Re-Os systematics in meteorites

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Extensive results have been obtained on the Re-Os system in iron meteorites, stony irons, and in chondrites. This has required the development of reliable techniques, with the single-most critical analytical consideration being the complete isotope equilibrium of tracer and sample. The work on iron meteorites has concentrated on whole rock measurements. Whole rock samples for irons of groups IAB, IIA, IID, IIIA, IVA and IVB have yielded a well defined isochron with deviations from the isochron for any single sample at the level of 2–3‰. The data yield a slope of 0.07863 ± 0.0003, corresponding to T = 4.615 ± 0.018 AE [$\lambda(^{187}Re) = 1.64 \times 10^{-11}$ a^{-1}] and initial $(^{187}Os/^{188}Os)_0 = 0.09560 \pm 0.0002$. There is a suggestion that group IVA irons are slightly older. Since the uncertainty in the ^{187}Re decay constant is ~3%, the isochron age can be renormalized to T/4.55 AE, corresponding to $\lambda(^{187}Re) = 1.664 \times 10^{-11}$ a^{-1}, in order to obtain agreement with U-Pb, Sm-Nd, and Rb-Sr ages on silicates. The well-defined whole rock isochron depends on substantial observed variations in Re/Os, which reflect chemical fractionation during initial fractional crystallization of FeNi masses, including as pods and as cores of early formed planetesimals. For iron meteorites, 'whole rock' samples measured are typically cubes of metal, 0.25 to 1g, several mm on the side. Given that the crystal size for metal phases in iron meteorites is similar, the close adherence of the data to a single isochron requires very limited fractionation of Re-Os after initial FeNi crystallization and during the later exsolution of the low-Ni phase (kamacite) from the initial taenite, at lower temperatures. Furthermore, since the whole rock samples do not show a hint of a Re-Os secondary isochron at times younger than the age of the primary isochron, then any melting of the FeNi masses at younger times must have also been characterized by limited Re/Os fractionation and thus very limited further fractional crystallization. We have also determined Re-Os in FeS and in massive schreibersites in irons. Apparent, single-stage distribution coefficients are D(FeNi/Sulphide) = $(2-4) \times 10^2$ for Re and 1.5×10^3 for Os. Similarly, D(FeNi/Schreibersite) = 7–14 for Re and 30–54 for Os. The distribution coefficients for sulphide are sufficiently large that the segregation of immiscible sulphide would not affect the Re-Os systematics in the FeNi whole rocks. Similarly, based also on the abundance of P and, consequently, the limited abundance of schreibersite, the formation of the schreibersite would also be of minor importance for the whole-rock Re and Os mass balance. Measurements of PGE adjacent to massive schreibersites show gradients in Re and in Os abundances (up to 25%) and in Re/Os (up to 10%) for distances 1–2 mm away from the schreibersite. The schreibersites themselves show low Re and Os abundances but large enrichments in Re/Os, highly radiogenic $^{187}Os/^{188}Os$ and a range of model ages from 4.5 AE down to 3.5 AE. These data clearly indicate that the minor phases in iron meteorites show an extensive evolution, including slow cooling of the metal and diffusion of minor and trace elements for extended times, after the time of primary crystallization of the FeNi recorded by the whole rock isochron. Given the distribution coefficients and the abundances of sulphides and schreibersites, it is clear that these processes are not reflected in the Re-Os systematics of whole rock iron meteorite samples. The Re-Os narrow time evolution for irons is consistent with the systematics of the short lived chronometers Pd-Ag and Hf-W.

