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Iron isotope fractionation during sulfide-rich felsic partial melting in early planetesimals

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ABSTRACT

New Fe isotope data of feldspar-rich meteorites Graves Nunataks 06128 and 06129 (GRA 06128/9) reveal that they are the only known examples of crustal materials with isotopically light Fe isotope compositions ($\delta^{56}Fe = -0.08 \pm 0.06‰$; $\delta^{56}Fe$ is defined as the *per mille* deviation of a sample's $^{56}Fe/^{54}Fe$ ratio from the IRMM-014 standard) in the Solar System. In contrast, associated brachinites, as well as brachinite-like achondrites, have Fe isotope compositions ($\delta^{56}Fe = +0.01 \pm 0.02‰$) that are isotopically similar to carbonaceous chondrites and the bulk terrestrial mantle. In order to understand the cause of Fe isotope variations in the GRA 06128/9 and brachinite parent body, we also report the Fe isotope compositions of metal, silicate and sulfide fractions from three ordinary chondrites (Semarkona, Kernouve, Saint-Séverin). Metals from ordinary chondrites are enriched in the heavier isotopes of Fe (average $\delta^{56}Fe = 0.15‰$), sulfide fractions are enriched in the lighter isotopes of Fe (average $\delta^{56}Fe = -0.14‰$), and the $\delta^{56}Fe$ values of the silicates are coincident with that of the bulk rock (average $\delta^{56}Fe = 0.03‰$).
The enrichment of light isotopes of Fe isotopes in GRA 06128/9 is consistent with preferential melting of sulfides in precursor chondritic source materials leading to the formation of Fe–S-rich felsic melts. Conceptual models show that melt generation to form a GRA 06128/9 parental melt occurred prior to the onset of higher-temperature basaltic melting (<1200 °C) in a volatile-rich precursor and led to the generation of buoyant felsic melt with a strong Fe–S signature. These models not only reveal the origin of enrichment in light isotopes of Fe for GRA 06128/9, but are also consistent with petrological and geochemical observations, experimental studies for the origin of Fe–S-rich felsic melts, and for the cessation of early melting on some asteroidal parent bodies because of the effective removal of the major radioactive heat-source, ^{26}Al. The mode of origin for GRA 06128/9 contrasts strongly with crust formation on Earth, the Moon, Mars and other asteroids, where mantle differentiation and/or oxygen activity are the major controls on crustal Fe isotope compositions.

1. Introduction

Planet formation studies rely on a robust understanding of how the outermost solid crust of a planet is formed. Most planetary bodies are currently only studied remotely, or from meteorites that originate from the crust of the body, and thus most of the chemical and physical information obtained on the planets formation, differentiation and cooling history is obtained from its crust. Direct study of terrestrial crust has shown a fundamental dichotomy of dense basaltic crust in the ocean basins formed at mid-ocean ridges through adiabatic decompression, and evolved more buoyant feldspar-rich (felsic) continental crust. Unlike oceanic crust, felsic continental crust cannot be formed by single-stage melting of peridotite. Many processes have been proposed for continental crust formation, all of which require complex multi-stage melting of primary or recycled materials since at least 3 Ga ago (*e.g.*, Rudnick and Gao, 2003; Rudnick, 1995; Taylor and McLennan, 1985).

By contrast, although it has been proposed that felsic melts may have formed early on some planetesimals (Cohen et al., 2004; Keil, 2010), the preponderance of crust formed in the early Solar System appears to have been basaltic (Taylor and McLennan, 2009).

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For example, angrite and howardite–eucrite–diogenite (HED) meteorites represent crustal materials formed within 3 to 8 Ma of calcium–aluminum-rich inclusions (CAIs); the first solid materials condensed from the solar nebula (Amelin, 2008; Blichert-Toft et al., 2002; Trinquier et al., 2008). These two meteorite groups are broadly basaltic in composition and probably formed early during global-scale differentiation (magma ocean) events and subsequent to core formation on their parent bodies (Riches et al., 2012; Day et al., 2012b). The identification of the paired achondrite meteorites GRA 06128/9 as evolved felsic crustal materials (Day et al., 2009a, 2012a; Shearer et al., 2010) has challenged the canonical view that the earliest planetary crusts were dominantly basaltic in composition. As rocks containing >70 modal percent sodic plagioclase, GRA 06128/9 represent a primordial felsic crust formed early in Solar System history – no later than 4517 ± 60 Ma (^{207}Pb–^{206}Pb age; Day et al., 2009a) – and before metallic core formation within their parent body. The bulk chemistry of GRA 06128/9 reflects broadly andesitic compositions, similar to the composition of bulk terrestrial continental crust (Day et al., 2009a, 2009b).

Geochemical and petrological evidence indicates that GRA 06128/9 represent the crustal differentiation complements to olivine-dominated brachinite achondrites that represent melt-depleted mantle restites within a planetesimal (Day et al., 2012a). These similarities include overlap in oxygen isotope compositions, complementary petrology and trace-element geochemistry, similar oxidation conditions, and crystallization model ages of 2–3 Ma after the first Solar System solids (Arai et al., 2008; Day et al., 2009a, 2012a; Shearer et al., 2010; Zeigler et al., 2008). Brachinite-like achondrites, which have more magnesian compositions than brachinites, appear to be related by similar melt-depletion processes to brachinites, but are unlikely to derive from the same parent body, but point to similar processes acting on more than one asteroid (Day et al., 2012a).

