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Nickel isotopic composition of the mantle

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Abstract

This paper presents a detailed high-precision study of Ni isotope variations in mantle peridotites and their minerals, komatiites as well as chondritic and iron meteorites. Ultramafic rocks display a relatively large range in δ^{60}Ni (permil deviation in $^{60}Ni/^{58}Ni$ relative to the NIST SRM 986 Ni isotope standard) for this environment, from 0.15 ± 0.07‰ to 0.36 ± 0.08‰, with olivine-rich rocks such as dunite and olivine cumulates showing lighter isotope compositions than komatiite, lherzolite and pyroxenite samples. The data for the mineral separates shed light on the origin of these variations. Olivine and orthopyroxene display light δ^{60}Ni whereas clinopyroxene and garnet are isotopically heavy. This indicates that peridotite whole-rock δ^{60}Ni may be controlled by variations in modal mineralogy, with the prediction that mantle melts will display variable δ^{60}Ni values due to variations in residual mantle and cumulate mineralogy. Based on fertile peridotite xenoliths and Phanerozoic komatiite samples it is concluded that the upper mantle has a relatively homogeneous Ni isotope composition, with the best estimate of $\delta^{60}Ni_{mantle}$ being 0.23 ± 0.06‰ (2 s.d.). Given that >99% of the Ni in the silicate Earth is located in the mantle, this also defines the Ni isotope composition of the Bulk Silicate Earth (BSE). This value is nearly identical to the results obtained for a suite of chondrites and iron meteorites (mean δ^{60}Ni 0.26 ± 0.12‰ and 0.29 ± 0.10‰, respectively) showing that the BSE is chondritic with respect to its Ni isotope composition, with little to no Ni mass-dependent isotope fractionation resulting from core formation.

Keywords: Nickel; Stable isotopes; Mantle geochemistry; Mineralogy; Meteorites; Core formation

1. INTRODUCTION

Nickel is a first-row transition metal that, under mantle melting conditions, behaves as a strongly compatible element. The Earth's upper mantle has a mean Ni concentration of 2000 μg/g, which means this reservoir contains >99% of the silicate Earth's Ni inventory (e.g. McDonough and Sun, 1995; Palme and O'Neill, 2014). In mantle-derived rocks Ni is primarily concentrated in olivine, the dominant silicate mineral in the upper mantle. In Mg-rich mantle olivine, Ni^{2+} substitutes for Mg^{2+} in octahedral coordination, leading to olivine Ni concentrations of around 3000 μg/g (e.g. Sato, 1977; Stosch, 1981; Deer et al., 1982; Witt-Eickschen and O'Neill, 2005). Spinel is the only other mantle mineral that can accommodate similar amounts of Ni, also predominantly in octahedral coordination (Stosch, 1981; Witt-Eickschen and O'Neill, 2005). However, as the modal abundance of spinel in upper mantle lithologies is <5%, its impact on the mantle Ni budget is minor. Orthopyroxene is the second most common mineral in the upper mantle and can hold smaller, but significant, amounts of Ni (<1000 μg/g), substituting into octahedral coordination space for Mg or Fe in the orthopy-

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roxene lattice structure (Stosch, 1981; Deer et al., 1982; Witt-Eickschen and O'Neill, 2005). Nickel can also be found in lower concentrations (<500 μg/g) in clinopyroxene and garnet, also situated in octahedral coordination in both minerals (Witt-Eickschen and O'Neill, 2005). Although the hosts of Ni in the lower mantle are less well constrained, Ni has been observed to be concentrated in ferropericlase inclusions within diamonds, where it is present in amounts of 1–2.5 wt.% (Kaminsky, 2012). Nickel has also been found in its native form (Kaminsky, 2012), which is potentially due to disproportionation of magneioswustite into bridgemanite which produces Fe–Ni metal (Frost et al., 2004; Wade and Wood, 2005; Williams et al., 2012).

Nickel stable isotopes are a relatively new geochemical tracer that has not been evaluated in detail in terrestrial high-temperature environments. A number of studies have attempted to quantify the degree of δ^{60}Ni (permil deviation in ^{60}Ni/^{58}Ni relative to the NIST SRM 986 Ni isotope standard) variation in igneous rocks, including mantle derived materials (Cameron et al., 2009; Steele et al., 2011; Gall et al., 2012; Gall et al., 2013; Gueguen et al., 2013; Chernonozhkin et al., 2015; Estrade et al., 2015; Ratié et al., 2015). However, most of these data are limited to rock standards or reference materials, and no systematic Ni stable isotope study of mantle rocks has been published. Other work on Ni stable isotopes in high-temperature environments has focused on meteorites (Cook et al., 2007; Moynier et al., 2007; Steele et al., 2011, 2012) and magmatic sulphide ore bearing bodies (Hofmann et al., 2014), while a number of studies have focused on the application of Ni isotopes in low temperature geochemistry (e.g. Porter et al., 2014; Cameron and Vance, 2014; Wasylenki et al., 2015; Ratié et al., 2015; Estrade et al., 2015).

