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Multi-stage mantle source evolution constrained by modelling Sr–Nd–Hf–Pb isotopes: Implications for the genesis of the West Kimberley lamproites

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The lamproites of the West Kimberley display some of the most extreme Sr–Nd–Hf–Pb isotopic compositions reported from global cratonic lamproites. Their initial Pb isotope ratios are relatively restricted yet distinctive, with low $^{206}Pb/^{204}Pb_i$ (17.21–17.56) and comparatively high $^{207}Pb/^{204}Pb_i$ (15.66–15.80) and $^{208}Pb/^{204}Pb_i$ (37.62–38.47). Further, these lamproites exhibit highly radiogenic Sr ($^{87}Sr/^{86}Sr_i$ = 0.7103–0.7196), unradiogenic Nd (εNd = −7.7 to −15.7), and unradiogenic Hf (εHf = −19.8 to −26.3). A three-stage Pb evolution model was previously proposed to explain the Pb isotopic systematics, invoking an extremely ancient, moderately high U/Pb reservoir, possibly very old subducted crust in the mantle source. More recent studies have emphasized a long-lived, mica-rich lithospheric mantle component formed during ancient subduction-related metasomatism to account for the enriched Sr–Nd–Hf characteristics. However, no study has yet evaluated whether Pb and Sr–Nd–Hf isotope models are mutually consistent within a single petrogenetic framework.

Here we integrate a multi-stage Pb isotope evolution model with forward modelling of Sr–Nd–Hf isotopes. We explore a spectrum of possible U/Pb versus time combinations for 3-stage models, but our preferred Pb model starts from an initial mantle reservoir (μ_1 = 8.4) that experienced enrichment in U/Pb at 2.5 Ga (t_1), followed by a second event of reduced U/Pb at 1.87 Ga (t_2), leading to the present-day Pb isotopic compositions of the West Kimberley lamproites. These timings coincide with major tectono-magmatic events, including amalgamation of the North Australian Craton at 2.5 Ga and widespread mafic and granitoid magmatism at 1865–1790 Ma in the Kimberley region. Forward modelling from 1.87 Ga (t_2) onward demonstrates that mixing between depleted, low-degree asthenospheric melts and enriched, metasomatized, phlogopite-bearing lithospheric mantle components reproduces the observed Sr–Nd–Hf compositions. We propose that this hybrid mantle domain, following its earlier multi-stage Pb evolution up to 1.87 Ga, became isolated within thick cratonic lithosphere, where prolonged radiogenic ingrowth over billion-year timescales generated the extreme Sr–Nd–Hf isotopic signatures. Reactivation of this long-lived mixed source at ~20 Ma, potentially driven by small-scale mantle convection at the craton margin, produced the West Kimberley lamproites.