Earth and Planetary Science Letters 400 (2014) 153–164

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Unlocking the zinc isotope systematics of iron meteorites

L.J. Bridgestock [a,*], H. Williams [b,c], M. Rehkämper [a,d,*], F. Larner [a,b], M.D. Giscard [a,d], S. Hammond [e], B. Coles [a], R. Andreasen [a], B.J. Wood [b], K.J. Theis [f], C.L. Smith [d], G.K. Benedix [g], M. Schönbächler [h]

[a] Department of Earth Science and Engineering, Imperial College London, SW7 2AZ, UK
[b] Department of Earth Sciences, University of Oxford, OX1 3AN, UK
[c] Department of Earth Sciences, Durham University, DH1 3LE, UK
[d] Natural History Museum, London, SW7 5BD, UK
[e] Centre for Earth, Planetary, Space & Astronomical Research, The Open University, Milton Keynes MK7 6BJ, UK
[f] Dept. School of Earth, Atmospheric and Environmental Sciences, University of Manchester, M13 9PL, UK
[g] Department of Applied Geology, Curtin University, Bentley, Western Australia, 6845, Australia
[h] Institut für Geochemie und Petrologie, ETH Zürich, Clausiusstrasse 25, 8092 Zürich, Switzerland

ARTICLE INFO

Article history:
Received 20 March 2013
Received in revised form 16 May 2014
Accepted 19 May 2014
Available online 6 June 2014
Editor: T. Elliott

Keywords:
iron meteorites
stable isotopes
Zn isotopes
volatile elements
core formation

ABSTRACT

Zinc isotope compositions (δ^{66}Zn) and concentrations were determined for metal samples of 15 iron meteorites across groups IAB, IIAB, and IIIAB. Also analyzed were troilite and other inclusions from the IAB iron Toluca. Furthermore, the first Zn isotope data are presented for metal–silicate partitioning experiments that were conducted at 1.5 GPa and 1650 K. Three partitioning experiments with run durations of between 10 and 60 min provide consistent Zn metal–silicate partition coefficients of ∼0.7 and indicate that Zn isotope fractionation between molten metal and silicate is either small (at less than about ±0.2‰) or absent. Metals from the different iron meteorite groups display distinct ranges in Zn contents, with concentrations of 0.08–0.24 μg/g for IIABs, 0.8–2.5 μg/g for IIIABs, and 12–40 μg/g for IABs. In contrast, all three groups show a similar range of δ^{66}Zn values (reported relative to 'JMC Lyon Zn') from +0.5‰ to +3.0‰, with no clear systematic differences between groups. However, distinct linear trends are defined by samples from each group in plots of δ^{66}Zn vs. 1/Zn, and these correlations are supported by literature data. Based on the high Zn concentration and δ^{66}Zn ≈ 0 determined for a chromite-rich inclusion of Toluca, modeling is employed to demonstrate that the Zn trends are best explained by segregation of chromite from the metal phase. This process can account for the observed Zn–δ^{66}Zn–Cr systematics of iron meteorite metals, if Zn is highly compatible in chromite and Zn partitioning is accompanied by isotope fractionation with $\Delta^{66}Zn_{chr\text{-}met} \approx -1.5$‰. Based on these findings, it is likely that the parent bodies of the IAB complex, IIAB and IIIAB iron meteorites featured δ^{66}Zn values of about −1.0 to +0.5‰, similar to the Zn isotope composition inferred for the bulk silicate Earth and results obtained for chondritic meteorites. Together, this implies that most solar system bodies formed with similar bulk Zn isotope compositions despite large differences in Zn contents.

1. Introduction

Cosmochemical studies reveal a clear preference for compositional investigations of primitive and differentiated stony meteorites because their diverse elemental and isotopic chemistry is more readily exploited to examine early solar system conditions and processes. Iron meteorites, however, are also worthy of investigation, as they constitute the only accessible samples of planetary cores. Differentiated bodies are common in the solar system, and studies of irons are, therefore, important to advance our understanding of core formation and bulk planetary compositions.

Iron meteorites fall into the two categories of magmatic and non-magmatic irons. The former are considered to be core fragments from differentiated and subsequently disrupted asteroidal parent bodies. This conclusion is based on the observation of siderophile trace element trends, which can be explained by models of fractional crystallization of solid metal (e.g., Scott, 1972). Different groups of magmatic irons, distinguished by distinct trace element trends, mirror a range in redox conditions as well as cooling

* Corresponding authors at: Department of Earth Science and Engineering, Imperial College London, SW7 2AZ, UK. Tel.: +44 20 7594 6391.
E-mail address: markrehk@imperial.ac.uk (M. Rehkämper).

http://dx.doi.org/10.1016/j.epsl.2014.05.029
0012-821X/© 2014 Published by Elsevier B.V.