We have determined Re-Os systematics also in pallasites. The data for whole-rock FeNi samples show a wide range in Re/Os and permit the determination of a metal whole rock isochron which is consistent with the measurements on iron meteorites. The data include measurements on Eagle Station, a meteorite with silicates preserving a unique oxygen isotope composition. While pallasites have been viewed as originating in core-mantle boundaries, in differentiated planetesimals, the Re-Os data on the FeNi phases are consistent with early formation and fast cooling by fractional crystallization, within 3‰ in age, or 14 Ma. The data are not consistent with slow cooling of the initial molten FeNi. Observed, slow metallographic cooling rates must reflect slow diffusion at low temperatures and the absence of substantial fractionation of Re/Os between exsolving metal phases. The Re-Os data are consistent with the pallasites having formed as metal-silicate breccias near the surface of early differentiated planetesimals. We have also determined the Re-Os systematics in iron meteorites bearing silicate inclusions. These inclusions have been dated earlier using Sm-Nd, Rb-Sr, U-Pb, and K-Ar. For example, while Sm-Nd ages on the Vaca Muerta mesosiderite silicate pebbles indicate a range in ages of 0.11 AE (or 2.4%), this is not reflected in the Re-Os systematics of the metal phases, which are consistent with the iron meteorite isochron to 3‰, or 14 Ma. In the case of Kodaikanal (a IAB iron, with K-rich glass), the Re-Os data are consistent with the iron meteorite isochron, even though the K-rich silicates indicate formation at 3.7 AE, by differentiation of the K-rich material at this young age from chondritic material. Our conclusion is that the FeNi phases have not been subjected to substantial fractional crystallization at times younger than ~4.55 AE ago. While it is possible to preserve molten iron cores in insulated planets, heated early by short-lived radionuclides (e.g. ^{26}Al, ^{60}Fe), the observation of extremely limited Re-Os fractionation, at times younger than 4.55 AE, requires that such FeNi cores have fractionally crystallized early, on small planets, in order to establish the Re/Os fractionation. Similarly, in order to mix molten metal with silicates to form stony irons, in near-surface environments, at later times, without further Re-Os fractionation, apparently melting of FeNi without further fractional crystallization is required.

Reliable Re-Os data have also been obtained on ordinary chondrites from all groups and for metamorphic grades from 3 to 6. Data on whole-rock fragments and metal-rich separates from the St. Séverin chondrites (LL6) are up to now unique in showing a large range in ^{187}Re/^{188}Os and in ^{187}Os/^{188}Os, which makes possible the determination of a Re-Os internal isochron on a chondrite, for the first time. This Re-Os fractionation may be due to partial melting of FeNiS with Re-Os fractionation and macroscopic redistribution of metal and sulphide. The St. Séverin data show a good correlation line on a ^{187}Re-^{187}Os evolution diagram. If this is considered to represent an internal isochron, it gives an age $T = 4.68 \pm 0.15$ AE [for $\lambda(^{187}\text{Re}) = 1.64 \times 10^{-11}\ \text{a}^{-1}$], or $T = 4.61 \pm 0.15$ AE [for $\lambda(^{187}\text{Re}) = 1.664 \times 10^{-11}\ \text{a}^{-1}$] and the initial $(^{187}\text{Os}/^{188}\text{Os})_0 = 0.0953 \pm 0.0013$. This age is, within error, in agreement with and possibly slightly older than the more precise ^{187}Re-^{187}Os age for the irons. Whole rock and metal-rich separates of additional chondrites (H, L and LL groups) yield restricted ranges in ^{187}Re/^{188}Os (0.42–0.47) and ^{187}Os/^{188}Os (0.128–0.133). There is a systematic difference between Re/Os in the metal extracted from a chondrite and each bulk chondrite. This shows that there is small but significant Re-Os fractionation within subsystems contained within each chondrite. The ordinary chondrite data plot close to the iron meteorite whole rock isochron, although the deviations are larger (up to 26‰) than found for the irons (<3‰). St. Séverin sulphide has very low Re and Os concentrations and shows a young Re-Os model age (2.3 AE), indicating relatively recent element remobilization. The Re-Os chronometer in iron meteorites is controlled by the Re-Os fractionation apparently governed by the fractional crystallization of liquid metal. Re-Os ages of iron meteorites give the time of crystallization of metal segregations and cores of early planetary bodies. In contrast, the behaviour in ordinary chondrites, while also dominated by the metal phase, must reflect fractionation and transport on a macroscopic scale within the chondrites between the metal phases after aggregation due to partial melting of FeNiS, or must represent variable Re-Os fractionation of the metal phases prior to the accretion of the chondrites. The mechanism for Re-Os fractionation in chondritic FeNiS is, at this time, not well understood.

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