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THE PORPHYRY Au-Cu DEPOSITS AND RELATED SHOSHONITIC MAGMATISM OF THE PALAEOZOIC MACQUARIE VOLCANIC ARC, EASTERN LACHLAN OROGEN IN NEW SOUTH WALES, AUSTRALIA, A REVIEW

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Abstract - Ordovician volcanic, volcaniclastic and intrusive rocks of calc-alkaline affinity in the Eastern Subprovince of the Lachlan Orogen were formed in the intraoceanic Macquarie Volcanic Arc. The Macquarie Arc was developed in response to west-dipping subduction along part of the boundary between eastern Gondwana and the proto-Pacific Plate and was situated on the Gondwana Plate, some 1000 km east of Precambrian continental crust. The intervening area was occupied by a back arc basin that developed on oceanic crust as the proto-PacificPlate rolled back eastwards after the Middle Cambrian Delamerian Orogeny. Subsequent extension, strike-slip translation and thin-skinned tectonics have structurally dissected the single arc into four north to NNE trending structural belts of Ordovician calc-alkaline rocks that are separated largely by younger rift basins and in part by coeval craton-derived turbidites.

Two of the belts host substantial porphyry style gold-copper, and epithermal gold deposits. The currently exploited porphyry gold-copper deposits are localised in two tight clusters in the Cadia and Goonumbla districts, which are approximately 100 kilometres apart, and fall within a major, long-lived, NW- to WNW-trending, semi-continental scale, structural corridor known as the Lachlan Transverse Zone.

The Cadia district comprises four porphyry style deposits, Ridgeway, Cadia Hill, Cadia Quarry and Cadia East, which have a combined resource of 1210 Mt @ 0.75 g/t Au, 0.32% Cu with a total of 905 tonnes (29 Moz) of contained gold. These ore deposits are spatially associated with Late Ordovician to Early Silurian, shoshonitic, porphyritic monzonite to quartz-monzonite phases of the Cadia Igneous Complex (CIC), intruding Late Ordovician coarse volcaniclastic rocks of similar composition to the CIC. The intrusive complex is represented as a stock at Cadia Hill and Cadia Quarry, a narrow restricted pipe at Ridgeway and as a series of dykes at Cadia East. The ore deposits occur as a string of mineralised centres within, and elongated parallel to, a 7 km long, NW- to WNW-trending corridor of alteration and mineralisation that is up to 2 km in width and has been intersected by drilling to a depth of more than 1600 m. Mineralisation occurs as sheeted quartz-sulphide veins at Cadia Hill, Cadia Quarry and Cadia East, as stockwork quartz veins at Ridgeway and Cadia Quarry and as disseminations at Cadia East, and, depending on the deposit, is hosted by either the CIC intrusive rocks alone, or by both the intrusive and volcaniclastic wallrocks. Veins are mainly quartz-calcite with bornite, grading outwards to chalcopyrite and pyrite. Alteration takes the form of an early sodic phase, overprinted by potassic alteration and pervasive propylitisation. Individual veins have selvages of potassic and calc-potassic alteration. Skarn bodies are found in adjacent carbonate bearing units, while phyllic alteration is generally restricted to late stage faults.

The Goonumbla district includes four economic deposits, Endeavour 22, 26, 27 and 48, hosted by Early Silurian shoshonitic intrusive and Late Ordovician volcaniclastic rocks of the Goonumbla Igneous Complex and lie within a 22 km diameter circular structure that embraces a series of mineralised centres. The four deposits had a combined pre-mining resource of 132 Mt @ 1.1% Cu, 0.5 g/t Au. Each is centred on a separate, narrow, pipe-like, vertical, quartz monzonite porphyry complex comprising up to nine intrusive phases. These intrusive complexes have lateral dimensions in the order of 50 to 150 m and minimum vertical extents of 600 to 900 m. The associated ore zones are up to 400 m in diameter at a 0.5% Cu equivalent cutoff. Main stage mineralisation at all four deposits is associated with the same K feldspar quartz monzonite porphyry and augite-K feldspar quartz monzonite porphyry intrusive phases and is characterised by multiple generations of stockwork and sheeted quartz, K feldspar, bornite, chalcopyrite and gold-bearing veins. Early Stage pervasive biotite-magnetite and propylitic alteration is overprinted by Main Stage mineralised veins that have halos of early K feldspar and later sericite-hematite. Sulphides are zoned from proximal bornite, through bornite and chalcopyrite, to chalcopyrite and peripheral pyrite.

Introduction

Numerous examples of well-preserved porphyry style copper-gold, copper-molybdenum and molybdenum mineralisation have been recognised from the Tasmanides of eastern Australia since the late 1950s. All have been either: i). of lower Palaeozoic age, principally Ordovician to Silurian, in the Lachlan Orogen of New South Wales, ii). associated with upper Palaeozoic intrusives, particularly those of Permo-Carboniferous age, emplaced to the west of the Bowen Basin in north Queensland, or iii). Permian to Triassic in the New England Orogen in northeastern New South Wales (NSW) and eastern Queensland. While the same magmatic episodes also produced epithermal gold deposits that have been economically exploited in all of these regions, none of the known porphyry style mineralisation had been mined on a significant scale until the development in 1993 of the Northparkes operation, based on the Endeavour deposits.

Porphyry gold-copper deposits are currently in commercial production in two districts in eastern Australia. Both have alkalic affiliations and are hosted by monzonitic and monzodioritic intrusions emplaced into Late Ordovician shoshonitic magmatic rocks of the Macquarie Volcanic Arc in the Eastern Subprovince of the Lachlan Orogen, New South Wales.

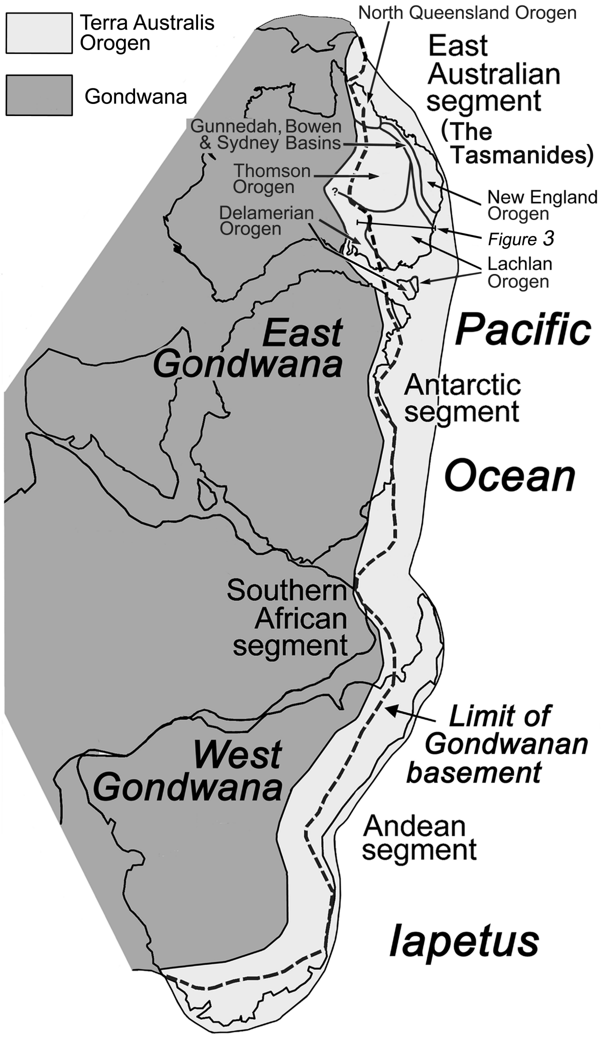


Figure 1: ***Location of the Tasmanides and Lachlan Fold Belt*** within the late Neoproterozoic to late Palaeozoic Terra Australis Orogen on the margin of the super continent Gondwana. See Fig. 2 for the location of the Macquarie Arc. *Modified after Cawood, (2005).*

The larger of these, the Cadia Valley Operations of Newcrest Mining Limited, is located some 20 km south of the city of Orange in an area of well developed pre-existing infrastructure, 200 km west of Sydney (Figs. 2 and 4). It comprises four deposits, Cadia Hill, Cadia Extended (previously known as Cadia Quarry), Ridgeway and Cadia East, which are embraced by a 7 km long, WNW-trending corridor of alteration and mineralisation. As at June 2004, the combined resource contained within the four deposits was 1210 Mt @ 0.75 g/t Au, 0.32% Cu, for a total of 905 tonnes (29 Moz) of contained gold (Newcrest 2003; Newcrest 2004). These resources place the operation in the top 10 largest known gold-rich porphyry districts in the world (Cooke *et al.,* 2002).

