Tectonic setting of porphyry copper-gold mineralisation in the Macquarie Arc

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Models of porphyry copper-gold ore formation involve magmatic volatile release from a crystallising intrusion. Incompatible elements are partitioned strongly into the aqueous phase, and fluid release probably commences at depths of several kilometres. Accumulation of volatiles beneath the already crystalline igneous carapace leads to hydrostatic pressures exceeding the combined lithostatic load and tensile strength of the surrounding rock mass, resulting in brittle failure and stockwork vein and/or breccia formation.

In this paper we explore the tectonic setting of porphyry copper-gold deposits in the context of evolution of the Ordovician Macquarie Arc in the Lachlan Orogen.

ARC EVOLUTION

There are four structural belts of subduction-related intermediate and mafic volcanics volcaniclastics and intrusives in the Eastern Lachlan Orogen of southeastern Australia. These are the Kiandra Volcanic Belt near the NSW-Victorian border and three belts in the central west of NSW: the western Junee-Narromine Volcanic Belt, the central Molong Volcanic Belt and the eastern Rockley-Gulgong Volcanic Belt.

Our structural and geochemical reconstructions show that these belts formed by the extension (and subsequent contraction) of a single arc. This arc, the Macquarie Arc, was an intraoceanic island arc developed along part of the boundary between the Australian and proto-Pacific plates from the earliest Ordovician to earliest Silurian. Data, especially from the western and central belts, show that over this time interval of ~50 myr, the arc evolved episodically. The western (Junee-Narromine) volcanic belt and the western and central parts of the Molong Volcanic Belt show evidence of 3 pulses of volcanism, separated by two major hiatuses in volcanism. Here, arc evolution consisted of pulse 1 Early Ordovician activity (~490-475 Ma), a hiatus of ~9 my centered on 470 Ma, pulse 2 Middle Ordovician activity (464-~455 Ma), another hiatus, especially in the west of up to 6.5 my around 452 Ma, and then pulse 3 Late Ordovician-earliest Silurian activity from ~450–~439 Ma. The eastern part of the Molong Volcanic Belt and the Rockley-Gulgong Volcanic Belt only show volcanic pulses 2 and 3, although these are not separated by an obvious hiatus in volcanism like further west. As a consequence, pulse 3 commenced around 454 Ma, developed above volcaniclastics of pulse 2 that become finer grained and more ‘distal’ upwards and eastwards. There is no evidence of pulse 1 volcanism in the eastern (Rockley-Gulgong) volcanic belt, but the presence of ~475 Ma cherts is similar to that in other belts.

The Early Ordovician volcanics are chemically unlike primitive intraoceanic arc lavas: their high ε_{Nd} values preclude their having traversed any significant thickness of continental crust. The nature of their substrate remains unclear, but our view is that it may be the thinned and extended forearc section of the Cambrian arc-backarc system exposed in the greenstone belts in Victoria and Tasmania.

The 470 Ma hiatus may reflect back arc spreading. However, the similarity of the geochemical and isotopic signatures of the Middle Ordovician and Early Ordovician Macquarie Arc rocks suggests that no significant tectono-magmatic break separated generation of these magmas between 480 and 466-455 Ma. Compositions include high-K monzogabbros, monzodiorites and more evolved rocks in the Narromine Igneous Complex, and mainly medium-K rocks in the Cowal Igneous Complex.

The Late Ordovician hiatus centred on 450 Ma in the west of the arc may reflect backarc spreading and/or flat subduction associated with temporary blocking effects of buoyant seamounts or some other presently unidentified collider on the oceanic plate. Subsequent Late Ordovician phase volcanic rocks are shoshonitic everywhere, as are coeval volcanic rocks in the eastern belt, and represent melting of a enriched mantle source that was apparently absent during Middle Ordovician arc evolution.

PORPHYRY GROUPS

Based on age data we recognise 4 groups of porphyry in the Macquarie Arc. Group1 porphyries occurred during the ending of phase 1 volcanism, group 2 porphyries were emplaced during phase 2 volcanism, with some evidence pointing to emplacement early as well as late in this phase of arc evolution. Group 3 porphyries were emplaced at the start up of phase 3 volcanism and Group 4 at the end of phase 3.

