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The carbonatite mineral system from inception to completion

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Carbonatites are currently enjoying something of a renaissance due to increasing awareness that these rocks are among our best sources of critical metals. The dominant petrogenetic paradigm suggests that economic rare-earth element mineralization in carbonatites forms only after protracted magmatic differentiation and post-magmatic overprinting by carbo(hydro)thermal fluids in the crust. There are indications, however, that some mantle sources – especially in collision zone settings – are more conducive to the formation of economic carbonatites than others, meaning that not all carbonatites were created equal with respect to metal budgets.

We investigate a global database of the radiogenic and stable isotope compositions of carbonatites through the past 3 billion years. In Sr-Nd-Hf isotope space, the carbonatite data array develops between a well-defined moderately depleted endmember, which is reminiscent of prevalent mantle, and a range of enriched isotopic components. The enriched components are highly heterogeneous and may represent ancient metasomatized mantle lithosphere or various types of recycled crust, including sediment, located within the mantle. Carbonatites from collision zones contain uniquely enriched ‘mantle’ flavours. Importantly, several isotopic tracers – and in particular the d^{11}B and d^{34}S compositions – show that recycled crustal components in the mantle sources of carbonatites became increasingly common after 1 Ga, possibly linked to Earth’s transition into a modern plate-tectonics regime at lower geotherms.

To further test the robustness of this secular evolution, we present new isotope data for rare Archean carbonatites from Greenland and Finland. Our Pb and Hf isotope data (for bulk carbonatites and their zircons), as well as SIMS-determined D^{33}S data for carbonatite-hosted sulphides, reveal a dominant mantle source signature without traceable inputs from Archean recycled crust components. Initiation of colder subduction mechanisms after 2.5 Ga promoted deeper levels of lithosphere transfer into the convecting mantle, including a more effective introduction of volatiles and sediment into the deep Earth. We therefore suggest that it is no coincidence that the richest rare-earth element deposits occur in post-Archean alkaline rock and carbonatite districts located in Proterozoic mobile belts and Phanerozoic collision zones, where their upper mantle sources received a much larger contribution of fertile components from recycled crust.