Current operations include: i). a large composite open pit removing over 100 Mt of ore and waste per annum, based on the Cadia Hill and Cadia Extended deposits, including +17 Mt of ore per annum at a head grade of around 0.7 g/t Au, 0.16% Cu, and ii). an underground, sub-level cave mine at Ridgeway, extracting +5 Mt of ore at a head grade of 1.96 g/t Au, 0.67% Cu. The Cadia Hill open pit commenced mining in 1997, while the Ridgeway underground mine was commissioned in 2002 (Newcrest Mining presentation, 2004).

The second district is exploited by Northparkes Mines at Goonumbla, approximately 100 km WNW of the Cadia Valley Operations and 30 km NW of the city of Parkes in NSW. This operation is based on four deposits, Endeavour 22, 26, 27 and 48, which are distributed over an interval of 5 km. Each is associated with a separate, narrow, pipe-like quartz monzonite porphyry complex. These deposits are members of a group of eleven mineralised centres recognised within a 22 km diameter circular feature defined by aeromagnetics and gravity (Heithersay *et al.,* 1990). The pre-mining resource in these four deposits totalled 132 Mt @ 1.1% Cu, 0.5 g/t Au (Lickfold *et al.,* 2003). Following initial open pit operations at Endeavour 22 and 27 beginning in 1993, an underground block cave mine was established at Endeavour 26, which during 2001 produced 5.425 Mt of ore with a head grade of 1.1% Cu, 0.32 g/t Au (Rio Tinto, 3002). Lift 1 of the block cave commenced mining in 1997 and was ‘tailed off’ in 2002-03, with Lift 2 scheduled to commence operation in 2004 (Rio Tinto, 2003). Endeavour 48 is the subject of a pre-feasibility study which commenced in 2002 (Lickfold *et al.,* 2003).

Editors Note:

The purpose of this paper is to provide up to date information on the regional and local setting of the most important of the known and mined porphyry gold and copper deposits within the Tasmanides of eastern Australia, and to describe the geology, alteration and mineralisation of each of the districts and individual ore deposits.

While R.A. Glen has contributed original material to the “Tectonic & Geological Setting” section, the remainder of the paper is a review of the most recently published information on the Cadia Valley and Endeavour group of deposits, largely drawn from Holliday *et al.,* (2002), Wilson *et al.,* (2003) and Lickfold *et al.,* (2003), complemented by a range of other sources. Other than the section detailed above, there is **no original input from the authors,** with attribution to the source for all information either within or at the end of each paragraph.

Tectonic & Geological Setting

The Ordovician Macquarie Volcanic Arc lies within the Eastern Subprovince of the Lachlan Orogen, one of the constituents of the Tasmanides of eastern Australia. The Tasmanides occupy the eastern third of Australia, fringing Precambrian cratons to the west. They record the rifting of a supercontinent in the Neoproterozoic, as the proto-Pacific Ocean opened, followed by convergent margin activity that lasted from the late Middle Cambrian (~520 Ma) until the Middle Triassic (~230 Ma) and the commencement of the Mesozoic Gondwanide Orogeny (Cawood 2005; Glen 2005).

The Tasmanides formed one sector or segment of the proto-Pacific margin of Gondwana that stretched almost 20 000 km, from Papua New Guinea southwards to Tasmania and New Zealand (Tuhua Orogen), into Antarctica (Ross Orogen), and then northwards up the Antarctic Peninsular into the western margin of South America to what is now northern Colombia (Fig. 1) (Cawood 2005, Glen 2005). Cawood (2005) called this the Terra Australis Orogen. It overlapped the Precambrian cratonic masses of Gondwana on one side and was bounded by proto-Pacific Ocean on the other margin (Cawood 2005).

The key point of the Tasmanides is that they record interaction between Gondwana and the proto-Pacific Plate and are therefore accretionary. The proto-Pacific Ocean never closed. Several authors (Crook, 1969; Crawford *et al.,* 2003; Cawood, 2005; Glen, 2005) have recognised that this contrasts with the classical textbook orogenic belt that developed by the opening and closing of an ocean basin (the Wilson cycle with its continent-continent collision).

The Tasmanides are divided into five orogenic belts, as well as the Sydney-Gunnedah-Bowen Basin system (Glen 2005) (Fig. 1). In the south, the Delamerian Orogen occupies eastern South Australia, western New South Wales and Victoria, and western Tasmania (where it is also known as the Tyennan Orogen). It passes eastwards into the Lachlan Orogen, which extends to the Tasman Sea in Victoria and southern New South Wales, and northeast into the Thomson Orogen across a concealed and poorly understood, curvilinear east-west boundary. Further to the northeast, the Lachlan Orogen is bounded by the Sydney and Gunnedah Basins, which in turn pass eastwards into the New England Orogen. The Thomson Orogen is almost completely obscured by the Great Australian Basin. It passes eastwards into the Bowen Basin and northwards into the North Queensland Orogen.

Although there is a general tendency for younger rocks to occur in the east, reflecting a stepping out of orogenic activity (Powell 1983), old strata are found in even the most outboard belts, the New England Orogen and the North Queensland Orogen (Glen 2005). Thus the North Queensland Orogen is built on Neoproterozoic inliers and its evolution extended from the Ordovician into the Triassic. The New England Orogen was probably developed, in part, on Precambrian igneous crust and contains an early Cambrian and Ordovician history, despite its major development as a convergent margin arc-forearc basin-accretionary complex system from the Late Devonian to the Triassic. Glen (2005) suggested that the early Palaeozoic strata were rifted-off fragments formed during rollback of the proto-Pacific Plate following the Delamerian Orogeny.

The Tasmanides reach a maximum width of ~1600 km in southeastern Australia, but only 200 km in Far North Queensland in the North Queensland Orogen, although rocks of either the North Queensland or northern New England Orogens occur in islands in the Coral Sea (summary in Glen 2005). The greater width in the south has been attributed to i) the opening and filling of a large back-arc basin (the Wagga Basin) in the Ordovician as a consequence of ocean retreat of the proto-Pacific Plate after the Delamerian Orogeny, and ii) to crustal extension leading to rifting and granite emplacement resulting from further ocean retreat of the Pacific Plate following the earliest Silurian Benambran Orogeny (Glen 2005).

Lachlan Orogen

The Lachlan Orogen extends from eastern Tasmania, through Victoria to New South Wales, where it occupies much of the state. The western boundary with the Delamerian Orogen is largely obscured by the Tertiary Murray Basin and the Great Australian Basin, but is exposed in Western Victoria. Although the east-dipping Moyston Fault has been accepted until recently as the surface expression of the boundary (VandenBerg *et al.,* 2000; Korsch *et al.,* 2002), results of recent Ar-Ar dating by Miller *et al.,* (2004) suggest that the Avoca Fault, ~100 km further east, may be the actual boundary (Glen 2005).

