Porphyry Au-Cu mineralization controlled by reactivation of an arc-transverse volcanosedimentary subbasin

Nathan Fox[1], David R. Cooke[1], Anthony C. Harris[2], Dean Collett[3], and Graeme Eastwood[2]
[1]Centre of Excellence in Ore Deposits (CODES), University of Tasmania, Private Bag 79, Hobart 7001, Tasmania, Australia
[2]Newcrest Mining Limited, Level 8, 600 St Kilda Road, Melbourne 3004, Victoria, Australia
[3]Macquarie Group, 50 Martin Place, Sydney 2000, New South Wales, Australia

ABSTRACT

Located in the accreted remnants of the Ordovician Macquarie Arc (Australia), Cadia East is the largest alkalic porphyry Au-Cu deposit currently known. The deposit is centered on a 2-km-long, northwest-trending volcanosedimentary subbasin, which was identified by mapping variations in the distribution and thickness of faulted sedimentary marker horizons. The normal faults that define the subbasin predate porphyry mineralization and are oriented parallel to a major arc-transverse lineament. Porphyry Au-Cu mineralization was controlled by reactivation of the subbasin during postorogenic extension as the Macquarie Arc was accreted to the Gondwana margin in the early Silurian. Dilation of the northwest-trending subbasin faults facilitated emplacement of alkalic porphyry dikes and associated sheeted quartz-sulfide veins that define the Cadia East orebody. During the middle Silurian, north-trending fault-bound marine basins buried Cadia East, significantly enhancing preservation of the ore system. These north-trending faults were optimally oriented for reactivation during Devonian east-directed compression, leaving the mineralized Cadia East volcanosedimentary subbasin largely intact. We identify the significance of reactivated premineralization structures within an arc-transverse lineament in controlling porphyry Au-Cu mineralization in a postsubduction setting. At Cadia East, the manifestation of such premineralization structures can be observed at regional, district, and deposit scales, and highlights the influence of preexisting crustal architecture on the structural character, geometry, and preservation potential of porphyry deposits throughout the arc life cycle.

INTRODUCTION

Alkalic porphyry deposits are a Au-rich subclass of porphyry Cu-Au-(Mo) deposits, notably associated with the tectonically complex Miocene and Pliocene intraoceanic arcs of the southwest Pacific (Harris et al., 2013). The occurrence of alkalic deposits in accreted arcs, including the Ordovician Macquarie Arc (Australia; Holliday et al., 2002; Fig. 1A) and the Triassic–Jurassic Quesnellia-Stikinia terranes of British Columbia (Lang et al., 1995; Logan and Mihalynuk, 2014), implies a similarly complex tectonic history.

Cadia Valley, 220 km west of Sydney, Australia (Fig. 1), comprises a linear array of alkalic porphyry Au-Cu deposits; Cadia East, the largest of these deposits, contains >1.05 × 10^6 kg of gold (>37 × 10^6 oz; www.newcrest.com.au). The unusually elongated orebody (~2 km long, 0.8 km wide, 1.5 km deep; Fig. 1B) is defined by steeply dipping quartz-sulfide veins striking parallel to alkalic porphyry dikes. This geometry contrasts the structural character of many porphyry deposits that are typically characterized by radial veins associated with cylindrically shaped intrusions (e.g., Titley and Heidrick, 1978; Tosdal and Richards, 2001; Gruen et al., 2010). Elongated porphyry orebodies are comparatively less common and are usually associated with porphyry dikes (e.g., Hugo Dummett, Mongolia; Sillitoe, 2010). The role of regionally extensive, long-lived premineralization structures such as oblique arc lineaments and intraarc fault zones (including backarc basins) in providing the locus for porphyry mineralization is well documented (Gow and Walshe, 2005; Sillitoe, 2010). While such structures influence the location and alignment of porphyry deposits at regional to district scales and clearly have direct exploration implications, their geological manifestation at the deposit scale is rarely clearly observed.