Published Ni isotope compositions for igneous rocks range between −0.1‰ and 0.3‰ in δ^{60}Ni (e.g. Cameron et al., 2009; Gueguen et al., 2013). This study investigates this surprisingly large range in isotope composition for a high-temperature environment. Our aim is to better define the Ni isotope composition of the mantle by presenting data from peridotites, komatiites and mantle mineral separates, and to discuss these in the context of published whole-rock data. Finally, we aim to compare the isotope composition of the Bulk Silicate Earth (i.e. the mantle) with that of meteorites, to estimate the impact of core formation on the Ni isotope system on Earth. For this chondrite and iron meteorite data are presented and compared with existing data on such materials.

2. SAMPLE SELECTION

2.1. Mantle xenoliths, peridotites and mineral separates

Most of the ultramafic xenoliths analysed in this study are from the Neogene volcanic province in Northern Tanzania, a part of the eastern Rift Valley of East Africa. These samples were selected for this study as they have been well characterised for a range of elemental and isotopic tracers and because they represent ancient sub continental lithospheric mantle. The majority of these samples were collected from the Lashaine volcano, an area famous for carbonatite lavas and the presence of ultramafic xenoliths similar to those from kimberlites (e.g. Dawson et al., 1970; Cohen et al., 1984; Dawson, 2002). The samples comprise two garnet lherzolites (BD730 and BD1355), three spinel harzburgites (BD774, BD822 and BD1542) and one alkaline pyroxenite (BD744). The garnet peridotites consist of varying proportions of red to purple garnet, emerald green clinopyroxene, orthopyroxene and magnesium-rich olivine (Fo_{90} for olivine from BD730), the latter without any signs of serpentinisation (Dawson et al., 1970). The spinel peridotites contain a much higher percentage of olivine (80–90 vol.% compared to 50–65 vol.% in the garnet peridotites) and lower amounts of orthopyroxene (5–12 vol.% versus 20–40 vol.% in the garnet peridotites), but similar amounts of clinopyroxene (1–3 vol.% only in both groups) (Dawson et al., 1970; Rhodes and Dawson, 1975; Reid et al., 1975). The pyroxenite sample consists of rounded iron-rich olivine (Fo_{84}), opaque phases (mainly chromite and magnetite), and clinopyroxene, surrounded by mica (Dawson and Smith, 1972). Other mantle rocks samples analysed were a kimberlite hosted garnet lherzolite xenolith from the Balfontain Mine in South Africa (e.g. Carswell and Dawson, 1970) and a dunite from the Appalachian peridotite massif in Jackson County, NC, USA (e.g. Kulp and Brobst, 1954; Stueber, 1969). These samples were both provided by the Natural History Museum in London. For inter-laboratory comparison we have also analysed the USGS reference materials DTS-1 and PCC-1 for their Ni isotope compositions. The reference sample PCC-1 is a partially serpentinised harzburgite from the Cazadero ultramafic massif, California, USA (Flanagan, 1967; Barnes and O'Neil, 1969; Flanagan, 1969) and DTS-1 is a dunite sample from the Twin Sisters Mountain, Washington, USA (Ragan, 1963; Flanagan, 1967; Flanagan, 1969).

In addition to whole rock mantle xenoliths we have analysed mineral separates from mantle xenoliths from of the Cameroon Line, which have previously been studied for Fe isotopes (Williams et al., 2004, 2005). The goal of these analyses was to determine the magnitude of inter-mineral Ni isotope fractionation and to compare the behaviour of Ni and Fe isotopes. The analysed samples comprise three spinel lherzolites from different volcanic centres in Cameroon: (1) olivine from C235A, Lake Baronbi Mbo near Mount Cameroon; (2) orthopyroxene from C273Q, Lake Enep near Oku in Cameroon; (3) olivine, orthopyroxene and clinopyroxene from P13, Ngaoundere Plateau, Cameroon (Lee et al., 1996). Two mineral megacrysts, garnet and clinopyroxene, were also analysed from sample N12, a harzburgite from the Biu Plateau in Nigeria. The three analysed spinel lherzolites contain 45–65 vol.% olivine, 25–35 vol.% orthopyroxene, 10–15 vol.% clinopyroxene and <5 vol.% spinel, while the Biu Plateau harzburgite contains 55–60 vol.% olivine and 40–45 vol.% orthopyroxene as well as small amounts (<5%) of clinopyroxene and garnet (Lee et al., 1996). In a previous study of the same samples, Williams et al. (2005) concluded that the