The eastern boundary with the largely younger New England Orogen is obscured by the coal-rich Permian to Triassic Sydney and Gunnedah Basins, although deep seismic reflection profiling indicates that the crust of the Lachlan Orogen extends east under the foreland fold-thrust belt of the New England Orogen (Glen, Korsch *et al.,* 1993; Korsch, Wake-Dyster *et al.,* 1993). The northern margin with the Thomson Orogen (largely in Queensland) lies beneath the Mesozoic sediments of the Great Australian Basin and is inferred to be a suture marked by early Palaeozoic oceanic and ?island arc igneous rocks (Glen 2005).

The Lachlan Orogen is a complex orogenic belt, different to classical orogenic belts that have a well defined foreland fold-thrust belt inboard of a more complex higher grade internal zone. Its evolution can best be described in terms of cycles.

Delamerian Cycle

The Delamerian cycle is best represented in the Delamerian Orogen, which underwent development from a rifted and passive margin in the Neoproterozoic, to a convergent margin that involved accretion of boninitic forearc crust and one or more arcs in the late Middle Cambrian (e.g. Crawford and Berry, 1992). The Delamerian Orogeny was followed in western Victoria by post-collisional volcanism and deposition of Late Cambrian turbidites of the Glenthompson and St Arnaud Groups (VandenBerg *et al.,* 2000; Crawford *et al.,* 2003; Miller *et al.,* 2004; Glen 2005).

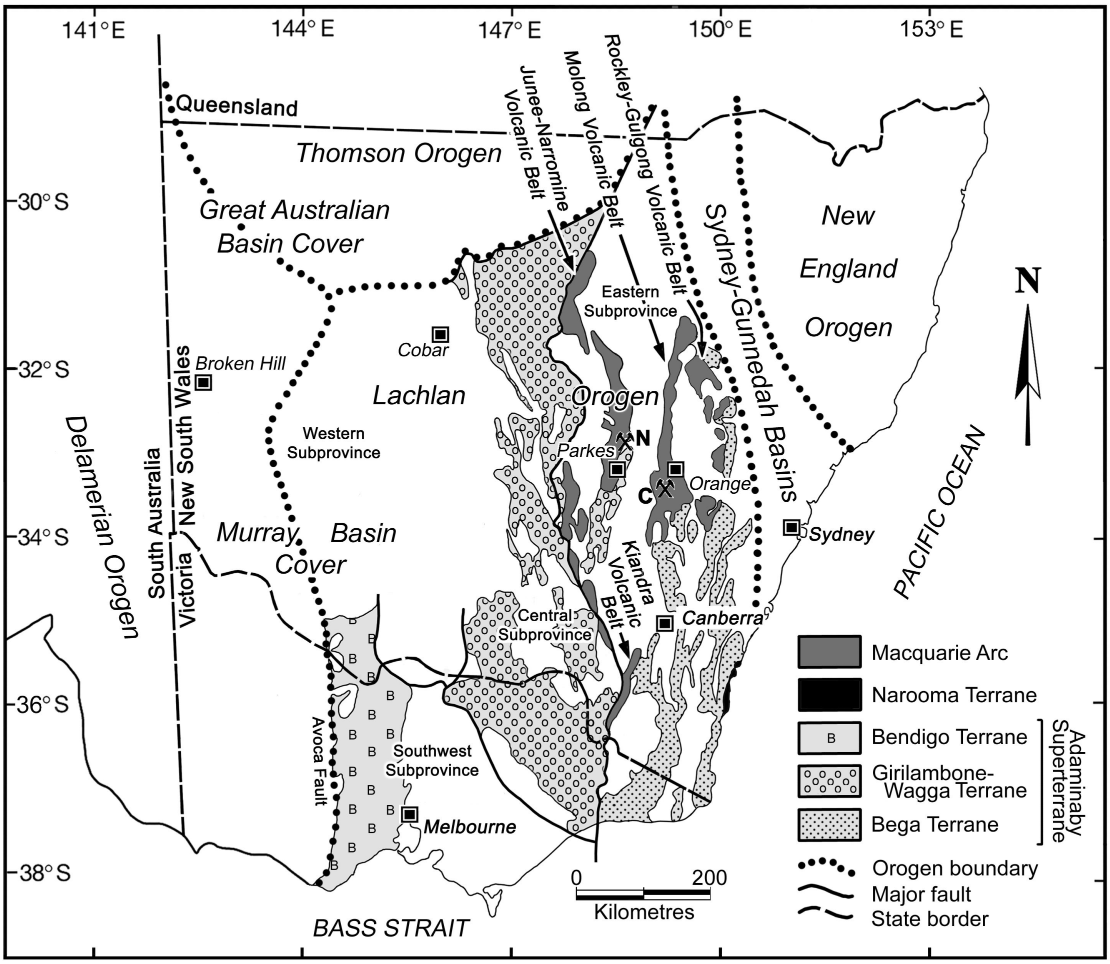


Figure 2: ***Distribution and setting of the Ordovician to Early Silurian volcanic (and intrusive) rocks of the Macquarie Volcanic Arc*** in the Eastern Subprovince of the Lachlan Orogen, New South Wales, and their context within the tectonic framework of southeastern Australia. These are represented by the Junee-Narromine, Molong, Rockley-Gulgong, and Kiandra volcanic belts. See Fig. 1 for location and continental scale setting and text for discussion. Cross picks show the Cadia Valley (**C**) and Northparkes (**N**) operations.

In the Lachlan Orogen, the Delamerian cycle is represented by Cambrian mafic, ultramafic and related rocks that are found in Victoria as several belts of greenstone that occur in the hangingwall of major thrusts, and underlie Ordovician turbidite packages (VandenBerg *et al.,* 2000).

Benambran Cycle

This cycle extends from the base of the Ordovician until the Llandoverian in the Early Silurian, when it was terminated by the multistage Benambran Orogeny (Glen 2005; Glen *et al.,* 2005). Several contrasting Ordovician lithotectonic associations are divided into separate tectonostratigraphic terranes (e.g. Glen 2004; 2005; Fig. 6).

i) *Adaminaby Superterrane:* This superterrane is spread across the four subprovinces of the Lachlan Orogen and is divided into three terranes that are restricted in outcrop to specific subprovinces. In the Eastern Subprovince, the *Bega Terrane* consists of the Early-Middle Ordovician Adaminaby Group, overlain by the Late Ordovician Bendoc Group, consisting largely of starved shales. In the Central Subprovince, the *Girilambone-Wagga Terrane* comprises the Early-Middle Ordovician Girilambone and Wagga Groups overlain by the Bendoc Group. Late Ordovician shales are largely missing from the *Bendigo Terrane* of the Southwestern Subprovince, where Early-Middle Ordovician turbidites thin eastwards and are locally overlain by Late Ordovician turbidites (VandenBerg *et al.,* 2000). In all three subprovinces, turbidites consist of slates, local cherts, siltstones and quartz-rich sandstones containing minor amounts of detrital feldspar and white mica, and which were derived from the Delamerian-Ross Craton to the west and south (Turner *et al.,* 1996).

ii) *Macquarie Arc:* an intraoceanic island arc developed, discontinuously, from the earliest Ordovician through to the Llandoverian (Early Silurian). This arc is described in more detail below.

iii) *Narooma Terrane:* A terrane of chert passing up into argillite, siltstone and sandstone that accumulated on the floor of the proto-Pacific Plate from the Middle Cambrian until the late Ordovician, before being accreted to the Bega Terrane in the Benambran Orogeny (Glen *et al.,* 2004)

iv) Basalt and mafic schists with MORB chemistry, near major faults east and west of the Junee-Narromine Volcanic Belt. This lithotectonic association is inferred to represent MORB-like tholeiitic basalts developed in a back arc setting west of the Macquarie Arc (Glen 2004).

v) A single outcrop of limestone at Waratah Bay in eastern Victoria (VandenBerg *et al.,* 2000).
vi) Zoned mafic-ultramafic complexes (Fifield Complexes) of inferred Late Ordovician age, intruding the Girilambone-Wagga Terrane and lying west of the Macquarie Arc (Suppel and Barron, 1986).

