ful constraint on core-formation models. Experimental studies have revealed that the combined effects of pressure and temperature conspire to produce conditions that can nearly satisfy the absolute and relative abundances of Co and Ni in the upper mantle by equilibration between molten silicate and molten metal at about 28 GPa and 2,300 K. These conditions imply metal segregation in a deep magma ocean[1,2].

A pressure of 28 GPa corresponds closely to the depth at which a peridotite mantle transforms from an upper mantle dominated by olivine and its polymorphs, to a lower mantle dominated by silicate perovskite. This mineral transition affects the melting behaviour of the mantle such that the melting curve becomes much steeper at pressures above the transition[4]. The high melting temperature of a perovskite-rich lower mantle means that the upper mantle may have been molten while the lower mantle was solid at the time of core formation; that is, metal and silicate could have equilibrated at the floor of a deep magma ocean as depicted in Fig. 1.

Modern theory for the origin of Earth has it that most of its mass accreted as a consequence of catastrophic impacts with large planetesimals[5]. Indeed, a popular model for the origin of the Moon is that it formed when a Mars-sized body hit the proto-Earth. This purported 'giant' impact would have occurred late in Earth's accretionary stage, and both impactor and Earth probably already had dense metal proto-cores. Numerical models indicate that much of the impactor core may have ploughed its way through the mantle and merged with Earth's core. Concurrently, the kinetic energy buried deep within the Earth would have been sufficient to melt a large portion of the silicate mantle[6,7].

Although the complex dynamics of this event are still being explored theoretically, it could have been that metal from the pre-impact cores of the proto-planets was excavated, re-mixed and re-equilibrated with the molten mantle. The Co and Ni contents of the upper mantle indicate that metal–silicate equilibration occurred at the base of the molten upper mantle; so, to form a core, the metal would have to migrate through the solid lower mantle (Fig. 1). During this final segregation stage, metal may have re-equilibrated to some degree with the major minerals of the lower mantle, silicate perovskite (about 85%) and magnesiowüstite (about 15%). An unknown factor is the effect this would have had on mantle abundances of Co and Ni.

In their provocative study, Tschauner *et al.*[3] used a powerful experimental and analytical combination — the laser-heated diamond anvil cell and secondary ion microprobe — to measure the partitioning behaviour of Co and Ni between Mg-perovskite and Fe-rich metal at lower-mantle pressures (up to 80 GPa, corresponding to a depth of around 1,900 km). These extremely difficult experiments provide the first measurements of metal–silicate partitioning over a range of lower mantle conditions, and the results indicate that the partition coefficients for Co and Ni both approach unity at very high pressure, and that D^{Ni}/D^{Co} is about one throughout the lower mantle. The implication of these data is that any re-equilibration between metal and silicate during migration to the core would increase the absolute abundance of Co and Ni in the lower mantle relative to the upper mantle, without fractionating the Co/Ni ratio.

For example, assuming a core that constitutes 30% of Earth's mass, metal–silicate partition coefficients of 42 and 46 for Co and Ni, respectively, are required to account for their upper mantle depletions. So partition coefficients of less than these values, and which approach unity in the lower mantle, would cause the silicate to be enriched in Co and Ni relative to observed depletions. Because the magma ocean model already accounts for the Co and Ni abundances, this creates something of a budgetary crisis.

The dilemma may be circumvented in three ways: by assuming that there was no re-equilibration in the lower mantle; by attempting to match the mantle Co and Ni depletions by developing a new model combining both upper mantle and lower mantle equilibration; and by assuming that a Co- and Ni-enriched lower mantle has remained chemically isolated for the past 4.5 billion years.

The study by Tschauner *et al.*[3] is the first of its kind at ultra-high pressures, and the implications of their work demonstrate the need for continued exploration into metal–silicate partitioning under lower-mantle conditions. For example, another unknown in core-formation models is the effect of metal–magnesiowüstite partitioning, as this mineral probably comprises about 15% of the lower mantle. Such studies can yield insights not only into the ancient process of core formation, but also the possible reaction of the outer core with lower-mantle minerals throughout geological time. □

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Daedalus

Slow-flowing metal

The whole of metallurgy is determined by the fact that molten metals have a very low viscosity. Casting them is easy and simple. Some metals can be forged as solids, by raising them to a temperature at which they can readily be deformed. But molten metals are not easily blown or drawn like glass, or spread like tarmac, or vacuum-formed like plastics. Such processes would need a metallic melt that was viscous and tacky. So Daedalus is inventing one.

What is needed, he says, is some sort of long-chain polymer that will dissolve in the molten metal without decomposing. Even in very low concentrations, it would thicken the melt dramatically, as linear polymers do in solution, or fine fibres in suspension. At first sight the chemistry looks discouraging. Organic polymers decompose at the temperature of most molten metals, and silicones would be immiscible with them. Some sort of long-chain silicone molecule with metallic side-chains might be feasible. But the obvious answer is that modern solution in search of a problem, the carbon nanotube.

Many alloys, especially those of iron, contain carbon inclusions, so problems of compatibility should not arise. Carbon nanotubes have a high (indeed, unknown) melting point. They have been filled with molten metal, so are clearly wetted by it; they can be made in micrometre sizes like chain-polymer molecules, and they are immensely strong. They are certainly expensive, but are rapidly getting cheaper. In any case only a small concentration of them should transform a runny molten metal into a viscous liquid. The resulting product should transform metallurgy.

The most immediate application would be to those shell structures — cans, boxes, containers, car-bodies and so on — which are now pressed or fabricated from sheet. An alloy which could be blow-moulded like glass would make it possible to form such products in one simple, effortless operation. Similarly, wire could be drawn in the finest sizes by simple melt-pulling, like glass fibre. Thin-wall metal tube and sheet could be blown continuously, like plastics layflat tubing. Light, strong metal foam or insulating and resilient metal wool could be made by blowing gas into the sticky melt at a well-judged velocity. Better still, all the resulting products could easily be repaired or modified with a simple blow-torch. Heated to tackiness, they could be annealed, augmented, deformed, or teased into new shapes by the skills of the traditional glassblower.

David Jones