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Resolving the Hf-Nd paradox of early Earth crust-mantle evolution

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One of the fundamental tenets of geochemistry is that the Earth's crust has been extracted from the mantle creating a crustal reservoir enriched—and a mantle depleted—in incompatible elements. The Hf-Nd isotope record has long been used to help understand the timing of this process. Increasingly, however, it has become apparent that these two isotope records do not agree for Earth's oldest rocks. Hf isotopes of zircon from juvenile, nominally mantle-derived rocks throughout the Eoarchean have broadly chondritic initial isotope compositions and indicate large-scale development of the depleted mantle reservoir started no earlier than ~ 3.8 Ga. In contrast, the long-lived Sm-Nd isotope record shows large variation in Nd isotope compositions. Most notably, Paleo- and Eoarchean terranes with chondritic initial Hf isotope compositions have significantly radiogenic Nd isotope compositions indicative of the development of a widespread depleted mantle reservoir very early in Earth's history which, by extension, requires extraction of significant volumes of enriched crust. These two isotope systems, therefore, indicate two fundamentally different scenarios for the early Earth and has been called the Hf-Nd paradox. However, an important unresolved question remains: Do these records represent primary isotopic signatures or have they been altered by subsequent thermomagmatic processes? We have been able to provide clarity in the Hf isotope record by analyzing zircon from Eo- and Paleoarchean magmatic rocks by determining its U-Pb crystallization age and linking this to its corresponding Hf isotope composition. We can do this unambiguously—even in complex polymetamorphic gneisses—with the laser ablation split stream (LASS) technique whereby we determine U-Pb age and Hf isotope composition simultaneously in a single zircon volume. The existing Nd isotope data, in contrast, are all from bulk-rock analyses. These analyses are potentially problematic in old, polymetamorphic rocks because of the inability to link the measured isotopic composition to a specific age. In addition, the REE budget in these rocks is hosted by accessory phases that can be easily mobilized during later metamorphic and magmatic events. We can now use the LASS approach in REE rich phases (e.g., monazite, titanite, allanite, apatite) to determine U-Pb age and Nd isotope composition in a single analytical volume. New Nd isotope data from the Acasta Gneiss Complex (Fisher et al., EPSL, 2020) show that REE-rich accessory phases are not in isotopic equilibrium with their bulk rock compositions and clearly demonstrate mobilization after initial magmatic crystallization. This post-magmatic open-system behavior may well explain the disagreement in the Hf-Nd isotope record in high-grade polymetamorphic terranes like Acasta. In less complicated, lower-grade rocks, such as in the Pilbara terrane, these REE-rich phases yield consistent U-Pb and Sm-Nd age and isotope compositions indicating that the Nd isotope system in

these rocks has remained closed since formation. Of particular note, in the Pilbara samples, the Hf and Nd isotope systems have consistent, broadly chondritic, initial Hf and Nd isotope compositions. In these less-complicated samples, where the Sm-Nd isotope system has remained closed, the Hf and Nd isotope systems agree and there is no Hf-Nd paradox.