Unequivocal evidence for a deep magma ocean from metal/silicate partitioning of Ta, V and Si during core formation

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Heterogeneous core formation models propose a stepwise accretion process generally starting with metal-silicate equilibration in small bodies at relatively reducing conditions (Wänke, 1981; O'Neill, 1991). Initially reducing conditions are required in these models to explain why moderately siderophile elements such as Si, V, and Cr have been depleted from the Earth's mantle. Studying the metal-silicate partitioning behaviour of refractory, undepleted elements such as Ta allows constraints to be placed on the lowest redox state under which significant terrestrial core formation could have taken place.

High-pressure experiments in the range of 2 - 24 GPa, temperatures of 1750 – 2600°C and low oxygen fugacities (ΔIW -1 to –5) have been performed using piston cylinder and multi-anvil devices. In two separate series of experiments, the metal-silicate partition coefficient for Ta was determined together with (a) Ga, In, Zn and (b) V, Cr, Mn, Ti, Nb. These elements were added as oxides in concentrations of 4-10 wt% to powdered starting mixtures of ~55 wt% synthetic peridotite and 35-40 wt% Fe-alloy (with 2 wt% Ni, 1 wt% Co, 9-17 wt% Si, and 0-7 wt% S).

Our data show that at pressures up to 6 GPa, Ta, Ga, In and Zn would have been strongly depleted from the mantle at the redox conditions required to extract V and Cr to the core. Moreover, the depletion of Ta would have been much greater than the depletion of Si required to explain the low Si/Mg ratio of the mantle compared to CI chondrite, if significant core/mantle equilibration occurred at low pressures. At higher pressures (≥18GPa) and very high temperatures, Si and V can be extracted into the core without depletion of Ta and without requiring strongly reducing conditions. This means that metal-silicate partitioning must have occurred in a relatively deep magma ocean during core formation and that the redox state of accreting material may, on average, have remained constant with time.

References

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Hf-Nd isotopic decoupling in enriched Icelandic lavas

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The range in isotopic and chemical compositions of Icelandic lavas is commonly interpreted as resulting from mixing between isotopically depleted and enriched components, thought to originate by melting an entire section of recycled oceanic crust [1,2]. In these models the gabbroic section forms the depleted endmember and the crustal layer forms the enriched component. Lead isotopic data has shown the mixing relationships to be more complicated than simple binary mixing, indicating that at least 5 separate components are needed to account for the compositional range [3].

The lavas most enriched in incompatible elements in Iceland, representing the closest approach to an enriched end-member, are found in the Snaefellsnes peninsula (SNP) and in the central volcanoes of southern Iceland (SI). We present new Nd-Hf-Pb isotopic data from these areas. The SNP and SI show $^{176}Hf/^{177}Hf$ ratios between 0.283077–0.283192 and 0.283076–0.283149 respectively. Nd-Hf ratios correlate with incompatible element enrichment, as elsewhere in Iceland, and thus also with Sm/Nd and Lu/Hf ratios. These correlations give minimum ages for the isotopic variation in SNP and SI of 200-350Ma. However, more recent partial melting events probably have reduced these ages.

Sources originating from recycled slabs are expected to have flat HREE patterns. Samples from the SNP and SI exhibit elevated Dy/Yb_N compared to other Icelandic regions. SNP shows lower Dy/Yb_N than SI indicating smaller garnet facies contributions, consistent with higher Lu/Hf ratios, whilst the high Dy/Yb_N and low Lu/Hf of SI are consistent with a larger contribution from the garnet field.

Samples from the SNP exhibit higher $^{176}Hf/^{177}Hf$ and $^{176}Lu/^{177}Hf$ for given $^{143}Nd/^{144}Nd$ and $^{147}Sm/^{144}Nd$ than those from SI forming 2 sub-parallel trends on Hf-Nd isotope and the equivalent parent/daughter diagrams. This implies that the Hf-Nd isotope decoupling is a product of ancient source differences in Lu/Hf and Sm/Nd, which have not been eliminated by garnet-facies melting. Calculations using the differences between the 2 correlations give ages which are partially corrected for melting and so may provide insight into earlier differentiation processes. Lu/Hf ages calculated for Eastern SNP and SI gave ages of ~550Ma. These ages are consistent with the lower Palaeozoic age proposed for the recycled slab based on lead isotopes [3]. This could indicate that the Hf-Nd decoupling between SNP and SI reflects heterogeneity within the recycled component.

References

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