1	The Anatomy of an Alkalic Porphyry Cu-Au System: Geology
2	and Alteration at Northparkes Mines, NSW, Australia
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19	Abstract
20 21 22	The Late Ordovician-Early Silurian (~455-435 Ma) Northparkes system is a group of silica-saturated, alkalic porphyry deposits and prospects which developed within the Macquarie Island Arc. The system is host to a spectacular and diverse range of rocks and alteration-mineralization textures
23 24	that facilitate a detailed understanding of its evolution, in particular into the nature and controls of porphyry-related propylitic alteration.
25 26 27	The first intrusive phase at Northparkes is a pre- to early-mineralization pluton that underlies all the deposits and varies in composition from a biotite quartz monzonite (BQM) to alkali feldspar granite (AFG). Prior to total crystallization, this pluton was intruded by a more primitive quartz
28	monzonite (QMZ) that marks the onset of a fertile fractionation series. Towards its upper levels, the

29 QMZ is porphyritic and locally rich in Cu sulfides. Subsequently, a complex series of syn-30 mineralization quartz monzonite porphyries (QMP) were emplaced. The QMP intrusions have a distinct pipe-like morphology and are ubiquitously K-feldspar altered with a crystal-crowded 31 32 porphyritic texture. The textures of the QMPs and common occurrence of porphyry-cemented 33 contact breccias indicate they were forcibly emplaced and of relatively low viscosity. The QMPs are therefore interpreted as crystal-bearing, silicate melt-aqueous fluid slurries that represent the 34 35 conduits through which deep-seated magmatic-derived ore fluid was discharged into the shallow 36 crust (1-2 km depth).

37 Each deposit is centred on a multiphase cluster of QMP intrusions that drove discrete hydrothermal 38 systems. Initial fluid evolution was similar in all the deposits, with three major alteration facies 39 developed as largely concentric zones around the QMP complexes. The innermost zone is host to 40 Cu sulfide ore and dominated by K-feldspar alteration. This transitions outwards through a shell of 41 magnetite ± biotite alteration, with pyrite and minor chalcopyrite, to an outer halo of propylitic 42 alteration. Generally, epidote, chlorite and pyrite are abundant in the most deposit-proximal 43 propylitic zone, with a decrease in the abundance of pyrite, and then epidote, with increasing 44 distance away from deposit centers.

45 Propylitic alteration, particularly within relatively low permeability rocks, is fracture-controlled and a 46 hierarchy of veins is observed. Veins of chlorite-quartz-pyrite \pm calcite \pm hematite \pm epidote \pm 47 chalcopyrite (P1) appear to represent the principal fluid conduits. They are surrounded by pervasive 48 and intense alteration halos with a distinct mineralogical zonation from vein-proximal chlorite-49 sericite (phengite) \pm epidote \pm pyrite, through hematite-sericite-chlorite \pm epidote, ultimately to a 50 vein-distal hematite-albite ± chlorite ± epidote assemblage. These P1 veins are surrounded by 51 regions in which smaller epidote-chlorite \pm calcite \pm guartz \pm pyrite veins (P2) are abundant, again 52 with zoned alteration envelopes: vein-proximal chlorite-sericite (phengite) ± epidote ± pyrite grades out into an epidote-rich zone, which in turn transitions into vein-distal albite-hematite ± 53 54 chlorite ± epidote. Areas of weakest propylitic alteration, distant from both P1 and P2 veins, are 55 characterised by small epidote-only veinlets (P3) with albite-hematite halos. Mineralogical 56 transitions across the propylitic zone are therefore repeated in the evolution from P1 to P3 veins, as well as in the halos around these veins. It is the overall vein abundance and overlap of associated 57 58 alteration halos which controls the intensity and appearance of propylitic alteration in most rocks. 59 Such scale-invariance and spatial relationships strongly suggests the transition from P1 to P3 veins 60 reflects a broadly decreasing outward flux of (magmatic-derived?) fluid that passed through the

fracture network and progressively reacted with country rocks. Further support for this hypothesis comes from cross cutting relationships and Rb-Sr dating of epidote (returning an age of 450 ± 11 Ma), which demonstrate the bulk of propylitic alteration was coeval with mineralization and potassic alteration.

65 Late-stage fluid evolution at each deposit was unique. Much of the E48 orebody and locally the 66 GRP314 deposit was overprinted by texturally-destructive, white sericite-albite-quartz-alunite ± 67 chlorite alteration. In the E26 deposit, and in regions of the GRP314 deposit, a series of quartzanhydrite ± pyrite ± Cu sulfide veins with distinctive, vein-proximal, sericite-dominant alteration 68 69 halos cut the primary, deposit-concentric alteration facies. The vein-distal mineralogy of these 70 alteration halos is controlled by their distance from deposit centers, changing from K-feldspar ± 71 biotite in deposit-proximal veins to chlorite ± epidote-albite in deposit-distal veins. Late-72 mineralization QMPs at E26 and GRP314 also appear to be related to the generation of anhydrite-73 guartz \pm sphalerite veins and a set of guartz-calcite-pyrite-sphalerite \pm chalcopyrite \pm galena veins. 74 Post-mineralization magmatic activity produced relatively primitive and barren monzonite 75 porphyries and younger alkali basalt dikes.

76 Introduction

Mining at Northparkes exploits a cluster of Late Ordovician-Early Silurian, silica-saturated, alkalic porphyry Cu-Au ore deposits, located 27 km northwest of Parkes, in central-west New South Wales, Australia (Fig. 1). The region consists largely of flat agricultural land, with extensive cover of Mesozoic to Quaternary sediments. All the Northparkes orebodies are blind at the surface and, consequently, the first discovery was not made until 1976, when exploratory drilling encountered the Endeavour (E) 22 deposit (Jones, 1985). Subsequent exploration defined the E27, E26, E48 and most recently GRP314 deposits, the latter named after the discovery drillhole.

84 Mineralization is focused within and around a series of multiphase quartz monzonite porphyry intrusions which appear to terminate below the surface (Fig. 2) and show a remarkable pipe-like 85 geometry, typically only ~50-100 m in diameter but extending to depths of >1 km. Copper sulfides 86 87 are disseminated throughout K-feldspar and quartz vein stockworks in areas of potassic alteration 88 which surround the margins and apices of the mineralizing porphyry bodies. The resulting ore 89 zones are vertically continuous, elliptical prisms, several hundreds of meters in diameter. These were accessed historically by open pits at E22, E26 and E27, and presently via block caving at E26 90 91 and E48. The total ore reserve at Northparkes is currently 106 Mt at 0.61% Cu and 0.26 g/t Au, with 92 a total measured, indicated and inferred resource of 497 Mt at 0.56% Cu and 0.18 g/t Au.

93 Initial reviews of mineralization in the Northparkes district were provided by Jones (1985) and 94 Heithersay et al. (1990), with later contributions dedicated to descriptions of deposit-specific 95 geology at E26 (House, 1994; Heithersay and Walshe, 1995; Harris, 1997), E27 (Squires, 1992) and 96 E48 (Wolfe, 1994; Hooper et al., 1996). This culminated in the work of Lickfold et al. (2002, 2003, 97 2007) who investigated the geochemistry and intrusive history of the Endeavour porphyries (E22, 98 E26, E27 and E48). Subsequently, the geology of GRP314 was outlined by Hendrawan (2011a) and 99 Johnson (2011); Hendrawan (2011b) also re-examined geology and alteration at the E48 deposit. 100 Additional, more targeted research focused on the origin of sericitic alteration at E26 and E48 101 (Wolfe, 1996; Harris and Golding, 2002), base metal veins near the E28 prospect (Kolkert, 1998), 102 copper isotope zonation around E26 and E48 (Li et al., 2010), and vein emplacement mechanisms 103 at E26 (Harris and Holcombe, 2014).

104 These studies have resulted in the definition of numerous intrusive phases, alteration facies and 105 vein types in the ore zones, whereas comparatively little attention has been paid to the more distal 106 portions of the systems. This is particularly true for the propylitic alteration footprint which has only 107 been previously considered in a small pilot study (Radclyffe, 1995), but is by far the most 108 widespread, covering an area some 20x greater than the potassic alteration domain and 109 dominating in the mine lease. Further, in the decades following most work on the Endeavour 110 deposits, several hundred kilometers of diamond drilling have been completed, both improving the 111 3D understanding of the systems and resulting in the discovery of new intrusive phases and 112 mineralized centers. These new data provide a timely opportunity to revise and update our 113 understanding of this classic alkalic porphyry district.

114 The aims of this paper are to: (i) provide an up-to-date review of the regional geology, principal 115 lithologies and igneous geochemistry, including the interpretation of 232 new whole rock analyses, 116 in order to characterise the Northparkes host units and their evolution; and (ii) present in this 117 context the results of detailed logging and observations that describe vein types and alteration in the system with a focus on the peripheral propylitic altered domains surrounding the E26 and E48 118 119 deposits. The latter is, to our knowledge, the most detailed description of propylitic alteration in 120 any porphyry district published to date. The observations and temporal relationships interpreted 121 here underpin a new model for propylitic alteration in porphyry systems to be published in 122 forthcoming contributions. Such understanding is important given the increasing use of propylitic 123 mineral chemistry in exploring for buried porphyry deposits.

124 **Regional geology**

125 The Northparkes deposits occur within the Junee-Narromine volcanic belt, one of four such belts 126 within the eastern Lachlan Orogen of New South Wales (Fig. 1). Together, these constitute the Early 127 Ordovician to earliest Silurian Macquarie Arc, comprising largely high-K, calc-alkaline to shoshonitic 128 volcanic-volcaniclastic sequences, with some intercalated Middle to Late Ordovician carbonates 129 (e.g., Crawford et al., 2007; Glen et al., 2012). As implied in the name, the Macquarie Arc is generally 130 thought to represent the accreted suprasubduction zone remains of an intra-oceanic arc developed 131 outboard of Gondwana (e.g. Glen et al., 1998; 2007; 2012; Cooke et al., 2007). In the Parkes region, 132 the Junee-Narromine Volcanic Belt is composed of three principal stratigraphic packages (Krynen 133 et al., 1990). These units and structural features of the area are described below with reference to 134 the geological map (Fig. 3).

135 The Nelungaloo Volcanics and Yarrimbah Formation

The Lower Ordovician Nelungaloo Volcanics are the oldest exposed rocks of the Junee-Narromine Volcanic Belt. They consist largely of high-K, calc-alkaline andesites to basaltic andesites and volcaniclastic rocks (Glen et al., 2007), with a combined estimated thickness of 1.5 km (Simpson et al., 2005). The minimum age of this package is constrained by intrusions of broadly comagmatic monzodiorite bodies, which provided a zircon U-Pb (SHRIMP) age of 481 ± 4 Ma (Simpson et al., 2005 after Butera et al., 2001).

The Yarrimbah Formation directly overlies the Nelungaloo Volcanics (Sherwin, 1979, 2000). It is described by Glen et al. (2007) as a 400-600 m-thick, broadly fining upwards sequence of volcaniclastic sandstones, siltstones and bedded mudstones deposited, based on fossil dating, between the Lancefieldian (~479 Ma) and Bendigonian (~476 Ma; Sherwin, 1979).

The Goonumbla Volcanics – Billabong Creek Limestone and Gunningbland Formation

147 The Middle to Late Ordovician Goonumbla Volcanics are separated from the underlying 148 Nelungaloo Volcanics by an inferred low angle unconformity, representing a depositional hiatus of ~10 Myr (Krynen et al., 1990; Percival and Glen, 2007). Trachyandesites are the dominant lithology 149 150 along with lesser basaltic andesites, volcaniclastic conglomerates and rare limestones, giving a total 151 thickness of 2.5-4 km. Many of the massive trachyandesites have peperitic upper and lower 152 contacts, suggesting they represent shallowly-emplaced sills (Kolkert, 1998; Simpson et al., 2005; 153 this study). A second generation of monzodiorite bodies intruded the base of the Goonumbla 154 Volcanics near Goonumbla, with a zircon U-Pb (SHRIMP) age of 450.8 ± 4.2 Ma (Butera et al., 2001), 155 providing a minimum age constraint on the volcanic sequence. However, as this monzodiorite does

not appear to directly intrude the trachyandesite sills (Simpson et al., 2005), the sills could still beyounger.

Around Gunningbland (Fig. 3), the shallow marine Billabong Creek Limestones and overlying deeper water Gunningbland Formation are intercalated with, and occur as lateral equivalents of, the Goonumbla Volcanics (Percival and Glen, 2007). The Billabong Creek Limestones and Gunningbland Formation have a maximum thickness of ~1.1 km and were dated by Pickett and Percival (2001) using a near continuous fossil record. Results indicated deposition between the Darriwilian (~465 Ma) and Eastonian (~452 Ma).

164 **The Wombin Volcanics**

The >3 km thick Wombin Volcanics directly overlie the Goonumbla Volcanics, although it remains unclear if there was a hiatus between their deposition. Together, these sequences comprise the Northparkes Group (Percival and Glen, 2007). Krynen et al. (1990) defined the Wombin Volcanics based on their more evolved chemistry and reddish-brown coloration. They are dominated by volcanic breccias and sandstones along with trachytes, ignimbrites and a series of trachyandesite sills, similar to those identified in the Goonumbla Volcanics (Simpson et al., 2005).

The age of the Wombin Volcanics is poorly constrained to the Late Ordovician or earliest Silurian. They must post-date the latest Eastonian age Goonumbla Volcanics (~450 Ma; Webby et al., 2004), and minimum constraints are imposed by several monzonite intrusions emplaced throughout the area. A monzonite body near Cooks Myalls returned a zircon U-Pb (SHRIMP) date of 439 \pm 5 Ma (Butera et al., 2001) and Lickfold et al. (2007) reported a further zircon U-Pb (SHRIMP) date of 444.2 \pm 4.7 Ma for the biotite quartz monzonite (BQM) at Northparkes.

177 Structural geology and regional metamorphism

Rocks within the Lachlan Fold Belt have experienced a protracted deformation history during continental accretion, with at least six individual orogenic events defined (Gray et al., 1997). However, based on a compilation of ⁴⁰Ar/³⁹Ar slate whole rock and white mica crystallization ages, Gray and Foster (2004) suggested most deformation in the Parkes region occurred between 410 and 380 Ma.

In the Parkes district, strain is strongly partitioned into thrust faults and less competent units. For
example, highly deformed and foliated deep marine sediments occur east of the Parkes Thrust (Fig.
3) in contrast to only gently folded and non-foliated volcanic rocks to the west. Ductile strain in
volcanic rocks is limited to the NNE-striking, gently plunging and open-hinged Forbes Anticline

and Milpose Syncline. These folds are cut by a conjugate set of ESE-striking sinistral and SSEstriking dextral faults, exemplified by the Dalveen Fault Zone. Regional mapping (e.g., Heithersay et al., 1990; Krynen et al., 1990; Arundell, 1997; Simpson et al., 2005) has shown that rocks of the largely Lower Devonian Trundle Group (Sherwin, 1996), which unconformably overlies the Wombin Volcanics, are unaffected by the Dalveen Fault. Faults related to the Dalveen Fault Zone have offset the Parkes Thrust (Fig. 3). These observations appear to constrain deformation to the Middle Silurian to Lower Devonian, at the oldest end of the estimate provided by Gray and Foster (2004).

