

Tectonic controls on the distribution of large copper and gold deposits in Southeast Asia to identify productive and non-productive structures

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Abstract. Ore deposits occur in a wide range of tectonic settings, and are highly variable in their local characteristics. In this paper, we focus on the distribution of copper and gold deposits in the Southeast Asia region, and investigate large-scale plate-tectonic controls on the distribution and characteristics of these porphyry copper and epithermal gold deposits. We then discuss the applicability of these results to exploration in older geological terranes, and suggest clues to distinguishing productive from non-productive geological structures.

Keywords: Porphyry Copper-Gold, Tectonics

1 Tectonics and mineralisation in SE Asia

Southeast Asia is a collage of ophiolitic, island and oceanic arc terranes that formed as part of a complex series of intra-oceanic and oceanic-continental subduction (Figure 1). These tectonic processes involved three oceanic plates (the Philippine Sea (PSP) and Caroline (CP) Plate in the east, and the oceanic part of the Indian-Australian Plate (IP) in the west) and, the margins of the continental Eurasian Plate and continental part of the Indian-Australian Plate (AP). In this paper, we have used the Cenozoic tectonic reconstructions of Hall (2002) and a database of mineral deposits first published by Rak (1999) but enhanced with more recent information, as a basis for examining the tectonic context of mineral deposits.

According to Hall (2002), the tectonics in the region are punctuated by the following main events: (a) 45 Ma, dextral tectonic escape of blocks in Indochina and subduction of the proto-South China Sea Plate (PSCSP), with development of a spreading ridge in the PSP; (b) 25 Ma, collision of Australia with the Philippines-Halmahera Arc and of the Ontong Java Plateau with the Melanesian arcs. Closure of the PSCSP, and opening of the South China Sea; thickening of crust in North Borneo through underthrusting of continental crust from the northwest. Commencement of the clock-wise rotation of the PSP; (c) 5 Ma, collision of the Philippines and the SE Asian continental margin and a resulting jump of the subduction zone from the west to the east of the Philippines.

The Sunda Arc in Western Indonesia has been the site of ongoing subduction of the IP below thin continental crust of SE Asia (Sundaland) during the entire Cenozoic period. No large porphyry systems are known in the continental arc section of Indonesia (Sumatra and Java), and only few epithermal gold occurrences, such as the Pungkut deposit. Most gold occurrences are located along the dextral Sumatran Fault, which initiated sometime in the Middle Miocene due to the oblique collision of the IP with SE Asia. To

the east, however, on Sumbawa, several porphyry systems are known, of which the largest is the 5 Million year-old Batu Hijau deposit. Tectonics in that region, east of longitude 115°E, consists of the consumption of the IP below the remnants of the Molucca Sea Plate (MSP), i.e. intra-oceanic subduction and the formation of island arcs.

In **Northern Indonesia**, dextral escape tectonics related to India-Asia collision resulted in the southward subduction of the proto-South China Sea Plate (PSCSP) below Borneo. This subduction ceased at about 24 Ma, with continent-continent collision and accretion of the sedimentary prism to northern Borneo. The cessation of subduction changed motion of the PSP, and collision of the AP with the Sunda Arc resulted in counter clockwise rotation of Borneo. In Sulawesi, northward subduction of a trapped fragment of the IP and final assembly of the Sulawesi terranes gave way to southward subduction of the Celebes Sea Plate (CSP) at about 7 Ma. At about the same time, trapped IP between Sulawesi and Halmahera, the Molucca Sea Plate (MSP) was subducted westward beneath the northern and eastern arms of Sulawesi. Earthquake data seem to suggest that the angle of the westward subduction of the MSP is steeper than the angle of southward subduction of CSP, making it plausible that subducted CSP is above the actively subducting MSP in this region. Further east, the Halmahera arcs are the result of the eastward subduction of the eastern margin of the MSP below the advancing CP. The MSP fragment was largely consumed by 1 Ma, resulting in the two subduction zones merging to a single west-dipping zone.