Tabberabberan Cycle

This cycle reflects development of the Lachlan Orogen in a back arc setting, as a consequence of rapid retreat of the proto-Pacific plate to the east after the Benambran Orogeny (e.g. Scheibner & Basden 1998; Glen 2005). The cycle is characterised by the formation of sedimentary basins (some filled with felsic volcanic and volcaniclastic rocks, and limited amounts of mafic volcanic rocks), their flanking shallower-water shelves, and the emplacement of large amounts of granites, many of which are elongated north-south and organised into major batholiths. Silurian to Middle Devonian basins are most common in the Eastern Subprovince. Multiple cycles of basin fill suggest these originated as extensional or transtensional basins. The Tabberabberan Cycle was terminated by the Middle Devonian Tabberabberan Orogeny dated at ~380 Ma. Earlier deformation around the Silurian-Devonian boundary, the Bindi Deformation, flanks the Kiandra Volcanic Belt, and seems to reflect strike-slip movement on major linked faults (Glen 2005).

Kanimblan Cycle

This cycle was synchronous with convergent margin activity in the New England Orogen to the northeast. High level S- and I-type granites and related volcanic rocks mark the lower part of the cycle in Victoria (VandenBerg *et al.,* 2000). To the north in central NSW, early rifting led to formation of A-type volcanic rocks and emplacement of A-type granites. In both areas, the bulk of the cycle is represented by deposition of a thick (~4 km) blanket of shales, siltstones and sandstones of the dominantly continental Lambie Facies that extends from the South Australian border to the Tasman Sea. The ~340 Ma (Early Carboniferous) Kanimblan Orogeny deformed all older units, but is best deciphered from the Lambie Facies. Deformation varies from kilometre scale wavelength folds in the Central Subprovince, to imbricate tight to isoclinal synclines in the Eastern Subprovince where they lie in the footwalls of major thrusts (Glen 1992). Post-orogenic effects are restricted to the emplacement of the cross-cutting Bathurst granites in the eastern part of the subprovince that were emplaced between 340 and 320 Ma (Glen 2005).

The Macquarie Arc

The Macquarie Volcanic Arc, which lies within the Eastern Subprovince of the Lachlan Orogen, is an intra-oceanic island arc developed on the Gondwana Plate in response to westwards subduction of the proto-Pacific Plate (Fig. 3) (Glen *et al.,* 1998; Glen *et al.,* 2003). Ordovician andesitic and basaltic rocks, particularly in a meridional zone passing through Orange and Molong, had been interpreted as products of Ordovician subduction in some of the earliest plate tectonic models of the Lachlan Orogen (e.g., Oversby, 1971; Solomon and Griffiths, 1972; Scheibner, 1973). Wyborn (1988, 1992) documented the shoshonitic character of many of these volcanics, and used their high K- contents to discount previous models of arc formation during Ordovician subduction. He suggested instead, that these volcanics were formed by Ordovician melting (due to asthenospheric upwelling) of lithosphere enriched in incompatible elements during Cambrian subduction. In a different model, Scheibner (1987) and Scheibner & Basden (1998) suggested that the shoshonitic nature of the volcanic rocks indicated the presence of Precambrian continental substrate. However, Glen *et al.,* (1998) showed that only the youngest parts of the arc were shoshonitic and older parts were K-rich calc-alkaline rocks similar to those found in other island arcs.

Intermediate and mafic volcanic, volcaniclastic and intrusive arc rocks occur in four belts in the Eastern Subprovince. Three in central NSW, namely: i). the western most *Junee-Narromine Volcanic Belt*; ii). the central *Molong Volcanic Belt*; and iii). the eastern *Rockley-Gulgong Volcanic Belt*; and one close to the NSW-Victoria border, iv). the *Kiandra Volcanic Belt* (Figs. 3 & 4) (Glen *et al.,* 1998; Holliday, *et al.,* 2002). These are structural belts, reflecting the combined effects of the Benambran, Tabberabberan and Kanimblan contractional orogenies, and importantly, crustal extension from the Early Silurian to the Middle Devonian (Glen *et al.,* 1998).

Whole rock geochemistry from a recent CODES-NSW Geological Survey study (summarised by Glen *et al.,* 2003, Glen *et al.,* 2004) confirmed the suggestion that these belts formed from a single arc (Crawford *et al.,* in press) which has undergone multiple contractional deformation and Palaeozoic extension and dislocation. Glen *et al.,* (1998), suggested that the western Junee-Narromine Volcanic Belt represented the core of the arc and the eastern two belts, the Molong and Rockley-Gulgong, are the visible parts of a large volcaniclastic apron, with lesser centres, and are not primary palaeogeographic features. Data, particularly that from the Junee-Narromine and western and central parts of the Molong Volcanic Belts, show that the arc evolved episodically over a period of ~50 Ma, with three pulses of igneous activity, separated by two significant hiatuses in volcanic activity (Glen *et al.,* 2003; Percival and Glen 2005) (Fig. 3). These are:

Pulse 1, Early Ordovician, from ~489 to 474 Ma, followed by a ~8 Ma hiatus;
Pulse 2, Middle Ordovician, from 466 Ma, and variably ending between 458 and 455 Ma across the arc, succeeded by a ~ 5.5 Ma hiatus in the west only; and
Pulse 3, Late Ordovician to earliest Silurian, variably commencing between 458 and 450 Ma in different parts of the arc and persisting to ~435 Ma.

In the eastern part of the Molong Volcanic Belt, and in the Rockley-Gulgong Volcanic Belt, pulses 2 and 3 are not separated by a discernible hiatus in volcanism as occurs to the west. While the first pulse has not been recognised in the Rockley-Gulgong Volcanic Belt, ~475 Ma cherts, similar to those in the other belts, were reported by Murray and Stewart (2000).

Lavas from the three igneous pulses have positive εNd values and primitive Pb/Pb ratios (Glen *et al.,* 1998; Carr *et al.,* 1995; Glen *et al.,* 2003), indicating development on igneous substrate and precluding continental basement. Because the pulse 1 volcanics are chemically unlike primitive intra-oceanic arc lavas, basement may consist of a rifted and thinned fragment of forearc igneous crust that was accreted to the Delamerian Orogen during the Delamerian Orogeny (Glen *et al.,* 2003; Crawford *et al.,* 2005) (Fig. 3). The hiatus in volcanism around 470 Ma was interpreted as reflecting back-arc spreading, and the hiatus at 450 Ma as reflecting the effects of either back arc spreading or shallow subduction caused by a buoyant seamount (Glen *et al.,* 1998) being subducted (Fig. 3). The Late Ordovician pulse volcanics are everywhere shoshonitic, representing melting of an enriched mantle source which was apparently absent (or untapped) during the Middle Ordovician (Glen *et al.,* 2003).

Intrusive Porphyries

Most gold-copper deposits in the Macquarie Arc are associated with porphyritic intrusives that range in composition from monzonitic to monzodioritic and monzogabbroic. Glen *et al.,* (2003) subdivided the intrusions of the Macquarie Arc into four temporal groups which they related to the evolution of the arc.