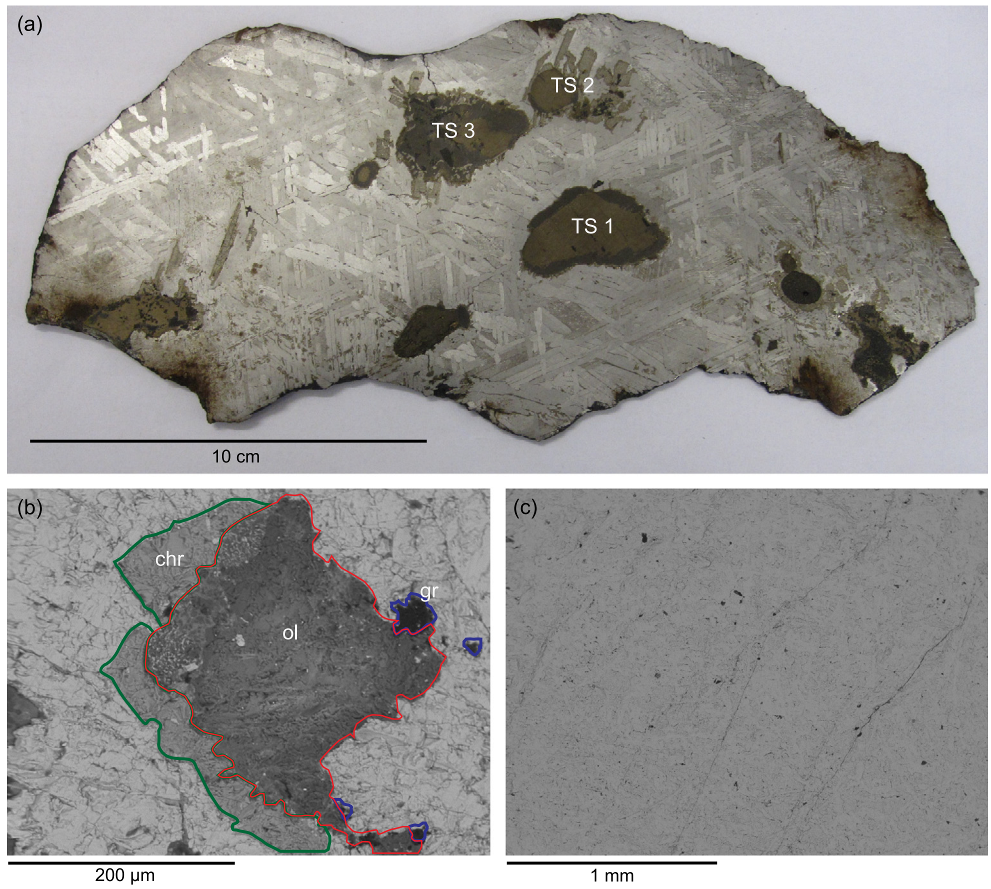

Fig. 1. Images of the Toluca (IAB) sample obtained for this study. Panel (a) shows a photograph of the entire Toluca IAB slab, indicating the positions of the three troilite nodules (TS1, TS2 and TS3) separated for analysis. Panel (b) shows a SEM electron backscatter image of an inclusion within TS3, with the main phases chromite (chr; green), graphite (gr; blue) and olivine (ol; red) highlighted in color. Panel (c) is an electron backscatter image of a fragment of TS1, showing graphite inclusions (as dark specs) within troilite. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

rates, indicating differences in starting composition and geochemical evolution (Mittlefehldt et al., 1998; Chabot and Haack, 2006; Benedix et al., 2013). In contrast, non-magmatic iron meteorites did not form as a single core in a differentiating asteroid. Possible models for their formation range from impact melting on the surface of an undifferentiated parent body (Choi et al., 1995; Wasson and Kallemeyn, 2002) to catastrophic impact, breakup and reassembly of a chondritic asteroid, which experienced partial metal–silicate differentiation (Benedix et al., 2000; Schulz et al., 2009; Theis et al., 2013).

Isotopic studies of iron meteorites are comparatively scarce because they are limited to analyses of siderophile and chalcophile elements (e.g., S, Mo, Ag, Os), which are sufficiently abundant in the metal to permit acquisition of precise data. Of more recent origin are stable isotope investigations of transition metals such as Fe, Ni and Cu (e.g., Zhu et al., 2001; Kehm et al., 2003; Luck et al., 2005; Moynier et al., 2007). Zinc isotopes are also potentially useful for the study of iron meteorites. Whilst only a very limited number of samples have been analyzed to date, the available results reveal significant Zn isotope variability (Luck et al., 2005; Moynier et al., 2007; Ghidan and Loss, 2011). More analyses are needed, however, before the isotopic data can be employed with confidence to constrain parent body processes and conditions.

The current study addresses this lack of data, through Zn isotope and concentration measurements for metal samples of 15 iron meteorites and analyses of inclusions from the group IAB iron Toluca. Further Zn data were obtained for samples from metal–silicate partitioning experiments that were conducted at 1.5 GPa and 1650 K. Together, these results were applied to (i) interrogate the processes responsible for the variable Zn contents and isotope compositions of iron meteorites and (ii) constrain the bulk Zn isotope compositions of the respective asteroid cores and parent bodies.

2. Samples and laboratory methods

2.1. Meteorite samples and sampling procedures

Metal samples of six group IIAB and six IIIAB iron meteorites were provided by the Natural History Museum, London, and obtained as solution aliquots of large samples (about 15 to 40 g; Table 1) that were digested for a companion study (Andreasen et al., 2012). For the IAB irons, an interior piece of Campo del Cielo and polished slabs of Toluca and Canyon Diablo were purchased from commercial vendors. Multiple pieces of metal were analyzed for Sikhote-Alin (IIAB) and the IAB irons Canyon Diablo and Toluca, to investigate small-scale heterogeneities in Zn isotope compositions and concentrations (Table 1).

Fragments of three troilite nodules were manually separated from the Toluca slab for additional analyses (Fig. 1). Inspection under reflected light revealed that the Toluca sulfide nodules TS1 and TS2 were composed of troilite with graphite rims, whilst TS3 contained a visible schreibersite exsolution and graphite inclusions within troilite. Fragments of TS1 and TS3 were further examined using scanning electron microscopy (SEM) at the Natural History Museum London (Fig. 1). This revealed that TS1 consisted of troilite with small inclusions of graphite and no other phases were observed. In contrast, TS3 featured troilite with abundant graphite