Regional metamorphism of volcanic rocks in the Parkes area appears to be limited to prehnitepumpellyite facies, with the widespread development of chlorite, calcite, prehnite, pumpellyite and quartz. Minor epidote, albite and zeolites are also observed, making the distinction between metamorphic and porphyry-propylitic assemblages potentially problematic. However, there is no evidence to suggest a resolvable metamorphic overprint of the Northparkes deposits, with all alteration assemblages appearing to be hydrothermal in origin.

200 The Northparkes deposits

The Northparkes deposits are a cluster of five Cu-Au ore zones: Endeavour (E) 22, 26, 27, 48 and GRP314, all of which occur in an area of only ~10 km² (Figs. 4-6). The deposits are hosted within both the Goonumbla and Wombin Volcanics, with mineralization-related intrusive rocks effectively forming part of the latter.

205 General features

Mineralization comprises disseminated Cu sulfides and fracture coatings within quartz vein 206 207 stockworks and zones of potassic alteration, both of which are spatially and temporally associated 208 with multiphase quartz monzonite porphyry (QMP) complexes. Bornite is the dominant sulfide in 209 the center of these magmatic-hydrothermal systems, transitioning outwards to a chalcopyrite-rich 210 shell and pyrite-dominant periphery. Highest Au grades are in the core of the systems, where Au is 211 present largely as fine, native inclusions in both silicates and bornite, and occurs with minor 212 tellurides (Müller et al., 1994; Lickfold, 2002; Butcher et al., 2011). Oxidation extends to ~80 m 213 below surface in the region. Consequently, the highest-level deposits, E22, E26 and E27, exhibit 214 thin, but well-developed oxide ore zones (Crane et al., 1998; McLean et al., 2004). These comprise 215 an uppermost zone of Cu phosphates, notably including sampleite and libethenite at E26, passing down through a layer of Cu carbonates to a small supergene enrichment horizon with native Cu, 216 217 cuprite and chalcocite (Clissold et al., 2005).

The QMP bodies form part of a series of silica-saturated alkaline intrusions that dominate in the mine area. The most voluminous phase is a pre- to early-mineralization pluton, variable in composition between a biotite quartz monzonite (BQM) and alkali feldspar granite (AFG). It underlies and partly hosts mineralization. QMP complexes at E22, E26, E27 and E48 were emplaced on the shoulders, and GRP314 within the center, of apophyses of this pluton (Figs. 4-6).

Rocks of the Goonumbla Volcanics are the principal host to the E22, E26, E27 and E48 deposits, although the upper parts of the BQM-AFG pluton and mineralized porphyries also intruded the overlying Wombin Volcanics. In contrast, GRP314 is hosted entirely within intrusive rocks, comprising QMP bodies contained within a larger, weakly-mineralized quartz monzonite phase, which is itself enclosed by the BQM-AFG pluton (Fig. 4).

228 Structural features

229 A distinctive feature of most of the mineralized porphyry intrusions is their elongate, pipe-like 230 geometry ('pencil porphyries'), being typically ~50-100 m in diameter and >1 km in vertical extent 231 (e.g., Figs. 5, 6). However, some porphyry intrusions also occur as dikes. At GRP314 drilling appears 232 to show dikes with a NE-SW trend and of similar orientation are a series of thin, post 233 mineralization, alkali basalt dikes which occur throughout Northparkes. In contrast, a distinctive 234 post-mineralization monzonite porphyry phase, known as the zero porphyry, occurs exclusively as NW-SE-striking dikes, which cut through the center of E26, are common at E37 and are further 235 236 recorded near E34 (this study; Fig. 4). Using orientated core measurements, Harris (1997) 237 demonstrated that stockwork veins in all the Endeavour deposits show a similar strike (~140-170°). 238 Harris and Holcombe (2014) further investigated the complex nature of vein orientations at the E26 239 deposit, once again revealing a preferred NNW-SSE trend. Consequently, it has been suggested 240 that the pipe-like morphology of the mineralizing bodies perhaps reflects emplacement at the 241 intersections of these fault-fracture sets (Harris, 1997; Crawford, 2001).

The Wombin and Goonumbla Volcanics at Northparkes are slightly tilted, with a broad SE dip of ~10-20° between E48 and E26. Porphyry bodies are subvertical indicating that tilting occurred premineralization. Post-mineralization deformation is remarkably limited: this may be partly owing to the underlying plutonic monzonite, effectively forming a strain-resistant crustal block (Scheibner, 1993).

The most significant post-mineralization structural feature, the Altona Fault (Figs. 3, 5, 6), has no surface outcrop, but is known from extensive drilling to be a large, shallowly (~15°) east-dipping planar structure. Displacement on this fault poses significant exploration challenges. The E28

prospect is the very top of another porphyry Cu-Au deposit located entirely within the hanging wall of the Altona Fault (Jones, 1985; Kolkert, 1998). The top of E48 and an upper section of the GRP314 system are both located in the footwall and are truncated by the fault. GRP314 was only discovered in 2004 during underground and subsequent surface drilling to explore below the structure (Lye, 2006). Although the sense of displacement has been debated, investigations based on drill core structures suggest the Altona Fault is a top-to-the-west thrust, with an offset of several hundreds of meters (Dalstra and Oosterwijk, 2005).

257 *Geochronology*

258 Radiometric dating studies at Northparkes have been relatively limited in number (Fig. 7). The age 259 of mineralization was first estimated as 439.2 ± 1.2 Ma by Ar/Ar dating of sericite at the E26 deposit (Perkins et al., 1990). Subsequently, Lickfold et al. (2003) provided biotite Ar/Ar age 260 261 estimates for the BQM (437.3 ± 2.1 Ma), alteration at E26 (441.3 ± 3.8 Ma), and biotite-rich QMP 262 intrusions at both E26 (448.6 ± 7.0 Ma) and E22 (446.5 ± 2.6 Ma). However, interpretation of these results is difficult, as the closure temperature for Ar in biotite is ~300°C and is variable both as a 263 264 function of Fe-Mg content and cooling rate (e.g., Harrison et al., 1985). Therefore, at best, such 265 dates reflect the point in time when samples cooled permanently below this threshold, and thus 266 provide minimum age constraints. Lickfold et al. (2007) reported two further age estimates based 267 on U-Pb (SHRIMP) dating of zircon from the BQM at E26 (444.2 ± 4.7 Ma), and from the zero 268 monzonite porphyry near the E37 prospect (436.7 ± 3.3 Ma). These intrusions, and therefore dates, 269 effectively bracket the period of mineralization.

As part of this study, Rb-Sr dating of fourteen epidote separates and ten whole rock samples, collected from around the E48 deposit, provided an estimate of 450 \pm 11 Ma for associated propylitic alteration (Fig. 8; Appendix A). Although not a precise isochron (which would require MSWD \leq 2), this relationship supports a limited time interval between volcanism, emplacement of plutonic rocks and hydrothermal activity within the propylitic alteration zone.

Currently available radiometric age constraints cannot, in isolation, establish the relative order of magmatic-hydrothermal events at Northparkes. They do, however, strongly suggest that most activity occurred in the latest Ordovician to earliest Silurian and demonstrate a temporal relationship between such activity and formation of the Wombin Volcanics.

279 **Principal lithologies**

Key lithological units at Northparkes are summarized below, and their typical occurrence is illustrated in Figure 9. Descriptions are based mainly on drill core logging at E26 and E48 but are supplemented where indicated by published literature and Northparkes Mines reports.

283 Country rock volcanics

284 Trachyandesites

285 Basaltic trachyandesites to trachyandesites form a significant proportion of the Goonumbla Volcanics and are also found within the Wombin Volcanics. They are dark brown to black and 286 ubiquitously porphyritic, comprising 20-50% of 1-4 mm plagioclase laths and minor pyroxene in a 287 288 very fine to aphanitic groundmass (Fig. 10a). Peperitic textures and hyaloclastic breccias (Fig. 10b-289 d) record magma-wet sediment interaction between trachyandesite units and volcaniclastic rocks in 290 both the Goonumbla and Wombin Volcanics. Such textures occasionally allow the distinction 291 between intrusive and extrusive units to be made, although this is often ambiguous in altered drill-292 core. Regardless, they attest to the water-saturated and poorly-consolidated nature of the volcanic 293 stratigraphy during this phase of magmatism.

294 *Volcanic conglomerates*

295 Massive packages of polymict, matrix-supported conglomerates, fining upwards into volcanic 296 sandstones, are present in the Goonumbla Volcanics. These comprise clasts of trachyandesite, 297 sandstone and siltstone in a silt and mud matrix (Fig. 10e). Trachyte clasts are also present in 298 matrix-supported conglomerates within the Wombin Volcanics.

299 Volcanic sandstones, siltstones and mudstones

Most volcanic sandstones comprise massive, fine to medium grained and moderately- to very wellsorted units composed of lithic fragments and rarer abraded crystals set in a fine silt to mud matrix (Fig. 10f). Internal bedding and lamination are relatively rare. Siltstones and mudstones are uncommon, but may show wet sediment deformation structures, including load casts, flame structures and minor slump folds (Fig. 10g).

305 Trachytes

Thin (<1-10s m) units of pink- to brick-red-colored trachyte occur within the Wombin Volcanics. These are typically aphanitic or finely porphyritic, with sparse, 1-3 mm euhedral plagioclase and rare K-feldspar, pyroxene, biotite and hornblende phenocrysts in an aphanitic K-feldspar-quartz groundmass (Fig. 10h).

310 *Trachytic volcanic breccia (ignimbrite)*

Trachytic volcanic breccias are restricted to the Wombin Volcanics and are inferred to be welded, lithic-crystal ignimbrites. They contain angular to sub-angular clasts of trachyte, trachyandesite and volcaniclastic rocks along with 10-30% euhedral and broken plagioclase, K-feldspar and pyroxene crystals. These are set in a welded, irregularly-banded aphanitic matrix with wispy patches of crystal-poor material, interpreted by Simpson et al. (2005) as pumice fragments (Fig. 10i).

316 Northparkes intrusive rocks

317 Monzodiorite

An equigranular, pre-mineralization monzodiorite is rarely observed as xenoliths within the BQM pluton (Fig. 11a). It consists 10-30% mafic minerals, most commonly augite and biotite, with lesser magnetite and hornblende, intergrown with 60-70% plagioclase and minor alkali feldspar (~10%).

321 Biotite quartz monzonite (BQM)

322 The BQM comprises a large intrusion in the Northparkes area, revealed by the ~12 km diameter 323 negative Bouquer gravity anomaly (Fig. 3). The rock exhibits a continuously variable texture from 324 coarse and equigranular, through to medium grained and porphyritic. The equigranular end-325 member comprises interlocking, 2-4 mm euhedral plagioclase and K-feldspar crystals with 10-20% 326 subhedral biotite; guartz is present as an anhedral interstitial phase (~5%) with further K-feldspar 327 (Fig. 11b). In the porphyritic end-member, euhedral 3-5 mm plagioclase phenocrysts dominate (40-328 60%), along with subhedral biotite (~10%) within a finer-grained (but still visibly crystalline) 329 interstitial mass of interlocking K-feldspar and guartz (Fig. 11c-d). Minor specks of chalcopyrite and 330 bornite are present within the BQM, and patches of chalcopyrite occur in rare pegmatitic 331 segregations.

332 Alkali feldspar granite (AFG)

333 The AFG (Fig. 11e) occurs as another distinct and voluminous lithology within the BQM-dominated 334 pluton. It appears to be a later differentiate of the BQM: contacts between the two are either 335 gradational over tens of meters, or distinct but irregular, with plagioclase phenocrysts observed to 336 pass over the contact (Fig. 11f). The AFG is coarse and relatively equigranular, typically consisting of 337 10-30% euhedral, 2-4 mm plagioclase crystals (commonly amalgamated together) surrounded by 338 only slightly finer, interlocking K-feldspar and guartz. Quartz is present locally as 1-2 mm anhedral 339 grains, the varying abundance of which shifts the composition between an alkali feldspar syenite 340 and alkali feldspar granite. Biotite is restricted to 1-5%.

341 *Quartz monzonite (QMZ)*

342 A large, NE-SW-trending QMZ body occurs within the BQM-AFG pluton at GRP314 and at depth around E26 and E48. Contacts with the pluton may be sharp or gradational over tens of meters. 343 344 Sub-rounded BQM xenoliths are common within the QMZ. Textures vary between strongly 345 porphyritic (Fig. 11g), with a fine-aphanitic groundmass, through to weakly porphyritic with a visibly crystalline groundmass (Fig. 11h). Phenocrysts typically range from 0.5 mm to 3 mm and 346 347 comprise 5-10% anhedral guartz, 30-70% characteristically subhedral to anhedral plagioclase and 348 10-40% euhedral to subhedral K-feldspar with minor biotite (1-5%). In rare instances, K-feldspar 349 forms larger phenocrysts (1-3 cm; Fig. 11i) that may overgrow anhedral plagioclase. Quartz-aplite 350 unidirectional solidification textures (USTs) are sometimes observed and Cu sulfides may be 351 present (Fig. 11h).

352 Quartz monzonite porphyries (QMP)

All major orebodies at Northparkes are spatially associated with small-volume QMP intrusions that occur as pipe-like to occasionally more elongate, dike-like bodies (Figs. 5, 6, 12a-g). Multiple magmatic pulses are recognizable, each of which are variably altered and may exhibit dramatic spatial variability in their size, shape, groundmass granularity and phenocryst abundance (40-90%).

K-feldspar phenocrysts are typically large (1-2 cm), euhedral and commonly zoned (Fig. 12f-g) but are also observed as angular broken fragments (Fig. 12b-d). Plagioclase phenocrysts are generally smaller (<1 cm), subhedral crystals that are locally overgrown by K-feldspar (Fig. 12e-f). The groundmass varies from aphanitic to finely crystalline and is largely composed of quartz and Kfeldspar. Biotite, augite and hornblende may be present as mafic phenocrysts and accessory apatite, titanite and zircon have been recorded (Lickfold, 2002).

Lickfold et al. (2003) petrographically distinguished three sub-types of QMP: (1) K-feldspar QMP -363 with <2% mafic phenocrysts (Fig. 12a-b); (2) augite-K-Feldspar QMP - with 2-5% mafic phenocrysts, 364 365 largely of augite and biotite (Fig. 12c-d); and (3) biotite QMP - with 5-10% mafic phenocrysts, 366 largely of biotite (Fig. 12e-f). Generally, the K-feldspar QMP bodies are most closely associated with 367 mineralization. However, there is no consistent temporal relationship between these sub-types and 368 practical application of this classification is challenging. Consequently, QMP intrusions are grouped 369 by Northparkes Mines based on their relative timing and spatial association with mineralization 370 (e.g. Figs. 4-6).

371 Monzonite porphyries

372 A distinct, crystal-crowded, post-mineralization monzonite porphyry (Fig. 12h) occurs as SE-striking dikes that cut through the E26 deposit. This phase is frequently referred to as the 'zero' porphyry, 373 374 due to its low Cu-Au concentrations (<10 ppm Cu, <1 ppm Au) which result in local grade dilution. 375 Only weak propylitic alteration and hematite reddening have affected the zero porphyry. It is 376 typically brownish red, with phenocrysts comprising 5-15% mafic minerals (augite, biotite and 377 magnetite), 60-70% plagioclase and 10-20% K-feldspar within an aphanitic K-feldspar groundmass. 378 Lickfold (2002) also reported the occurrence of primary anhydrite phenocrysts. As with the QMP 379 intrusions, plagioclase and K-feldspar phenocrysts may be zoned and either euhedral or fragmental. Along some dike margins and sometimes occurring as highly irregular shaped 380 381 xenoliths in the zero porphyry (Fig. 12i) is a dark brown, plagioclase-phyric basaltic trachyandesite 382 (the 'mafic zero'). This appears to represent commingling of two magmatic phases, with the zero porphyry emplaced into the same structure as the earlier, mafic zero, before it had totally solidified 383 384 (Keith et al., 1998; Lickfold et al., 2007).