Group 1 ~484Ma porphyries were emplaced at the end of the first cycle of volcanism in Junee-Narromine Volcanic Belt. They are represented by the Condobolin Road Intrusive Complex and have high-K calc-alkaline geochemistry; they are almost certainly comagmatic with the early Ordovician Nelungaloo Volcanics that they intrude. Other monzonites, preserved only as occasional clasts in Early Ordovician conglomerates, have high-K and shoshonitic affinities. No mineralisation has been found in Group 1 porphyries to date.

Group 2A ~465 Ma porphyries were emplaced around the initiation of the 2nd phase of volcanism in the Junee-Narromine Volcanic Belt. In the Narromine Igneous Complex, these intrusives range from monzogabbros to monzonites, and form a high-K magmatic suite little different compositionally from the Group 1 porphyries.

Group 2B ~455 Ma porphyries were emplaced near the end of the 2nd phase of arc volcanism in the Junee-Narromine Volcanic Belt

GROUP 3 ~450-445 Ma porphyries constitute the Copper Hill Suite, emplaced at the beginning of the 3rd phase of arc volcanism. Intrusives of this age form common but relatively small-volume mainly felsic intrusives in each of the volcanic belts. Mainly of dacitic composition, although sometimes extending to dioritic to gabbroic compositions, this suite is expressed mineralogically by the common quartz and hornblende phenocrysts in rocks with >60% SiO_2. These rocks have medium K calc-alkaline affinities. These porphyries contain significant amounts of mineralisation in the Molong Volcanic Belt (Copper Hill, Cargo) and in the Narromine Igneous Complex in the Junee-Narromine Volcanic Belt.

GROUP 4~439 Ma porphyries were emplaced at the end of the 3rd phase of arc volcanism in all belts except the Kiandra Volcanic Belt. Intrusives are shoshonitic monzodiorite-monzonite, comagmatic with the most of Late Ordovician volcanics in the arc. Mineralised Group 4 porphyries comprise the world-class gold-copper resources at Northparkes and at Cadia-Ridgeway, as well as scattered mineralisation in the Forest Reefs area.

CHEMICAL CONTROLS ON FORMATION OF PORPHYRY COPPER-GOLD DEPOSITS, MACQUARIE ARC

Previous workers have shown that the oxidation state of the magma appears to impart a strong control on whether a given porphyry system is gold-enriched. Transport of gold and copper together with sulphur from the igneous source regime is most readily accommodated in oxidized melts where sulphur can be transported in high concentrations as SO_2, together with copper and gold. In more reduced igneous melts, sulphur occurs as H_2S, and this has the capacity to form immiscible sulphide liquids that will scavenge copper and gold from the melts and retain them in the igneous source regime. Shoshonites are a particularly favourable oxidized magma composition for gold-rich porphyry copper-gold formation. Shoshonitic magmas are especially common in the third phase of activity in the Macquarie Arc (Group 4 porphyries). However, the presence of shoshonitic group 1 porphyries also means that these rocks form an exploration target as well. The Cowal example shows that intrusives that formed from a less oxidised and lower K rich magma can host major structurally controlled gold deposits.

Key trace element characteristics of the Group 3 Copper Hill suite porphyries, especially the strikingly high Sr/ Y values (80-95) compared with trachytic rocks in the Cowal (5-11) and Parkes region (mainly 30-70), invite comparison with adakitic lavas. However HREE patterns are flat to slightly MREE depleted, ruling out adakitic affinities. Although Group 3 porphyries seem to be less well-endowed in copper and gold than the shoshonitic porphyries, many of the Chilean porphyry copper-gold deposits have this signature, the significance of which is keenly debated.