Building on a stratigraphic framework defined by Harris et al. (2014), we reconstruct the structural architecture of a 2-km-long volcanosedimentary subbasin, centered directly on the Cadia East deposit, and occurring within the trend of the Lachlan Transverse Zone, a regionally extensive, cross-arc lineament (Fig. 1A). The subbasin compartmentalized a larger volcanosedimentary basin within the Ordovician Macquarie Arc and provided structural preconditioning for porphyry dike emplace-

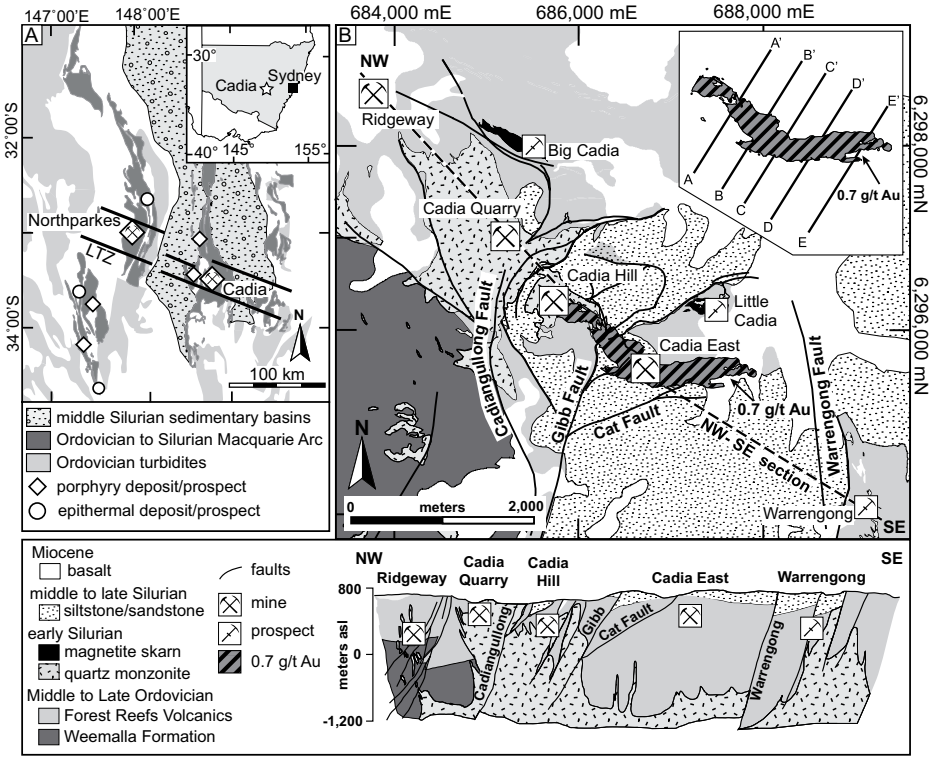

Figure 1. A: The Macquarie Arc exposed in eastern Australia with porphyry and epithermal mineralization and the Lachlan Transverse Zone (LTZ; modified from Glen et al., 2007). B: Geological map and northwest-southeast long section through the Cadia Valley and location of studied section lines (inset). The 0.7 g/t Au contour is projected to the surface from the 0 m asl (above sea level) mine level.

doi:10.1130/G36992.1
© 2015 Geological Society of America. For permission to copy, contact editing@geosociety.org.

ment and Au-Cu mineralization at Cadia East in a postsubduction setting following arc accretion. It is significant that, despite effects of postmineralization deformation, the architecture of this subbasin has remained largely intact since its inception in the Late Ordovician. Volcanosedimentary basins, including those developed within arc-transverse lineaments, represent significant exploration targets in both ancient (i.e., older than 200 Ma) and modern arcs, and may include terranes that were not previously considered prospective for porphyry mineralization.