Despite detailed petrological, geochemical and experimental studies on GRA 06128/9 (*e.g.*, Day et al., 2009a, 2012a; Gardner-Vandy et al., 2013; Shearer et al., 2010), uncertainties remain in the formation mechanisms for GRA 06128/9, brachinites and brachinite-like achondrites. In particular, inter-element fractionations of highly siderophile elements in GRA 06128/9 and brachinites indicate complex melting processes and, possibly, more than a single-stage process in their formation. Elucidating the mode of formation of asteroidal felsic crust is important not only for comparison with continental crust formation on Earth, but because early formation of felsic asteroidal crust offers a potential mechanism for the loss of radioactively generated heat within planetary bodies early in their history (Day et al., 2012a). This process would occur through the direct loss of ^{26}Al, a short-lived radioisotope (half life of 7.17×10^5 yrs) and which is considered to be a major heat source during the initial stages of planetary melting (Mittlefehldt, 2007).

Iron isotopes have the potential to allow discrimination between models for asteroidal crust formation because of their potential to be fractionated during various magmatic differentiation processes, such as partial melting, mineral fractionation and fluid exsolution (Dauphas et al., 2009; Heimann et al., 2008; Liu et al., 2010; Poitrasson and Freydier, 2005; Schoenberg and von Blanckenburg, 2006; Schuessler et al., 2009; Sossi et al., 2012; Telus et al., 2012; Teng et al., 2008; Wang et al., 2012a; Weyer et al., 2005). In particular, iron isotopes can provide useful constraints on the origins of melts and melt residues from chondritic precursor materials because of the distinct Fe isotope fractionations observed between sulfide and metal phases (Needham et al., 2009). Here we show that Fe isotopes are powerful tracers of planetesimal differentiation processes during partial melting and provide constraints on the petrogenetic processes responsible for GRA 06128/9, brachinites and brachinite-like achondrites.

2. Samples and methods

2.1. Sample description

Iron isotope compositions for ungrouped achondrite stones GRA 06128, GRA 06129, six brachinites, three brachinite-like achondrites, and phase separates (metal, silicate and sulfide) from three ordinary chondrites (Tables 1 and 2) were analyzed in this study. Two geostandards, AGV-2 and BCR-2, were prepared and measured during the same analytical sessions with the meteorite samples and are also reported.

Ungrouped achondrites GRA 06128/9 are paired feldspathic stony meteorites. They are relatively coarse-grained stones with granoblastic textures and are dominated by sodic plagioclase (oligoclase; ∼80 vol%), orthopyroxene and clinopyroxene (∼10 vol%), Fe-rich olivine (∼10 vol%), and minor amounts of Ca-phosphate (apatite and merrilite), sulfide (troilite and pentlandite) and FeNi metal (Arai et al., 2008; Day et al., 2009a, 2012a; Shearer et al., 2010; Zeigler et al., 2008). Their oxygen isotope and major/minor element bulk compositions show complementarity with brachinites, and are distinct from other extra-terrestrial plagioclase-rich rocks, such as lunar anorthosites (Day et al., 2009a; Shearer et al., 2010; Zeigler et al., 2008). GRA 06128/9 was formed early in Solar System history, with a metamorphic age of 4517 ± 60 Ma (Day et al., 2009a), which is consistent with the 4565.9 ± 0.3 Ma age inferred from ^{26}Al–^{26}Mg chronology (Shearer et al., 2008). The oxygen fugacity (fO_2) is estimated to be between iron-wüstite buffer (IW) −0.1 and IW +1.1 (Shearer et al., 2010). GRA 06128/9 is hypothesized to have formed by low-to-moderate-degree (13–30%) Fe–S bearing partial melting of a primitive, volatile-rich source region from an asteroid that had not fully differentiated a metallic core (Day et al., 2009a; Shearer et al., 2010).

Six brachinites were studied here: Brachina, Elephant Moraine (EET) 99402, Northwest Africa (NWA) 1500, NWA 3151, NWA 4872 and NWA 4882. Brachinites are dunitic wehrlites and they contain a majority of olivine (usually >80 vol%), with variable amounts of augite, chromite, Fe-sulfide, phosphate, and Fe–Ni metal (Day et al., 2012a; Mittlefehldt et al., 1998). Like GRA 06128/9, brachinites are ancient, with a ^{53}Mn–^{53}Cr age of 4563.7 ± 0.9 Ma for Brachina (Wadhwa et al., 1998). It has previously been suggested that brachinites represent igneous cumulates (Mittlefehldt, 2007), but recent work indicates that they are partial melt residues (Day et al., 2012a).

Three ungrouped meteorites NWA 5400, NWA 6077 and Zag (b) (referred to as brachinite-like achondrites; Table 1) were also analyzed for their bulk Fe isotope compositions. They are all olivine dominated ultramafic achondrites, with similar mineralogy and geochemical composition to brachinites (Day et al., 2012a). NWA 5400 and NWA 6077 are possibly paired and they have an oxygen isotope composition close to the terrestrial fractionation line and are clearly distinct from brachinites (Day et al., 2012a). These differences in the oxygen isotope composition, as well as differences in the absolute and relative highly siderophile element abundances compared with brachinites, indicate that they were probably formed on different parent-bodies, but formed by similar partial melting processes (Day et al., 2012a).

Phase separations (metal, sulfide, silicate) were done on three extensively studied ordinary chondrite falls of various chemical class and petrologic type. Semarkona (LL3.0) is recognized as one of the least metamorphosed ordinary chondrites (Huss et al., 1981; Sears et al., 1980). Kernouve (H6) and Saint-Séverin (LL6) are two equilibrated ordinary chondrites.