Group 1 - high-K calc-alkaline intrusions aged ~484 Ma, emplaced towards the end of the first pulse of active volcanism in the Junee-Narromine Volcanic Belt, but with no known associated mineralisation.

Group 2a - a high-K magmatic suite, comprising mainly monzogabbroic and monzonitic rocks, chemically little different from Group 1, but emplaced at ~465 Ma in the Junee-Narromine Volcanic Belt, close to the initiation of the second pulse of volcanism.

Group 2b - a second group of intrusive rocks in the Junee-Narromine Volcanic Belt that was emplaced towards the end of the second pulse of volcanism at ~455 Ma.

Group 3 - the Copper Hill Suite, which intruded at ~450 to ~445 Ma, at the beginning of the third pulse of volcanism, is represented in all of the volcanic belts by small, predominantly dacitic porphyries (but with some dioritic and gabbroic examples). They have medium-K calc-alkaline affinities and commonly have quartz and hornblende phenocrysts in porphyries with >60% SiO_2. This suite is associated with significant mineralisation in the Molong Volcanic Belt (e.g. the Copper Hill and Cargo porphyry prospects) and in the Narromine Igneous Complex of the Junee-Narromine Volcanic Belt.

Group 4 - emplaced at the end of the third pulse of volcanism in all but the Kiandra Volcanic Belt. These mainly porphyritic intrusions are all high-K, alkalic to shoshonitic, monzodioritic to monzonitic and are comagmatic with most of the Late Ordovician volcanic rocks in the arc. Porphyries belonging to Group 4 host the Cadia Valley gold-copper and Endeavour copper-gold deposits.

Recognition of these different temporal groups suggest that intrusions were not emplaced during steady-state subduction, but during critical events in the evolution of the arc (Glen *et al.,* 2003), when the angle of subduction

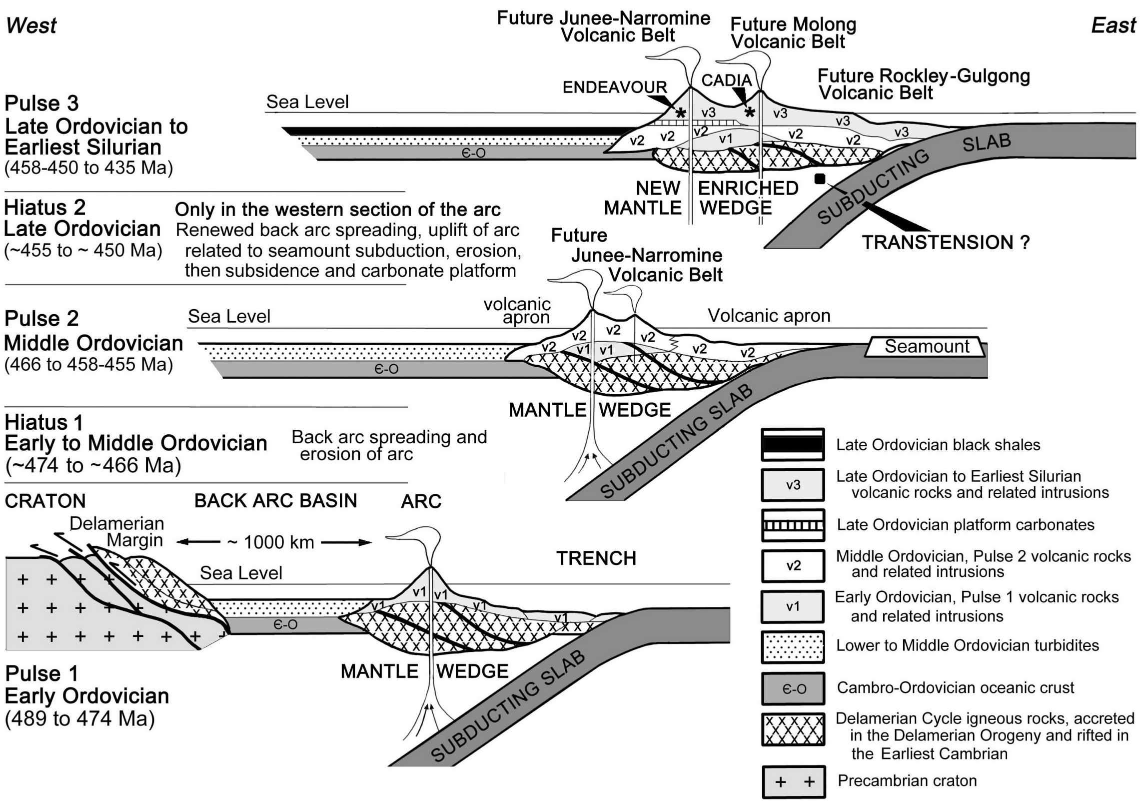


Figure 3: ***The plate tectonic evolution of the Macquarie Arc*** and setting of the Cadia Valley and Endeavour (Goonumbla District) porphyry copper-gold deposits before rifting in the Silurian abd Devonian. See Fig. 1 for the section of the Lachlan Orogen this diagram represents.

shallowed, or subduction ceased as a consequence of either back arc spreading, or jamming of the subduction zone. Glen *et al.,* (2003) argued that porphyries were not emplaced at times of maximum tension, when they would have vented to the surface and not fractionated. Rather, they were emplaced in a compressive stress regime that allowed magmas to pond and fractionate in high- level chambers in crust thick which was strong enough to hold such chambers. To form a deposit, these chambers had to subsequently be breached, either by fluid build-up, or by reduction in differential stress, focussed along new or pre-existing fractures. Conditions for breaching established magma chambers were initiated by transient switches in the stress state of the Macquarie Arc during critical events in the evolution of the arc, as listed above. Significantly, the mineralised Group 4 porphyries were emplaced after the cessation of volcanism, during the Benambran Orogeny and during formation of transient extensional or transtensional basins. The regional compression that prevented Llandoverian magmas venting to the surface was provided by deformation within the arc and by the weight of overlying, structurally thickened volcanic and sedimentary rocks (Glen *et al.,* 2003).

Previous workers (Wyborn 1992; Mueller *et al.,* 1992, 1993, 1995) have shown that magmas with a high oxidation state were more likely to produce gold-enriched porphyry systems. This is because highly oxidised magmas transport gold and copper more readily than their reduced counterparts since sulphur is present as SO_2 rather than H_2S. Magmas containing H_2S tend to form immiscible sulphide liquids that scavenge gold, copper and other metals and retain them in the igneous source regime. Shoshonites are thus an especially favourable oxidised magma composition for the formation of gold rich porphyry copper-gold mineralisation. Such magmas are particularly common in the third pulse of magmatism, and Group 4 porphyries host the known key porphyry copper-gold deposits in the Macquarie Arc. Group 3 porphyries are less well endowed in gold and copper than those of the shoshonitic Group 4, although they have a similar signature to Andean host porphyries in Chile (Glen *et al.,* 2003).

Distribution of Cu & Au Mineralisation

The Late Ordovician to Early Silurian igneous complexes of the Macquarie Arc host a range of copper-gold and gold mineral occurrences and deposits (see Fig. 4), including both porphyry and epithermal styles.

The largest cluster and most economically significant are the *Cadia Valley* deposits (including *Cadia Hill, Cadia Quarry, Cadia East* and *Ridgeway*) described later in this paper, which are within the Molong Volcanic Belt (MVB). Other deposits of note in the MVB include the sub-economic, calc-alkaline (not shoshonitic) *Copper Hill* and *Cargo* porphyry prospects and the *Junction Reefs* iron-gold skarn. *Copper Hill* has a resource of 6.6 Mt @ 0.8% Cu, 0.8 g/t Au (Golden Cross Resources web site, 2004) within 34 Mt @ 0.54 g/t Au, 0.43% Cu, embraced in turn by a larger body of porphyry style mineralisation with grades of 0.1 to 0.15% Cu (Scott, 1978, Chivas and Nutter, 1975). *Cargo* (Richardson, 1976) comprises simple gold rich pyrite-chalcopyrite veins with a current resource of 3.7 Mt @ 1.24 g/t Au (Golden Cross Resources web site, 2004). *Junction Reefs* had an initial reserve of 1.4 Mt @ 4.1 g/t Au prior to mining (Overton, 1990; Gray *et al.,* 1995).

