectable Mg isotope fractionation in geological and biological processes (e.g., Young and Galy, 2004). Previous studies demonstrated that during continental weathering, the residual products (e.g., soil or saprolite) are enriched in heavy Mg isotopes compared to their precursors (e.g., Brenot et al., 2008; Li et al., 2010; Liu et al., 2014; Pogge von Strandmann et al., 2008; Teng et al., 2010a; Tipper et al., 2006a,b, 2010, 2012a,b; Wimpenny et al., 2010). These studies have attributed this enrichment to a preferential uptake of  $^{26}\text{Mg}$  by secondary silicate minerals (e.g., smectite) in the residues, leading to isotopically light weathering fluids. Such a mechanism is confirmed by the light Mg isotopic compositions observed for pore waters and river waters draining from silicate rocks (e.g., Tipper et al., 2006a, 2010).

Based on the Mg isotopic compositions of the world's largest rivers, Tipper et al. (2006a) estimated the flux weighted average  $\delta^{26}\text{Mg}$  value of global runoff at  $-1.09 \pm 0.05\text{‰}$ , which is much lighter than that of

seawater ( $-0.83 \pm 0.09\text{‰}$ , Foster et al., 2010; Ling et al., 2011). This difference indicates that the oceanic Mg budget is not at steady state and/or that the Mg isotope ratios are fractionated in the ocean (Tipper et al., 2006a). The former hypothesis is inconsistent with variations of the seawater Mg concentrations and Mg/Ca ratios over the past 30 Ma (e.g., Holland, 2005; Rausch et al., 2013), while the latter is in agreement with Mg uptake from the ocean by marine dolomite precipitation and hydrothermal sink (Tipper et al., 2006a). At steady state, where riverine input and hydrothermal and dolomite output sustain the oceanic Mg mass balance (Tipper et al., 2006a), estimates of the hydrothermal sink of Mg at mid-ocean ridges vary from 61% to 100% (Beinlich et al., 2014; Elderfield and Schultz, 1996; Holland, 2005; Tipper et al., 2006a). Such large amounts of hydrothermal sink of Mg may modify Mg isotopic compositions of the AOC, as seawater and fresh MORBs have distinct Mg isotopic compositions.

Teng et al. (2010a) speculated that the bulk AOC should have lighter Mg isotopic compositions relative to fresh MORBs; however, they did not consider dolomite output for the ocean. Another study on cratonic eclogites with affinity to oceanic crust from South Africa attributed the observed light Mg isotopic compositions ( $\delta^{26}\text{Mg}$  as low as  $-0.80\text{‰}$ ) to the AOC precursor (Wang et al., 2012). However, these studies only indirectly constrained the Mg isotopic compositions of the AOC. This significantly hampers our understanding of Mg isotope geochemistry

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with respect to several issues that need to be constrained, including (1) Are the Mg isotopic compositions variable in a profile through the AOC as is observed for Li and O isotopic compositions (e.g., Gao et al., 2012)? (2) What is the average Mg isotopic composition of the AOC? (3) Does the bulk AOC have a lighter Mg isotopic composition relative to fresh MORBs, as speculated by previous studies (Teng et al., 2010a)? Knowledge of these issues is of great importance to understand the behavior of Mg isotopes during hydrothermal alteration and to evaluate whether Mg isotopes can be used to trace the recycled AOC and distinct mantle reservoirs as defined by Li–O–Sr–Nd–Pb isotope systematics (e.g., Eiler, 2001; Elliott et al., 2004; Hofmann, 1997; Zindler and Hart, 1986).

To better constrain these issues, we report for the first time Mg isotopic compositions of altered basalts and gabbros recovered from the IODP site 1256 on the Cocos plate in the eastern equatorial Pacific Ocean (Wilson, 1996). Previous studies showed that although both low temperature seawater alteration and high temperature hydrothermal alteration occurred in these mafic rocks (e.g., Alt et al., 2010; Gao et al., 2012), the abundance of carbonates is low, as indicated by petrological studies and their relatively low loss on ignition (LOI <4.71 wt.%, Neo et al., 2009; Teagle et al., 2006). Although these altered rocks display large variations in  $\delta^{18}\text{O}$  and  $\delta^7\text{Li}$  values (Gao et al., 2012), our results show limited Mg isotopic variations that are similar to global oceanic basalts and mantle peridotites. Therefore, fractionation of Mg isotopes is limited during hydrothermal alteration of oceanic crust and the light Mg isotopic compositions of the mantle must result from the contamination of the low  $\delta^{26}\text{Mg}$  carbonates rather than the recycled carbonate-barren AOC.

## 2. Geological settings and sample descriptions

IODP site 1256 (6°44.2'N, 91°56.1'W) is located in the Guatemala Basin on the Cocos plate in the eastern equatorial Pacific Ocean (Fig. 1). The oceanic crust at the drill site formed ca. 15 Ma ago during a sustained episode of superfast ocean ridge spreading with rates up to 200 mm/yr (Wilson, 1996; Wilson et al., 2003). Basement rocks were recovered from Holes 1256C and 1256D, but the uppermost lavas were sampled only in Hole 1256C (Wilson et al., 2003). Pilot Hole 1256C penetrated a 250.7 m sediment section and extends 88.5 m into basement that consists of a 32 m thick lava pond with thin sheet flow above and below (Fig. 2). The main Hole 1256D is located ~30 m to the south, starts coring at 276 m below seafloor (mbsf), and extends to a depth of 1507.1 mbsf (Fig. 2).

