The Influence of Core Formation on Nb-Ta Budgets of Terrestrial Planets

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All the major reservoirs of the silicate Earth display subchondritic Nb/Ta ratios, although Nb and Ta are expected to behave as geochemical twins during silicate differentiation. Possible explanations of this “Nb-paradox”, include (1) the existence of an isolated reservoir of subducted eclogite [1] and (2) the siderophile behaviour of Nb at high pressures [2], leading to selective depletion of Nb relative to Ta in the silicate Earth after core formation. To evaluate these hypotheses we analyzed Nb/Ta, Zr/Hf and Lu/Hf by isotope dilution in representative samples from Earth, Moon, Mars and HED. Using a mixed ^{180}Ta-^{94}Zr-^{180}Hf-^{176}Lu tracer and the MC-ICPMS in Münster, we are able to achieve external precisions and accuracies of ±0.6% for Zr/Hf and of ±4% for Nb/Ta (all 2σ), resulting in a nearly 10-fold improvement in analytical resolution compared to older techniques.

A major problem in assessing bulk planetary Nb/Ta and Zr/Hf values is that both ratios are fractionated during internal differentiation of silicate reservoirs. However, during clinopyroxene controlled melting processes, Nb/Ta and Zr/Hf are expected to correlate positively, because Ta and Hf are slightly more compatible than Nb and Zr. If all of the Nb is hosted in the silicate reservoir, any planetary Nb/Ta vs. Zr/Hf array should overlap with the chondritic values (Nb/Ta = 17.6±1, Zr/Hf =34.2±0.3). This feature is observed for Mars (Nb/Ta = 13-21, Zr/Hf =22-34), Moon (Nb/Ta =13-22, Zr/Hf =27-41) and HED (Nb/Ta =17-20, Zr/Hf =34-36).

In contrast, the terrestrial array (peridotites, MORB, OIB, continental crust and Archean greenstones) (Nb/Ta =8-17, Zr/Hf =10-45) lies significantly below the chondritic Nb/Ta value (Nb/Ta =13-16 at the chondritic Zr/Hf of 34.2). Subchondritic Nb/Ta in both MORB and OIB indicate that subduction processes play a minor role in fractionating Nb from Ta on Earth. Since the OIB reservoir reflects compositions of subducted oceanic crust it appears unlikely that a hidden reservoir of eclogitic composition can balance the Nb deficit in the other terrestrial reservoirs. Rather, the terrestrial Nb deficit confirms experimental predictions that Nb is slightly siderophile at high pressures (>20 GPa) [2]. Among terrestrial planets, such pressures were only achieved during core-mantle equilibration on Earth. For Mars, HED and Moon, core-mantle equilibration occurred at much lower pressures (<10 GPa), which is consistent with the higher bulk silicate Nb/Ta of these planets.

The difference in bulk Nb/Ta between the silicate Earth and the Moon also has important implications for the early history of the Earth-Moon system. Since the silicate Earth has a lower bulk Nb/Ta, the Moon forming event must have occurred before core-mantle segregation on Earth was completed.

[1] Rudnick et al. 2000, Science 287, 278-281. [2] Wade & Wood 2001, Nature 409, 75-78.

Melting and melt/rock reaction in extending mantle lithosphere: trace element and isotopic constraints from passive margin peridotites

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Many mantle peridotites exhumed along ancient and present-day passive continental margins, along slow spreading ridges and fracture zones are too fertile to be the residue of partial melting processes alone. Most of these mantle rocks are variably depleted spinel peridotites, but plagioclase peridotites are also found. Here we use trace element and isotope data to infer that many peridotites have been modified by reactions with basaltic to refractory liquids producing plagioclase-bearing peridotites with a fertile composition that is superposed on an older ‘subcontinental’ history.

We measured clinopyroxene (cpx) by means of LA-ICP-MS in 20 partially serpentinized peridotites sampled along a zone of exhumed continental mantle, which is a remnant of ancient Tethyan lithosphere situated between continental and oceanic crust, and now exposed in the Eastern Central Alps. Cpx from the proximal parts has variably depleted trace element patterns with a weak LREE to HREE fractionation and no Eu anomaly, while cpx from the distal part shows convex upward REE patterns with $(Gd/Yb)_n > 1$ and a significant negative Eu anomaly, indicating equilibration with plagioclase. Cpx with highly fractionated REE patterns similar to depleted cpx from abyssal peridotites was found locally in the same outcrop as the plagioclase-bearing peridotites.

To test whether cpx with highly fractionated and concave upward REE patterns was formed during the same process, we analyzed 6 cpx separates for their Nd isotopic composition. The Nd isotope ratios of 5 samples agree with the values obtained from associated MOR basalts and gabbros and are similar to present-day MORB, while one sample analyzed in duplicate exhibits extremely depleted isotopic compositions different from present-day MORB. Model age calculations indicate a Permian age of depletion (294±14 Ma), which is more than 100 Ma years older than the MOR basalts and gabbros (161±1 Ma). These results suggest that partial melting of the mantle is not genetically linked with the formation of the mafic crust. They also suggest that melt infiltration within extending mantle lithosphere modifies ancient subcontinental lithospheric mantle, and this process may account for the fertile composition of many peridotites from passive margins and slow spreading ridges.