The strong compositional overlap between the Cowal intrusives and the Copper Hill suite rocks suggests that either the dominant medium-K rocks in the Cowal Igneous Complex are of similar age to the Copper Hill suite (450-445 Ma), or, if the Cowal rocks are indeed older, that similar sources and magma generation conditions existed in the Mid and Early Late Ordovician time in the Macquarie Arc.

KEY CONTROLS ON FORMATION OF PORPHYRY COPPER-GOLD DEPOSITS, MACQUARIE ARC

Porphyries in the Macquarie Arc did not form during steady state subduction, but during critical events in the evolution of the arc. That is, either when subduction became shallower, or turned off, (Group 1, ?Group 2b, Group 4) due to back arc spreading, jamming of subduction zone, or during subduction reversal. Porphyries of Group 2a appear to have been emplaced when subduction recommenced in the Middle Ordovician after a hiatus of ~9 myr.

We can interpret these relationships in terms of stress states required to promote the formation of porphyries. Porphyries in the Macquarie Arc were not intruded in areas or times of maximum tension. Rather, they formed from magmas that fractionated in a crust that was thick and strong enough to hold magmas chambers. A compressive stress regime may assist in preventing lavas venting directly to the surface, and allow magmas to pond in high-level chambers (enabling extended fractionation). The actual formation of porphyry copper-gold deposits required these chambers to be breached, either by magma/fluid pressure build up, and/or by a reduction in differential stress. Release of magma and fluids were focused either along old structures or new structures, with pipe-like intrusions (probably dykes coming off magma chambers) controlled by the prevailing crustal stress field (sigma 1 vertical and sigma 3 horizontal).

These conditions seem to have best been served by transient switches in the stress state of the Macquarie Arc, caused by changes in the direction, rate of subduction or by coupling across the plate boundary. Such switches are facilitated if convergence across the plate boundary was oblique, the most common situation, which sets up a transpressional or transtensional component in arc deformation.

Significantly, the highly mineralised Group 4 Llandovery porphyries were emplaced after arc volcanism had shut down, and during arc deformation and formation of coeval transient basins. The absence in the stratigraphic record of any extrusive equivalents of these intrusives implies either very efficient erosion, or that the intrusives (= plugged dykes) that did not vent to the surface. The regional compression that prevented venting to the surface was associated with deformation within the arc and the weight of overlying structurally thickened volcanics and/or Llandovery basin sediments during the collision between the arc and its backarc.

DISTRIBUTION OF PORPHYRY COPPER-GOLD DEPOSITS, MACQUARIE ARC

Porphyry copper-gold deposits in the Molong Volcanic Belt are concentrated within the Lachlan Transverse Zone, a key arc-normal WNW-trending structure that lies parallel to the transform boundary along the southern margin of the restored Macquarie Arc. Included in this setting are the Cadia Intrusive Complex, intrusives in the Forest Reefs and older volcanics, as well as the Swatchfield intrusive in the Rockley-Gulgong Volcanic Belt. This zone thus underwent (apparently repeated) dilation in the Ordovician, especially near the termination of, or intersection, with arc-parallel structures. The Lachlan Transverse Zone appears to have set up a regional differential stress regime with WNW sigma 1 and NNE sigma 3, which permitted emplacement of WNW elongate porphyries in the Cadia region and Cargo. At Cadia, this stress field also provided a strong control on fracture development, resulting in the formation of sheeted vein arrays.

Whereas intrusives east of Orange also lie within the Lachlan Transverse Zone, the Copper Hill intrusives and those further north at Comobella do not. However, in the reconstructed arc they appear to lie on a WNW trending zone that includes intrusives near Sofala and Gulgong in the Rockley-Gulgong Volcanic Belt.

Further west, porphyry copper-gold deposits and porphyries are spread along the length of In the Junee-Narromine Volcanic Belt, with clusters west and northwest of Parkes lying in dilational zones that were repeatedly reactivated during arc evolution. In contrast to the Cadia porphyries, those at Northparkes show less evidence of emplacement in a differential stress regime. Their location may have been controlled by local jogs within an arc-parallel structure, the Endeavour ‘linear’, especially at the intersection with WNW structures.

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