The oceanic crust sampled at the Hole 1256D was subdivided into six sections based on the igneous stratigraphy, including, from top to bottom, the lava pond, inflated flows, sheet and massive flows, transition zone, sheeted dyke complex, and plutonic complex (Fig. 2) (Teagle et al., 2006; Wilson et al., 2003, 2006). The lava pond (~276–350.3 mbsf), inflated flows (350.3–533.9 mbsf), and sheet and massive flows (533.9–1004.2 mbsf) can be further classified on the basis of the processes involved in their alteration (Alt et al., 2010). The upper volcanic section (down to 946 mbsf) has experienced low-temperature (<100 °C) seawater alteration in reducing conditions as evidenced by the presence of saponite ± pyrite and the low abundance of oxyhydroxide enriched alteration halos. The lower volcanic section below 964 mbsf has suffered elevated alteration temperatures as indicated by the presence of pyrite alteration halos, mixed-layer chlorite/smectite, and anhydrite (Alt et al., 2010; Teagle et al., 2006). Overall, the volcanic section is slightly to moderately altered, but a highly altered 41 cm interval occurs at 648 mbsf and may well result from a narrow zone of focused fluid flow (Alt et al., 2010).

The transition zone (1004.2–1060.9 mbsf) is characterized by subvertical intrusive contacts and greenschist-facies metamorphism as indicated by the presence of chlorite, albite, and actinolite (Teagle et al., 2006). In this section, both low-temperature seawater alteration and high-temperature hydrothermal alteration occur, indicating that it is a mixing zone between the upwelling hydrothermal fluids and downwelling seawater (Alt et al., 1996, 2010). The sheeted dyke complex (1060.9–1406.6 mbsf) consists of rocks that are highly to completely altered (Teagle et al., 2006). Within the dykes, the alteration intensity and grade increase downhole with alteration temperatures increasing from ~250 °C at the top to ~400 °C at the bottom (Alt et al., 2010; Teagle et al., 2006). The lowermost dykes (1348.3–1406.6 mbsf) are partially to completely re-crystallized to distinctive granoblastic textures caused by contact metamorphism by underlying gabbroic intrusions at temperatures of ~900–1050 °C (Alt et al., 2010; Koepke et al., 2008). The plutonic complex (1406.6–1507.1 mbsf) contains a 52-m-thick upper gabbro and a 24-m-thick lower gabbro separated by a granoblastically recrystallized dyke screen. Metamorphic conditions in this section are similar to those in the lower dykes (Alt et al., 2010), but the margins of the gabbro bodies are moderately altered and consist of secondary minerals such as chlorite, amphibole, epidote, laumontite, and prehnite (Teagle et al., 2006).

Forty-four altered basalts and gabbros from IODP site 1256 (2 samples from Hole 1256C and 42 samples from Hole 1256D) were analyzed for Mg isotopic compositions. These samples cover six sections of the altered oceanic crust at the East Pacific Rise, are well-characterized,

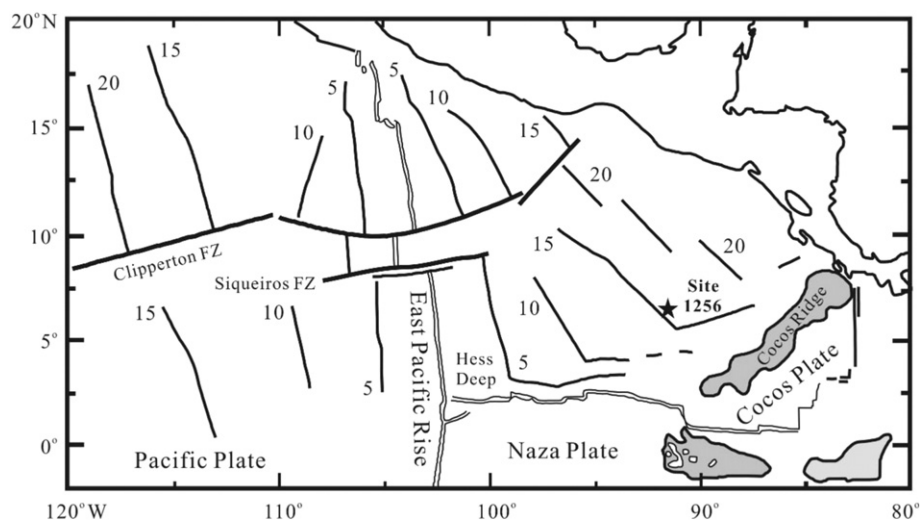


Fig. 1. Simplified geological map showing the location of IODP site 1256 (modified after Gao et al., 2012). Isochrones with 5 Ma intervals are also shown.

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