The less well exposed Junee-Narromine Volcanic Belt to the west, also hosts significant deposits and occurrences. These include the *Endeavour* porphyry copper-gold deposits of the Goonumbla District described in this paper (Heithersay *et al.,* 1990; Heithersay & Walshe, 1995; Lickfold *et al.,* 2003 and references cited therein), the high sulphidation *Peak Hill* gold deposit with 16 Mt @ 1.3 g/t Au (Alkane Exploration Ltd web site), the low sulphidation carbonate-base metal-gold *Cowal* or *Endeavour 42* (Miles & Brooker, 1998) deposit with a total reserve+resource of 111 Mt @ 1.13 g/t Au (Barrick Gold web site, 2004), including 66 Mt @ 1.5 g/t Au (McInnes *et al.,* 1998), the high sulphidation *Gidginbung* gold deposit at Temora (Thompson, *et al.,* 1986), which had pre-mining reserves of 4.5 Mt @ 2.5 g/t Au, 5.4 g/t Ag (Lindhorst & Cook, 1990) and the currently sub-economic *Marsden* porphyry prospect with 115 Mt @ 0.3 g/t Au, 0.5% Cu (Newcrest Mining).

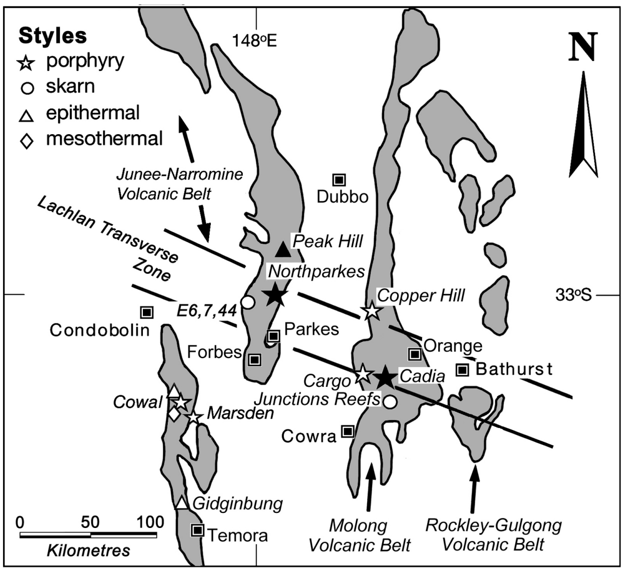


Figure 4: *Copper-gold mineral occurrences of the Macquarie Volcanic Arc* in the Eastern Subprovince of the Lachlan Orogen (refer to Fig. 2). The Junee-Narromine Volcanic Belt hosts the *Endeavour 22, 26, 27 & 48* porphyry copper-gold deposits at Northparkes; porphyry copper-gold mineralisation at *Marsden*; high-sulphidation epithermal gold mineralisation at *Peak Hill* and *Gidginbung*; intrusion-related gold-zinc mineralisation at *Lake Cowal*; and lead-zinc skarn deposits at *E6, E7 & E44*. The Molong Volcanic Belt hosts the *Cadia-Ridgeway* cluster of gold-copper deposits at Cadia and the *Copper Hill* and *Cargo* porphyry gold-copper deposits. Filled symbols = mines; outline symbols = prospects. The Lachlan Transverse Zone is a crustal linear feature that appears to have controlled Late Ordovician igneous complexes and also the distribution of the Late Ordovician porphyry copper-gold deposits (Glen and Walshe, 1999). *Based on information from Holliday et al., (2001), Wilson et al., (2003) and Lickfold et al., (2003).*

Table 1*: Published resources at the Newcrest Mining Cadia Valley Operations deposits*

Deposit	Mt of ore	Au (g/t)	Cu %	Contained Au (t)	Contained Cu (Mt)	Mined from
Cadia Hill						1997
Pre-mine total resource [1]	352	0.63	0.16	221.3	0.56	
Total resource, June 2003 [3]	260	0.7	0.16	180.4	0.42	
Ridgeway						2002
Pre-mine total resource [2]	54	2.5	0.77	132.6	0.42	
Total resource, June 2003 [3]	78	1.96	0.67	149.3	0.52	
Cadia Quarry						2001
Pre-mine total resource [2]	40	0.40	0.21	16.0	0.08	
Total resource, June 2003 [3]	50	0.40	0.23	21.7	0.11	
Cadia East – Open pit						Un-mined
Total resource, June 2004 [4]	300	0.46	0.37	133.7	1.11	
Cadia East – Underground						Un-mined
Total resource, June 2004 [4]	530	0.81	0.33	435.0	1.8	
Total Resource, June 2004	1210	0.75	0.32	905.4	3.89	

Total resource = Measured + Indicated + Inferred resource, calculated to the specifications of the Australian JORC Code for reporting of 'ore reserves'.
[1] Newcrest Mining Limited (1997); [2] Newcrest Mining Limited (2000); [3] Newcrest Mining Limited (2003); [4] Newcrest Mining Limited (2004).
Mt = Million tonnes; t = tonnes (1 Moz = 31.10348 tonnes); g/t = grams/tonne.

Although significant historical gold was mined in parts of the Rockley-Gulgong Volcanic Belt, no mineralisation of economic importance has been recorded recently.

The main porphyry copper-gold deposits and prospects associated with the Molong Volcanic Belt, as listed above, and a number of the key deposits in the Junee-Narromine Volcanic Belt, all fall within a broad NW- to WNW-trending structural corridor, the Lachlan Transverse Zone (Fig. 4) (Glen, *et al.,* 2003). This zone is a key arc-normal structure that can be recognised stretching across NSW from the current Pacific coastline to the western half of the state, where it marks the boundary between the Kanmantoo and Thompson Orogens. In its western sections it is marked by a series of WNW trending faults, while in the Eastern Lachlan Orogen it is defined by a corridor of WNW-trending folds and faults that disrupt the major folds and faults defining the orogen's regional grain. This structure has been active throughout the development of the Lachlan Orogen, from at least the Late Ordovician, and has influenced the partitioning of upper crustal extension and contractional deformation, the emplacement of igneous bodies and the distribution of copper and gold mineralisation (Glen and Walshe, 1999).

In the structurally restored Macquarie Volcanic Arc, the Cadia Intrusive Complex falls within, and is elongated parallel to, the Lachlan Transverse Zone (LTZ), as is the markedly elongate mineralised corridor defined by the deposits of the Cadia Valley, which are also individually elongated NW to WNW. The LTZ underwent (apparently repeated) dilation during the Ordovician, particularly near the termination of, or intersection with, arc parallel structures. It apparently established a regional differential stress regime with WNW $\sigma 1$ and NNE $\sigma 3$, which influenced the emplacement of NW to WNW elongate intrusives. As well as the Cadia Valley deposits, both Cargo and Copper Hill were developed within the zone, as are the Endeavour deposits in the Junee-Narromine Volcanic Belt, although the latter are not elongated parallel to the structure, but follow the grain of the orogen. Deposits such as Cowal, Marsden and Gidginbung are outside of the LTZ.