REGIONAL GEOLOGICAL SETTING

Geochemical, structural, and stratigraphic restorations indicate that the Macquarie Arc originated as an intraoceanic island arc, located offshore from eastern Gondwana in the Ordovician (Scheibner, 1973; Glen et al., 2007; Crawford et al., 2007). The arc records periods of episodic volcanism and magmatism punctuated by volcanic hiatuses, uplift, and erosion prior to collision of the arc with Gondwana in the early Silurian Benambran orogeny (Glen et al., 2007). Economically significant porphyry mineralization is associated with high-K calc-alkaline to alkalic intrusions emplaced at Northparkes (444 ± 4.7 Ma; Lickfold et al., 2007) and Cadia (440.1 ± 4.2 to 437.1 ± 3.5 Ma; Squire and Crawford, 2007; Wilson et al., 2007). The Lachlan Transverse Zone, a major northwest-trending structural zone along which Cadia and Northparkes are aligned (Fig. 1A), was likely inherited from the Precambrian Australian craton (Glen and Walshe, 1999). This cross-arc lineament appears to have provided a structural focus for alkalic magmatism during arc accretion in the early Silurian (Glen et al., 2007). Despite being partially exhumed, porphyry mineralization at Cadia is largely well preserved below middle Silurian shallow-marine sedimentary rocks deposited in north-trending rift basins (Washburn, 2008).

SEDIMENTARY MARKER HORIZONS

Mineralization at Cadia East is hosted by basaltic andesite lava, volcaniclastic rocks, and minor sedimentary rocks of the Middle to Late Ordovician Forest Reefs Volcanics (Figs. 1B and 2; Harris et al., 2014). Two sedimentary marker horizons occur in the upper 500 m of stratigraphy (Fig. 2). The lower marker horizon is 50–100 m thick (Fig. 2) and comprises calcareous sandstone containing Late Ordovician fossils (456–450 Ma; Packham et al., 1999). Although unexposed at the surface at Cadia East, this unit crops out to the northeast at Little Cadia (Fig. 1B). The upper marker horizon, comprising laminated siltstone and tuff, ranges in thickness between 25 m and 50 m and is separated from the lower marker horizon by volcanic breccia (Fig. 2). Both marker horizons were intruded by porphyritic basaltic-andesite sills and dikes (Fig. 2) representing the final stages of Macquarie Arc volcanism in the latest Ordovician.

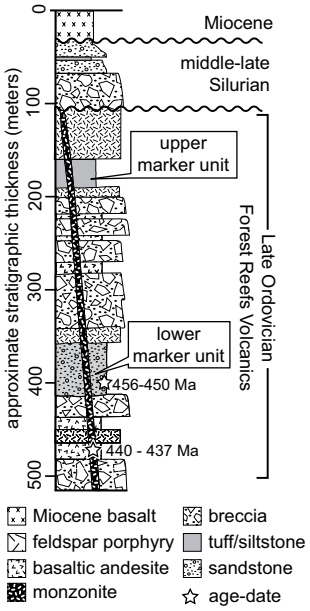

Figure 2. Schematic log of the upper stratigraphy at Cadia East, highlighting the position of the lower and upper sedimentary marker horizons.

MARKER HORIZON OFFSET—DEFINING THE BASIN

The top and bottom surfaces of each marker horizon, intersected in more than 200 diamond drill holes, were modeled using three-dimensional (3-D) software. Variations in the distribution, geometry, and thickness of the sedimentary marker horizons are controlled by previously unmapped synsedimentary extensional faults shown on representative northeast-southwest–oriented section lines (Figs. 1B and 3). The newly defined faults define a broadly northwest-trending volcanosedimentary subbasin with a horst and graben morphology in the western (A-A', B-B') and central sections (C-C', D-D'; Fig. 3), and a half-graben geometry in the easternmost section (E-E'). Evidence for synsedimentary displacement along the subbasin bounding faults is clearest in the eastern sections (D-D', E-E'), with thickening of the lower marker horizon and the upper marker horizon into the hanging wall (Fig. 3). The lower marker horizon was partially deposited over the horst blocks (Fig. 3), whereas deposition of the upper marker horizon was restricted to the downthrown part of the subbasin (Fig. 3).

