Planetary formation

One step to Earth

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In the Earth sciences, Occam's razor is often dulled by the rock-hard reality of the complexity of geological processes. Models for Earth accretion are no exception. Did the Earth form homogeneously, with a continuous supply of material of essentially unchanging composition, and a single phase of differentiation into metallic core and silicate mantle? Or was accretion a complex, heterogeneous process with many stages? Until a few years ago the simpler model had been buried in favour of complex models of heterogeneous accretion, but homogeneous accretion has begun to re-emerge as a viable alternative, because of new experimental data on the partitioning of siderophile (iron-loving) elements. Mantle abundances of many moderately siderophile elements, such as nickel and cobalt, can be accounted for by homogeneous accretion and equilibrium core formation in a deep magma ocean^{1,2}. Now Righter and Drake³ show that the same is true of a highly siderophile element, rhenium (Re).

Siderophile elements in the upper mantle hold important clues to Earth's early history. They are typically divided into two groups: the moderately siderophile elements, or MSE (P, Fe, W, Co, Ag, Ni, Sb, As, Ge and Mo); and the highly siderophile elements, or HSE (Os, Re, Ir, Ru, Pt, Rh, Au and Pd). With the exception of gold, HSE are refractory and so should not be fractionated from one another by cosmochemical processes. Indeed, HSE occur in the mantle in the same relative proportions^{4,5} (Fig. 1) as in carbonaceous chondrites — primitive Solar-System material.

To test whether the core formed by a simple equilibrium segregation of metal from silicates, we need to find metal/silicate partition coefficients ($D^{M/S}$) for siderophile elements over a wide range of physical conditions. $D^{M/S}$ for the HSE are difficult to determine experimentally because the HSE have very low solubilities in silicates (solids or melts), especially at the low partial pressures of oxygen necessary for core segregation in the Earth. One tack is to measure the solubilities of pure HSE metals in silicate melts at one atmosphere and over a range of oxygen pressures, and to calculate $D^{M/S}$ using known or estimated thermochemical data for the equivalent solubilities in iron-rich metal⁶. Using this method, and assuming that metal segregation occurs close to the surface (at low pressure) and that $D^{M/S}$ are essentially constant with temperature, the observed abundances of Re, Ir, Pd and Au in the mantle are orders of magnitude greater than expected (Fig. 1).

Furthermore, calculated $D^{M/S}$ and measured sulphide/melt partition coefficients for HSE show that metal or sulphide

Figure 1 Depletion of iron-loving elements in the Earth's mantle. (Abundances are relative to those from primitive meteorite data.) Calculations of depletion at high pressures and temperatures match observed abundances well, including that of the highly siderophile element rhenium³. This supports a simple model of homogeneous Earth accretion, with the core and mantle separating in a deep magma ocean.

segregation to the core should have caused large fractionations among the HSE, resulting in non-chondritic relative proportions. So homogeneous accretion with equilibrium core segregation at low pressure appears not to explain observed abundances.

Heterogeneous accretion models, which successfully account for the abundances and relative proportions of HSE in the mantle, have reigned for well over a decade. They postulate that the first 93% or so of Earth's mass was primitive chondritic material accreted under reducing conditions. During this stage, siderophile elements were almost entirely scavenged into the iron-rich metal that segregated to form the proto-core. Then about 7% more of Earth's mass was added as more oxidized material, giving the present upper mantle its high oxidation state and contributing most of its volatile elements. This stage also re-enriched the mantle in HSE and MSE, but small amounts of metal and sulphide segregation to the core subsequently stripped the silicate mantle of HSE, while leaving MSE little changed. A final 'late veneer', less than 1% by mass, of oxidized but volatile-element-depleted material was added, bringing the HSE up to observed mantle abundances at chondritic relative proportions⁷. But no models explain adequately the origin of these proposed components of the solar nebula (from which the planets formed).

Conversely, in homogeneous accretion the material accreted to Earth had constant composition, on average, and metal segregation to form the core was an equilibrium process. In such models, the currently observed abundances of siderophile elements in the mantle reflect the conditions of core seg-

regation. In recent years, experimentalists have had much success in measuring the effects of pressure, temperature and composition on partition coefficients^{2,3,8-10} for many of the MSE. Righter *et al.*² parametrized available partitioning data for P, Fe, Ni, Co, W, Mo and S, and by extrapolation to high pressure, found that the abundances of these elements in the mantle can be accounted for by metal-silicate equilibrium in a magma ocean at around 28 gigapascals and 2,200 K, in general agreement with the values² previously inferred for Ni and Co. These results have made homogeneous accretion competitive with heterogeneous accretion, and imply that differentiation occurred deep in a magma ocean, rather than near the surface.

But can homogeneous accretion account for the HSE too? Righter and Drake³ show that rhenium abundances in the mantle can be accounted for by equilibrium metal segregation in a deep magma ocean and, within their uncertainties, for the same conditions as predicted for the MSE (Fig. 1). Although this is tremendous support for homogeneous accretion, the foundation is still shaky.

Chondritic relative proportions of HSE in the mantle place a very tight constraint on homogeneous accretion, because they mean that core segregation must have occurred under conditions where partition coefficients for all HSE were essentially the same, leaving them unfractionated in the mantle. Given the known variability⁶ in the chemistry of the HSE, this would be very surprising. It should be noted that there is considerable uncertainty in mantle abundances of many HSE, and it has been claimed that they may not have chondritic relative proportions¹¹. But recent isotopic data⁵ indicate strongly that the Archaean mantle had a chondritic Re/Os ratio. The critical next step is to determine $D^{M/S}$ for osmium, which is very challenging experimentally.

At least a new edge is beginning to form on the proverbial razor, and further work will determine whether it is needed to slice out a choice between the simple and the complex. □

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- Li, J. & Agee, C. B. *Nature* **381**, 686–689 (1996).
- Righter, K., Drake, M. J. & Yaxley, G. *Phys. Earth Planet. Inter.* **100**, 115–134 (1997).
- Righter, K. & Drake, M. J. *Earth Planet. Sci. Lett.* **146**, 541–553 (1997).
- McDonough, W. F. & Sun, S.-S. *Chem. Geol.* **120**, 223–253 (1995).
- Foster, J. G., Lambert, D. D., Frick, L. R. & Maas, R. *Nature* **382**, 703–706 (1996).
- O'Neill, H. St. C., Dingwell, D. B., Borisov, A., Spettel, B. & Palme, H. *Chem. Geol.* **120**, 255–273 (1995).
- Newsom, H. E. in *Origin of the Earth* (eds Newsom, H. E. & Jones, J. H.) 273–288 (Oxford Univ. Press, New York, 1990).
- Walker, D., Norby, L. & Jones, J. H. *Science* **262**, 1858–1861 (1993).
- Hilgert, V. J., Drake, M. J. & Rubie, D. C. *Science* **264**, 1442–1445 (1994).
- Walter, M. J. & Thibault, Y. *Science* **270**, 1186–1189 (1995).
- Pattou, L., Lorand, J. P. & Gros, M. *Nature* **379**, 712–715 (1996).