

Tectonic controls on magmatic-hydrothermal gold mineralization in the magmatic arcs of SE Asia and the SW Pacific

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Abstract

The magmatic arcs of SE Asia and SW Pacific contain some of the world's major magmatic-hydrothermal gold deposits. Most gold deposits in SE Asian and SW Pacific arcs formed during periods of plate reorganization rather than during periods of normal or steady state subduction. These plate reorganizations were caused initially by the collisions of the Australian Craton with the Philippines-Halmahera Arc and the Ontong Java Plateau with the Melanesian Arc at ~25 Ma. A second Mid-Miocene period of mineralization accompanied plate reorganization following maximum rotation or extrusion of Indochina and cessation of spreading in the South China Sea at ~17 Ma. However, the vast majority of deposits from New Zealand to Taiwan formed since 7 Ma during an important period of tectonic reorganization that accompanied and followed changes in the relative motion between the Indian-Australian and Pacific plates between ~8 and 3.5 Ma. Magmatism in unusual tectonic settings produced the most abundant and largest deposits with many deposits associated with high-K calc-alkaline, shoshonite, adakite and alkaline magmatism. In particular peak mineralization appears related to melting of sub-arc lithosphere that has been previously modified by subduction. During large-scale plate reorganization this can occur towards or at the end of a period of normal subduction, following arc collision or accompanying subduction reversal at approximately the same time in different parts of a complex system of arcs such as in SE Asia and the SW Pacific.

Introduction

The magmatic arcs that surround the Pacific Ocean are richly endowed with magmatic-hydrothermal gold deposits. Although a spatial and temporal link between these types of metal deposit and subduction-related magmatism has been recognised for some time (Mitchell and Garson 1972; 1976; Sillitoe 1972; 1989), deposits are most abundant within specific arc sectors and during specific periods (e.g. Sillitoe 1989; 1997). This strongly suggests that tectonic factors other than normal or steady state subduction of oceanic lithosphere are important for the formation and localisation of magmatic-hydrothermal gold deposits in magmatic arcs.

The magmatic arcs of SE Asia and the SW Pacific formed during the Cenozoic as a result of the convergence of the Indian-Australian, Philippine-Pacific and Eurasian plates. This area contains some of the world's largest and richest gold deposits and has experienced relatively rapid changes in plate configuration and rates of tectonic processes. It is thus a key area for assessing the

effects of regional tectonics on the distribution of magmatic-hydrothermal gold deposits. Barley et al. (2002) superimposed a database of gold deposit ages and styles on Hall's (1996; 1998) animated tectonic reconstruction of SE Asia to evaluate tectonic controls on mineral deposit formation in that region. In this study the deposit database has been updated and extended to include deposits in Fiji and New Zealand and superimposed on the animated tectonic reconstruction of SE Asia and the SW Pacific, presented by Hall (2002) and available from <http://www.gl.rhul.ac.uk/seasia/>. A version of this reconstruction that includes the location of gold deposits is included on the CD version of this conference proceedings. Readers are referred to Barley et al. (2002) for a fuller description of deposit types, arc magmatism and source references for the SE Asian deposits.

Gold deposits and tectonics in SE Asian and SW Pacific arcs

Major SE Asian and SW Pacific, magmatic-hydrothermal gold deposits (containing more than 10 tonnes of gold) are dominantly high- or low-sulphidation epithermal deposits or porphyry Cu-Au deposits. Skarn, sediment-hosted, and gold-bearing carbonate-hosted base metal deposits are less abundant. All principal deposits in SE Asian and SW Pacific magmatic arcs formed after 25 Ma with the majority dated between 7 and 1 Ma (Late Miocene to Pleistocene). It has been suggested that the preponderance of young deposits reflects increased likelihood of erosion with increasing age (Sillitoe 1989). Though erosion will certainly remove older near surface metal deposits, pre-Late Miocene volcanic and high-level intrusive rocks are common in SE Asian and SW Pacific arcs with little evidence that they were as richly mineralised. Hence it is likely that the dominance of Late Miocene to Pleistocene gold deposits is not caused solely by the removal by erosion of older deposits, but may be related to the tectonic evolution of the arcs.

