

<https://doi.org/10.1038/s43247-026-03642-5>

# Transient mantle–crust interaction restores porphyry copper–molybdenum fertility during continental collision

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Porphyry copper–molybdenum deposits are typically linked to subduction, yet some of the largest form during continental collision. Here, we investigate when mantle processes become effectively coupled to the crust to enable large-scale metal transfer. We combine seismic imaging with zircon and apatite mineral chemistry and whole-rock isotopes from southeastern Iran, where metal-poor and metal-rich magmas formed in the same crustal region. Despite similar mantle sources, fertile magmas show higher oxidation state (more oxidising conditions relative to a standard mineral buffer), higher melt sulphur contents (greater than 100 micrograms per gram), and signatures of deep, high-pressure differentiation (strontium to yttrium ratios above 40). These changes coincide with evidence for lateral inflow of hot mantle material. We interpret this as a transient transfer of heat and oxidising, volatile-rich components into the crust, destabilising sulphide minerals and releasing copper and molybdenum. Porphyry formation in collision zones, therefore, reflects short-lived thermochemical coupling rather than persistent mantle enrichment.

Magmatic porphyry copper–molybdenum (Cu–Mo) deposits supply more than three-quarters of the world's copper and are essential for meeting the rapidly increasing demand for metals required by the global energy transition<sup>1</sup>. Their formation is classically linked to oxidised, water- and chlorine-rich magmas generated above subduction zones, where slab-derived fluids metasomatize and oxidise the mantle wedge and subsequent melting produces fertile magmas that release ore-forming fluids at mid-crustal levels<sup>2</sup>. However, several of Earth's largest porphyry systems occur during continental collision, in settings where slab rollback, slab break-off, or progressive attenuation of subduction modifies—but does not necessarily terminate—mantle dynamics<sup>3</sup>. This paradox highlights a broader Earth-system problem: how and when does mantle-derived heat, oxidation, and volatile flux become effectively transmitted into the continental crust after slab termination? Here we define “mantle–crust coupling” explicitly as the efficiency with which mantle-derived heat, oxidants (Fe<sup>3+</sup>), and volatile species (H<sub>2</sub>O–Cl–S) are transferred across the Moho into lower- to mid-crustal magma reservoirs, and retained long enough to modify their redox state, sulphur solubility, and metal mobility.

This usage differs from geometric or kinematic mantle–crust coupling, which refers to mechanical transmission of strain between mantle and crust<sup>3,4</sup>. In this study, coupling is used exclusively in a thermochemical sense, describing the efficiency of heat, oxidant, and volatile transfer across the Moho. In this framework, coupling is not treated as a primary tectonic descriptor, but rather as a thermochemical state that reflects the efficiency of transfer of heat, oxidants, and volatiles across the Moho under specific tectonic boundary conditions, that can be evaluated using three measurable parameters: (i) change in magma oxidation state ( $\Delta$ FMQ) recorded by zircon Ce anomalies, (ii) reconstructed melt volatile budgets (Cl–F–S) from apatite–melt partitioning, and (iii) evidence for prolonged deep-crustal storage (e.g., amphibole  $\pm$  garnet-dominated differentiation and high Sr/Y). “Decoupling” refers to conditions in which mantle heat is present but fails to induce sustained redox and volatile modification of crustal reservoirs. This thermochemical framework implicitly requires a preceding state of physical or kinematic decoupling within the lithosphere. Processes such as slab break-off, lithospheric delamination, or progressive slab attenuation reduce mechanical coupling between the subducting slab and overriding plate, allowing asthenospheric material to migrate laterally and approach the base

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