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Snapshots of an evolving planet from noble gases

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Elemental and isotopic abundance patterns of the noble gases (He, Ne, Ar, Kr, and Xe) preserve information about volatile origins, gas loss during accretion, early-formed heterogeneity, and differential processing and outgassing of mantle reservoirs over Earth's history. The large array of noble gas isotopes available for study enables systematic investigation of these super-imposed signatures of volatile origins and transport, providing key insights into processes important to the establishment and sustenance of clement, habitable conditions on Earth's surface.

Modern mantle primordial Ne and Xe isotopes can be explained by mixing between solar nebular gas dissolved during a magma ocean stage, volatiles delivered by carbonaceous rocky materials, and atmospheric influx associated with subduction. Contrasting noble gas signatures in the mantle sources of plumes and mid-ocean ridge basalts (MORBs) provide a glimpse of early separation into at least two mantle reservoirs by the end of accretion: a relatively dry ancient plume source received a limited contribution from volatile-rich carbonaceous rocky materials [1]. The resulting viscosity contrast between the ancient plume and MORB reservoirs may have helped to preserve early-formed radiogenic isotope heterogeneity in the ^{129}I-^{129}Xe system [1,2].

Pairing a model of noble gas accretion with a model of isotopic evolution due to outgassing, atmospheric influx, and radioactive decay indicates that the plume mantle experienced less outgassing over Earth's history and had a lower initial Xe concentration than the ancient MORB source, though initial He concentrations were similar [1]. High-precision isotopic analyses of noble gases in ancient samples of varying age can be used to reconstruct the history of volcanic outgassing over time.

Both plume and MORB noble gas signatures are well-explained as intrinsic to highly processed mantle reservoirs that have experienced extensive outgassing and incorporation of subducted slabs bearing atmospheric gas. Slabs mixed into the plume source may have been wetter on average [3,4], with implications for net volatile transport over time. No noble gas contribution from the core or other hidden primordial reservoir is needed [4].

[1] Parai, 2022, *PNAS*; [2] Mukhopadhyay, 2012, *Nature*; [3] Zhang et al., 2024, *EPSL*; [4] Parai, 2025; *Treatise on Geochemistry*.