A monzonite porphyry body that is located near the E34 prospect also appears to be postmineralization. It cuts chlorite-quartz-epidote-albite (P1) veins in intensely propylitically-altered rocks. Xenoliths of these veins, pervasively epidote-altered country rock, sericitic (quartz-sericitepyrite) veins and BQM are also observed. The intrusion comprises ~40% phenocrysts, dominantly <2 mm subhedral plagioclase feldspar with lesser biotite and typically larger (1 mm – 1 cm) euhedral K-feldspar, set in an aphanitic K-feldspar groundmass (Fig. 12j). Porphyry-cemented breccias occur at the margins.

392 Basaltic dikes

Thin (30 cm to 1.5 m), broadly NE-striking, post-mineralization dikes of alkali basalt have been documented at E22 and E27 (Jones, 1985; Lickfold et al., 2003), E48 (Wolfe, 1994; Hooper et al., 1996), E34 (this study) and GRP314 (Hendrawan, 2011a). Although most are unaltered, some dikes are pervasively overprinted by strong sericitic alteration. Alkali basalt has also been emplaced along the Altona Fault (Hooper et al., 1996).

398 Breccias and magmatic-hydrothermal features

399 Porphyry-hydrothermal phenomena

K-feldspar-rich, syn-mineralization QMP bodies in all the deposits may contain highly irregular
 segregations of quartz-K-feldspar-sulfide ± anhydrite ± fluorite intergrown with aplite (Fig. 13a-b).
 In some instances, these patches appear layered and exhibit unidirectional, comb-quartz growth

403 (Fig. 13c). Similar, irregular segregations of quartz-magnetite-chalcopyrite are also observed,404 notably at E26.

Vein dikes (<1-5 cm wide) are common and spatially associated with QMP. First described at E26,
they consist of either quartz veins with a central aplitic fill, or a predominantly aplitic fill with coarse
segregations and central intergrowths of hydrothermal quartz-K-feldspar-sulfide (Heithersay and
Walshe, 1995).

409 Pebble dikes

Pebble dikes, typically 1 cm to 1 m wide, are post-mineralization, polymict hydrothermal breccia dikes that occur within all the known deposits (e.g., Jones, 1985; Heithersay et al., 1990; Lickfold, 2002; this study). Clasts do not necessarily reflect immediately adjacent wall rocks and comprise sub-angular to well-rounded fragments of all volcanic and intrusive lithologies, except for basaltic dikes, in a fine, dark rock flour matrix, together with some hydrothermal quartz-carbonate-pyrite cement (Fig. 13d). Clasts may be mineralized and/or show pervasive potassic, sericitic or propylitic alteration, and locally contain truncated veins.

417 Porphyry-cemented breccias

Porphyry-cemented breccias are relatively common in all the QMP complexes at Northparkes. At E27, the margins of syn- to late-mineralization QMP bodies are characterized by large zones of jigsaw-fit intrusion breccias in which angular clasts of mineralized host rock are cemented by plagioclase-phyric aplitic porphyry. This aplitic cement has commonly penetrated <1 mm wide fractures and is typically intergrown with coarse segregations (examples up to several cm long) of hydrothermal quartz-K-feldspar-bornite (Fig. 13e).

Early open-pit operations at E27 also recovered large blocks (up to several meters long) of matrixsupported hydrothermal breccia with a cement of grey 'greasy' quartz and massive bornite (Fig. 13f). Euhedral K-feldspar crystals reaching 6 mm in length are contained within the bornite (Fig. 13g) and clasts are strongly potassically-altered.

428 At E34, a post-mineralization monzonite porphyry (Fig. 12j) exhibits brecciated contacts. With 429 increasing distance from the intrusion, these grade from a porphyry-cemented breccia (Fig. 13h) 430 into an extensive zone of brecciated country rock fragments, with irregular patches of porphyry 431 locally surrounded by intensely chloritized rock flour (Fig. 13i). These rock flour breccias are very 432 similar in texture to the pebble dikes observed elsewhere (Fig. 13j). It is possible, therefore, that the

433 sequence logged at E34 records the generation of pebble dikes at the point of explosive434 interaction between late porphyry intrusions and water-saturated country rocks.

435 Pegmatites

Pegmatitic dikes (<4 m), intersected at the base of GRP314, contain large (several cm long)
interlocking crystals of K-feldspar and anhydrite, with accessory bornite, chalcopyrite, magnetite,
biotite, muscovite and actinolite (Hendrawan, 2011a).

439 Bornite clots

Unusual, irregular ~2-40 cm diameter 'clots' of massive bornite, with accessory chalcopyrite, Kfeldspar and quartz occur in the QMP and QMZ intrusions, particularly at E22, E27 and GRP314 (Fig.
13k). In some cases, veins of pure bornite appear to emanate from large clots (Fig. 8e of Lickfold et
al., 2003).

444 Lithogeochemistry

Whole rock geochemical analyses were conducted on 204 samples collected from logged diamond
drill core. Data for a further 28 samples were provided by Rio Tinto and are here combined with the
analyses of Johnson (2011), Lickfold (2002), Crawford et al. (2001), Morrison and Blevin (1997),
Radclyffe (1995), Müller et al. (1994), Wolfe (1994), Hall (1993), Heithersay (1991) and Clarke (1990).
Analytical details and the resulting data for 540 samples are provided in Appendix B.

450 In this paper, to best represent fresh rocks, we exclude all samples identified as strongly-altered 451 based on original descriptions (where provided) and/or those which plot upon alteration 452 trajectories within the feldspar K-Na general element ratio control diagram (Stanley and Madeisky, 453 1993). The only exceptions are data for five samples of potassically-altered QMP, six samples of 454 moderately sericitically-altered monzonite porphyry (zero and mafic zero) and two samples of 455 mafic dikes, which are retained to ensure adequate representation of these relatively rare phases 456 within the dataset. The final 73 excluded analyses are indicated in Appendix B. Nevertheless, most 457 remaining samples are altered to a minor extent, so that results for potentially mobile minor and 458 trace elements must be treated with caution. Furthermore, a majority of the Northparkes magmatic 459 rocks contain phenocrysts, typically of plagioclase with variable biotite and K-feldspar, so that 460 whole rock analyses may not be fully representative of the parental magma.

461 Country rock volcanics

462 The Goonumbla and Wombin Volcanics follow near identical fractionation trends to one another 463 (Fig. 14). As demonstrated by total Na₂O + K_2O vs. SiO₂ (TAS; Fig. 14a) and K_2O vs. SiO₂ plots (Fig.

464 14b) they are typically considered high-K to shoshonitic in character (Heithersay and Walshe, 1995; 465 Crawford et al., 2007; Lickfold et al., 2007). In contrast, the Nelungaloo Volcanics are more 466 consistently classified as basalts to trachyandesites with distinctly lower K₂O, Na₂O and Al₂O₃ as 467 well as higher overall Fe₂O₃, CaO, TiO₂ and V concentrations, defining subtly different fractionation 468 trends.

Intrusions within each volcanic package follow the same fractionation trends and REE profiles as the host volcanics, suggesting they were broadly comagmatic. REE profiles for all the volcanic packages (Fig. 15) lack Eu anomalies, suggesting limited plagioclase fractionation, and only the Wombin Volcanics begin to show a trough-shaped depletion in the middle REE indicative of fractionation of hornblende from the magma prior to eruption or emplacement.

474 Nearly all fractionation trends (Fig. 14) are smooth and demonstrate compatible behavior of Fe, Ca, 475 Mg, Mn, Ti, V and Sr, likely driven by the continual fractional crystallization of pyroxene and 476 magnetite which are common phases in all the volcanic rocks. Plagioclase phenocrysts are also 477 ubiquitous, but the lack of Eu anomalies and mostly incompatible behavior of Na suggests it was 478 not significantly fractionated, and/or crystallized late in the sequence. Fractionation trends in Al₂O₃ 479 are only evident in the Goonumbla and Wombin volcanic rocks; these initially show increasing 480 Al_2O_3 until SiO₂ \approx 56%, followed by slight depletion with increasing silica (Fig. 14d). The constant 481 decrease in P₂O₅ with increasing silica (Fig. 14g) indicates accessory apatite crystallization throughout. Continual incompatible behavior is displayed by Zr and U in all rocks, except some 482 483 Wombin intrusions, which trend toward lower Zr concentrations in the most silicic samples (Fig. 484 14n). This feature is more prominent in the Northparkes intrusive rocks.

The trachyandesites are the most primitive rocks, although, for most elements, they plot broadly along the same fractionation trends as the Goonumbla and Wombin Volcanics (Fig. 14). REE profiles for the trachyandesites are most similar to the Goonumbla Volcanics (Fig. 15). The trachyandesites thus represent potential parental magmas for the entire magmatic suite present in the district.

490 Northparkes intrusive rocks

491 Standard TAS classification (Fig. 16a) shows the suite encompasses monzodiorite through to 492 syenite and granite, with an almost exclusive shoshonitic affinity (Fig. 16b). This agrees with 493 classification based on primary mineralogy, which clearly shows the rocks are dominantly alkaline, 494 i.e. monzonitic to syenitic. Furthermore, significantly-altered samples have been excluded and all 495 remaining samples, regardless of the type or intensity of any hydrothermal alteration developed, 496 follow the expected fractionation trajectory for K and Na. Thus, the overall classification as 497 shoshonitic does not appear to be influenced by the occurrence of any potassic alteration.

498 Generally, Al₂O₃, Fe₂O₃, CaO, P₂O₅, MqO, MnO, TiO₂, Eu, V and Sr demonstrate compatible behavior 499 with increasing silica, in agreement with continual fractional crystallization of plagioclase, biotite, 500 magnetite, apatite and minor pyroxene and hornblende (Fig. 16). Some samples, primarily of the 501 BQM, are markedly enriched in MnO and plot above the well-defined fractionation trend illustrated 502 by most of the data (Fig. 16i). This feature is accounted for by the fact that these samples are 503 propylitically-altered and are located within the whole rock Mn-Zn halo that surrounds the E48 504 deposit. However, these samples are not obviously anomalous in other elements, hence they are 505 retained in the database.

506 The intrusive rocks appear to define two distinct fractionation trends (Fig. 16). Initial emplacement 507 and crystallization of the BQM-AFG pluton defines the first 'barren' fractionation series, reaching 508 values of SiO₂ \approx 66% and in which all HFSE behave incompatibly (e.g., Figs. 16n-g). Subsequent 509 QMZ intrusions appear to have more primitive compositions, at SiO₂ \approx 58%, defining the start of a 510 second 'fertile' fractionation trend toward the K-feldspar-rich QMP intrusions, which ultimately 511 reach SiO₂ \approx 74%. By comparison, this second series exhibits lower MnO, P₂O₅, TiO₂ and Eu, along 512 with slightly higher Sr concentrations for any given silica content. There is also a highly distinctive, 513 progressive depletion in all HFSE with increasing evolution (e.g., Figs. 16n-g); a feature not 514 observed in the BQM-AFG series. Some BQM samples do however lie upon this trend for U, Ho and Yb, and comparable Zr depletion is apparent in Wombin intrusions (Fig. 14n). 515

In terms of the REE, there is a systematic lowering in the absolute abundance of all REE (c.f. Fig. 17a-e) and an increasing upward inflection in the HREE (Er, Yb, Lu) from the BQM-AFG pluton, through the QMZ, to the QMP bodies. This is most pronounced in the most REE-depleted, oreassociated, K-feldspar-rich QMP samples, which also start to display positive Eu anomalies (Fig. 17e). There is a return to more typical REE levels in the post-mineralization E34 monzonite porphyry, and even elimination of the Dy minimum in the zero porphyries to yield REE patterns similar to most of the volcanic rocks (c.f. Figs. 15, 17).

523 Modelling by Lickfold (2002) demonstrated that the depletion in REE cannot be reproduced by 524 simple fractionation of the REE-rich phases apatite or titanite from a BQM-type melt, however the 525 assumption of this being the direct precursor to the quartz monzonites is open to question. Zircon 526 fractionation is unlikely given the constant concentration of Zr across a broad range of SiO₂ for the 527 QMZ and various QMPs. Given that REE profiles for all Northparkes intrusive phases, except the

528 mafic zero and basaltic dikes, show preferential depletion in the middle-heavy REE, essentially Gd 529 to Yb (Fig. 17), it is likely that hornblende fractionation played an important role in controlling the 530 REE geochemistry. This feature is also observed in samples of the Wombin Volcanic Group, with 531 which the Northparkes intrusions appear to be comagmatic, and attests to relatively more hydrous 532 magmatic conditions in comparison to the Goonumbla and Nelungaloo Volcanics. BQM samples 533 may exhibit positive or, more rarely, weak negative Eu anomalies, probably depending on the 534 degree of crowding or dispersion of plagioclase phenocrysts rather than differences in 535 crystallization history (Fig. 17a). The AFG displays a negative Eu anomaly, consistent with 536 plagioclase fractionation (Fig. 17b).

The mafic zero monzonite porphyry reflects a return to more mafic compositions, with $SiO_2 \approx 48\%$. Its composition contrasts markedly with the more evolved zero and E34 monzonite porphyries (Figs. 16, 17e). The latter two both plot upon the same fractionation series as the QMZ and QMP bodies, suggesting they are related. The last stage of magmatic activity, represented by the basaltic dikes, is the most primitive and samples display the flattest REE profiles, with no evidence of crystal fractionation (Fig. 17f).

543 Alteration and veining

Eight diamond drillholes, totalling ~8 km, were selected to provide broadly lateral traverses away from the central ore zone into distal propylitic alteration at the E26 and E48 deposits (Figs. 4-6). Detailed logging of the lithologies and alteration mineralogy through these holes (Figs. 18, 19) defined three principal alteration facies that occur as largely concentric zones around each deposit/QMP complex. These comprise: (1) innermost K-feldspar alteration; (2) a shell of magnetite ± biotite alteration; and (3) outermost propylitic alteration (Figs. 5, 6).

550 There is no significant overprinting of the distal alteration assemblages onto the center of the 551 systems. However, sericitic alteration may patchily overprint system centers and also occurs in 552 association with particular vein types. Hematitic reddening of the rock is a further weak alteration 553 type. Argillic alteration is not observed at Northparkes, but a small outcrop of advanced argillic 554 alteration is located nearby at the Nash's Hill prospect (Fig. 3) and potentially represents the 555 remnant of a lithocap.

556 The characteristics and broad paragenesis of each alteration facies, together with the veins that 557 occur within them, are summarized together; veins that traverse alteration zones are discussed 558 separately. The spatial relationships between veins and alteration zones are illustrated in Figure 20.

