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Article

Chromite-induced magnesium isotope fractionation during mafic magma differentiation

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ABSTRACT

To better understand the mechanism of Mg isotopic variation in magma systems, here we report high precision Mg isotopic data of 17 bulk rock samples including dunite, clinopyroxenite, hornblendite and gabbro and 10 pairs of dunite-hosted olivine and chromite separates from the well-characterized Alaskan-type Xiadong intrusion in NW China, which formed by continuous and high degree of lithological differentiation from mafic magmas. Chromite separates have highly variable δ^{26}Mg values from 0.01‰ to 0.40‰, and are consistently heavier than coexisting olivine separates (−0.39‰ to −0.15‰). Both mineral δ^{26}Mg values and the degrees of inter-mineral fractionation are well correlated with geochemical indicators of magma differentiation, indicating that these inter-sample and inter-mineral Mg isotope fractionations are caused by magma evolution. The δ^{26}Mg values range from −0.20‰ to −0.02‰ in the dunite, −0.43‰ in the clinopyroxenite, −0.43‰ to −0.28‰ in the hornblendite, 0.18‰ in the chromite-bearing hornblendite, and −0.56‰ to −0.16‰ in the gabbro. The Mg isotopic variations in different type of rocks are closely related to fractional crystallization and accumulation of different proportions of oxides vs. silicates. Chromite crystallization and accumulation is the most important factor in controlling Mg isotope fractionation during the formation of the Xiadong intrusion. Compared to basaltic and granitic magmas, differentiation of the Alaskan-type intrusions occurs at a relatively high oxygen fugacity, which favors chromite crystallization and consequently significant Mg isotope fractionations at both mineral and whole-rock scales. Therefore, Mg isotope systematics can be used to trace the degree of magma differentiation and related-mineralization.

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1. Introduction

Magnesium isotopic variation has been increasingly reported in igneous rocks and was attributed to various mechanisms. Source heterogeneity is a main factor controlling Mg isotopic variations in volcanic rocks [1–6]; silicate-carbonatite liquid immiscibility and carbonatite magma differentiation can result in significant Mg isotope fractionation [7], whereas diffusive Mg-Fe exchange with melt or chromite produces large Mg isotope fractionation in olivine [8–11]. Although Mg isotope fractionation during the differentiation of granitic and basaltic magma is limited [3,12–15], magma differentiation involving chromite can potentially produce large Mg isotope fractionation. This is because spinel/chromite usually is enriched in heavy Mg isotopes compared with coexisting silicates during mafic magma differentiation [16,17]. Differentiated igneous rocks with different proportions of oxides vs. silicates should therefore have different Mg isotopic compositions. However, studies of Mg isotope fractionation relevant to chromite crystallization are still limited as yet.

Alaskan-type mafic-ultramafic intrusions have several characteristics that make them ideal candidates for studying the Mg isotope fractionation during mafic magma differentiation. (1) They are considered to represent a series of cumulates derived from fractional crystallization of hydrous and oxidized primitive arc basalts [18–21] without significant crustal contamination [22,23]; (2) They are characterized by concentric occurrence of a dunite core zoned sequentially by wehrlite, clinopyroxenite, hornblendite and gabbro at the margin [19,24,25], and the different

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lithological units are composed of a relatively simple mineral assemblage of olivine, clinopyroxene and hornblende, and are usually dominated by a single mineral phase [26,27]; (3) Their mineral chemistry is usually characterized by Mg-rich olivine, Ca-rich diopsidic clinopyroxene, high Fe-Cr and low Al chromite, and calcic hornblende with a wide range in composition [19,28]; (4) Alaskan-type intrusions commonly host platinum group element (PGE) and chromite ore deposits, reflecting high temperature partial melts and large amount of chromite accumulation [29,30]; (5) Their enrichments in chromite, ilmenite and magnetite [24,30] predict substantial inter-mineral and inter-lithology Mg isotope fractionation resulting from significantly different Mg-O coordination environment in iron oxides and silicates [17].

Here, we report high-precision Mg isotopic data for a well-characterized Alaskan-type intrusion exposed in Xiadong, NW China. The results reveal significant mineral- and lithological- scale Mg isotope variations, reflecting Mg isotope fractionation during fractional crystallization, especially when chromite is involved. Our study suggests that Mg isotopes could be fractionated in highly oxidized magmas and consequently can be used to trace petrogenesis of mafic-ultramafic intrusions and related mineralization.

2. Samples and methods

The petrology and geochemistry of the Xiadong Alaskan-type intrusion has been reported in literatures [31–34] and the broader geological context has been given by Qin et al. [35] and Su et al. [36]. The Xiadong intrusion contains a full spectrum of lithology of a typical Alaskan-type intrusion. It consists of dunite, hornblende clinopyroxenite, hornblendite and hornblende gabbro (Fig. 1a). All these rocks are characterized by a dominance of cumulate crystals with insignificant crystallization of inter-cumulus minerals filling the interstitial spaces (Fig. 1b-e). The dunites are made up of olivine (80%–95% in volume) and chromite (5%–20%) with accessory hornblende and clinopyroxene (<1%–2%). Chromite rhythmic layers are commonly observed in the dunite (Fig. 1b). The hornblende clinopyroxenite and hornblendite display gradual transitive or intrusive contact (Fig. 1c) and are mainly composed of clinopyroxene and hornblende with accessory magnetite and/or chromite (Fig. 1d). Hornblende gabbro is the dominant rock type in the Xiadong intrusion (Fig. 1a) and displays an equigranular texture with a mineral assemblage of plagioclase, clinopyroxene, hornblende, magnetite, ilmenite and titanite (Fig. 1e).