Deposits in western and central Borneo are dominated by low sulphidation epithermal and porphyry copper-gold deposits, which were developed at ca. 20 Ma, at the time when subduction of the PSCSP stopped (e.g. Mount Muro and Mirah). Other deposits developed between 13 and 9 Million Years ago and include one large porphyry copper-gold deposit (Mamut) and several low sulphidation epithermal deposits (e.g. Bau District).

Deposits in northern Sulawesi include porphyry copper-gold systems (e.g. Sungai Mak) as well as epithermal systems (e.g. Gunung Pani) emplaced between 5 and 1 Ma. The deposits are potentially linked to the cessation of subduction of the MSP and the complex interaction of the west-dipping and shallower south-dipping subduction zones beneath northern Sulawesi (CSP and MSP).

In the Halmahera arcs, the Gosowong (epithermal) and Kaputusan (porphyry) deposits are most likely related to the cessation of eastward subduction and subsequent start of westward subduction during the past 10 Million Years.

Papua New Guinea comprises the northern margin of the Australian Craton in the south, and a series of oceanic fragments and oceanic arc terranes in the north. Active oceanic arcs are still developing east of the main island in New Britain and New Ireland, and further southeast along the interface between the Solomon Sea Plate and the Pacific Plate.

The younger oceanic (arc) fragments of the main island were accreted in the late Miocene during oblique convergence in relation to the rotation of the PSP and convergence of the CP. The main island of Papua New Guinea hosts some world-class porphyry and epithermal gold deposits including Grasberg, Ok Tedi, Frieda River, Porgera, Wafi, Hidden Valley and Mt Kare. Most of these deposits are either located on or near the remnants of the longitudinal suture zones, most notably the Ramu-Markham and Bismarck fault zones (RMB, Figure 1), or along transverse faults, such as the Mapenduma (Grasberg), Ok Tedi and Porgera faults.

The **Philippines** comprises a series of island arc terranes that have been accreted during the Pliocene. These terranes comprise a variety of oceanic arcs that were translated from the south since the Middle Miocene through the rotation of the PSP, and juxtaposed in their present position sometime in the Pliocene. The westward movement of the Pacific Plate since that time has resulted in the final accretion of the Philippine arcs, and resulted in a shift of the subduction from the Manila Trench (west) to the present Philippine Trench (east). These drastic changes in tectonic regimes over the past 5 Million Years lie at the basis of the significant gold endowment of the Philippines. The main porphyry copper-gold deposits are located east of the crustal-scale sinistral Philippine Fault Zone (FFZ, Figure 1) but do not appear to be primarily controlled by this crustal feature (e.g. the Baguio and Mankayan districts). In fact most of the deposits lie along the axes of Pliocene to Quaternary volcanic arcs. Extensional jogs are believed to play a role in the mineralisation of vein-type copper-gold.

2 Plate tectonic models and mineral endowment

It has been generally accepted that not all arc systems produce economic deposits. Fertile magma systems include potassic alkaline magmas, alkaline arc magmas and adakitic magmas. The latter demonstrate characteristics that can be plausibly explained only by the participation of partial melts from the subducting oceanic slab. Partial melting of subducting oceanic crust, however, only takes place in specific circumstances, including the cessation of subduction, slow or very oblique subduction, flat subduction and subduction of very young (hot) oceanic lithosphere (Mungall, 2002). The Plate Tectonic mechanisms that have been active in SE Asia during the Cenozoic included the formation and destruction of various segments of ocean crust. Subduction of oceanic crust resulted in the formation of an Andean-type arc along the southern margin of the SE Asian crust in western Indonesia; the formation of oceanic arcs and subsequent accretion of these to the Australian crust in eastern Indonesia and Papua New

Guinea; and the juxtaposition of a series of oceanic arcs and final accretion of those to SE Asian crust in the Philippines.