At around 25 Ma, collision of the Australian Craton with the Philippines-Halmahera Arc and the initial "soft" collision of Ontong Java Plateau with the Melanesian Arc caused major tectonic reorganization in the SE Asian and SW Pacific region (Hall 1996; 2002; Hill and Hall, 2003). The direct effects were a change in the tectonic regime in the Papua New Guinea region from near orthogonal subduction to sinistral strike-slip and clockwise rotation of the Philippine Sea plate. Other effects may have included a reversal of subduction beneath the Philippines. This period coincided with gold deposits in the Isabella-Didipio district (Luzon) and in New Britain.

During the Middle Miocene, the SE Asian arcs experienced more rapid convergence and plate rotation following the maximum extrusion or rotation, of Indochina (e.g. Tapponier et al. 1982) and the opening of the South China Sea. A tectonic response to spreading in the South China Sea was southwards directed subduction under Borneo. Cessation of subduction between 18 and 15 Ma and associated crustal thickening may be related to the formation of deposits such as Kelian between 24 and 18 Ma. As maximum spreading of the South China Sea was reached at around 17 Ma, a subduction reversal occurred in the Philippines, from the proto-Philippine trench in the east to the modern Manila and Sulu-Masbate trenches in the west. This coincided with gold deposits in the Camarines Norte district, eastern Philippines, and the Negros, Masbate, Batangas and Baguio districts along the western side of the archipelago. Middle Miocene gold deposits (15 to 12 Ma) also formed in the Maramuni Arc of northern New Guinea following collision with the Philippine-Caroline Arc (Hill and Hall 2003)

A major tectonic reorganization has occurred in the SE Asian and SW Pacific region since about 8 Ma approximately the time of change in the direction and increase in velocity of relative movement of the Pacific Plate possibly linked to the loss of a subduction zone and/or the "hard" phase of the Ontong Java Plateau collision (Cox and Engebretson 1985; Harbert and Cox 1989; Atwater and Stock 1998). In the SW Pacific, plate reorganization involved initiation of the present obliquely convergent character of the boundary between the Pacific and India-Australian plates in the South Island of New Zealand between ~8 and 6 Ma (e.g. Norris et al., 1990; Kamp et al., 1992; King 2000) leading to uplift of the Southern Alps. To the north of a zone of

compression associated with the convergence and clockwise rotation of the Hikurangi margin, volcanism in the Coromandel Peninsular (between 14 and 4 Ma) followed collision of the Northland and Colville Arcs (Brathwaite and Skinner 1997). Major gold deposits, including Golden Cross and Waihi in the Hauraki goldfield, accompanied episodes of caldera forming volcanism at ~7 and 6 Ma respectively (Mauk and Hall 2004). Further north Fiji experienced significant counter clockwise rotation between ~5 and 3 Ma following the collision of the Melanesian Border Plateau and fragmentation of the outer Melanesian Arc, with the Emperor deposit forming at this time (Begg and Gray 2002). Subduction was also initiated on the New Britain-San Cristobal-Vanuatu trenches following cessation of subduction on the Kilinailau trench. The Panguna deposit on Bougainville and the Ladolam deposit on Lihir Island in the Tabar-Feni arc formed at this time. In Irian Jaya and Papua New Guinea subduction was initiated at the New Guinea trench and Late Miocene to Pliocene magmatism was associated with significant gold deposits, including Ertsberg-Grasberg, Ok Tedi, and Porgera in the New Guinea Orogen.

In SE Asia the Philippine Arc collided with the Eurasian plate in Taiwan at ~5 Ma (Hall, 1996). At this time the rate of rotation of the Philippine Sea plate increased and its pole of rotation changed (Hall, 1996). The consequent effects on neighbouring terranes were widespread. In the Philippines, subduction appears to be transferring from the Manila trench, where subduction has slowed since 5 Ma, to the modern Philippine trench, where subduction commenced at around 5 Ma. Significant gold deposits formed in the eastern Philippines, and particularly the Baguio and Mankayan districts in Luzon as well as in Mindanao. Subduction was initiated in the Pliocene at the north Sulawesi trench, also associated with subduction reversal. Associated gold deposits include those in the Tombulilato/Gorontalo and Ratatotok/Kotamobagu districts.

