

Non-chondritic magnesium and the origins of the inner terrestrial planets

Uwe Wiechert ^{a,*}, Alex N. Halliday ^b

^a *Institute for Isotope Geology and Mineral Resources, Department of Earth Sciences, ETH Zurich, Sonneggstrasse 5, CH-8092 Zürich, Switzerland*

^b *Department of Earth Sciences, University of Oxford, Park Road, Oxford, OX1 3PR, United Kingdom*

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Abstract

High-precision magnesium (Mg) isotope data obtained using a large geometry high resolution MC-ICPMS are reported for 9 carbonaceous and ordinary chondrites, 9 eucrites and diogenites generally considered to originate from Asteroid 4 Vesta, together with 4 martian meteorites, and a variety of terrestrial and lunar materials. The variation in Mg isotopic composition found for mafic and ultramafic rocks, mafic minerals and chondrites is smaller than reported previously. The range of $\delta^{26}\text{Mg}$ and $\delta^{25}\text{Mg}$ of 0.6‰ and 0.3‰ defines a single mass-dependent fractionation line consistent with a homogeneous mix of nucleosynthetic components. Data for the Earth, Mars and Vesta display no systematic Mg isotopic differences despite large variations in the level of depletion in moderately volatile elements. Lunar mare basalts exhibit a significant range in $\delta^{26}\text{Mg}$ (−0.53‰ to +0.05‰) and $\delta^{25}\text{Mg}$ (−0.27‰ to +0.02‰) attributable to magmatic differentiation in the lunar magma ocean (LMO). Lunar basalts derived from early segregated cumulates and thought to be the most primitive are on average slightly $\sim 0.17\%$ ($\delta^{26}\text{Mg}$) heavy relative to basalts from the Earth, Mars and Vesta. However, the difference is not well-resolved. More strikingly, all differentiated planets and planetesimals, as sampled, have Mg that is on average isotopically heavy compared with most chondrites analyzed thus far. Chondrules and CAIs also are generally heavy in terms of Mg, so this might reflect sorting of material in the proto-planetary disk. Such an explanation would be similar to one previously proposed (Hewins R. H. and Herzberg C. T. (1996) *Earth Planet. Sci. Lett.* 144, 1–7.) to explain the non-chondritic Si/Mg of the Earth. In this model chondrule-like objects separate from volatile rich planetary dust by accumulation in stagnant regions between eddies in the solar nebula. Small (~ 1 km) planetesimals formed by accumulation of such molten material then develop into planetary embryos and thence to larger terrestrial planets by combinations of runaway growth and collisions. As such accumulation of molten chondrule-like droplets provides an explanation that obviates some of the dynamic difficulties associated with the onset of planetary accretion. The non-chondritic Mg isotopic composition of the Earth is consistent with data for Li and has important implications for Earth's bulk composition and putative hidden reservoirs.

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1. Introduction

Our solar system is chemically heterogeneous with the volatile-poor, rocky terrestrial planets dominating its innermost portions. The silicate reservoirs as sampled

* Corresponding author. Present address: Institute für Geologische Wissenschaften, Freie Universität Berlin, Malteserstrasse 74-100, Haus B, 12249 Berlin.

E-mail address: wiechert@zedat.fu-berlin.de (U. Wiechert).

from the Earth, Mars, the Moon and the HED parent body (thought to be Asteroid 4 Vesta), as well as the various chondritic meteorite groups, exhibit large apparent differences in volatile element budgets, but also in other respects such as Mg/Si and refractory element contents e.g. [1]. The origin of this chemical heterogeneity and the causes of differences between differentiated objects and chondrites have been unclear, although several theories have been considered, all of which might play some role. These are conveniently divisible into planetary and disk-related mechanisms.

