ENSTATITE CHONDRITES: AN IRON AND ZINC ISOTOPE STUDY

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Introduction: Enstatite chondrites formed in a very reducing environment and consist predominantly of FeO-free enstatite, with varying amounts of Fe,Ni metal and troilite [1]. Elements which are normally lithophile under more oxidising conditions occur in chalcophile or siderophile associations, giving rise to a variety of rare minerals. A number of models for the formation of enstatite chondrites have been proposed. One theory holds that both EH and EL chondrites formed on a single stratified parent body [2,3]. The alternative scenario is that EH and EL chondrites formed in separate parent bodies [e.g. 4-5].

Rationale: Iron is a moderately volatile element with a 50% condensation temperature of 1334K [6] and the isotopes of iron may be fractionated during high temperature solar nebula processing [e.g. 7]. Zinc is more volatile than iron with a 50% condensation temperature of 726K [6]. We examine the accretion and parent body history of the enstatite chondrites within the framework of Fe- and Zn-isotopes.

Method: The method for analysing Fe- and Zn-isotopes by multiple collector inductively coupled plasma mass spectrometry has been described previously [8,9]. The precision at the 2σ level achieved for iron is δ^{56}Fe ± 0.06 permil and δ^{57}Fe ± 0.08 permil with respect to IRMM-014 and for zinc is δ^{66}Zn ± 0.05 permil and δ^{68}Zn ± 0.07 permil with respect to IMP-Zn.

Samples: The following enstatite chondrites were analysed: Abee (EH,EH4-5), Kota-Kota (EH3), Indarch (EH4), St. Marks (EH5), Happy Canyon (EL/EL6), Atlanta (EL6), Hvittis (EL6), Khairpur (EL6) and Yilmia (EL6). The isotopic composition of Happy Canyon, which is an impact melt [1], may have been altered by terrestrial residence (discussed below).

Results – Fe-Isotopes: Iron isotopes display a fractionation of between 0.11 and 0.19 permil/amu (Figure 1). EL6 chondrites show no significant range in fractionation and the average value is –0.35 permil. EH chondrites (excluding Happy Canyon) show an average δ^{56}Fe of -0.24. The minimum difference between the EH and EL6 groups is 0.08 permil, which is greater than the error range for these measurements. Thus, EL6 chondrites (excluding Happy Canyon) are lighter than EH chondrites.

Results – Zn-Isotopes: Zn-isotopes are fractionated between 0.54 to 3.42 permil/amu (Figure 2). The range of δ^{66}Zn = 5.76 permil. EL6 chondrites (Atlanta, Hvittis, Khairpur and Yilmia) are fractionated between 2.67 to 3.42 permil/amu. St. Marks (EH5) is fractionated by 1.74 permil/amu. Happy Canyon (EL6, see below) is fractionated by 0.96 permil/amu. Abee (EH4-5), Kota-Kota (EH3) and Indarch (EH4) are fractionated by between 0.24 and 0.61 permil/amu. The isotopic composition of Abee and Indarch overlap within error, but the isotopic composition of Kota-Kota is heavier.

FIGURE 1

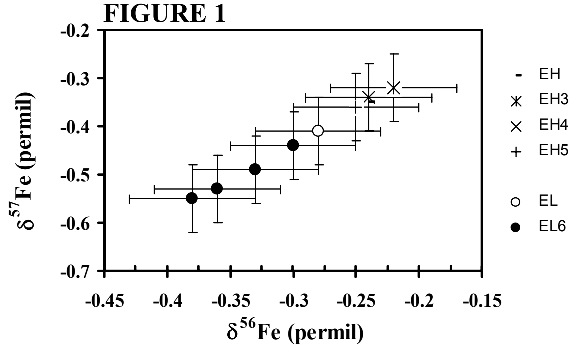


FIGURE 2

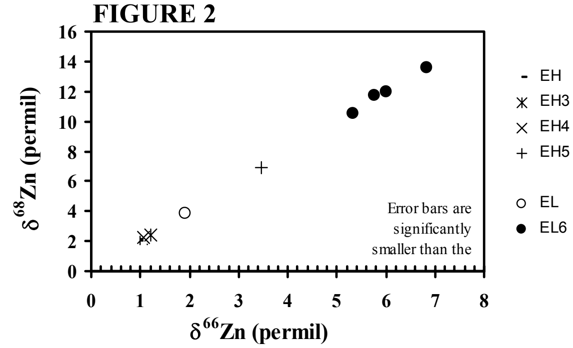
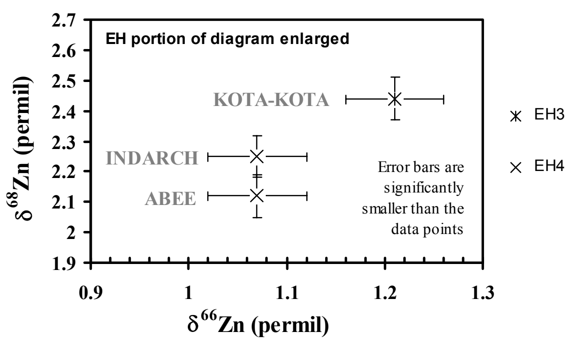


FIGURE 3



Discussion :

Happy Canyon: Happy Canyon is an impact melt that has been heavily weathered [1,10]. It was initially classified as an enstatite achondrite [10] but more recently it has been classified as EL [11] or EL6 [12].