PORPHYRY INTRUSIONS AND MINERALIZATION

Hydrothermal alteration and mineralization at Cadia East is zoned around early Silurian porphyritic monzonite dikes that intrude the Forest Reefs Volcanics (Wilson, 2003; Fox, 2012). The structural trend of these dikes and associated mineralized quartz-carbonate-sulfide (QCS) veins define the distinctive orebody geometry (Figs. 3 and 4A). In the east (sections D-D', E-E'), both the dikes and QCS veins strike west-northwest and mostly dip steeply northeast (Fig. 4A), parallel to the half-graben bounding fault (Fig. 3). Toward the central section (C-C'), the west-northwest–striking dikes and veins dip steeply northeast and southwest (Fig. 4A), converging to define a nearly vertical orebody (Fig. 3). At the western end (A-A', B-B'), the dikes, veins, and consequently the orebody, strike northwest, and dip mostly southwest, largely correlating with the southwest-dipping subbasin bounding fault (Figs. 3 and 4A).

DISCUSSION

Premineralization Subbasin Architecture

Fossil age constraints from the calcareous lower marker unit indicate that the Cadia East subbasin was established within the Macquarie Arc at least by 456–450 Ma. This subbasin structurally compartmentalized a regional volcanosedimentary basin in which the host rocks at Cadia were deposited (Harris et al., 2014). The oblique trend of the subbasin relative to the arc axis was likely inherited from the northwest-trending Lachlan Transverse Zone (Fig. 1A), inferring that this structural zone had propagated into the Macquarie Arc by the Late Ordovician. Displacement along the subbasin bounding normal faults formed horst and graben blocks, generating intrabasinal topography (Fig. 4) that controlled the deposition of both sedimentary marker horizons.

Subbasin Reactivation and Porphyry Mineralization

Termination of Macquarie Arc volcanism by the earliest Silurian (ca. 444 Ma) was coincident with the onset of the Benambran orogeny as the arc was accreted to the Gondwana margin (Glen et al., 2007). Porphyry emplacement at Cadia East coincides with a transition from the initial compressive stage of Benambran deformation to a period of postorogenic extension. Dilation of the preexisting subbasin faults facilitated the intrusion of mineralizing alkalic porphyry dikes. Associated brittle fracturing and hydrothermal fluid flow generated the high-grade sheeted QCS veins and porphyry-related alteration. The orientation of the minimum principal stress, σ^3, perpendicular to the strike of the veins (e.g., Sibson, 2001), implies broadly northeast-southwest–directed extension during mineralization (Fig. 4B). Subbasin reactivation could have occurred either during arc-normal compression or during postcollisional extensional relaxation perpen-

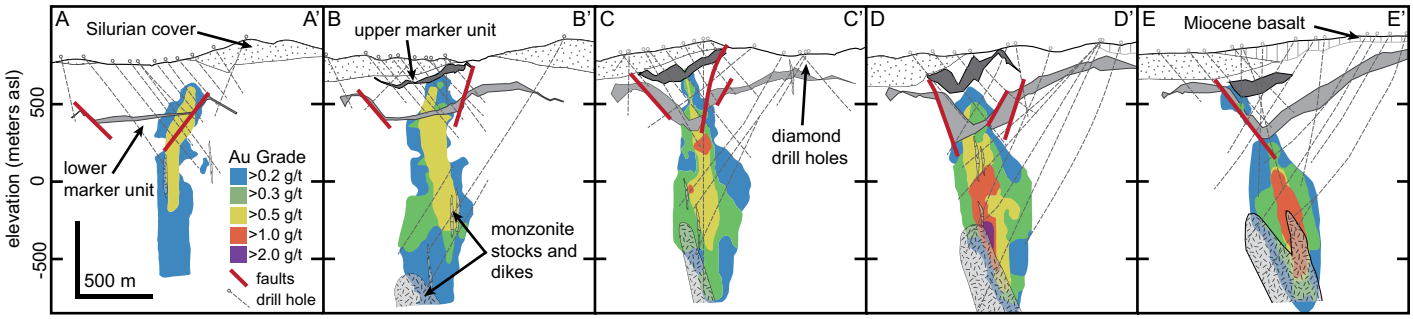

Figure 3. Simplified northeast-southwest–oriented geological section lines (section locations shown in Fig. 1B) indicating fault offset (bold red lines) of the marker units. Gold contours are from resource models by Newcrest Mining Ltd., Melbourne, Australia. Thin gray dashed lines are diamond drill hole traces. Asl—above sea level.