Cadia Valley Gold-Copper Deposits

Four porphyry gold-copper deposits have been delineated within the 7 km long Cadia-Ridgeway mineralised corridor, hosted by a suite of Late Ordovician shoshonitic intrusives and broadly coeval volcaniclastics and lavas, on the western margin of the Molong Volcanic Belt. These deposits are the Ridgeway, Cadia Hill, Cadia Quarry and Cadia East-Far East deposits, which together accounted for an original combined resource of 1210 Mt @ 0.75 g/t Au, 0.32% Cu, and a total of 905 tonnes of contained gold (Table 1).

Geological Setting

The Cadia Valley porphyry gold-copper deposits are hosted by the Late Ordovician to Early Silurian Cadia Intrusive Complex (CIC) and by the Late Ordovician Forest Reef Volcanics and underlying Weemalla Formation, towards the western margin of the Molong Volcanic Belt. The CIC is a product of magmatic pulse 3 of the Macquarie Arc (Fig. 5). The deposits and their hosts are in part discordantly overlain by siltstones and sandstones of the Silurian Waugoola Group and by a relatively thin layer of Tertiary basalt and gravel (Holliday *et al.,* 2002).

The *Weemalla Formation* is the lowest stratigraphic unit exposed in the Cadia district. It is at least 1000 m in thickness and comprises a fine grained unit of thinly laminated, carbonaceous to volcanic siltstones, with minor arenaceous volcanic beds (Holliday *et al.,* 2002).

The *Forest Reefs Volcanics* (FRV) conformably overlie, but are partly coeval with, the Weemalla Formation with a 40 to 50 m thick transitional contact comprising a gradual upwards coarsening of grain size from volcanic siltstones to lapilli volcaniclastics (Holliday *et al.,* 2002). Five lithofacies have been recognised within the FRV in the Cadia district (Wilson *et al.,* 2003), as follows:

i) Intermediate volcanic lithic conglomerates, breccias and sandstones, comprising the bulk of the FRV. At Ridgeway, this facies is composed of massive bands that are >50 m thick of intercalated volcanic lithic conglomerates to breccias, and bedded volcanic sandstone. Clasts in the coarse units are well rounded clinopyroxene- and hornblende-phyric basaltic to feldspar-phyric basaltic-andesites supported by volcanic sandstones of the same composition as the clasts. Intercalated with these bands are packages up to 100 m thick of plagioclase crystal rich volcanic sandstones that normally show graded bedding on scales of metres to tens of metres.

ii) Bedded calcareous volcanic sandstone, largely confined to the east and north where it occurs near the top of the FRV and has been altered to host both the Big Cadia and Little Cadia skarns.

iii) Laminated siliceous volcanic siltstone, which occurs in minor amounts in the upper part of the FRV on the eastern end of the district at Cadia East, where it stratigraphically overlies lithofacies 2.

iv) Massive basaltic to basaltic-andesite flows which occur throughout the district, but are more abundant to the east.

v) Basaltic to andesitic hypabyssal to sub-volcanic intrusions, locally termed pyroxene- or plagioclase-porphyries, depending upon the dominant phenocryst (Wilson *et al.,* 2003).

In the Ridgeway area, the FRV, particularly lithofacies 1, are "predominantly intermediate" in composition, characterised by feldspar- and hornblende-phyric clasts within the fragmental volcanic rocks. To the east of the Cadiangullong Fault (Figs. 5 and 6), at Cadia Hill and Cadia East, the volcaniclastics are more "intermediate to basic", with predominantly pyroxene- and lesser feldspar-phyric clasts. The relationship between these two volcaniclastic facies has not been established. However, the "predominantly intermediate" facies at Ridgeway, which immediately overlie the Weemalla Formation, are assumed to in turn be stratigraphically overlain by the "intermediate to basic" facies found to the east of the Cadiangullong Fault, where the Weemalla Formation is at a depth below the current limit of drilling (see Fig. 6) (Holliday *et al.,* 2002).

The subvolcanic intrusions and possible related extrusives of lithofacies 5 are more frequent in the upper part of the sequence to the east of the Cadiangullong Fault. At Cadia East and near Little Cadia, the local globular peperitic margins of these intrusives suggest they were emplaced as shallow sills and dykes in soft, unconsolidated, wet volcaniclastics and sediments of the Forest Reefs Volcanics (Wilson *et al.,* 2003; Ian Tedder, Newcrest Mining, pers. comm., 2004). These intrusions, which include pyroxene-

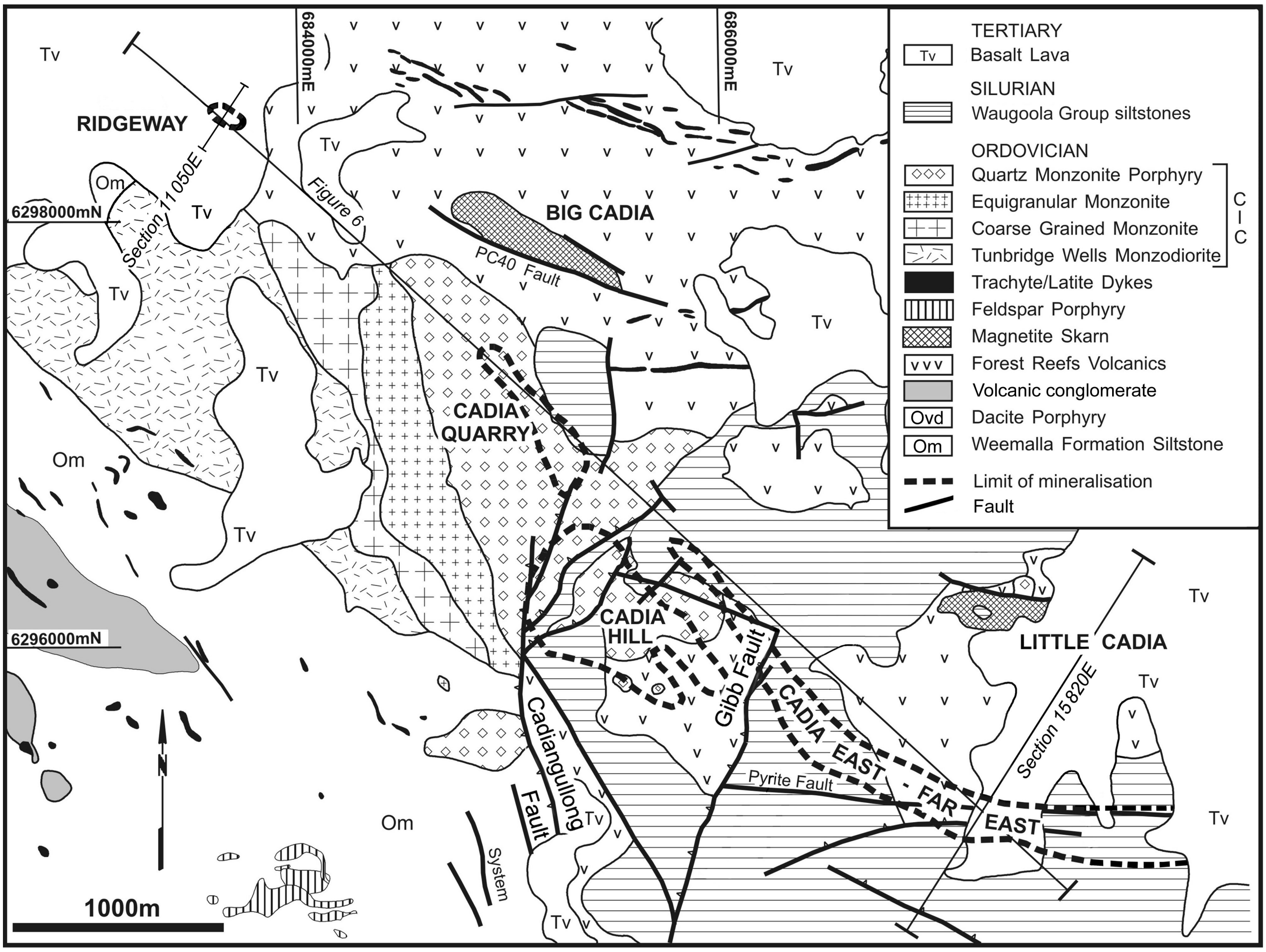


Figure 5: ***Geology of the Cadia-Ridgeway district*** and location of the principal zones of porphyry- and skarn-related gold-copper mineralisation. The locations of sections 11 050E at Ridgeway, 15 820E at Cadia East and the longitudinal section in Figure 6 are also shown. Abbreviations: CIC = Cadia Intrusive Complex. *Modified from Tedder et al., (2001), with information from Holliday et al. (2002) and Wilson et al., (2003).*

