ECONOMIC GEOLOGY

Copper conundrums

The metal content of magmas erupted at subduction zone arcs is thought to be derived from the mantle. A correlation between crustal thickness and copper content in arc magmas worldwide, however, reveals an important role for the crust in the upper plate.

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Most of the world's copper ore deposits are associated with porphyries — rocks with a unique texture generated by the crystallization of magma at shallow depths. Porphyries can occur in any type of volcanic environment, but copper-bearing porphyries are exclusively found in subduction zone volcanoes. This implies that water derived from the water-rich subducting slab plays a role in copper enrichment[1,2]. However, it has been unclear whether the metal content of copper-porphyry deposits is mostly imparted by a source in the mantle[3–5] or a source in the crust of the overriding plate[1,6,7]. Writing in *Nature Geoscience*, Massimo Chiaradia[8] reports a statistical assessment of the geochemical signature of magmatic rocks from arcs worldwide and shows that copper enrichment is inversely correlated with the thickness of the overriding plate, suggesting that the crust plays an important but counterintuitive role in copper-porphyry ore formation.

Hypotheses for the origin of copper porphyries abound, but broadly follow two distinct lines of argument. One view is that these deposits derive their copper from an anomalously copper-rich source in the subducting slab or mantle. In this scenario, melting of the down-going slab or mantle wedge destabilizes sulphide and releases copper, a sulphide-loving element, to the magma[3–5]. The magma then transports the copper into the overriding crust where it accumulates as a porphyry deposit. An alternative view, however, suggests that copper enrichment is caused by magmatic processes that operate entirely within the crust of the upper plate, without contributions from the mantle or subducting slab[1,6,7].

The formation of copper-porphyry ore deposits also seems to depend on tectonic setting. Within subduction zones, copper porphyries occur more frequently in continental arcs (where oceanic lithosphere subducts beneath a continent) than in island arcs (where oceanic lithosphere subducts beneath oceanic lithosphere)[9]. For example, copper porphyries are common in the Andes Mountains, where the Nazca Plate subducts beneath the South American continent, and in some parts of western North America, where oceanic lithosphere has been subducting beneath the western North American continent. However, they are absent from the Aleutian, Japanese and most of the western Pacific island arcs, where both the down-going and over-riding plates are oceanic. This difference between continental and oceanic settings suggests that the overriding crust, rather than the mantle, influences the metal content of porphyry magmas. Yet, there are notable exceptions to this rule, such as the occurrence of copper porphyries in the Philippines island arc and their absence in the Cascades continental arc. The precise controls on porphyry copper ore formation are therefore unclear.

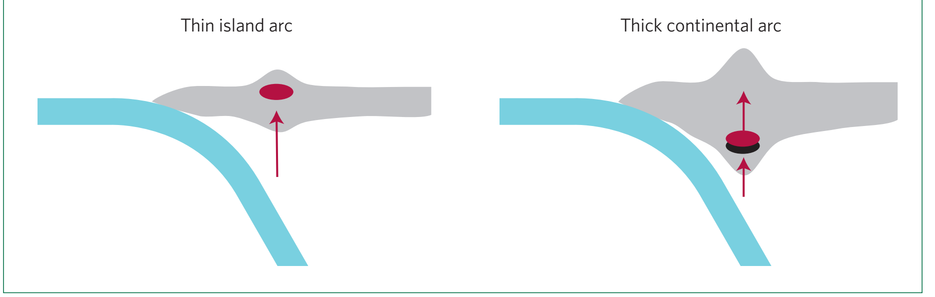

Figure 1 | Schematic illustration of thin island and thick continental arcs. Mantle-derived magmas (red) intrude into the cold upper plate (grey) of subduction zones, generating crystallizing magma chambers. Chiaradia[8] finds that magmas evolving in the thick crust of continental arcs become depleted in copper, yet copper-porphyry ore deposits are mostly found in continental arc settings. To explain this counterintuitive relationship, Chiaradia proposes that iron depletion and magnetite fractionation in continental arc magmas triggers the precipitation of sulphides. The sulphides strip the magma of copper, explaining the depletion, and copper-rich cumulates are formed at the base of the crust (black). As the arc matures, these deep-seated cumulates may re-melt, releasing the copper for subsequent deposition in copper porphyries. In contrast, magmas evolving within thin island arc crust may not become iron-depleted or sulphide-saturated. The magmas remain copper-rich, but, without the formation of a thick accumulation of copper-rich sulphide cumulates, copper-porphyry ore deposits do not form.

Massimo Chiaradia[8] presents an exhaustive statistical assessment of more than 40,000 published geochemical analyses of copper systematics in magmatic arc systems worldwide. He finds that the copper content of arc magmas correlates inversely with crustal thickness — magmas passing through thick crust become depleted in copper and those passing through thin crust become moderately enriched. The existence of this statistical relationship between crustal thickness and copper content confirms that the tectonic environment does indeed affect the deposition of copper. However, continental arcs are generally thicker than island arcs, so this inverse correlation between copper enrichment and crustal thickness seems counterintuitive.

A hint towards understanding this conundrum comes from iron. Chiaradia shows that iron and copper contents in arc magmas are also highly correlated — in the thicker crust of continental arcs, magmas become depleted of iron as well as of copper. Iron depletion is linked to magnetite crystallization[10,11], which should in turn trigger the precipitation of sulphides[12,13]. Chiaradia argues that because copper is a sulphide-loving element, it will be stripped from the magmas by the sulphides, explaining why magmas in thicker crust become copper-depleted. Together, the copper and sulphides form thick accumulations at the base of the crust (Fig. 1). According to this view, it is only after these deep-seated sulphide-bearing cumulates have been re-melted by subsequent magmatic events that the concentrated copper is released and transported to shallower depths in the continental crust to form copper-porphyry deposits.

If correct, copper porphyries are generated only after large amounts of sulphide-bearing cumulates form — a condition that is met following maturation and thickening of continental arcs. In contrast, thin island arcs do not develop thick accumulations of sulphide-bearing cumulates. So, even though the magmas that build island arcs have high copper contents, such enrichments do not seem to be sufficient to generate copper porphyries. With this view, Chiaradia joins a small but growing chorus of studies concluding that copper porphyries derive from intracrustal processes rather than from the mantle or subducting slab[1,6,7].

An important implication of this study bears on our understanding of the formation of continents, because continental crust has geochemical similarities to differentiated magmas, which are iron-depleted. It has been hinted that arc magmas would become depleted in iron as the crust thickens[14], but this suggestion has since been forgotten, discounted or ignored. Chiaradia's comprehensive study now shows conclusively that the iron-depleted nature of arc magmas increases with crustal thickness[8]. He suggests that high water contents may trigger iron depletion, implying that water plays an important role in making continental crust as well as copper deposits. Although the importance of water is not new, this result provocatively implies that the thickness of the upper plate modulates the water content of arc magmas, even though the initial source of water is thought to come from the subducting plate.

Massimo Chiaradia[8] demonstrates an inverse correlation between the copper content of magmas and crustal thickness in subduction zone arcs worldwide. These findings support the emerging view that the physics of magma transport through the lithosphere provide a key control on the chemical evolution and thus the metal content of arc magmas. ❐

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