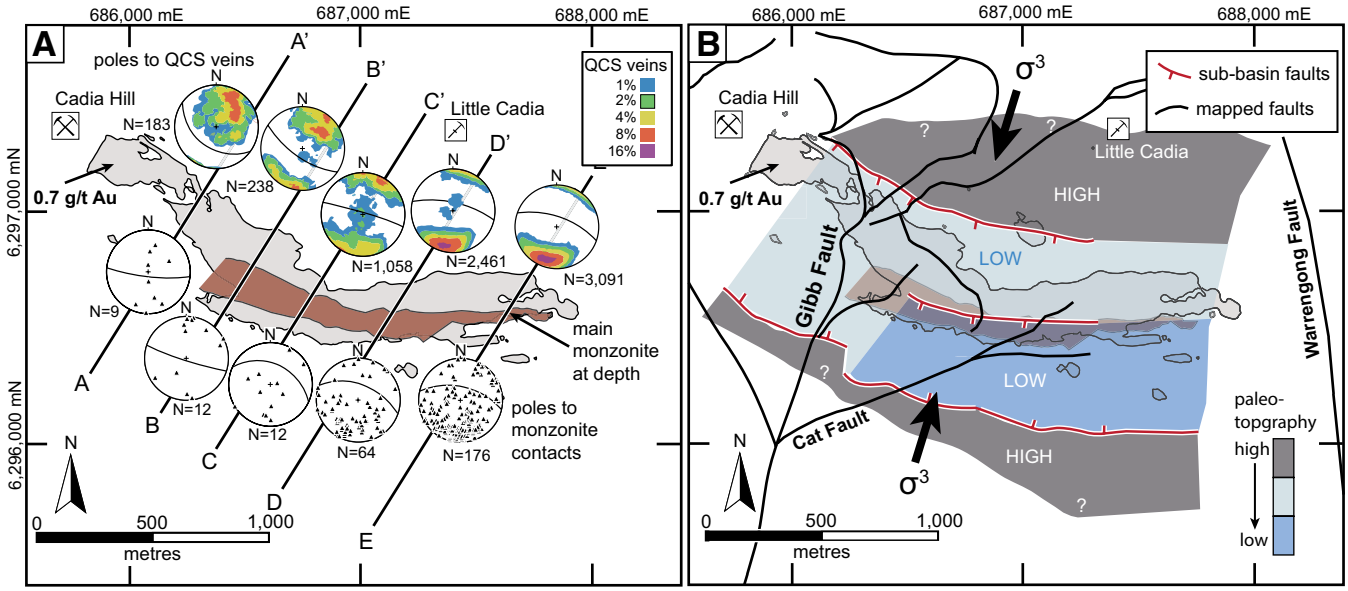

Figure 4. A: Equal area, lower hemisphere stereographic projections of poles to monzonite dike contacts (black triangles) and contoured poles to quartz-carbonate-sulfide (QCS) veins. Mean orientations are shown as bold black planes. The 0.7 g/t Au contour and main monzonite outline are projected from 0 m asl (above sea level) and –500 m asl levels, respectively. B: Projection of the interpreted subbasin faults (red) to the surface, and interpreted paleotopographic highs (horst blocks) in gray and lows (grabens, half-grabens) in blues, defining the volcanosedimentary subbasin. Faults mapped at the surface are shown in black.

dicular to the accreted arc. This is in contrast to arcs under high rates of arc-normal convergence where mineralizing intrusions may be emplaced along inverted arc-parallel basin faults (Titley and Heidrick, 1978; Cooke et al., 2005; Gow and Walshe, 2005; Sillitoe, 2010). The orientation of the Cadia East subbasin, almost parallel to the direction of Benambran shortening, appears to have been favorable to prevent basin inversion. The apparent absence of strike-slip reactivation suggests that despite the overall complexity of the geodynamic setting, transient far-field stresses preferentially reactivated preexisting structures to control porphyry mineralization. The Lachlan Transverse Zone likely provided the deep crustal conduit for Au-rich alkalic magmas derived from the subduction-modified lithosphere, a characteristic feature of postcollisional arc environments (Richards, 2009).