559 Hematite reddening

560 Hematitic reddening is a result of <1 µm hematite inclusions developed within micro- to nanoscale 561 pores/cavities in both K-feldspar and plagioclase (Putnis et al., 2007; this study). Three distinct 562 types of this 'hematite dusting' are recognized based on associated alteration minerals, relationship 563 to veins and spatial extent.

The earliest and most widespread hematite reddening phase affected intrusive rocks and Kfeldspar-rich volcanic units, imparting a brick red hue (Fig. 11c,e,h,i). Only patches of BQM and premineralization monzodiorite are unaffected (Fig. 11a,b). It is typically weak, but very pervasive and is accompanied by weak, selective sericitization of plagioclase and chloritization of mafic minerals. With increasing intensity, plagioclase is further sericitized and reddened, giving a brown appearance (Fig. 11d,f). This reddening shows no clear relationship to any specific veins, and intervals of uniform alteration may be encountered that lack macroscopic veins.

571 Minor, secondary, but strong and selective, hematite dusting of plagioclase in intrusive rocks has 572 affected the outer portions of sericitic alteration halos developed around faults and base metal 573 veins.

The most intense hematite reddening is associated with propylitic alteration. This imparts a characteristic bright, cherry-red coloration to pre-existing K-feldspar around propylitic veins. Secondary albite formed in the outer halo of such veins is also consistently hematite reddened. Pervasive propylitic alteration of intrusive rocks is further associated with additional hematite dusting of feldspars, which may produce dark brownish-red plagioclase.

579 K-feldspar alteration and associated veins

580 The center of each QMP intrusive complex is characterized by potassium silicate-dominated 581 alteration that encloses the ore zone and comprises K-feldspar-biotite ± bornite ± chalcopyrite ± 582 magnetite. The alteration exhibits a clear spatial and temporal relationship to the K1, K2 and K3 583 veins described below (Figs. 20, 21).

584 *K1: Biotite veinlets*

Irregular, often discontinuous veinlets of quartz ± magnetite (<1 to 2 mm wide) are surrounded by a texturally-destructive biotite halo 3-10 mm wide (Fig. 21a). This biotite halo is the most distinctive and consistent component of the veins, and sometimes the central quartz seam may be absent. These veins represent the earliest potassic alteration and are consistently cross cut by all other vein types.

590 K2: K-feldspar-sulfide veinlets

591 Fine, irregular and discontinuous quartz-K-feldspar-bornite ± chalcopyrite veinlets (<1.5 mm wide) 592 are surrounded by 1-3 mm wide K-feldspar alteration halos which bleed out into the surrounding 593 rock; these veinlets form extensive, intricate networks in the cores of the deposits (Fig. 21b-e). At 594 least two generations are observed at E26 and E48, where they both cut, and are cross cut by, K3 595 veins.

596 K3: Quartz-sulfide veins

597 The principal quartz vein stockwork within the deposits comprises reasonably straight, quartz-598 bornite ± chalcopyrite ± anhydrite veins (Figs. 12a, 21d-h). These are typically 5-20 mm wide but 599 range between 3 mm and 20 cm. Sulfides are sparsely disseminated throughout the vein or, 600 together with K-feldspar, may form margin-parallel trails indicative of reopening. Vein margins are 601 sharp but locally undulate. They characteristically have pink K-feldspar alteration halos, except 602 where these have been obliterated by later sericitic overprinting (Fig. 21g). At least two generations 603 exist at E26 and E48, where these veins are observed to cross cut one another.

604 Quartz-K-feldspar-sulfide veins (K2 and K3) are responsible for ore-grade mineralization and are 605 intimately related to large-scale, pervasive alteration. Where these veins are developed in felsic host rocks (trachytes, ignimbrites and BQM-AFG pluton) the K-feldspar alteration halos are the 606 607 widest (Fig. 21b-d,f). In areas of particularly high vein density, K-feldspar-guartz alteration floods 608 the surrounding rock, and irregular patches of biotite and disseminated sulfides are developed 609 throughout this zone of flooding (Fig. 21b,i). In relatively mafic host rocks (e.g., trachyandesites and 610 volcaniclastics), K-feldspar alteration halos are limited to only a few millimeters wide, and the 611 surrounding rock is pervasively biotite-magnetite altered (Fig. 21e,h), again with disseminated 612 sulfides throughout.

613 Magnetite ± biotite alteration and associated veins

With increasing distance from centers of mineralization, the density of K2 and K3 quartz-Kfeldspar-sulfide veins decreases from hundreds of veins per meter to approximately ten or less per meter. This is accompanied by a strong decrease in K-feldspar and Cu sulfides, a minor decrease in biotite, and a simultaneous increase in the abundance of disseminated magnetite, thus defining a magnetite ± biotite alteration shell around the deposits (Figs. 18-20). Although K2 and K3 veins may sparsely persist into this zone, K1 veins do not (Fig. 20). The vein types that are characteristic of this zone are magnetite veinlets (M1) and magnetite-chalcopyrite ± quartz veins (M2).

621 M1: Magnetite veinlets

622 Minor, irregular, magnetite-only veinlets (<5 mm wide) are found rarely throughout the magnetite-623 biotite alteration shell that developed in mafic volcanic rocks (Figs. 20, 21h). The veinlets are 624 considered early, lateral equivalents of K1 biotite veinlets, and are cross cut by K2 and K3 quartz-K-625 feldspar-sulfide veins.

626 M2: Magnetite veins

Veins, 1-5 cm wide, dominated by magnetite with minor chalcopyrite ± quartz occur rarely within
 the magnetite ± biotite alteration shell. Their timing is uncertain, but the mineralogy suggests they
 were broadly synchronous with magnetite-biotite alteration.

630 The transition from innermost K-feldspar to magnetite ± biotite alteration typically occurs over 631 100-200 m. Host lithology strongly controls the occurrence and appearance of the magnetite ± 632 biotite shell. Within mafic host rocks it is encountered ~200-300 m laterally from the system center 633 and comprises intense and pervasive, fine, disseminated magnetite and biotite that impart a dark 634 grey to black coloration which obscures original textures (Fig. 21h,k). Within felsic rocks, magnetite ± biotite alteration may not be encountered until ~500 m from the system center, where it forms 635 disseminated clots of magnetite with minor biotite around original mafic crystal sites. Minor, weak 636 637 and selective sericitic alteration of plagioclase and K-feldspar is also observed (Fig. 21j).

Further biotite-magnetite is weakly, but pervasively, developed within mafic volcanic rocks adjacent
to the BQM-AFG pluton, effectively forming a contact metamorphic aureole. This assemblage
shows no relationship to veins and may be strongly overprinted by propylitic alteration.

641 **Propylitic alteration and associated veins**

With continued distance from centers of mineralization, disseminated specks of epidote and 642 chlorite begin to occur within high permeability volcanic units in the outer parts of the magnetite-643 644 biotite alteration shell. Within relatively impermeable intrusive rocks, epidote and chlorite first 645 occur as selective replacement minerals, developed in and around mafic crystal sites. Eventually, 646 epidote veinlets (P3) are encountered and followed, with increasing vein density, by larger epidote-647 chlorite-albite (P2) and chlorite-quartz-epidote-albite (P1) veins (Fig. 20; see vein descriptions 648 below). These are accompanied by further development of disseminated epidote, chlorite, pyrite 649 and hematite-reddened albite, which together define the propylitic alteration zone. Rare actinolite has also been reported from the innermost part of the propylitic alteration zone at E27 (J. Hoye, 650 651 2015, pers. comm.). Epidote and chlorite are typically developed at the expense of any pre-existing 652 magnetite and biotite. The transition between magnetite-biotite and propylitic alteration zones

typically occurs over 100-200 m. In the Northparkes area, propylitic alteration is the most
widespread facies, visibly extending 2-3 km from mineralized centers, but is generally most intense
at distances of 1-1.5 km.

656 Propylitic alteration is most pervasive within mafic volcanic and volcaniclastic lithologies, probably 657 as a result of their intrinsic elevated permeability and relatively high Fe, Mg and Ca contents (e.g., 658 Fig. 22a-d). Fluid flow was clearly controlled by both fractures and intergranular permeability within 659 the volcano-sedimentary packages (Fig. 22b), with propylitic alteration being strongest in regions 660 of high vein density and in the most permeable, coarse grained units, following and highlighting original bedding and laminations (Fig. 10e-g). Alteration mineral grain size is generally related to 661 662 that of the original rock components that have been replaced, although distinct clots of epidote ± 663 guartz ± chlorite formed locally (Fig. 22c-d).

In all competent, relatively low permeability igneous rocks, propylitic alteration is distinctly fracture-controlled. Intense alteration is only observed within and around large veins (mostly P1) or in zones of high vein density (mostly P2), grading out into moderate to weak alteration associated with numerous epidote veinlets (mostly P3; Fig. 20). Chlorite ± epidote replacement of original mafic minerals and albite-hematite replacement of plagioclase are the features noted furthest from veins (Fig. 22e,l,u). Between propylitic domains, rocks containing relict magnetite with only mild hematite reddening may be preserved.

Propylitic alteration is most weakly developed in the AFG, trachytes and trachytic ignimbrites, probably owing to the abundance of relatively unreactive K-feldspar (Fig. 22f). Nonetheless, epidote-dominated veins (P2 and P3) do occur in these units and plagioclase, biotite or mafic phenocrysts are selectively propylitically-altered whenever they are present.

675 P1: Chlorite-quartz-epidote-albite veins

676 Complex veins comprising central infills of chlorite-quartz-pyrite \pm calcite \pm hematite (dark red) \pm 677 epidote ± rare chalcopyrite are characteristically surrounded by pervasive and intense alteration 678 halos with a distinct mineralogical zonation (Fig. 20g-I). The vein-proximal assemblage consists of 679 chlorite and sericite (phengite) ± epidote ± pyrite; this grades outwards to hematite-sericite-680 chlorite \pm epidote and, eventually, to hematite-albite \pm chlorite \pm epidote. Plagioclase and biotite 681 in the proximal halo are usually selectively replaced by near pure chlorite, with an intergrowth of 682 phengite-chlorite grains ($\leq 10 \mu m$) replacing all other minerals, including K-feldspar. Plagioclase in 683 the outermost halo is replaced by albite, which is hematite reddened along with original K-feldspar;

biotite is still chloritized. These mineralogical transformations imply at least some metasomaticaddition of H, Mg and Fe, the latter reaching furthest from the vein.

The veins themselves range from 5 mm to 15 cm wide and are typically sheared, with marginparallel traces of hematite and/or pyrite providing evidence of reopening. The original vein fill appears limited to quartz-chlorite ± pyrite, with the majority of calcite and hematite precipitated later. Corresponding vein halos are particularly large, with alteration extending 4 cm to >4 m either side of the center, in proportion to the width of the vein fill (Fig. 22I). These features suggest the fluid was in strong disequilibrium with the wall rock.

692 P2: Epidote-chlorite-albite veins

693 The most abundant propylitic veins (Fig. 22m-r) are typically straight and contain a central fill, 2-20 694 mm wide, of epidote-chlorite \pm calcite \pm guartz \pm pyrite. When present, guartz-calcite-pyrite form 695 an interstitial cement to epidote crystals, which are interspersed with occasional chlorite and occur 696 along the vein edges, growing inwards from each margin (Fig. 22r). Epidote may also locally 697 infiltrate a few millimeters into the wall rock, making the margin appear indistinct. Surrounding 698 these veins is a characteristically zoned alteration halo with three main sub-divisions (Fig. 22m-p). 699 Vein-proximal alteration consists of intense chlorite and sericite (phengite), often with minor 700 epidote and pyrite, as described for P1 veins. This grades out into a middle envelope, rich in 701 epidote, that is present either as a distinct vein-parallel layer or series of patches. Vein-distal 702 alteration is dominated by albite which, along with relict K-feldspar, is markedly hematite 703 reddened; minor patches of chlorite and epidote alteration also persist. Alteration intensity then 704 gradually decreases back into weak but pervasive 'background' propylitic alteration. The alteration 705 halo of these veins extends for 3-20 cm either side of the vein center, again depending on vein width. 706

707 P3: Epidote veinlets

708 Fine (~1 mm wide), erratic and often discontinuous epidote ± chlorite ± pyrite veinlets are found 709 throughout the propylitic zone, particularly within igneous rocks where they may be the only 710 observable evidence of fluid migration in areas of moderate to weak propylitic alteration. Epidote is 711 developed to a variable extent around the veinlets into surrounding wall rocks, especially where 712 plagioclase crystals were intersected, producing a highly irregular, blebby margin (Fig. 22s-u). 713 Alteration halos, typically 1-2 cm wide, are developed around these veinlets, characterized by 714 hematite reddening of any pre-existing feldspar and selective replacement of plagioclase and 715 biotite by epidote and chlorite respectively.

716 Vein relationships and timing

717 Propylitic veins exhibit a consistent spatial relationship to one another. The largest and rarest P1 718 (chlorite-quartz-epidote-albite) veins are typically surrounded by zones in which P2 (epidote-719 chlorite-albite) veins dominate. The P2 veins have compositional characteristics that are essentially 720 intermediate between P1 and P3 veinlets and are routinely enclosed by areas rich in P3 epidote 721 veinlets (Fig. 18). Thus, the vein types appear to be related and are interpreted to represent a 722 continuum (P1 \rightarrow P2 \rightarrow P3) reflecting a broadly decreasing outward flux of fluid that passed through 723 the fracture network. Although all propylitic veins appear broadly synchronous, it is noted that 724 some P1 and P2 veins may cut P3 veinlets.

The occurrence and intensity of all observed propylitic alteration is directly controlled by three factors: (1) distance from mineralized centers; (2) permeability, as a result of lithology, geological contacts and the abundance of microfractures through to large fracture/fault zones; (3) host rock composition/reactivity. There is no observable correlation between the intensity and/or occurrence of propylitic alteration with the BQM-AFG pluton.

Country rock xenoliths within the BQM and AFG show no signs of previous alteration. In contrast, xenoliths within QMP units frequently show evidence of prior biotite-magnetite and, in the latest QMP units, K-feldspar-sulfide alteration-mineralization in the form of truncated veins. Fragments of P1 and P2 veins and propylitically-altered rocks are found within both post-mineralization monzonite porphyries and pebble dikes (Figs. 13h, 22k,v). Base metal veins have cut and reopened P1 veins and are themselves included as fragments within the pebble dikes.

These observations are consistent with the bulk of propylitic alteration forming during mineralization as the distal equivalent to the central potassic zones, driven by the focused release of magmatic fluid through the QMP intrusions. A close relationship to mineralization is again indicated by the rare presence of chalcopyrite, K-feldspar and, at E26, anhydrite within P2 veins (Fig. 22q). Nonetheless, some late stage, relatively weak propylitic alteration, mainly limited to disseminations around P3 veinlets, must have taken place after mineralization because it occurs within post-mineralization monzonite porphyries and exploited pebble dikes (Fig. 22w).

743 Regional metamorphism vs. propylitic mineral assemblages

The Northparkes propylitic alteration halo is visually distinct from the surrounding low-grade, regional metamorphic assemblage. The latter is dominated by chlorite, but commonly contains prehnite, pumpellyite and zeolites. Albite occurs locally, but no feldspars are hematite reddened and no pyrite is present. Metamorphic epidote is rare and, in comparison to propylitic alteration, is fine grained (usually only 10-30 µm). Also, despite being exceptionally pervasive, development of the metamorphic assemblage shows no clear link to fractures or veins which are relatively uncommon. When encountered, veins are typically only a few millimeters wide, are composed of calcite with lesser epidote and lack distinct alteration halos, indicating near fluid-rock equilibrium.