The geochemistry of these rocks suggests derivation of high-degree partial melting from a depleted mantle source. The bulk intrusive rocks are characterized by extremely low trace element abundances and flat REE patterns with mantle-like $\varepsilon_{Nd}(t)$ [33]. The constituent olivine has high forsterite (Fo) numbers (92.3 to 96.6) and NiO contents (up to 0.76 wt%) [31,32]. Clinopyroxene and hornblende are MgO-rich diopside and magnesio-hornblende, respectively. In addition to the mafic silicates, various types of oxides are present in the Xiadong intrusion, displaying an Fe enrichment trend from Cr-Al-rich spinel to Fe-rich chromite to Cr-magnetite and ilmenite, with increasing degree of magma differentiation. The presence of abundant hornblende and oxides indicates that the parental magmas of the Xiadong intrusion are hydrous and oxidized [32,34]. This is consistent with the whole rock enrichments in large ion lithophile elements relative to high strength field elements, oceanic-trend $(^{87}Sr/^{86}Sr)_i$ variation and higher-than-mantle $\delta^{18}O$ values, all of which indicates overprinting of the depleted mantle source by subduction-related materials [33].

Eighteen samples with comprehensive geochemical datasets [32,33] were selected for Mg isotope analyses in this study to cover the full range of lithology. They comprise 10 dunite, one clinopyroxenite, three hornblendite and four gabbro samples. Paired olivine and chromite separates were handpicked from the 10 dunite samples under a binocular microscope. They were cleaned with Milli-Q water for 3 × 10 min in an ultrasonic bath, and dried down under a heat lamp before dissolution.

Magnesium isotope analyses were carried out at the Isotope Laboratory of the University of Washington, Seattle, following the method described by Teng et al. [14,15,37]. Both whole-rock powders and mineral separates were dissolved in a combination of HF-HNO_3-HCl in sealed 7-mLTeflon beakers and heated on a hot plate in a laminar flow exhaust hood. The samples were then dried and re-dissolved in 1 mol/L HNO_3 for chromatographic separation. Magnesium was purified on a cation exchange resin (Bio-rad AG50W-X8) in 1 mol/L HNO_3 media. The same column procedure was performed twice in order to effectively remove matrix elements. Magnesium isotopic ratios were measured on a Nu Plasma multi-collector inductively coupled plasma mass spectrometer. Three standards (JB-1 basalt, PCC-1 peridotite and Hawaiian seawater) were processed and analyzed with each batch of samples to assess accuracy and reproducibility. One analysis of basalt standard (JB-1) yielded $\delta^{26}Mg$ value of −0.22‰; two analyses of

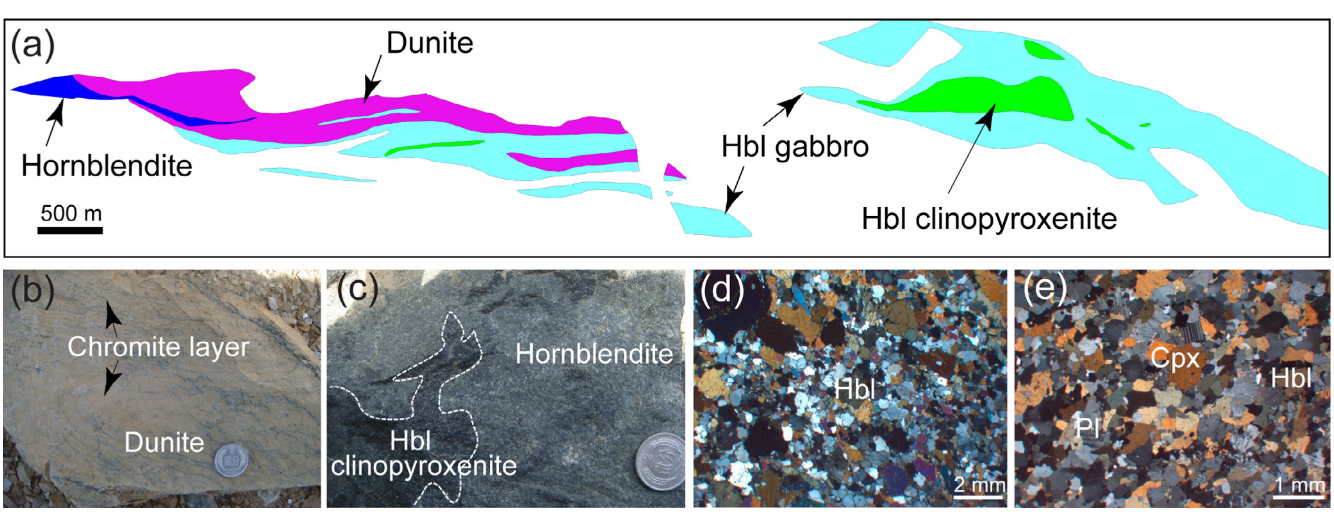

Fig. 1. Geological map of the Xiadong mafic-ultramafic intrusion (a) and photomicrographs of the rocks (b–e). (b) Partly bent chromite layer in dunite; (c) Intrusive relation between hornblende (Hbl) clinopyroxenite and hornblendite; (d) Adcumulate texture of hornblendite (cross polarized); (e) Typical mineral assemblage of plagioclase (Pl), clinopyroxene (Cpx) and Hbl in fresh Hbl gabbro sample (cross polarized).

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