The Fe-isotopic composition of Happy Canyon is intermediate between EL6 and EH chondrites and it is isotopically heavier than its fellow EH6 group members. This fractionation difference may be attributed to its impact origin rather than terrestrial alteration as impact processing could volatilise the lighter Fe-isotopes. However, terrestrial modification of the Fe-isotope signature cannot be ruled out. Zn-isotopes of all EL6 chondrites analysed here are all heavier than +2.67 permil/amu compared to our standard, but Happy Canyon is only fractionated by +0.96 permil/amu. It is expected that impact melting of Happy Canyon protolith material would have volatilised isotopically light zinc, especially if it has modified the less volatile isotopes of iron. Thus, it seems likely that isotopic exchange of zinc with terrestrial zinc may have produced the Zn-isotope signature. As the isotopic composition of Happy Canyon may have been compromised during terrestrial residence the data for this meteorite will be excluded from the following discussion.

Abee: The Fe-isotope composition of Abee (EH4-5) is identical to Indarch (EH4) and both of these meteorites have Fe-isotope compositions which fall within error of the other EH chondrites analysed here. However, the Zn-isotopic composition of Abee is identical to Indarch (EH4) and is distinct from St. Marks (EH5). This hints at a possible relationship between petrologic type and Zn-isotopes. In the following discussion we group Abee with Indarch.

Isotopic Reservoir: Many researchers believe that the bulk EH and EL compositional differences are inherited from the nebula, rather than generated by parent body processes, and that each group represents an individual parent body [e.g. 1 and references therein]. The differences in Fe-isotope fractionation between EH and EL are slight but significant indicating that Fe-isotopes were heterogeneously distributed in the region of the solar nebula where the enstatite chondrites accreted. Although parent body processing cannot be ruled out, it is likely that the enstatite chondrites accreted their heterogeneous Fe-isotope signatures. Zinc is significantly more volatile than iron. EL6 chondrites are significantly heavier than all other enstatite chondrites analysed here. A tentative explanation for this feature is that the EL parent body accreted closer to the Sun than the EH parent body allowing for increased volatilisation of zinc in the material which accreted to form the EL parent body.

Metamorphism: Increased degree of metamorphism from EH3 to EH5 indicates that these chondrites represent a metamorphic sequence [e.g. 1]. Zn-isotopes become increasingly heavy with increased petrologic type, with a separation of over 1 permil/amu between EH3-4 and EH5 and between EH5 and EL6. However, the difference between EH and EL6 may reflect their origin on separate parent bodies.

Shock Stage: The given shock stage for the meteorites studied here [11] is inversely proportional to the extent of Zn-isotope fractionation. Kota-Kota (EH3) and Indarch (EH4) (both S4) are least fractionated, St. Marks (EH5, S3) is intermediate, and Atlanta, Hvittis, Khairpur and Yilmia (EL6, S2) are heavy (although EL6 chondrites may originate on a separate parent body). This is the opposite to the fractionation expected if shock resulted in loss of zinc. Thus, it is not unlikely that fractionation systematics are related to the degree of shock processing.

Impact Brecciation: The following enstatite chondrites have been brecciated by impact during parent body residence: Abee (EH/EH4) [13-15], Atlanta (EL6) [16], and Hvittis (EL6) [17-18]. The Fe-isotope composition of Abee is irresolvable from the other EH chondrite samples. Atlanta and Hvittis contain the isotopically heaviest iron of the EL6 group. These data indicate that impacting has not significantly volatilised the lighter Fe-isotopes. The data for Zn-isotopes also indicates that impact processing has not significantly shifted the composition of the EH and EL impact breccias away from their group members. Abee (EH4) is indistinguishable from Indarch (EH4).

Summary: Although many EC remain to be analysed, we can draw some tentative, but useful, conclusions. Zn-isotopes may be used to classify enstatite chondrites. Metamorphism appears to have modified Zn-isotope composition, but shock and impact brecciation have not. Based on Fe-isotope data, EH and EL chondrites originated on separate parent bodies and it is possible that the EL parent body accreted closer to the Sun.

References: [1] Keil, 1989, Meteoritics 24, 195-208. [2] Biswas et al., 1980, GCA 44, 2097-110. [3] Kaczaral et al., 1988, Proc. NIPR Symp. Ant. Met. 1, 113-21. [4] Baedecker and Wasson, 1975, GCA 39, 735-65. [5] Sears et al., 1982a, GCA 46, 597-608. [6] Lodders, 2003, Astro. Jl. 591, 1220-1247. [7] Mullane et al., 2005, EPSL (submitted). [8] Mullane et al., 2003, In: Plasma Source Mass Spectrometry, Royal Society of Chemistry, 351-61. [9] Mason et al., 2004, J. Anal. At. Spectrom. 19, 209-17 and 218-26. [10] Olsen et al., 1977, Meteoritics 12, 109-23. [11] Grady, 2000, Catalogue of Meteorites, Cambridge Univ. Press. [12] Graham et al, 1985, Catalogue of Meteorites, Univ. of Arizona Press, Tucson. [13] Dawson et al., 1960, GCA 21, 127-44. [14] Rubin and Keil, 1983, EPSL 62, 118-31. [15] Sears et al., 1982b, EPSL 62, 180-192. [16] Rubin, 1983c, Meteoritics 18, 113-21. [17] Keil, 1982, LPI Tech. Rep. 82-02, 65-83. [18] Rubin, 1983a, LPSC 14th, B293-300.