Postmineralization Sedimentation and Deformation

Postmineralization, north- to northeast-striking extensional marine basins, oriented perpendicular to the trend of the Ordovician subbasin, buried the Cadia East deposit during the middle Silurian. This is in contrast to the Pebble porphyry Cu-Au-Mo deposit in Alaska, where basin subsidence and sedimentation that preserved mineralization was controlled by reactivation of mineralized structures (Lang et al., 2013). At Cadia East, the preferential reactivation and partial inversion of the Silurian basins by east-west–directed shortening during the Devonian Tabberabberan orogeny accommodated the majority of postmineralization deformation in the district (Washburn, 2008). Displacement along the curviplanar to northeast-trending Cadiangullong, Gibb, and Warrengong thrust faults (Fig. 4) minimized postmineralization reactivation (e.g., strike-slip displacement) of the Ordovician subbasin. Maximum displacement of ~600 m along the Gibb fault thrust the Cadia Hill Intrusive Complex over the western end of Cadia East (Figs. 1B and 4B). Consequently, the shallower dip of the QCS veins on section A-A' (Fig. 3) and the northwest trend in the western part of the orebody may be influenced by block rotation at the western end of Cadia East.

CONCLUSIONS

The Cadia East porphyry deposit developed in a volcanosedimentary subbasin that provided a structurally preconditioned environment for the emplacement of Au-rich alkalic dikes in a postsubduction setting. The geometric relationship between the subbasin and the northwest-trending Lachlan Transverse Zone highlights the influence of long-lived cross-arc structures in volcanosedimentary basin forma-

tion prior to porphyry emplacement. While the role of preexisting structures in porphyry deposit formation has been previously recognized (including Bingham Canyon, Utah; John, 1998; La Escondida, Chile; Richards et al., 2001), the manifestation of these structures at the deposit scale may be masked by localized stress regimes during mineralization and postmineralization deformation. At Cadia East, we are able to directly relate the structural character of porphyry mineralization to a protracted structural evolution inherited from a regional scale arc-transverse lineament. Postmineralization burial enhances preservation of porphyry deposits in the geological record and is influenced by the orientation of both premineralization and postmineralization structural features relative to later deformation. For exploration, volcanosedimentary basins developed in regionally extensive arc-transverse lineaments represent strategic targets for porphyry mineralization in active postsubduction and accreted arcs. Identification of premineralization structures (e.g., by mapping stratigraphic offset) can assist with porphyry exploration while also contributing to the refinement of existing genetic models for porphyry deposit formation.

ACKNOWLEDGMENTS

We thank Newcrest Mining Ltd. for permission to publish this study and for providing research funding, and Newcrest geologists Colin McMillan, Ian Tedder, Anne Eastwood, Cathy Evans, John Holliday, and Fraser MacCorquodale for valuable geological insights. We also thank reviewers Jon Hronsky and Thomas Bissig for their constructive comments, and Richard Goldfarb, Richard Tosdal, and John Thompson for critical reviews that improved this manuscript.

REFERENCES CITED

Cooke, D.R., Hollings, P., and Walshe, J.L., 2005, Giant porphyry deposits—Characteristics, distribution and tectonic controls: Economic Geology and the Bulletin of the Society of Economic Geologists, v. 100, p. 801–818, doi:10.2113/gsecongeo.100.5.801.