752 Sericitic alteration

753 Where analysed via SEM-EDS, all alteration minerals referred to as sericite are dominated by 754 phengite/phengitic muscovite, but the field term sericite is retained in this paper because not all 755 examples have been investigated in detail. Several distinct, sericite-dominant alteration facies can 756 be recognized at Northparkes. The most common is locally developed around late- to post-757 mineralization faults, often comprising total, but texturally enhancing replacement by variously 758 colored assemblages of sericite-quartz ± pyrite (Fig. 23a-b). However, more distinctive are the 759 pervasive and texturally-destructive regions of characteristically white sericite-albite-guartz-alunite 760 ± chlorite alteration that overprint the potassic core of E48 (Fig. 21g), and have been encountered 761 at GRP314 (Wolfe, 1994; Hendrawan, 2011a). This alteration is most extensive at depth within 762 favorable felsic lithologies, particularly the BQM-AFG pluton, and contains tennantite as a major 763 Cu-bearing phase. Wolfe (1996) demonstrated a magmatic fluid origin for this alteration at E48. 764 Sericitic alteration is also a defining characteristic of the sericitic veins described below.

765 Veins that transect alteration zones

766 Barren quartz veins

Two generations of sharp, straight-walled, quartz-only veins (5-30 mm wide) occur in a low-density barren stockwork at 1.2 km depth, ~600 m east of E26 (e.g., Fig. 20); vein halos consist only of hematite reddening of feldspars. The source and significance of these veins is unknown. Timing is also poorly constrained, but they are probably pre- to early- mineralization, given that they are both overprinted and reopened by P3 epidote veinlets, and cut by the base metal veins. Wolfe (1994) reported similar veins at depth below E48.

773 Sericitic veins

Within and around E26 and GRP314, sericitic (variably phengitic muscovite) alteration is localized around a distinct set of veins that are typically straight and commonly sheeted. Vein centers are typically thin (<1 mm to 20 mm wide) and comprise quartz and/or anhydrite ± pyrite ± chalcopyrite ± molybdenite ± magnetite. These are enclosed by proportionally much wider (1 to 150 cm respectively), well-developed and notably zoned alteration halos (Fig. 22c-o).

779 Vein-proximal alteration consists of intense, pervasive and texturally-destructive grey quartz-780 sericite-pyrite ± molybdenite, and vein intersections may be associated with large domains of such 781 alteration. These vein-proximal zones are enveloped by an outer fringe of variable mineralogy. At 782 E26, this vein-distal assemblage progressively changes from a well-developed K-feldspar and 783 biotite assemblage (Fig. 23c-e) near the center of the deposit, to small biotite spots that die out 784 with distance (between ~150-300 m; Fig. 23f-g). With still increasing distance, between ~300-600 785 m, chlorite ± sericite (phengite) is developed instead (Fig. 23h-I) and is accompanied by epidote-786 hematite at >600 m (Fig. 23m-o) to give propylitic alteration. The width of the sericitic veins and 787 associated alteration halos also generally decrease to <5 mm and 2-3 cm, respectively, with 788 progression away from E26.

At least two generations of sericitic veins exist. These can cut one another and may either cut, or be cut by, K-feldspar veinlets (K2), quartz-sulfide veins (K3) and epidote veinlets (P3). This implies a temporal overlap between the sericitic veins and mineralizing magmatic-hydrothermal activity. A magmatic origin for the sericitic alteration halo of these veins around E26 was also established by Harris and Golding (2002). Consequently, the sericitic veins are a pertinent example of how a magmatic-derived ore fluid can drive not only potassic and sericitic, but also propylitic alteration, dependant on physicochemical conditions.

796 Base metal veins

Quartz-calcite \pm anhydrite veins, typically <1-10 cm wide, containing pyrite, sphalerite and chalcopyrite with minor galena, bornite and molybdenite (Fig. 24a-d) are present within the core and periphery of all Northparkes deposits, but are most abundant in relatively distal locations. Veins are internally zoned from pyrite-quartz-dominant margins to sphalerite-chalcopyritedominant centers and are surrounded by pervasive, texturally-destructive quartz-sericite (phengite) \pm pyrite \pm chlorite alteration halos extending ~0.3-2 m either side. Sphalerite shows a characteristic internal zonation from low-Fe, light honey-brown cores to black, high-Fe rims (Fig. 24b-d).

The base metal veins may cut and reopen both sericitic and P1 propylitic veins (Figs. 20, 24c,d), but are in turn cut by gypsum-anhydrite veins (Fig. 24a,d). Although clearly late-mineralization in timing, the exact origin of the base metal veins remains poorly constrained. However, the occurrence of sphalerite in some anhydrite-quartz veins (Fig. 24o), and a lack of cross cutting relationships between the base metal and anhydrite-quartz veins perhaps suggests the two are related.

810 Anhydrite-quartz veins

Veins, 1-30 cm wide, of dark purple anhydrite, or gypsum, and quartz (locally with comb growth textures) ± pyrite ± chalcopyrite ± magnetite ± sphalerite, are found around and within the central intrusive complex at E26 and GRP314 (Fig. 20). Irregular segregations of purple anhydrite within aplitic, late-mineralization, K-feldspar-rich QMP intrusions, with surrounding intense K-feldsparbiotite alteration (Figs. 13b, 24e-h), are probably the origin of these veins.

Where observed immediately adjacent to QMP intrusions, the anhydrite-quartz veins are surrounded by strong K-feldspar-biotite alteration and contain limited sulfides (Fig. 24i,j). However, in relatively deposit-distal locations, the anhydrite-quartz veins display quartz-sericite halos and contain chalcopyrite, pyrite, magnetite and rare sphalerite (Fig. 24k-p). Most of the anhydritequartz veins occur adjacent to, or within, sericitic veins, which they have reopened and brecciated (Fig. 24k-n).

822 *Gypsum-anhydrite veins*

Barren, pale pink to light purple anhydrite veins (± rare pyrite), <1-50 cm wide and lacking alteration halos are observed around E26 and GRP314 (Fig. 24p-r). At shallow depths, the anhydrite has been hydrated to distinctive, fibrous gypsum (Figs. 23k, 24r). Such veins are most frequently observed to have cut, or more rarely reopened, sericitic veins (Fig. 24q), anhydrite-quartz veins and base metal veins (Fig. 24a). P3 epidote veinlets are consistently truncated by the gypsum-anhydrite veins (Fig. 24r).

829 Calcite veins

Veins of calcite ± rare quartz consistently occur along fractures and are particularly common within the center of the base metal veins (Fig. 24b) and anhydrite-quartz veins, recording a final stage of reopening. The calcite veins commonly display central, crystal-lined vugs, comb textures and calcite locally cements brecciated fragments of previous vein material. These are the latest vein generation recognized at Northparkes.

835 **Discussion: Geological evolution of the Northparkes system**

The Goonumbla and Wombin Volcanics document the Middle to Late Ordovician development of the Macquarie Island Arc. These dominantly submarine volcano-sedimentary packages reflect an overall transition toward more felsic, evolved magmatism of shoshonitic affinity. However, a bimodality is demonstrated by the emplacement of large volumes of basaltic trachyandesite sills into the succession, at least in part whilst it was still water-saturated and unconsolidated. Conglomerates and volcanic breccias at Northparkes are considered lateral equivalents to generally deep-water sands and silts elsewhere in the district, with occasional shallow water limestone intercalations. Thus, the envisaged depositional environment is upon the flanks of a largely submerged volcanic edifice, host to debris avalanches and surrounding carbonate banks (Simpson et al., 2005), perhaps behind the main arc front. At least part of the volcanic system was emergent by the Late Ordovician, with explosive eruptions documented by welded ignimbrites.

847 It is unclear if surface volcanism continued during porphyry magmatic-hydrothermal activity, although the Northparkes intrusive rocks share a similar geochemistry and broad timing to rocks of 848 849 the Wombin Volcanics, indicating a potential genetic relationship. There is no evidence of wetsediment interaction during emplacement of the monzodiorite or BQM-AFG plutons, and a 850 851 magmatic body of such volume would be unlikely to stall and crystallise close to the surface with 852 the observed coarse, equigranular (plutonic) textures. This is supported by several fluid inclusion 853 studies of mineralized veins which suggest that, assuming lithostatic fluid pressures, ore formation 854 occurred at minimum depths of 1-1.7 km (1-1.7 km given by Lickfold et al., 2003; 1.7 km calculated 855 here using the fluid entrapment pressures of 400-500 bar reported by Heithersay and Walshe, 856 1995).

Unfortunately, an emplacement sequence cannot be resolved by geochronology given that available age estimates of several intrusive phases overlap within error. However, the data demonstrate that most intrusive activity and associated alteration took place in the latest Ordovician to earliest Silurian. In comparison, the relative timing of magmatic-hydrothermal events is particularly well constrained by field relationships and forms the basis for the following interpretation of the geological evolution at Northparkes.

863 Stage 1: Pre-mineralization magmatism

864 Initial pre- to early-mineralization emplacement of the BQM-AFG pluton resulted in biotite-865 magnetite hornfelsing of the surrounding volcanics and would have likely driven any formation 866 waters away from the system. Prior to total solidification, bodies of QMZ were then injected into 867 the pluton. This magmatic phase marks a brief return to slightly more primitive magmatism and the 868 initiation of a fertile and significantly more hydrous fractionation series. The QMZ shares some 869 characteristics with the later QMPs: upper portions of the intrusions are porphyritic, with K-feldspar 870 phenocrysts and disseminated Cu sulfides. However, the QMZ is not associated with any well-871 developed veining, rather, it appears that any fluids remained trapped in the melt.

872 Stage 2: Principal magmatic-hydrothermal activity

Subsequent magmatism generated the highly evolved QMP complexes and mineralizing hydrothermal systems. By this time, all presently observed levels of the BQM, AFG and QMZ had completely solidified. Several QMP intrusions are present in each deposit and similar porphyries are associated with the many prospects across the Northparkes district. Multiple QMP intrusions are present in each intrusive complex and may span the mineralizing episodes. However, those QMPs most enriched in K-feldspar and containing fewer mafic minerals are associated with the strongest mineralization and appear to be most intimately linked to the hydrothermal systems.

The QMPs are ubiquitously crystal crowded and K-feldspar altered. Such crowding in a typical felsic magma would commonly be thought to produce a very high viscosity, yet, at Northparkes, these magmas infiltrate into even the smallest fractures (<1 mm) in surrounding volcanic rocks. Further, large zones of USTs, irregular miarolitic cavities and broken, angular phenocrysts are present, and intrusive brecciation is commonplace. All such observations attest to the forceful, possibly explosive, emplacement of a highly volatile-rich, low viscosity 'magma', perhaps better thought of as a crystal-bearing, silicate melt-aqueous fluid slurry (R. Armstrong, 2015, pers. comm.).

887 At a particular depth (confining pressure), magmatic fluid was discharged around the margins and 888 through the apices of the intrusions. The timing of intrusive activity and mineralization at each 889 deposit, relative to one another, remains unknown. However, initial fluid evolution appears similar 890 across all the QMP complexes. Early-mineralization QMP units are associated with biotite-891 magnetite alteration, including biotite and magnetite veins (K1 and M1). Subsequent K-feldspar-892 rich QMP units generated overprinting K-feldspar-sulfide veinlets and guartz-sulfide stockwork 893 veins (K2 and K3), in turn forming the deposit-central K-feldspar alteration zone. At least two 894 generations of K2 and K3 veins are present at E48 and E26 as a result of multiple QMP intrusions, 895 helping to boost ore grade.

896 Intense, deposit-peripheral, magnetite-biotite and propylitic alteration shells are constrained to 897 occur simultaneously with mineralization and the central K-feldspar alteration. The clear spatial and 898 temporal links between these alteration facies strongly suggests they were formed by a dominantly 899 magmatic fluid as it was expelled outwards from the intrusive complexes, progressively cooling and 900 equilibrating with the country rock. Fluid evidently infiltrated through permeable volcanic units and 901 fracture zones. Within the magnetite ± biotite shell, fine, disseminated magnetite and biotite was 902 developed throughout permeable volcanics or formed distinct alteration clots in intrusive rocks; 903 magnetite veins (M2) occur across the facies. Within the propylitic zone, fluid was principally

supplied through large fractures in which chlorite-quartz-epidote-albite (P1) veins formed; these grade into progressively smaller-scale epidote-chlorite-albite (P2) veins and epidote veinlets (P3) that appear to represent the more distal parts of a linked fracture mesh. The ubiquitous alteration halos documented around these propylitic veins attest to a fluid in strong disequilibrium with wall rocks. Disseminated and clotty epidote and chlorite were also developed throughout most permeable units.

910 Late stage evolution of the Northparkes deposits is variable. At E22 and E27 there is no further 911 significant alteration, but late-mineralization QMP intrusions and sericitically-altered faults are 912 recognized. In the core of E48 (and parts of GRP314), an acidic magmatic fluid of uncertain origin 913 caused intense, pervasive and texturally-destructive white sericite-albite-guartz-alunite ± chlorite 914 alteration. At E26 and GRP314, cooler, late magmatic fluid was structurally focused, forming the 915 sericitic veins, characterized by vein-proximal grey quartz-sericite ± pyrite alteration halos. These 916 halos grade outwards into a variable, vein-distal assemblage in which mineralogy is broadly 917 controlled by distance to the intrusive complexes.

918 Stage 3: Late-stage magmatic-hydrothermal activity

919 Late-mineralization QMP intrusions were emplaced at E26 and GRP314. They contained a 920 significant amount of immiscible fluid, represented by common anhydrite-quartz-aplite ± biotite 921 segregations and USTs. Such large quantities of anhydrite suggest oxidized conditions prevailed. 922 Escape of this fluid, mostly through pre-existing weaknesses (sericitic veins), appears to have 923 generated anhydrite-quartz veins, some of which contain notable sphalerite. Base metal veins, also 924 characterized by sphalerite, are present throughout Northparkes and may be genetically related to 925 this event. The exact origin of the base metal veins remains unknown, although certain phases 926 must post-date the propylitic (P1 and P2) and sericitic veins. Remaining fluid activity at E26 and 927 GRP314 was restricted to barren anhydrite ± pyrite veining.

928 Stage 4: Post-mineralization magmatism

929 Continued post-mineralization magmatism is evidenced by the mafic zero and zero monzonite 930 porphyries, which were emplaced as SE-striking composite dikes. Their compositions again indicate 931 a return to relatively primitive magma conditions.

The exact timing of the post-mineralization monzonite porphyry at E34 is presently unknown but intrusion of this phase appears to have generated at least some of the widespread pebble dikes. If these breccia dikes were generated by phreatomagmatic activity, then the local country rock units must have been water-saturated by this time, perhaps indicative of surface exhumation, or ingress

936 of water as a result of significant cooling of the magmatic system. The pebble dikes cut all 937 mineralization and veins, including the sericitic, base metal and propylitic (P2 and P3) veins; Lickfold 938 (2002) also reported fragments of the zero porphyry within them.

939 Weak propylitic alteration persisted slightly beyond this late magmatic activity, affecting the 940 monzonite porphyries and locally exploiting pebble dikes as conduits. It is limited to P3 epidote 941 veinlets and selective replacement of mafic minerals and, more rarely, plagioclase.

