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Protracted formation of reduced protoplanets in the innermost Solar System constrained by Pb-Pb anchoring and Mg-Fe-Si nucleosynthetic systematics

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Highly reduced achondrites are widely interpreted as products of planetesimal formation in the innermost Solar System, but their ultramafic and Al-poor compositions hinder conventional ^{26}Al-^{26}Mg isochron dating. We investigated a suite of reduced meteorites spanning aubrites (NWA 11377, NWA 17941), an EL impact-melt breccia (Al Haggounia 001), and three ungrouped Mg-rich clinopyroxenites/diopsidites (NWA 13307, NWA 15915, Ksar Ghilane 022). High-precision MC-ICP-MS measurements of Mg, Fe, and Si isotopes were combined with progressive acid-dissolution Pb-Pb dating of Ksar Ghilane 022 to provide an absolute chronological anchor and to assess nucleosynthetic provenance. In an inverse Pb-Pb diagram, Ksar Ghilane 022 defines a linear dissolution array with a y-intercept age of 4562.2 ± 4.1 Ma, interpreted as its solidification age. The six samples yield indistinguishable μ^{26}Mg* despite variable ^{27}Al/^{24}Mg (0.006-0.106), with μ^{26}Mg* ranging from -2.4 ± 1.6 to 1.0 ± 3.0 ppm and a weighted mean of -1.2 ± 0.8 ppm. Relative to CI chondrites, the reduced suite is offset by -4.1 ± 0.9 ppm, consistent with a maximum expected reservoir deficit of ~5 ppm. Deficit-dating models imply minimum differentiation ages of 4.5 Myr after CAIs for homogeneous ^{26}Al, or 2 Myr after CAIs if the inner disk started with reduced ^{26}Al. Fe isotope compositions yield μ^{54}Fe = 4.6 ± 2.0 ppm (2.9 ± 4.6 to 10.2 ± 6.8 ppm), and Si isotope data yield μ^{30}Si = 7.0 ± 1.8 ppm (2.6 ± 5.1 to 9.3 ± 3.6 ppm), defining a coherent inner-disk non-carbonaceous signature that plots within the Solar System μ^{54}Fe-μ^{30}Si trichotomy (Fig. 1). Together, these constraints support protracted accretion and late melting of highly reduced planetesimals when ^{26}Al heating was largely exhausted, requiring collisional growth and/or gravitational energy release, with direct relevance to Mercury-like inner-disk building blocks.