Crawford, A.J., Meffre, S., Squire, R.J., Barron, L.M., and Falloon, T.J., 2007, Middle and Late Ordovician magmatic evolution of the Macquarie Arc, Lachlan Orogen, New South Wales: Australian Journal of Earth Sciences, v. 54, p. 181–214, doi:10.1080/08120090701227471.

Fox, N., 2012, Controls on alteration and mineralisation at the Cadia East alkalic porphyry Au-Cu deposit, NSW [Ph.D. thesis], Hobart, University of Tasmania, 222 p.

Glen, R.A., and Walshe, J.L., 1999, Cross-structures in the Lachlan Orogen: The Lachlan Transverse Zone example: Australian Journal of Earth Sciences, v. 46, p. 641–658, doi:10.1046/j.1440-0952.1999.00734.x.

Glen, R.A., Crawford, A.J., and Cooke, D.R., 2007, Tectonic setting of porphyry Cu-Au mineralisation in the Ordovician–Early Silurian Macquarie Arc, Eastern Lachlan Orogen, New South Wales: Australian Journal of Earth Sciences, v. 54, p. 465–479, doi:10.1080/08120090701221672.

Gow, P.A., and Walshe, J.L., 2005, The role of preexisting geologic architecture in the formation of giant porphyry–related Cu ± Au deposits: Examples from New Guinea and Chile: Economic Geology and the Bulletin of the Society of Economic Geologists, v. 100, p. 819–833, doi:10.2113/gsecongeo.100.5.819.

Gruen, G., Heinrich, C.A., and Schroeder, K., 2010, The Bingham Canyon porphyry Cu-Mo-Au deposit. II. Vein geometry and ore shell formation by pressure driven rock extension: Economic Geology and the Bulletin of the Society of Economic Geologists, v. 105, p. 69¬90, doi:10.2113/gsecongeo.105.1.69.

Harris, A.C., Cooke, D.R., Blackwell, J.L., Fox, N., and Orovan, E.A., 2013, Volcanotectonic setting of world-class alkalic porphyry and epithermal Au ± Cu deposits of the southwest Pacific, *in* Colpron, M., et al., eds., Tectonics, metallogeny, and discovery: The North American Cordillera and similar accretionary settings: Society of Economic Geologists Special Publication 17, p. 337–359.

Harris, A.C., Percival, I.G., Cooke, D.R., Tosdal, R.M., Fox, N., Allen, C.M., Tedder, I., McMillan, C., Dunham, P., and Collett, D., 2014, Marine volcanosedimentary basins hosting porphyry Au-Cu deposits, Cadia Valley, New South Wales, Australia: Economic Geology and the Bulletin of the Society of Economic Geologists, v. 109, p. 1117–1135, doi:10.2113/econgeo.109.4.1117.

Holliday, J.R., Wilson, A.J., Blevin, P.L., Tedder, I.J., Dunham, P.D., and Pfitzner, M., 2002, Porphyry gold-copper mineralisation in the Cadia district, eastern Lachlan Fold Belt, New South Wales, and its relationship to shoshonitic magmatism: Mineralium Deposita, v. 37, p. 100–116, doi:10.1007/s00126-001-0233-8.

John, D.D., 1998, Geological setting and characteristics of mineral deposits in the central Wasatch Mountains, Utah, *in* John, D.A., and Ballantyne, G.H., eds., Geology and ore deposits of the Oquirrh and Wasatch Mountains, Utah: Society of Economic Geologists Guidebook Series 29, p. 11–33.

Lang, J.R., Stanley, C.R., and Thompson, J.F.H., 1995, Porphyry copper-gold deposits related to alkalic igneous rocks in the Triassic–Jurassic arc terranes of British Columbia: Arizona Geological Society Digest, v. 20, p. 219–236.

Lang, J.R., Gregory, M.J., Rebaglaliati, C.M., Payne, J.G., Oliver, J.L., and Roberts, K., 2013, Geology and magmatic-hydrothermal evolution of the Giant Pebble porphyry Cu-Au-Mo deposit, southwest Alaska: Economic Geology and the Bulletin of the Society of Economic Geologists, v. 108, p. 437–462, doi:10.2113/econgeo.108.3.437.