Final, thin, alkali basalt dikes cut through the Northparkes district and are either unaltered or
selectively overprinted by cream-colored quartz-sericite. Some dikes were emplaced along the
Altona Fault.

As a consequence of the underlying plutonic mass, the Northparkes area escaped major deformation during tectonic accretion and related orogenies. The low angle Altona Fault is the most significant feature developed during deformation, transecting the top of the E48 and GRP314 mineralized systems.

949 **Conclusions**

950 The geology at Northparkes records over 60 Ma of volcanic evolution within the Macquarie Island 951 Arc, culminating in latest Ordovician to earliest Silurian porphyry Cu-Au mineralization. All volcanic 952 and intrusive rocks are silica-saturated but distinctively alkaline/shoshonitic in character. Most 953 magmatism occurred prior to ore formation, including both extensive seafloor volcanism and 954 coeval intrusions into the volcanic pile. The deposits are located within a major volcanic-plutonic 955 center, founded upon a large monzonite to alkali granite intrusion that may represent an original 956 shallow crustal magma chamber. The emplacement of trachyandesite sills, the QMZ and several 957 post-mineralization monzonite porphyry phases provide evidence for periodic returns to more 958 primitive magmatic conditions.

959 Mineralization was caused by the forcible, periodic escape of low viscosity, crystal- and volatile-rich 960 magmas. These exploited pre-existing structural intersections and focused the discharge of large 961 quantities of magmatic fluids from the underlying chamber. The fluids circulated in intricate 962 fracture networks to produce K-feldspar-sulfide veinlets and quartz-sulfide stockwork veins, 963 surrounded by K-feldspar-dominated alteration. Ore grades are exclusively located within the potassic alteration zones, although some have been sericitically overprinted. Spent fluids continued 964 965 to be driven outwards, presumably as a result of thermal buoyancy and magmatic overpressure, infiltrating both laterally and upwards into the surrounding pluton and volcano-sedimentary 966 967 packages through pre-existing faults/fractures and permeable units. Progressive cooling and

968 equilibration of these fluids toward lower water:rock ratios formed a shell of magnetite-biotite 969 alteration and, ultimately, they appear to have driven the widespread peripheral propylitic 970 alteration. The mineralogy, complex alteration halos and spatial relationships between propylitic 971 veins provides compelling evidence of such an outwards flux of fluid as it progressively approached 972 near-equilibrium conditions with the country rocks via physical and chemical exchange. Indeed, the 973 appearance of each alteration facies at any point is a function of host rock composition, 974 permeability, vein/fracture density and distance from the system center.

Despite broadly similar characteristics, each individual deposit at Northparkes is unique and 975 976 generated a distinct hydrothermal system. Magmatic-hydrothermal breccias are common at E27, 977 whereas anhydrite is particularly abundant only at E26 and GRP314, where it is associated with late-978 mineralization QMP intrusions. Significant sericitic alteration is lacking at E22 and E27, but 979 uniformly overprints much of the core at E48 and is vein-related at E26 and GRP314. Systematic 980 spatial changes to the alteration envelope around sericitic veins at E26 (from deposit-proximal K-981 feldspar ± biotite to deposit-distal chlorite-epidote-hematite) provide a key example of how a 982 magmatic fluid can evolve to create numerous alteration domains.

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1154 Figure Captions

1155 Figure 1

1156 Map showing the location of Northparkes and other porphyry deposits hosted within Ordovician 1157 age volcanic belts, as labelled, which constitute the Macquarie Arc in New South Wales. Outcrop of 1158 volcanic belts partly interpreted from aeromagnetic data; modified from Scheibner and Basden 1159 (1998) and Glen and Walshe (1999), after Lickfold (2002).

1160 Figure 2

1161 Red quartz monzonite porphyry emplaced into dark trachyandesite volcanics; exposed in the E271162 open pit.

1163 Figure 3

Geological map of the Northparkes region (area shown in Figure 1). Geological lines from Simpson et al. (2005) and Arundell (1997), after Krynen et al. (1990) and Heithersay et al. (1990). Note all contacts are inferred owing to thick cover; dashed contacts to monzonitic intrusions reflect disagreement between authors on their exact position. Ages for intrusions are from Butera et al. (2001), after Simpson et al. (2005). Gravity anomaly from Northparkes Mines ground survey. Coordinates are in meters with respect to GDA94 MGA Zone 55.

1170 **Figure 4**
1171 Geological plan of the E26, E48 and GRP314 deposits, below the level of the Altona Fault (~780 m

1172 below surface); area annotated on Figure 3. Lines of section indicated through E26 and E48 are

1173 provided as Figures 5 and 6 respectively. Geological detail is from Northparkes Mines, constrained

by the entire drill core database and gravity modelling. Alteration detail is based both on the

- overall drill core database model and detailed logging of diamond drillholes as part of this study
- 1176 (Figs. 16, 17), the paths of which are indicated and show 100 m markings.

1177 Figure 5

1178 Cross section through the E26 deposit; color scheme and details as for Figure 4. Porphyry bodies 1179 are interpretively projected onto the section (unless indicated) to match all known occurrences in 1180 the plane of the section; this avoids them appearing as discontinuous lenses. For clarity, details of 1181 volcanic country rock facies are omitted, however examples are provided in Figure 7. Alteration 1182 minerals: Ab = albite; Bn = bornite; Bt = biotite; Ccp = chalcopyrite; Chl = chlorite; Epi = epidote; 1183 Hem = hematite; Kfs = K-feldspar; Mag = magnetite; Py = pyrite; Qtz = quartz.

1184 Figure 6

1185 Cross section through the E48 deposit; color scheme and details as for Figure 4. Porphyry bodies 1186 are projected as for Figure 5.

1187 Figure 7

Summary of geochronological data; listed from bottom to top in relative order of formation. Color of age bars corresponds to the dating method. Also shown is the deposition interval of the Billabong Creek Limestone-Gunningbland Formation from Pickett and Percival (2001), after Percival and Glen (2007). The Ordovician-Silurian boundary shown is that of Cohen et al. (2013).

1192 Figure 8

1193 Rb-Sr isochron plot for both whole rock samples and epidote separates from propylitic alteration

around the E48 deposit. Note the mean square weighted deviation (MSWD) = 13 for the proposed isochron' shown.

1196 Figure 9

1197 Semi-schematic scaled cross section to illustrate the occurrence, form and relationships between 1198 major lithologies at Northparkes; based off a NE-trending cross section through E26.

1199 Figure 10

1200 Volcanic and volcaniclastic lithologies at Northparkes; all scale bars = 1 cm. (a) plagioclasepyroxene-phyric trachyandesite, GD654/729 m; (b) peperitic contact - an intimate mixture of fine 1201 1202 chloritized sediment and reddish brown trachyandesite cut by epidote-albite veinlets (P3), 1203 E34D3/648 m; (c) irregular sedimentary layer/(?dike) separating epidote-albite-hematite altered 1204 trachyandesite; E34D3/322 m; (d) chloritized hyaloclastic breccia on the surface of a trachyandesite 1205 unit, E34D3/277 m; (e) volcanic conglomerate with reddish trachyandesite and dark sedimentary 1206 lithic clasts in a silt-mud matrix, strongly and pervasively epidote-chlorite-albite altered, 1207 E48D134/417 m; (f) fine volcanic sandstone showing relatively rare broken plagioclase and K-1208 feldspar crystals, strong epidote-chlorite alteration is selectively more pervasive in the coarser 1209 interbed, E48D134/311 m; (g) rare laminations between grey mudstone and chloritized siltstone, 1210 deposited on a coarser crystal-bearing sandstone, E48D134/385 m; (h) fine trachyte, E26D460/650 1211 m; (i) welded, trachytic lithic-crystal ignimbrite showing red trachyte, central trachyandesite and 1212 possible wispy pumice clasts, in fine banded matrix containing plagioclase, K-feldspar and 1213 pyroxene crystals, E26D459/134 m.

1215 The principal plutonic rocks at Northparkes; all scale bars = 1 cm. (a) pre-mineralization 1216 monzodiorite xenolith in the BQM pluton, CND5/641 m; (b) equigranular end-member of the BQM, from an area lacking hematite reddening, E26D460/950 m; (c) equigranular to weakly porphyritic 1217 1218 BQM, weakly hematite reddened, E48D147/617 m; (d) weakly porphyritic BQM with subhedral, 1219 weakly sericitized plagioclase and smaller K-feldspar and chloritized biotite crystals in a hematite reddened groundmass of K-feldspar and guartz, E48D147/359 m; (e) AFG to guartz alkali feldspar 1220 1221 syenite, large weakly sericitized plagioclase and chloritized biotite crystals are surrounded by 1222 interlocking K-feldspar with interstitial, anhedral quartz, E26D361/ 341 m; (f) distinct but diffuse contact between AFG and BQM, E48D147/221 m; (**q**) porphyritic variety of QMZ with characteristic 1223 1224 anhedral plagioclase and guartz, but euhedral K-feldspar, in groundmass containing much granular anhedral guartz and K-feldspar; disseminated chalcopyrite throughout, E26D467/440 m; (h) weakly 1225 1226 porphyritic QMZ with patches of quartz-bornite-chalcopyrite, BZD10/580 m; (i) K-feldspar 1227 megacryst poikilitically enclosing plagioclase in strongly porphyritic QMZ, BZD10/~600 m.

1228 Figure 12

1229 Quartz monzonite and monzonite porphyries at Northparkes, note the high degree of crystal 1230 crowding; all scale bars = 1 cm. (a) K-feldspar, early-mineralization QMP cut by quartz stockwork veins (K3), E48D237/261 m; (b) K-feldspar QMP with glassy groundmass and broken, angular K-1231 1232 feldspar phenocryst, E48D147/255 m; (c-d) syn- to late-mineralization porphyries, with notable mafic biotite and augite phenocrysts as well as both broken, angular and euhedral K-feldspar 1233 1234 phenocrysts, E26D497/~360 and 683 m respectively; (e) late-mineralization, dominantly 1235 plagioclase-guartz-biotite-phyric QMP, groundmass is rich in K-feldspar which also rims 1236 plagioclase, E22D279/458 m; (f) late-mineralization QMP with biotite as the mafic phase; note 1237 xenoliths of quartz-veined BQM and complex zoning of K-feldspar that forms a euhedral outer pink 1238 overgrowth on earlier irregular (partly resorbed?) grey K-feldspar crystals, K-feldspar also 1239 overgrows some plagioclase, BZD32/~770 m; (g) enlarged view of zoned K-feldspar crystal in QMP; 1240 shows initial subhedral grey crystal overgrown by euhedral pink K-feldspar, which poikilitically encloses plagioclase; bornite and chalcopyrite specks are trapped at the contact, E26D545/~630 m; 1241 (h) typical texture and coloration of the zero porphyry phase, E26D459/377 m; (i) irregular-shaped 1242 1243 xenoliths of dark brown basaltic trachyandesite within the reddish brown zero porphyry, note 1244 epidote veinlets (P3) that are associated with propylitic alteration, E26D440/223 m; (j) typical 1245 texture and coloration of the post-mineralization monzonite porphyry at E34, E34D3/849 m.

1246 Figure 13

1247 Breccias and magmatic-hydrothermal features at Northparkes; all scale bars = 1 cm. (a) irregular blebs and patches of K-feldspar and aplite surrounded by guartz with bornite and chalcopyrite in 1248 QMP, E26D467/204 m; (b) patches/miarolitic cavities of anhydrite and guartz surrounded by aplitic 1249 1250 QMP, E26D507/1164 m; (c) UST comprising chalcopyrite, fluorite and anhydrite on sericitically-1251 altered aplitic QMP substrate, followed by a comb quartz layer and further aplitic QMP, growth direction inferred from top right to bottom left, E26D507/1062 m; (d) pebble dike with rounded 1252 1253 clasts of trachyandesite (AND), BQM, AFG and guartz-sericite-altered vein fill with chalcopyrite, 1254 E26D411/249 m; (e) jigsaw-fit breccia of strongly biotite-magnetite altered trachyandesite clasts 1255 (containing truncated guartz-bornite K2 veinlets and a K1 vein with strong magnetite-biotite halo); 1256 aplite QMP cement contains occasional plagioclase phenocrysts and segregations/miarolitic 1257 cavities of interlocking quartz-K-feldspar-bornite, E27 open pit; (f) bornite-K-feldspar-quartz 1258 cemented stockwork breccia containing clasts of guartz and strongly potassically-altered host rock, 1259 E27; (g) euhedral K-feldspar crystals within bornite, from the same block in (e); (g) intrusive breccia with fragments of dark trachyandesite, BQM, light-colored sericitized rock and a propylitic P1 vein 1260 1261 (top left comprized of chlorite-quartz-calcite-pyrite-hematite), cemented by a post-mineralization 1262 monzonite porphyry at E34 (Fig. 12j), E34D3/779 m; (i) the highly undulate contact of the porphyry 1263 unit in (g) and Figure 12j with surrounding country rock, which is now a fine chloritized rock flour 1264 breccia, E34D3/677 m; (j) with increasing distance from the intrusion, the breccia of (i) contains 1265 larger clasts, here of trachyandesite (AND), BQM and quartz veins in fine chloritized and quartz-1266 calcite-pyrite cemented rock flour matrix - a texture identical to the pebble dikes observed 1267 elsewhere, E34D3/680 m; (k) irregular bornite clot in QMP, bornite encloses K-feldspar and shows 1268 minor chalcopyrite on its margins, E22D279/449 m.

1269 Figure 14

1270 Major, minor and selected trace element geochemistry of country rock volcanics, as indicated in the 1271 legend. (**a**) total alkali vs. silica classification, TB = trachybasalt, BTA = basaltic trachyandesite, TA = 1272 trachyandesite, TR = trachyte, fields after Le Maitre et al. (1989); (**b**-**o**) Harker variation plots for 1273 elements as indicated, division of subalkalic rocks in (b) is after the summary of Rickwood (1989). 1274 Note 224 available analyses are plotted on (a-j), numbers of available analyses for plots (k-o) is 1275 variable and shown separately as n = x. Trachyandesites are shown separately as they occur in both 1276 the Goonumbla and Wombin Volcanics.

1277 Figure 15

1278 N-MORB normalized REE plots for $(\mathbf{a}-\mathbf{b})$ country rock volcanic packages and (\mathbf{d}) trachyandesites; 1279 number of samples shown as n = x. Normalising values from Sun and McDonough (1989).

1280 Figure 16

1281 Major, minor and selected trace element geochemistry of Northparkes intrusive rocks, as indicated 1282 in the legend; BQM = biotite quartz monzonite, AFG = alkali feldspar granite, QMZ = quartz monzonite, QMP = quartz monzonite porphyry. (a) total alkali vs. silica classification, AB = alkali 1283 basalt, MG = monzogabbro, MD = monzodiorite, GD = gabbroic diorite, MO = monzonite, QM = 1284 1285 quartz monzonite, fields after Middlemost (1994); (b-q) Harker variation plots for elements as 1286 shown, division of subalkalic rocks in (b) is after summary of Rickwood (1989). Note 225 analyses are plotted on (a-j), numbers of available analyses for plots (k-q) is variable and shown separately 1287 1288 as n = x.

