Recent advances in Nb-Zr chronometry and early Martian silicate differentiation

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Introduction: The short-lived ^{92}Nb-^{92}Zr decay system is a powerful chronometer to date processes in the early solar system. The *p*-process isotope ^{92}Nb decays to ^{92}Zr with a half-life of ~37 Myr. Niobium and Zr are fractionated from each other during early silicate differentiation. For this reason, the Nb-Zr chronometer can be applied to date early silicate differentiation on planets (i.e. Earth and Mars), but also on smaller planetary bodies as sampled by meteorites (e.g. basaltic achondrites). Hence, the Nb-Zr chronometer provides important, complementary information to the short-lived ^{146}Sm-^{142}Nd chronometer (half-life ~103 Myr) regarding planetary differentiation. The initial ^{92}Nb abundance of our solar system, furthermore, provides constraints on the *p*-process nucleosynthesis e.g., [1,2]. Most applications of the Nb-Zr decay system require the knowledge of a well-defined initial ^{92}Nb abundance of our solar system. While early work suggested that the initial ^{92}Nb/^{93}Nb ratio of our solar system could be as high as ~10^{-3} [2,3], the first study using internal Nb-Zr isochrons yielded a much lower ratio of < 3 × 10^{-5} [4]. Here, we use basaltic achondrites, mesosiderites and calcium aluminum rich inclusions (CAIs) to better define the initial ^{92}Nb abundance of our solar system and assess the homogeneous distribution of Nb and Zr isotopes in the solar system. We also applied the Nb-Zr chronometer to constrain early silicate differentiation on Mars, which complements previous evidence from the ^{182}Hf-^{182}W and ^{146}Sm-^{142}Nd decay systems.

Methods: Antarctic meteorites are extremely valuable for such studies, because they provide unique and important samples that complement the meteorite record from falls and hot deserts. We combined our Nb-Zr data with Pb-Pb ages from the same samples to obtain a robust, high precision estimate on the initial ^{92}Nb/^{93}Nb ratio of our solar system. We also complemented our Martian meteorite samples with precious Antarctic meteorites.

Results and Discussion: *Basaltic achondrites* – We determined internal Nb-Zr isochrons and Pb-Pb ages for basaltic achondrites (i.e. the angrite NWA 4590, the eucrite Agoult, and the ungrouped achondrite Ibitira) [5]. The Nb–Zr and Pb–Pb data for NWA 4590 yielded the most reliable initial ^{92}Nb/^{93}Nb ratio of 1.4 (± 0.5) × 10^{-5} at 4557.93 ± 0.36 Ma. This corresponds to a ^{92}Nb/^{93}Nb ratio of 1.7 (± 0.6) × 10^{-5} at the time of the CAI formation. The result is consistent with the internal isochron obtained for the ungrouped meteorite ASUKA881394 and previous isochrons for an ordinary chondrite and a mesosiderite [4]. The data for Agoult and Ibitira [5] also yielded consistent Nb-Zr ages for the time intervals obtained from the Pb–Pb chronometer for pyroxene and plagioclase. This provides evidence that ^{92}Nb was homogeneously distributed in their source regions of the protoplanetary disk.

Mesosiderites – Rutiles and zircons were separated from several mesosiderites (Vaca Muerta, NWA 1242, A882023, Estherville). The Nb-Zr data defines an initial ^{92}Nb/^{93}Nb ratio of 7.5 (± 0.4) × 10^{-6} at the time of their formation in the mesosiderite parent body [6]. The Pb-Pb age of the zircons is 4527.2 ± 1.1 Myr, and combined with the Nb-Zr results, corresponds to an initial ^{92}Nb/^{93}Nb ratio of 1.6 (± 0.1) × 10^{-5} for the solar system. This is in good agreement with the results from basaltic achondrites, but significantly more precise.

CAIs – The Nb-Zr data for CAIs [7, 8] with rare earth element pattern other than Group II yielded an initial ^{92}Nb/^{93}Nb ratio of 1.6 (±1.5) x 10^{-5}. This is again consistent with the results above and provides strong evidence for a homogeneous distribution of ^{92}Nb in the solar system in the region where CAIs, ordinary chondrites, basaltic achondrites and mesosiderites formed. So far the only evidence for some ^{92}Nb heterogeneity stems from Group II CAIs, which show initial ^{92}Nb/^{93}Nb ratios of up to 3 × 10^{-5}. This heterogeneity is inherent to Group II CAIs only and may reflect the preserved signature of presolar *p*-process enriched dust. It did not affect the other analyzed solar system materials. Therefore, the currently best estimate for the initial ^{92}Nb/^{93}Nb ratio of our solar system is 1.57 (± 0.09) × 10^{-5}.

Early silicate reservoir formation on Mars – Taking advantage of the overall homogeneity for Nb-Zr chronometry in the inner solar system and the new improved estimate for the initial ^{92}Nb/^{93}Nb ratio of our solar system, we applied the Nb-Zr system to Martian meteorites. Their ε^{92}Zr data display identical isotopic composition to chondrites. The exception is ALH84001, which is slightly positive. The overall results are in agreement with the conclusion obtained with previous Sm-Nd data [9], and reflect the formation of early silicate reservoirs on Mars with the first ~50 Myr.

References

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