Lickfold, V., Cooke, D.R., Crawford, A.J., and Fanning, C.M., 2007, Shoshonitic magmatism and the formation of the Northparkes porphyry Cu-Au deposits, New South Wales: Australian Journal of Earth Sciences, v. 54, p. 417–444, doi:10.1080/08120090601175754.

Logan, J.M., and Mihalynuk, M.G., 2014, Tectonic controls on early Mesozoic paired alkaline porphyry deposit belts (Cu-Au ± Ag-Pt-Pd-Mo) within the Canadian Cordillera: Economic Geology and the Bulletin of the Society of Economic Geologists, v. 109, p. 827–858, doi:10.2113/econgeo.109.4.827.

Packham, G., Percival, I., and Bischoff, G., 1999, Age constraints on strata enclosing the Cadia and Junction Reefs ore deposits of central New South Wales, and tectonic implications: Geological Survey of New South Wales Quarterly Notes, v. 110, p. 1–12.

Richards, J.P., 2009, Postsubduction porphyry Cu-Au deposits and epithermal Au deposits: Products of remelting of the subduction-modified lithosphere: Geology, v. 37, p. 247–250, doi:10.1130/G25451A.1.

Richards, J.P., Boyce, A.J., and Pringle, M.S., 2001, Geological evolution of the Escondida area, northern Chile: A model for spatial and temporal localization of porphyry Cu mineralization: Economic Geology and the Bulletin of the Society of Economic Geologists, v. 96, p. 271–305, doi:10.2113/gsecongeo.96.2.271.

Scheibner, E., 1973, A plate tectonic model of the Palaeozoic tectonic history of New South Wales: Geological Society of Australia Journal, v. 20, p. 405–426, doi:10.1080/00167617308728826.

Sibson, R.H., 2001, Seismogenic framework for hydrothermal transport and ore deposition: Reviews in Economic Geology, v. 14, p. 25–50.

Sillitoe, R.H., 2010, Porphyry copper systems: Economic Geology and the Bulletin of the Society of Economic Geologists, v. 105, p. 3–41, doi:10.2113/gsecongeo.105.1.3.

Squire, R.J., and Crawford, A.J., 2007, Magmatic characteristics and geochronology of Ordovician igneous rocks from the Cadia-Neville region, New South Wales: Implications for tectonic evolution: Australian Journal of Earth Sciences, v. 54, p. 293–314, doi:10.1080/08120090601147001.

Titley, S.R., and Heidrick, T.L., 1978, Intrusion and fracture styles of some mineralized porphyry systems of the southwestern Pacific and their relationship to plate interactions: Economic Geology and the Bulletin of the Society of Economic Geologists, v. 73, p. 891–903, doi:10.2113/gsecongeo.73.5.891.

Tosdal, R.M., and Richards, J.P., 2001, Magmatic and structural controls on the development of porphyry Cu ± Mo ± Au deposits: Reviews in Economic Geology, v. 14, p. 157–181.

Washburn, M., 2008, Architecture of the Silurian sedimentary cover sequence in the Cadia porphyry Au-Cu district, NSW, Australia: Implications for postmineral deformation [M.S. thesis]: Vancouver, Canada, University of British Columbia, 165 p.

Wilson, A.J., 2003, The geology, genesis and exploration context of the Cadia gold-copper porphyry deposits, NSW, Australia [Ph.D. thesis]: Hobart, University of Tasmania, 335 p.

Wilson, A.J., Cooke, D.R., Stein, H.J., Fanning, C.M., Holliday, J.R., and Tedder, I.J., 2007, U-Pb and Re-Os geochronologic evidence for two alkalic porphyry ore-forming events in the Cadia district, New South Wales, Australia: Economic Geology and the Bulletin of the Society of Economic Geologists, v. 102, p. 3–26, doi:10.2113/gsecongeo.102.1.3.

Manuscript received 22 May 2015
Revised manuscript received 28 June 2015
Manuscript accepted 5 July 2015

Printed in USA