The most widely considered planetary mechanism is core formation. Non-chondritic abundances of some lithophile elements (e.g. Si, K, Nb) in the silicate Earth as sampled, have been explained in terms of partial siderophile behaviour (e.g. [2–4]). It has also been proposed by some that the silicate Earth as sampled is simply unrepresentative. Noting the striking similarities with the Earth's O, Cr and N isotopic compositions, Javoy [5] has proposed an enstatite chondrite model with a complementary hidden reservoir in the lower mantle. Similarly, Boyet and Carlson [6] recently proposed a complementary enriched primordial reservoir to balance the isotopic composition of Earth's Nd. It has also been proposed that some of the distinctive chemical features of the Earth and Moon relate to accretion. Strontium isotopes provide evidence of significant losses of moderately volatile elements during the late (>10 Myr) accretion history of the material that formed the Earth and Moon [7]. The non-chondritic Mg/Fe of the Earth may also relate, in part, to late accretion effects [8], (H. Palme pers. comm. 2003).

Notwithstanding the potential importance of some of these mechanisms and models, the primary control on the common features of all silicate reservoirs from the inner solar system are more likely to relate to processes operating within the proto-planetary disk. This provided the raw materials for the Earth, Mars, Vesta and Theia (the putative impacting planet considered to have formed the Moon). The dominant “disk” model of chemical heterogeneity has been condensation from a hot nebular gas. Nebula models predict temperatures that were sufficiently high to prevent complete condensation of moderately volatile elements in the terrestrial planet forming region [9]. Some (but not all) moderately volatile lithophile elements show a pattern of depletion that corresponds with condensation temperature [10]. The lack of fractionation of K isotopes also seems consistent with this model [11]. The slightly volatile elements such as Li, Mg, Si, Cr, Fe and Ni may also be affected in this way. Indeed, Ringwood [12] proposed that the Earth's non-chondritic Si/Mg reflected loss of

more volatile Si and condensation at greater heliocentric distance.

It is now known that the inner solar system was formed from a mixture of both hot and cold material. The discovery of sub-micron particles of variable nucleosynthetic origin in chondrites provides evidence that not all material condensed from a hot gas [13]. Some of these presolar grains have never been heated to more than 80 °C and cannot have experienced the high temperatures associated with calcium–aluminum-rich refractory inclusion (CAI) and chondrule formation [14]. Therefore, components of cold dust must have been admixed between the time of chondrule formation and chondrite parent body accretion.

To what extent the disk materials from which the terrestrial planets formed was uniform and similar to chondrites in terms of its proportions of CAIs, chondrules, gas, presolar grains and other dust, has been unclear and is of fundamental importance if one is to address issues like Earth's hidden reservoirs. For example, Hewins and Herzberg [15] proposed that Earth's non-chondritic Si/Mg could be the product of sorting of chondrules in the protoplanetary disk. On average chondrules have Si/Mg that is virtually identical to that of the Earth's mantle obviating the need for models based on core partitioning.

In this paper magnesium (Mg) isotopes are used to address these issues. Using high resolution multiple collector inductively coupled plasma mass spectrometry (MC-ICPMS) it is shown that the Earth, Moon, Mars and Vesta, as sampled, all have Mg that is fractionated to slightly heavy compositions relative to chondrites. Striking mass-dependent Mg isotope fractionations have already been detected for CAIs [16,17]. MC-ICPMS also has been able to resolve much smaller differences such as those among chondrules [16,18,19]. Here we report precise Mg isotope data for lunar basalts, eucrites, martian meteorites and chondrites. In addition, a suite of olivines, clinopyroxenes and orthopyroxenes from spinel lherzolites have been analyzed to estimate more precisely the Mg-isotope composition of the Earth.

2. Methods and samples

Approximately 2 mg of sample powder was digested in Savillex® screw-top beakers with 2 ml concentrated HF–HNO₃ (1:1) mixtures on a hot plate for 24 h at 180 °C. The solution was evaporated and the residue redissolved and dried down three times in 0.2 ml 6 M HCl. Finally the sample was dissolved and stored in 6 M HCl. Teflon columns with a volume of 2.1 ml and 6 mm internal diameter were packed with Bio-Rad AG1-X8

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