1289 Figure 17

1290 N-MORB normalized REE plots for Northparkes intrusive rocks, as indicated. Presented from (a) to 1291 (f) in order of emplacement; number of samples shown as n = x. Normalising values from Sun and 1292 McDonough (1989).

1293 Figure 18

1294 Lithology and alteration logs for selected diamond drillholes around E26, depth in meters from 1295 collar. Drillhole positions shown on Figures 4 and 5. The division of alteration zones is based on the logged mineralogy. Lithological codes: AFG = alkali feldspar granite; AND = trachyandesite; BQM = 1296 1297 biotite guartz monzonite; CON = volcanic conglomerate; HBX = hydrothermal breccia (veins and 1298 pebble dikes); IBX = intrusion cemented breccias; MPOR = monzonite porphyry; MZO = mafic zero monzonite porphyry; QMP = quartz monzonite porphyry; QMZ = quartz monzonite; SST = volcanic 1299 1300 sandstone; TBX = autoclastic trachyte breccia; TR = trachyte; TRS = trachytic sill; TVB = trachytic 1301 volcanic breccia/ignimbrite; ZRO = zero monzonite porphyry.

1302 Figure 19

Lithology and alteration logs for selected diamond drillholes around E48, including E34, depth in meters from collar. Drillhole positions are shown on Figures 4 and 6. All details as defined in Figure 1305 16. Alteration zones indicated where appropriate; sericitic alteration at the base of E48D134 is part 1306 of the sericite-albite-quartz-alunite ± chlorite overprint to the core of E48. Other sericitic alteration

1307 is spatially associated with faults.

1308 Figure 20

Schematic diagram illustrating the spatial distribution of vein types, as well as their relationship to each other, major alteration facies and QMP intrusions at Northparkes. The vein density shown approximates the relative changes observed. Veins associated with particular alteration facies are mostly spatially restricted to that zone, and are numbered with respect to their paragenesis within it, e.g. K1 to K3 for potassic veins. The latest gypsum-anhydrite veins and calcite veins are omitted. Note the barren guartz veins, sericitic veins and anhydrite-guartz veins are not necessarily present

1315 in all the Northparkes deposits.

1316 Figure 21

1317 Potassium silicate alteration and principal associated vein types; all scale bars = 1 cm. (a) K1 quartz veinlet with biotite halo developed in trachyte, E48D134/857 m; (b) network of K2 guartz-K-1318 1319 feldspar-bornite veinlets surrounded by K-feldspar alteration halos and biotite spots within 1320 trachytic ignimbrite, E26D459/5 m; (c) as for (b) but developed in trachyte and lacking biotite spots, 1321 E48D134/875 m; (d) K3 guartz-anhydrite-chalcopyrite vein with strong K-feldspar alteration halo in 1322 trachytic ignimbrite, E26D460/41 m; (e) K3 guartz-bornite ± chalcopyrite stockwork cutting K-1323 feldspar veinlets (K2) in biotite altered trachyandesite, E48D163/~400 m; (f) two generations of quartz-bornite (K3) veins in K-feldspar-rich QMP, note increased width of K-feldspar alteration 1324 halos compared to (e), E48D134/92 m; (g) original stockwork of K3 veins in AFG, pervasively 1325 overprinted by sericite-albite-quartz-alunite alteration; E48D134/~900 m; (h) K3 vein with thin K-1326 feldspar halo cutting irregular magnetite veinlet in magnetite-biotite altered trachyandesite, 1327 1328 E48D134/657 m; (i) intense potassium silicate alteration of BQM in the center of E26, comprising 1329 biotite patches and surrounding K-feldspar flooding, E26D507/1070 m; (j) magnetite-biotite clots in 1330 BQM, surrounded by weak K-feldspar alteration of groundmass and sericitic clouding of 1331 plagioclase, typical appearance of BQM within the magnetite-biotite alteration shell, E26D507/735 1332 m; (k) examples showing the effect of fine disseminated magnetite-biotite alteration on original 1333 trachytic ignimbrite, from least altered (top) to most altered (bottom), E26SD107, 498-545 m.

1334 Figure 22

1335 Propylitic alteration and principal vein types; all scale bars = 1 cm. (a) volcanic sandstone with 1336 epidote-chlorite spots developed around clasts, in chloritized matrix with disseminated pyrite, 1337 E48D134/413 m; (b) P3 epidote veinlet cutting a siltstone bed in volcanic sandstone, note fluid was 1338 forced away from the vein at the contact, E48D134/445 m; (c-d) epidote-guartz patches: (c) with weak hematite reddened albite halos in volcanic sandstone, E48D134/239 m, (d) surrounded by 1339 chlorite halos developed in trachyandesite, GD654/483 m; (e) pervasive alteration of BQM with 1340 1341 selective hematite-sericite (phengitic) replacement of plagioclase and epidote-chlorite replacement 1342 of biotite, E26D361/141 m; (f) epidote veinlet (P3) cutting BQM-AFG contact, note more extensive 1343 epidote-chlorite alteration in more mafic, reactive, BQM, E48D147/488 m; (g-k) P1 veins with zoned 1344 alteration halos: (g) in trachyandesite, E34D3/644 m, (h) in AFG, with chalcopyrite, E26D460/787 m, 1345 (i) in BQM, E48D147/473 m, (j) in trachyandesite, E34D3/332 m, (k) truncated by E34 monzonite 1346 porphyry, E34D3/759 m; (I) examples of large scale alteration associated with P1 veins in BQM, left 1347 = chlorite-quartz-calcite-hematite-pyrite vein fill, middle left = vein-proximal chlorite-sericite 1348 (phengitic)-quartz-epidote alteration, middle right = hematite-sericite-chlorite alteration, right = 1349 most vein-distal hematite reddening of pre-existing K-feldspar with minor albitization of 1350 plagioclase and chlorite-epidote developed around original biotite, E48D147, 499-782 m; (m-r) P2 1351 veins with distinct zoned chlorite-epidote-albite-hematite halos described in text: (m) in BQM, 1352 E48D147/630 m, (n) in BQM, E34D3/945 m, (o) in fine volcanic sandstone, E34D3/1216 m, (p) halo

1353 in BQM showing transition from total chlorite to epidote alteration, E34D3/1133 m, (q) rare 1354 anhydrite and K-feldspar in vein center, E34D3/~1216 m, (r) inwards growth of epidote from vein 1355 margins into quartz, re-fractured by calcite and fringed by chlorite-pyrite-epidote, in 1356 trachyandesite, GD654/297 m; (s-u) P3 epidote veinlets with irregular blebby margins fringed by 1357 hematite reddened albite: (s) in trachyandesite, E48D134/216 m, (t) in volcanic conglomerate, E26D361/739 m, (u) in BQM, E48D147/775 m; (v) pebble dike containing epidote fragments and 1358 1359 truncating epidote veinlet (P3), GD654/346 m; (w) epidote-albite-hematite alteration occurring 1360 within, and radiating from, a pebble dike, unknown drillhole.

1361 Figure 23

1362 Sericitic alteration and sericitic veins; all scale bars = 1 cm. (\mathbf{a} - \mathbf{b}) pervasive guartz-sericite ± pyrite alteration of BQM-AFG around faults and base metal veins, hematite reddening of plagioclase in 1363 (b) often occurs on the periphery of these alteration zones; (a) E34D3/574 m, (b) E48, unknown 1364 1365 drillhole; (c-o) sericitic veins with guartz and/or anhydrite centers and zoned alteration halos, 1366 quartz-sericite ± pyrite alteration is consistently developed proximal to the vein, but the distal 1367 assemblage is variable. Generally, samples closest to E26 (c-e) show outermost K-feldspar ± biotite 1368 alteration, with increasing distance from the deposit this diminishes (f-g) and weak (h-i) to ultimately strong (j-o) chlorite-sericite alteration forms instead, epidote and hematite may also be 1369 1370 present (m-o). Details: (c) in trachytic volcanics with anhydrite-pyrite fill, E26D460/319 m, (d) in volcanic conglomerate with chalcopyrite-quartz-anhydrite fill, E26D459/83 m, (e) large example in 1371 1372 BQM with guartz-pyrite-anhydrite fill and strong outer K-feldspar-biotite development, 1373 E26D507/1070 m, (f) in volcanic conglomerate with anhydrite-chalcopyrite-pyrite fill, E26D459/5 m, 1374 (g) in BQM with anhydrite-chalcopyrite fill, E26D507/1197 m, (h) in BQM, E26D507/314 m, (i) in 1375 BQM with pyrite-anhydrite-quartz fill, E26D507/643 m, (j) in BQM with anhydrite fill, E26D507/630 1376 m, (k) in BQM with guartz-anhydrite fill, cut by gypsum-anhydrite veins, E26D507/362 m, (l) in BQM with highly irregular halo and quartz-anhydrite fill, E26D507/372 m, (m) in BQM with anhydrite-1377 1378 quartz-pyrite fill and fine epidote in outermost halo, E26D507/385 m, (n) in BQM with distinct green epidote in outer hematite reddened halo (magnified in inset), center reopened by gypsum-1379 anhydrite vein, E26D507/385 m, (o) close up view of epidote-chlorite in outer halo, E26D507/463 1380 1381 m.

1382 Figure 24

1383 Examples of the base metal, anhydrite-quartz, gypsum-anhydrite and calcite veins, along with 1384 anhydrite occurrences; all scale bars = 1 cm. (a-d) quartz-sphalerite base metal veins: (a) with chalcopyrite, brecciated by a barren anhydrite-gypsum vein, E26D460/924 m; (b) with pyrite in 1385 brecciated guartz, cemented by late barren calcite, E26D361/643 m, (c) reopening a P1 propylitic 1386 vein, E48D147/501 m, (d) with chalcopyrite, reopening the chlorite-sericite core of a P1 vein and cut 1387 by a gypsum-anhydrite veinlet, E48D147/729 m; (e-g) irregular anhydrite patches within QMP 1388 1389 bodies and surrounded by K-feldspar-biotite alteration: (e) intergrown with aplitic QMP, E26D507/1172 m, (f) appearing almost fracture controlled, E26D507/1164 m, (g) intergrown with 1390 bladed biotite, E26D544/446 m; (h) anhydrite appearing to form a breccia cement within K-1391 feldspar-biotite altered BQM, likely recording fluid escape, E26D510/178 m; (i-j) anhydrite-quartz 1392 1393 veins with strong surrounding K-feldspar-biotite alteration: (i) in trachytic ignimbrite, E26D459/95 1394 m, (j) showing comb guartz growth, in BQM, E26D507/1128 m; (k-o) anhydrite-guartz veins with 1395 limited sericitic halos: (k) with pyrite and chalcopyrite, brecciating and reopening a sericitic vein, 1396 E26D460/237 m, (I) with pyrite and chalcopyrite, cutting the strongly guartz-sericite-pyrite altered 1397 halo of a sericitic vein, still, a secondary sericite-quartz halo can be observed, E26D460/304 m, (m) with molybdenite and chalcopyrite cementing brecciated guartz-sericite altered fragments of a 1398 1399 large sericitic vein, the fragments contain most of the molybdenite and are probably the source of 1400 molybdenum in the anhydrite, E26D460/240 m, (n) with sphalerite and pyrite, formed along a reopened sericitic vein and cut by a gypsum-anhydrite vein, E26D507/364 m, (o) with sphalerite, chalcopyrite, pyrite and anhydrite, E26D507/461 m; (**p-r**) barren anhydrite-gypsum veins: (p) sheared alongside an earlier purple anhydrite-quartz vein, all in the center of a sericitic vein, E26D507/893 m, (q) as cement to a brecciated sericitic vein, E26D459/559 m, (r) cutting P3 epidote veinlets in BQM, E26D507/276 m.













Billabong Creek Lst. & Gunningbland Fm.	Ordovician	Silurian	Date of:	Method	Result (Ma)	Reference
Late-to post- mineralization		-+	Zero porphyry (E37)	Zircon U-Pb (SHRIMP)	436.7 ± 3.3	Lickfold et al. (2007)
	-+-		(Biotite) QMP (E22)	Biotite Ar/Ar	446.5 ± 2.6	Lickfold et al. (2003)
Mineralization		+	Sericitic alteration (E26)	Sericite Ar/Ar	439.2 ± 1.2	Perkins et al. (1990)
	-		Propylitic alteration (E48?)	Epidote and whole rock Rb-Sr	450 ± 11	This study
	-		Biotite alteration (E26)	Biotite Ar/Ar	441.3 ± 3.8	Lickfold et al. (2003)
	-		(Biotite) QMP (E26)	Biotite Ar/Ar	448.6 ± 7.0	Lickfold et al. (2003)
			BQM (E26)	Zircon U-Pb (SHRIMP)	444.2 ± 4.7	Lickfold et al. (2007)
Pre- to early- mineralization		+	BQM (E26)	Biotite Ar/Ar	437.3 ± 2.1	Lickfold et al. (2003)
460	450	440				































agnetit dote -hlorite K-feldspar alteration i i : ; İ Mag ± Bt alteration i Epi + Chl alteration Fine clastic Conglomerates and clastic breccias, matrix supported Conglomerates, often clast supported Porphyritic volcanics Semi-porphyritic intrusions Porphyritic intrusions Hydrothermal segregations 111 and mineralized xenolith in QMP Intrusion related brecciation

E26D460



Abundance of alteration minerals:

·---- Common (weak to moderate alteration)

Abundant (strong alteration)



E26D507

Symbols:

Fault, or faulted contact if full width of column

- Zone of shearing/fracturing
- Gradational contact over arrowed distance

_ Sedimentary laminations

Very abundant (intense alteration)























Appendix A - Rb-Sr Data

Rb and Sr isotope analyses were conducted on 14 epidote separates from propylitically altered samples related to the E48 deposit, 1 epidote separate from a regional metamorphic sample and 10 powdered whole rock separates of freshest country rocks. All Sr and Rb isotope analyses were conducted at the Natural Environment Research Council Isotope Geosciences Laboratories (NIGL) at the British Geological Survey, Keyworth, Nottingham. Sr and Rb was extracted from samples by acid digestion and column chemistry.

For each sample, approximately 20 mg of epidote separate, or 150 mg of whole rock power, was weighed into 15 ml Teflon beakers. Subsequently, whole rock samples were leached in warm 6M HCl to liberate any labile Sr into solution; the leachate was discarded via centrifuging and the samples dried and reweighed to quantify any loss. ⁸⁴Sr and ⁸⁷Rb isotope tracers were weighed and added to all samples, along with a mixture of 1-2 ml of 16M HNO3 and 5-10 ml of 29M HF. Beakers were then sealed and left on a hotplate at 105° C for one week to facilitate complete sample dissolution. After this period, samples were evaporated to dryness before a further 1-2 ml of HNO₃ was added to the beakers, which were left on the hotplate overnight. Samples were then converted into chloride form by addition of 10 ml of calibrated 2.5M HCl in preparation for column chemistry.

1 ml of sample solution was pipetted onto a quartz-glass column which contained 4 ml of EICHROM AG50x8 cation exchange resin, and washed into the column using 1 ml of calibrated 2.5M HCl. Matrix elements were washed off the column using a further 24 ml of 2.5M HCl, and discarded. Rb was collected in a subsequent 6 ml of 2.5M HCl. Ca was next eluted and discarded in 18 ml of 2.5M HCl, before Sr was collected in 12 ml of 2.5M HCl, and evaporated to dryness. Rb fractions were loaded onto one side of an outgassed double Re filament using 0.6M HCl and analysed using a Thermo-Scientific Triton thermal ionisation mass spectrometer (TIMS) in static multi-collection mode. Sr fractions were loaded onto outgassed single Re filaments using a TaO activator solution and analysed in a Thermo-Electron Triton TIMS in multi-dynamic mode; data are normalised to ⁸⁶Sr/⁸⁸Sr = 0.1194.