In **western Indonesia**, subduction has been going on continuously, with the consumption of the Indian plate below thin crust of SE Asia. The oblique vector of this subduction results in the formation of an important dextral shear zone on Sumatra, the Sumatran Fault Zone. No significant porphyry systems are known in western Indonesia. The subducting oceanic plate in this region comprises cold Eocene crust, while the thin lithosphere of SE Asia is also relatively cold. These factors suggest that the subducting oceanic plate never had time to heat up sufficiently to significantly contribute to the melts within the arc and could explain the apparent paucity of economic porphyry systems.

In **Eastern Indonesia** the tectonic drivers become significantly more varied. In Borneo, earlier southward subduction of the PSCSP was immediately followed by rotation of Borneo and formation of crustal scale structures, providing conditions in which the slab may have been trapped and heated sufficiently to induce partial melting. It is worth noting that the older systems (e.g. Mount Muro) appear to be located along the southeastward extension of faults which accommodated the dextral escape tectonics and lateral ramp architecture related to collision of India with Asia during the Miocene. In northern Sulawesi, the earthquake data support a lower angle of subduction of the CSP compared to the westward subducting MSP between Sulawesi and Halmahera. Devolatilisation of the hot MSP and additional heat from trapped metasomatised mantle wedge, together with shallow subduction of the CSP, would facilitate higher degrees of partial melting of the subducted CSP, resulting in low sulphidation oxidised melts, suitable for the generation of porphyry copper-gold systems in the region.

In **Papua New Guinea**, the main tectonic driver was the transverse accretion of young oceanic arcs to the Australian Craton. This transverse movement induced extensional jogs which facilitated the emplacement of some of the porphyry systems. In contrast to the IP below western Indonesia, the oceanic crust of the PSP and CP is relatively young and hot, while subduction was very oblique with respect to the Australian craton. These factors would have possibly facilitated the partial melting of the subducting slab and the formation of adakitic melts to form fertile porphyry systems.

The **Philippines** is the site of various recent subduction zones, and accretion of relatively young oceanic arc fragments. Subduction along the western side of the islands, in the Manila trench, ceased with the docking of the intra-oceanic arc assemblage to the SE Asian margin. This docking triggered the start of subduction to the east, in the current Philippine trench, which is the driving force of active volcanism on the islands now. The cessation and reprisal of subduction, as well as the relatively young nature of the oceanic arcs and crust would favour the melting of subducted oceanic slab to form richly endowed adakitic melts, explaining the fertility of the archipelago. We note that most mineral systems are localised along the sinistral FFZ or associated extensional jogs.

3 Ancient systems

Preservation is a key issue in identifying features in older geological terranes. The epithermal and porphyry systems in SE Asia are young, and form at a relatively high level in the crust, in actively emergent landscape systems. Their preservation potential is therefore quite low, and in similar settings in older systems will definitely be a limiting factor of any analysis. A review of the global distribution of pre-Cenozoic deposits shows that most porphyry and epithermal deposits form in linear belts at once-active (convergent) margins, suggesting that collision- or accretion-related magmatism are the main first-order ingredients to the formation of world class orebodies of that type.

The analysis of the distribution of these deposits in southeast Asia highlights that subduction alone is no guarantee for the emplacement large porphyry copper-gold or epithermal gold deposits, but that these deposits form at times when tectonic mechanism changes dramatically, such as the cessation or start of subduction. It is postulated that the main reason behind this is related to the thermodynamic conditions of the subducted lithosphere (Mungall, 2000). In ongoing subduction the participation of this subducting lithosphere is limited to

devolatilisation and resultant destabilisation and participation of the upper plate. In contrast, cessation of subduction results in longer residence times of the subducted lithosphere, allowing it to actively participate in the formation of melts. This participation will further be enhanced if the subducted plate is relatively young and hot, or if through the interaction of a new oblique subduction system, devolatilisation of the new subducting plate destabilises not only the lower parts of the upper plate, but also the detached fossil slab, as could be the case for northern Sulawesi.

