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What Makes Plate Convergent Zones Fertile in Metals?

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1 Introduction

Many large porphyry Cu deposits are hosted by magmatic arcs and occur broadly parallel to subduction zones. Their distribution and other features have been used to suggest a genetic link between mineralization and subduction processes (e.g., Sillitoe, 1972). However, a close examination of the igneous rocks associated with some deposits shows that these rocks may not be directly associated with subduction processes. Examples include alkaline igneous rocks hosting porphyry deposits that formed long after subduction (e.g., Richards, 2009; Bissig & Cooke, 2014). Igneous rocks that host large porphyry deposits in the western US, such as the giant Bingham deposit and deposits in Arizona, are Late Cretaceous-Paleogene in age, but they originated from Proterozoic subcontinental lithospheric mantle (e.g., Farmer & DePaolo, 1984). In addition, the discovery of porphyry Cu deposits in collisional belts, such as in Tibet and some in Iran, without a relationship to contemporaneous subduction, has raised questions whether subduction processes are essential for porphyry Cu mineralization, and whether porphyry Cu deposits form in juvenile arc systems. Here I argue that subduction processes are indeed integral to the formation of porphyry deposits.

2 Evidence for Subduction Processes

The most compelling evidence for the role of subduction in porphyry deposits is the oxidized nature of the igneous rocks associated with mineralization, as has been noted by many researchers. Shunso Ishihara (1977) first made the empirical observation of oxidized intrusions (he called them magnetite series) and porphyry Cu deposits; subsequent studies confirmed that fertile belts contain intrinsically oxidized igneous rocks (e.g., Sillitoe, 2010). The asthenospheric mantle is relatively reduced fO_2 , ~ FMQ-1, as well documented in mid-oceanic ridge basalts and rift-related magmas (e.g., Bézous & Humler,

2005), and it cannot produce oxidized magmas. Oxidized mantle can only be formed in mantle wedges where oxidized species are introduced during the subduction process. Many studies confirm the oxidized nature of mantle wedges, greater than FMQ+1 (e.g., Kelley & Cottrell, 2012). These values suggest that subduction processes increased the oxidation state of average subarc mantle by more than three logarithmic units. Oxidized mantle can produce oxidized mafic melt, which then evolves to form felsic magmas (e.g., DeHoog et al., 2004).

Data from granitic rocks closely related to giant porphyry Cu deposits shows that these rocks are more oxidized than most subduction-related igneous rocks. Examples include granitic rocks associated with the Chuquicamata-El Abra belt in northern Chile (Ballard et al., 2002). Recent work by Shen et al. (2014) also shows exceptionally high fO_2 , FMQ+3, for intrusions associated with deposits in the Central Asian orogenic belt.

The occurrence of oxidized magmas in close association with large porphyry Cu deposits is consistent with their enhanced capacity to transport high concentrations of metals and sulphur (need a ref). By contrast, in reduced magmas, sulphides form during magma crystallization, and both metals and sulphur are scavenged by sulphides without the ability to reach shallow crustal levels.

3 Factors Controlling the Oxidation State of sub-arc Mantle

The oxidation conditions in subduction zones are controlled by the subduction geometry and nature of the subducted material. In oceanic subduction zones, pelagic sediments on incoming oceanic plates are subducted. Pelagic sediments consist of carbonates, silica, and clay. Among these, carbonate sediment is the most abundant on the ocean floor, as it forms biogenic shells; it is an oxidant. In shallow subduction zones, not only carbonates but minor evaporites, also an oxidant, may be present. These oxidants are scarce on the deep ocean floor because

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they dissolve in the water column below carbonate compensation levels. Therefore, subduction zones with deep trenches are less likely to receive an oxidized flux.

Sediments can contain not only oxidants but also reductants, such as bitumen and gas as gas hydrate. Such reductants are abundant in some sediments, such as the methane hydrate-rich Nankai trough in southwestern Japan and Costa Rica forearc sediments (e.g., Kurihara et al., 2009). The subduction of such sediments lowers the oxidation state, as shown in rocks of the Austral subduction zone at the southern tip of South America (Wang et al., 2007).

The geometry of subduction zones is also an important factor that influences the nature of subducted material. Sediments on incoming plates may be fully subducted or scraped off to be accreted. In some subduction zones, the overlying plates may also be eroded to supply upper crustal material to the mantle wedge.

4 Fertile vs Barren Subduction Systems

The creation of an oxidized mantle wedge as a major requirement for a fertile magmatic arc can explain the apparently different metal endowments of subduction-related belts. An evaluation of the geometry of past subduction provides a clue to the potential production of fertile belts. For example, several belts in the Tibetan plateau host moderate-sized porphyry Cu deposits. The plateau was produced by thickening of lithosphere during the subduction of the Indian continent below the Asia continent. The northern margin of the Indian continent was covered by shallow marine sediments, such as limestones and evaporites (e.g., Mukherjee et al., 2003), and these oxidized sediments likely contributed to the formation of an oxidized lithospheric mantle below the southern margin of the Asian continent. Another good example supporting the linkage between metal fertility and subduction of oxidized species is New Zealand and Japan. These two long-lasting arcs are known to lack porphyry Cu deposits. The geometry of their subduction zones suggests a poor source for oxidized sediments, since the trenches have been far deeper than the depth of carbonate compensation at 4,000 m.

5 Other Factors Essential for the Fertility of a Belt

The existence of oxidized mantle is essential, but it does not necessarily lead to the formation of large porphyry Cu deposits; other factors are required, including magma generation after the development of oxidized mantle, and repeated intrusion of these magmas into focused areas, as observed in many deposits. This requirement, focused sites for magmas, requires an overall mildly compressional rather than extensional regime (e.g., Takada, 1994).

In summary, a combination of several factors is required to form a fertile belt for large porphyry Cu deposits. They include the formation of an oxidized lithospheric mantle by subduction of oxidized sediments, and later partial melting in the mantle under a mildly compressional regime in the lithosphere to produce loci for magmas and fluids to ascend from the mantle to felsic magma reservoirs at shallow crustal depths. A lack of such features may explain why all subduction-related arcs do not contain large porphyry Cu deposits.

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