Tungsten isotopes, the initial $^{182}Hf/^{180}Hf$ of the solar system and the origin of enstatite chondrites

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Hafnium (Hf) and tungsten (W) are both refractory elements whose relative proportions are strongly fractionated between silicate and metal. ^{182}Hf decays with a half-life of 9 Myr to ^{182}W such that the W isotopic composition will be a function of the initial abundance of ^{182}Hf in the early solar system and the timing of Hf/W fractionation, hence that of silicate-metal segregation (Lee and Halliday, 1995, 1996, 1997; Halliday *et al.*, 1996; Lee *et al.*, 1997). Previous studies have shown that iron meteorites and metal separates of ordinary chondrites contain W that is less radiogenic than chondritic, and this has been attributed to early metal segregation within their respective parent bodies during the lifetime of ^{182}Hf (Lee and Halliday, 1995, 1996). In contrast, basaltic achondrites such as eucrites and SNC meteorites exhibit clear evidence of chondritic to radiogenic W, indicating rapid accretion, differentiation and core formation on asteroid 4 Vesta and Mars (Lee and Halliday, 1997). Despite a high Hf/W, the silicate Earth yields a W isotopic composition identical to that of carbonaceous chondrites (Lee and Halliday, 1995, 1996; Lee *et al.*, 1997), implying that the Earth's core did not form until = 50 Myr after the formation of the solar system, unless Earth's accretion was slower than generally modelled (Halliday *et al.*, 1996). More interestingly, the Moon yields chondritic to slightly radiogenic W among various types of lunar samples (Lee *et al.*, 1997). This provides critical constraints regarding the age and origin of the Moon (Lee *et al.*, 1997). Despite all the recent advances that have been made on the Hf-W system, the determination of the initial abundance of ^{182}Hf in the solar system was still hindered by analytical difficulties. Consequently, it has been estimated from the differences in W isotopic composition between the carbonaceous chondrites and the least radiogenic W yet measured (Lee and Halliday, 1995), which corresponds to a bulk solar system initial $^{182}Hf/^{180}Hf$ of $(2.4 \pm 0.6) \times 10^{-4}$ (Lee and Halliday, 1996). Even though such a level of initial $^{182}Hf/^{180}Hf$ was favoured by both experimental (Lee and Halliday, 1996) and theoretical (Wasserburg *et al.*, 1996) considerations, it is critical to establish whether internal isochrons can be resolved in chondritic materials. Such a direct confirmation for the former presence of ^{182}Hf in the solar system will not only serve as a cornerstone for future Hf-W studies, but also offer more precise constraints on the timing of planetary differentiation and astrophysical consideration for the production of r-process nuclides.

Two ordinary chondrites, Forest Vale (H4) and Richardton (H5), and two enstatite chondrites, Indarch (EH4) and ALHA81021 (EL6), have been studied to test if internal isochrons can be resolved. We have analysed only three fractions, metal, bulk silicates and whole rock in this preliminary study. Prior to crushing, each sample was leached with distilled HCl (~1 N) to remove potential contamination from cutting. All the samples were crushed with an aluminium oxide mortar in a flow of filtered laminar air. A hand magnet was used to separate metal from silicates, and both were cleaned in an ultrasonic bath of distilled ethanol. The W isotopic data of metal separates from Forest Vale and Richardton have been previously reported (Lee and Halliday, 1996). However, to avoid systematic variations, the metal separate of Forest Vale was re-analysed. The result is consistent with the previous study. In addition to the bulk metal measurement, a portion of the metal separates from Forest Vale, Indarch and ALHA81021 were treated first with hot 6 N HCl until most of the metals were dissolved. The solution was then separated from the residue, which was undergoing additional dissolution steps.

In general, a positive correlation is observed in each of the samples in a plot of Hf/W *vs.* W isotopic composition, phases with higher Hf/W exhibiting more radiogenic W. The best-fit line regressed through all the data of Forest Vale also intercepts the data of carbonaceous chondrites Murchison and Allende (Lee and Halliday, 1996), and corresponds to a slope of $(1.87 \pm 0.16) \times 10^{-4}$ and an initial $^{182}W/^{184}W$ of 0.86471. Similarly, the best-fit line regressed through the data of Richardton also intercepts the two carbonaceous chondrites, corresponding to a slope of (1.9 $\pm$ 0.8) 10^{-4}, comparable to that of Forest Vale. Taking into account the possible 5 Myr difference in age between Forest Vale and Allende CAI, the initial $^{182}Hf/^{180}Hf$ of the solar system is estimated to be (2.75 $\pm$ 0.24) $\times$ 10^{-4} with a solar system $^{182}W/^{184}W$ initial of 0.86455 $\pm$ 4 (ε_W = -5.03 ± 0.46) based on the slope of best-fit line of Forest Vale. This is consistent with previous estimates (Lee and Halliday, 1995, 1996; Wasserburg *et al.*, 1996). The whole rock data for carbonaceous chondrites line on both ordinary chondrite isochrons, suggesting that both chondrites originated from a common chondritic reservoir. There is, therefore, little doubt that these are internal isochrons and that they represent the best evidence thus far that 'live-^{182}Hf' was indeed present in the early solar system.

In striking contrast, the silicate and whole rock separates of both enstatite chondrites show a clear offset to the right of the chondritic isochron. Two independent whole rock measurements of Indarch display clear and significant ^{182}W deficits ($\geqslant$ 2 ε_W units) relative to the mean of carbonaceous chondrites and that of the silicate Earth. This is inconsistent with a genetic link between the Earth and enstatite chondrites as sometimes inferred from oxygen isotope data. The data of the metal leachates, residues and bulk metals for both enstatite chondrites fall on a straight line which intercepts the data of both Murchison and Allende with a slope of (1.67 $\pm$ 0.22) $\times$ 10^{-4}, consistent with that of the ordinary chondrites. In addition, a straight line that goes through the silicates of both enstatite chondrites also intercepts the bulk carbonaceous chondrites data, but with a slope of (5.7 $\pm$ 0.8) $\times$ 10^{-5}. Therefore, instead of invoking a non-chondritic origin, the W data seem to suggest that a major portion of chondritic materials might have accreted to the original parent body of the enstatite chondrites, which was also chondritic, at a late (~50 Myr) stage. The unradiogenic W of the Indarch whole rock measurements reflects a mixture of different portions of early and late accreted chondritic materials. More data for enstatite chondrites are needed to test if this hypothesis is self-consistent.

References

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