Replicate analyses (n = 26) of the NBS987 standard yielded 87 Sr/ 86 Sr = 0.710254 ± 0.000004 (6 ppm, 1 σ), which is within error of both the certified value (0.710340 ± 0.000260) and long term laboratory average (0.710250). The natural Columbia River Basalt rock standard (BCR-2) was also treated and analysed as for samples, returning values of 44 ppm Rb and 334 ppm Sr, in good agreement with the certified ranges of 48 ± 2 ppm and 346 ± 14 ppm respectively. Consequently, data were accurate and no secondary calibration was required; analytical precision in 87 Sr/ 86 Sr is to the 5th or 6th decimal place.

Results are tabulated below and were used to construct Figure 8 in the main text. Note that errors quoted are those associated with analytical precision and, as such, do not take into account any possible natural in-sample variability.

		Sample			Rb	Sr				
Sample ID	Sample type ^A	weight (mg)	weight loss, labile Sr (mg) ^B	ppm	± 2σ x10 ⁻²	ppm	± 2σ	⁸⁷ Rb/ ⁸⁶ Sr	⁸⁷ Sr/ ⁸⁶ Sr	± 2σ x10 ⁻⁵
NP12AP033	Epi (E48)	21.81	-	9.927	0.1	1289.22	0.03	0.0223	0.704318	0.7
NP12AP036	Epi (E48)	23.18	-	5.073	0.1	1735.77	0.13	0.0085	0.704303	0.8
NP12AP040	Epi (E48)	22.75	-	23.630	0.1	1435.55	0.06	0.0476	0.704631	0.9
NP12AP045	Epi (E48)	20.75	-	2.055	0.0	3078.79	0.16	0.0019	0.704308	0.9
NP12AP073	Epi (E48)	23.22	-	16.065	0.1	1323.50	0.04	0.0351	0.704352	0.7
NP12AP093	Epi (E48)	25.90	-	14.734	0.1	2277.50	0.10	0.0187	0.704222	0.9
NP12AP097	Epi (E48)	22.29	-	14.771	0.1	1994.46	0.06	0.0214	0.704234	0.7
NP12AP115	Epi (E48)	22.81	-	15.284	0.1	2364.43	0.12	0.0187	0.704249	0.9
NP13AP016	Epi (E48)	22.62	-	24.992	0.1	1746.88	0.07	0.0414	0.704379	0.7
NP13AP040	Epi (E48)	22.63	-	27.670	0.1	2133.56	0.06	0.0375	0.704417	0.9
NP13AP049	Epi (E48)	23.79	-	34.893	0.2	2736.39	0.23	0.0369	0.704536	1.0
NP13AP249	Epi (E48)	21.38	-	35.142	0.2	914.14	0.02	0.1112	0.705055	0.6
NP13AP275	Epi (E48)	22.23	-	112.981	0.5	574.51	0.01	0.5690	0.707759	0.5
NP13AP312	Epi (E48)	23.85	-	69.184	0.1	1090.28	0.03	0.1836	0.705481	0.6
NP13AP318	Epi (Meta.) ^C	20.29	-	0.315	0.2	9886.28	0.87	0.0001	0.704617	0.7
NP12AP079	WR (AFG)	152.75	1.72	84.205	0.4	286.05	0.01	0.8518	0.709530	0.6
NP13AP013	WR (AND)	153.22	3.68	59.739	0.1	1131.90	0.11	0.1527	0.705209	0.8
NP13AP027	WR (AFG)	157.65	5.76	97.391	0.2	415.73	0.02	0.6778	0.708535	2.7
NP13AP063	WR (BQM)	155.25	4.46	70.389	0.5	1106.33	0.09	0.1840	0.705344	0.7
NP13AP100	WR (BQM)	154.90	4.89	66.391	0.2	1013.50	0.06	0.1895	0.705373	0.6
NP13AP102	WR (BQM)	150.49	1.34	68.228	0.2	1083.30	0.07	0.1822	0.705291	0.7
NP13AP244	WR (AND)	150.57	5.09	43.715	0.1	1325.96	0.15	0.0954	0.704759	0.8
NP13AP282	WR (AND)	158.19	3.87	41.047	0.1	1264.71	0.18	0.0939	0.704804	0.9
NP13AP283	WR (BQM)	155.93	8.74	58.527	0.1	1109.20	0.11	0.1526	0.705085	0.7
NP13AP311	WR (AND)	150.45	5.02	50.715	0.4	1341.62	0.13	0.1093	0.704896	0.7

Footnotes:

Sample types: Epi = Epidote mineral separate; WR = Powdered whole rock sample. Where applicable, lithology is indicated in parentheses as: AFG = Alkali feldspar granite; AND = Basaltic trachyandesite; BQM = Biotite quatz monzonite.

^B Weight loss is the difference between original sample mass and that measured after leaching of labile Sr in warm HCl.

^C Metamorphic sample, for comparison purposes only. It is an outlier to, and thus not used to construct, the isocon in Figure 8 of the main text.

Appendix B - Whole rock data

Whole rock geochemistry data are contained in Table B1. Explanatory notes, limit of dectection and error values are provided in separate sheets.

Analytical protocol:

Whole rock geochemical analyses were conducted by ALS Minerals Ltd Brisbane on 204 samples collected from logged diamond drill core. Major elements and 31 trace elements (including the REE) were analysed, following lithium metaborate fusion, by ICP-AES and ICP-MS respectively. The abundance of C and S was determined by combustion and infrared detection in a LECO C/S analyser. Base metal concentrations (including Ag, Cd, Cu, Mo, Ni, Pb, Zn and Sc) were determined by ICP-AES after four acid digestion, and precious metal (Au, Pt and Pd) concentrations were determined by fire assay ICP-MS. Volatile elements (As, Bi, Hg, Sb, Se and Te) were determined by ICP-MS after aqua regia digestion. The analytical limit of detection and calculated 1 σ precision for each element is provided in Table B2. Mean compositional data for replicate analyses of laboratory standards matched preferred reference values within ± 1 σ , suggesting results are accurate. Data sourced from Rio Tinto were aquired using the same analytical procedures.

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Appendix D: Whole rock sample descriptions and major element geochemistry

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Appendix D: Whole rock sample descriptions and major element geochemistry

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Appendix D: Whole rock sample descriptions and major element geochemistry

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Appendix B - Whole rock data							
Data is contained in Table B1, a separate sheet in this workbook.							
Explanatory information for Table B1:							
Footnote Ref.	Explanatory Information						
А	Samples from this study are referred to using the format NPxxAPyyy in which: NP = Northparkes, xx = last two digits of collection year, AP = initials of the principal investigator and yyy = sample number.						
В	The ID of the drillhole from which samples were collected (if appropriate). The majority of drillholes are indicated in the main text on Figures 4-6. Hole depth is the distance along the drillhole measured from the collar.						
с	The location of samples is provided as grid coordinates (eastings and northings) in meters with respect to MGA Zone 55 utilizing the GDA94 datum. Coordinates are also provided as decimal latitude and longitude utilizing the WGS84 datum.						
D	Sample types are indicated as: DC = Diamond drill core; RC = Rock chip drill core; OC = outcrop; SC = subcrop						
E	Sample lithology is indicated as: AFG = alkali feldspar granite; AND = trachyandesite; APL = aplite; BQM = biotite quartz monzonite; B-QMP = biotite-quartz monzonite porphyry; BSLT = basalt; BTA = basaltic trachyandesite, used by Lickfold (2002) to refer to the 'mafic zero'; CON = volcanic conglomerate; E34POR = monzonite porphyry in drillhole E34D3; FLT = fault rock, mostly hydrothermally cemented breccias or samples of vein centers; IBX = intrusion breccia, usually pure igneous or mix of igneous-hydrothermal cement; K-QMP = K-feldspar-quartz monzonite porphyry; MAG = vein sample dominated by magnetite; MON = monzonite; MZD = monzodiorite; MZO = the 'mafic zero' porphyry; PEP = pepperite, with a mix of AND and SST; SST = volcanic sandstone; SYN = syenite; TR = trachyte; TRS = trachytic sill; TVB = trachytic volcanic breccia/ignimbrite; ZRO = the 'zero' porphyry. The suffix '-S' is used to indicate samples containing quartz stockwork veining.						
F	Samples are grouped into larger lithological classifications to facilitate plotting and comparison of data. For example, syenites and trachytic sills known to be part of the overall biotite quartz monzonite pluton are all grouped under BQM. Also, samples of no interest for igneous geochemistry (CON, FLT, IBX, MAG, PEP, SST, TVB) are simply grouped as not applicable (N/A). Definitions are as given above (for footnote E), with the addition of: DKB = mafic dykes (alkali basalt); NEL INT and VOL = intrusions and volcanic rocks belonging to the Nelungaloo Volcanics; GOO INT and VOL = intrusions and volcanic rocks belonging to the Nelungaloo VOL = intrusions and volcanic rocks belonging to the Wombin Volcanics.						
G	Alteration in all samples was classified as either: PRO = propylitic; SER = sericitic; MAG = magnetite ± biotite; KFS = K-feldspar. The intensity of alteration in all samples was also classified based on the visually observed abundance of alteration minerals and veins. For SER, MAG and KFS this was on a simple scale of 1 to 3, with 1 indicating the least intense alteration/almost fresh, through to 3 being intense and usually texturally-destructive alteration. For PRO, this was on a scale of 0-4, in which 0 is almost fresh and 4 represents total textural destruction and replacement by alteration minerals; the scale is equal and marks a progressively increasing abundance of alteration minerals and/or veins.						
Н	If samples are dominated by, or consist entirely of vein fill they are designated as 'mainly vein'.						
I	Column used to indicate igneous samples which were excluded from investigation of petrogenesis in this paper because their geochemistry is likely not representative of the original rock/parent magma. This is based on: (1) observed alteration intensity: samples excluded if they contain appreciable vein material and/or have an alteration intensity >PRO3, >SER2, >MAG2 or >KFS2; and (2) the feldspar K-Na general element ratio control diagram of Stanley and Madeisky (1993): samples excluded if they plot along trajectories associated with alteration, in particular potassic and sericitic alteration. Samples designated as "*" are those which would have been excluded in point 2, but are retained to ensure adequate representation of all magmatic phases in the dataset. Although not all the remaining data represent entirely fresh/unaltered rocks, it is thought the bulk whole rock geochemistry of these samples is unlikely to be significantly affected for use in identifying/interpreting primary trends in igneous geochemistry.						
J	A general description of each sample is provided in this column, often along with any particular reason why the sample was collected. Although in most instances the entirety of the described sample was analysed, some were collected in two parts: one part retained for subsequent work, the other analysed. In this case any differences between the two parts are also described, e.g. presence of a vein only in one part etc.						
к	Details of the mineralogy of any veins are given in this column; minerals in brackets were observed within the vein fill, others in the alteration halo, i.e. (<i>vein fill minerals</i>) + <i>halo minerals</i> .						

Appendix B - Table B2

The limit of detection (LOD) and analytical precision for whole rock data obtained in this study is given for each element in the table below. For most analytical techniques, typically between 13-15 randomly selected samples were analysed twice, and several replicate analyses were conducted on 3-5 different laboratory standards. One standard deviation (10) was calculated for each element using each set of replicate data (for both standards and natural samples) in which the element was >LOD. The mean of these standard deviation values encapsulates analytical precision, and is given for each element (i) as 10, below, based on n, number of analyses of n, number of samples. Analytical precision is also given as a percentage of the mean values determined from n, number of analyses. Missing values are when an element was not detected or only detected at the LOD.

Element (i)	Units	Limit of detection	1 σ _i	1σ _i (%)	n _a	n _s
SiO ₂	wt. %	0.01	0.2	0.4	49	18
AI_2O_3	wt. %	0.01	0.1	0.8	49	18
Fe_2O_3	wt. %	0.01	0.04	0.7	49	18
CaO	wt. %	0.01	0.04	1.7	49	18
MgO	wt. %	0.01	0.01	0.7	49	18
Na ₂ O	wt. %	0.01	0.03	2.5	49	18
K ₂ O	wt. %	0.01	0.02	0.7	49	18
Cr ₂ O ₃	wt. %	0.01	-	-	49	-
TiO ₂	wt. %	0.01	0.01	1.4	49	18
MnO	wt. %	0.01	0.002	1.1	49	18
P ₂ O ₅	wt. %	0.01	0.004	3.8	49	18
BaO	wt.%	0.01	0.003	8.2 2.1	49	17
C.	wt. %	0.01	0.002	2.1	37	10
S	wt. %	0.01	0.02	2.1	37	15
LOI	wt. %	0.01	0.05	1.2	29	9
Ba	ppm	0.5	13	1.6	47	18
Ce	ppm	0.5	2	2.5	47	18
Cr	ppm	10	3	3.7	47	10
Cs	ppm	0.01	0.03	3.6	47	18
Dy	ppm	0.05	0.3	2.4	47	18
Er	ppm	0.03	0.2	3.2	47	18
Eu	ppm	0.03	0.04	3.5	47	18
Gd	ppin	0.05	0.0	2.5	47	18
Hf	maa	0.2	1	3.6	47	18
Но	ppm	0.01	0.1	3.3	47	18
La	ppm	0.5	1	4	47	18
Lu	ppm	0.01	0.03	3	47	18
Nb	ppm	0.2	0.3	2.8	47	18
Nd	ppm	0.1	0.9	2.5	47	18
Pr	ppm	0.03	0.3	2.5	47	18
Rb	ppm	0.2	3	2.7	47	18
Sill	ppm	0.03	0.3	4.3	47	18
Sr	ppm	0.1	13	4.5	47	18
Та	ppm	0.1	0.3	7.3	47	18
Tb	ppm	0.01	0.04	2.5	47	18
Th	ppm	0.05	0.2	5	47	18
Tm	ppm	0.01	0.06	4.1	47	18
U	ppm	0.05	0.2	3.7	47	18
V	ppm	5	3	5.1	47	17
W	ppm	1	0.4	16	47	16
Y Vh	ppm	0.5	3	2.5	47	18
70 7r	ppin	0.03	0.2	3.2	47	10
As	maa	0.1	0.2	2.2	37	16
Bi	ppm	0.01	0.02	3.5	37	14
Hg	ppm	0.005	0.004	14.1	37	13
Sb	ppm	0.05	0.1	3.3	37	16
Se	ppm	0.2	0.1	8.4	37	16
Te	ppm	0.01	0.01	7.9	37	15
Ag	ppm	0.5	0.1	2	37	5
Cd	ppm	0.5	0.1	3.2	37	5
C0	ppm	1	0.3	1.5	37	16
Cu Mo	ppm	1	1	2.0 7 9	5/ 38	10 1 <i>1</i>
Ni	ppm	1	12	11.8	38	14
Pb	ppm	1	10	6.3	38	16
Zn	ppm	2	7	1.3	42	18
Li	ppm	10	-	-	38	8
Au	ppb	1	5	1.4	17	5
Pt	ppb	0.5	15	3.8	17	2
Pd	ppb	1	5	4.6	17	4