Discussion

There is a clear relationship between the age of gold deposits in SE Asian and SW Pacific magmatic arcs and the tectonic reorganizations caused by changes in the regional tectonic regime. The most important of these started at about 8 Ma. The resulting intensely mineralized belt extends from New Zealand, through Fiji, the Solomon Islands, Papua New Guinea, eastern Indonesia, Sulawesi, the Philippines to Taiwan and contains many of the world's largest magmatic-hydrothermal Au deposits.

How tectonic reorganizations control the location of mineralised districts is less certain. Sillitoe (1989; 1997) observed that all mineralised districts occurred in arcs with evidence for active extension or uplift at the time of mineralization, with the largest deposits associated with unusual rather than normal arc settings and high-K calc-alkaline, shoshonite, adakite and alkaline magma types. Further more, many mineralised districts with high gold content (e.g. Baguio/Mankayan Luzon, east Mindanao, north Sulawesi, Panguna Bougainville) occur in volcanic arcs following a reversal in subduction polarity (Solomon 1990). In such a setting, local extension may result from slowing subduction (and possibly rollback of the slab) on one side of the volcanic arc and incipient subduction on the other. Magmatism may result from either dehydration or melting of the slab, or inflow of hot mantle as subduction slows, or during slab rollback. Solomon (1990) also suggested that this would induce melting of sub-arc mantle that had been both metasomatized and previously melted by earlier episodes of subduction and that such magmas may be intrinsically gold rich.

Melting of metasomatized (subduction modified) mantle may generate fluid-rich highly oxidised magmas as well as destabilising mantle sulphides to release Cu and Au (McInnes and Cameron 1994). Important new evidence from veined peridotite xenoliths sampling the mantle beneath the Tabar-Feni arc, which hosts the Ladolam deposit, shows that they are strongly enriched in Cu, Au, Pt and Pd relative to surrounding depleted arc mantle, and also have similar Os isotopic compositions to the Ladolam gold ores, indicating the primary source of the metals was the subduction-modified mantle (McInnes et al. 1999).

Gold deposits that follow subduction reversal occur in Late Oligocene, Middle Miocene and Pliocene rocks of Luzon and Pliocene rocks of Mindanao, north Sulawesi and Bougainville. Further possible districts with this setting are Romang-Wetar islands in Indonesia, New Britain, New Ireland and the Solomon Islands. Subduction cessation and reversal appear to be a common regime for formation magmatic-hydrothermal gold deposits. However, in Mindanao, it is unlikely that the Celebes Sea slab had penetrated to sufficient depth to provide a source for shoshonitic and adakitic magmas associated with Pliocene mineralization (Macpherson and Hall, 1999; Sajona and Maury 1998). Also the magmas associated with gold deposits of the New Guinea Orogen including the prodigious Ertsberg-Grasberg district (the highest gold tonnage in the region), Ok Tedi and Porgera follow arc accretion and cannot be easily linked to either coeval subduction, or subduction reversal. Thermal or tectonic reactivation of subduction-modified mantle beneath a thickened arc or orogen, with melting in the mantle and lower crust, seems a more likely cause for magmatism in both cases.

In all cases magmas associated with magmatic-hydrothermal gold mineralization in SE Asian and SW Pacific magmatic arcs have geochemical features indicating their origins are linked to subduction processes. However, in several important provinces, including many of those with the largest gold deposits, magmatism is not directly linked to an actively subducting slab. Examination of the spatial and temporal distribution of gold deposits relative to the regional tectonic model shows that most gold deposits did not form during periods of normal or steady state subduction. Rather periods of plate reorganization characterised by magmatism in unusual arc-related settings produced the most abundant and largest deposits. In particular peak mineralization appears related to melting of mantle that has been previously modified by subduction. During large-scale plate reorganization this can occur at the end of a period of normal subduction, following the cessation of subduction, following arc collision, or accompanying subduction reversal at approximately the same time in different parts of a complex system of magmatic arcs such as those in SE Asia and the SW Pacific. Such tectonic controls may be impossible to recognise in older orogenic belts where recognition of a major change in tectonic style and unusual magma types may be the best guides to mineralization.

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