4 Conclusions

Understanding the tectonic events that can trigger mineralisation is an important factor in assessing the exploration potential of different structures. However, unravelling a detailed tectonic history in poorly preserved pre-Cenozoic terrains is much more difficult than in younger terrains. It is our view, however, that detailed mapping and structural analysis, combined with targeted geochronology and rock geochemistry in these older terrains can help, to some degree, to identify the potential tectonic triggers that can lead to large mineral porphyry and associated epithermal deposits, and help classify productive vs. non-productive crustal structures.

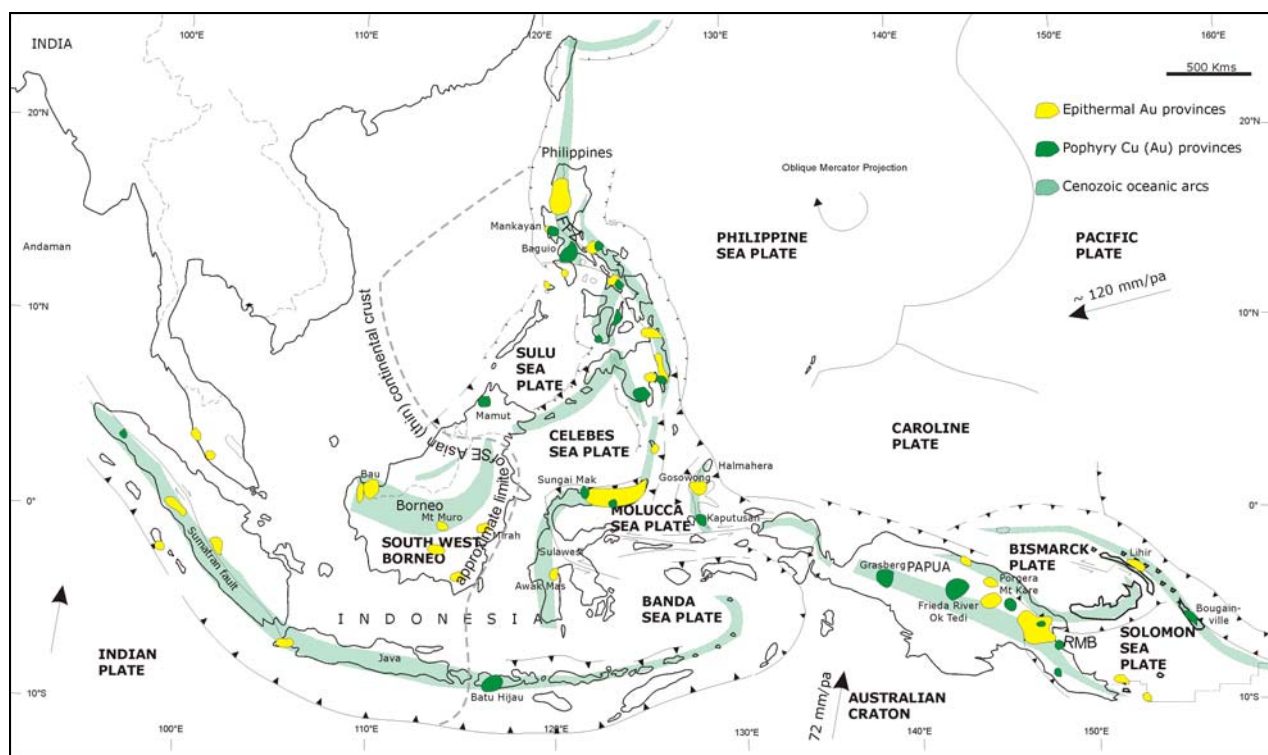


Figure 1. Regional tectonic map of SE Asia, showing the main porphyry Cu-Au and epithermal Au deposits

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