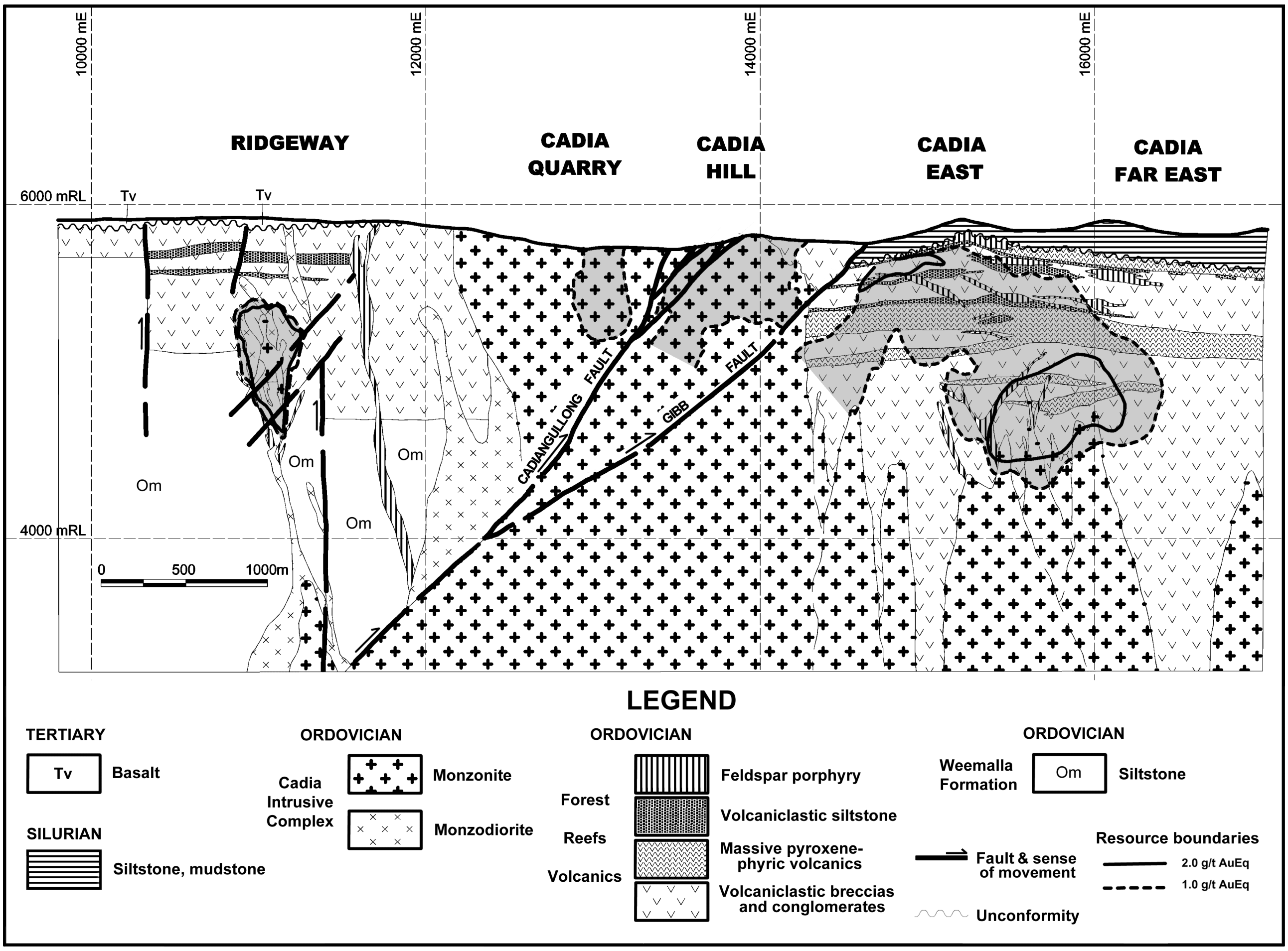


Figure 6: ***Schematic geological long section of the Cadia-Ridgeway mineralised corridor*** showing projected ore deposit outlines. See Fig. 5 for location. Note that the lithologies of the Forest Range Volcanics differentiated on this figure are subdivided differently to lithofacies units 1 to 5 described in the text. *Modified from Tedder et al., (2001).*

phyric basalt to basaltic andesite dykes and younger plagioclase-phyric andesite dykes, cut all Ordovician lithologies in the Cadia district with the exception of the Late Ordovician Cadia Igneous Complex and the Silurian cover sequence (Holliday *et al.,* 2002).

Lithofacies 2 is high in the volcaniclastic suite to the east of the Cadiangullong Fault, where it is a carbonate-rich, sandy volcaniclastic that marks the upper limit of the pyroxene-phyric suite and is host to the Big Cadia and Little Cadia gold-copper-hematite-magnetite skarns. Fauna from these carbonates have yielded similar palaeontological ages to the host Weemalla Formation at Junction Reefs, 20 km south. This has been taken to imply that the Weemalla Formation may in part be a distal lateral facies equivalent of the Forest Reef Volcanics (Holliday *et al.,* 2002).

The unconformably overlying Silurian *Waugoola Group* is predominantly composed of dark grey to green, fine-grained siltstones with wispy bedding laminations, subunits of fine grained, light grey quartz sandstone and a pink crinoidal limestone band with latest Llandovery age fauna. It is at least 200 m thick at Cadia East, thickening to the east. The base of the unit is marked by a one to two metre thick calc-rudite composed of coral fragments and volcanic grit. To the north, the sequence is covered by 50 to 80 m of *middle Miocene basalts*, comprising at least two layers. To the south, at a lower elevation, *Tertiary gravels* predominate (Packham *et al.,* 1999; Holliday *et al.,* 2002).

The *Cadia Intrusive Complex* (CIC) occurs as a NW- to WNW-elongated, 3x1.5 km, composite stock which comprises the mafic Tunbridge Wells Diorite in its western end, while phases of the Cadia Hill Monzonite occupying the remainder of the complex. There is a strong compositional zonation within the complex, ranging from pre-mineralisation monzodiorite, diorite and minor gabbro to the west, to coarsely orthoclase- and plagioclase-phyric quartz monzonite porphyry at the eastern extremity. The boss of quartz monzonite at Cadia Hill, the monzodiorite and monzonite encountered at depth in drilling on the eastern end of Cadia East and at Ridgeway to the west (described below), are petrographically and compositionally identical to the exposed CIC, while a swarm of latite/trachyte dykes to the north of the main exposed CIC are believed to be differentiates of the CIC. All of these observations have been taken to indicate the presence of an extensive magma chamber at depth (Holliday *et al.,* 2002, Wilson, *et al.,* 2003).

The Lachlan Transverse Zone (as described above) appears to have influenced the structural grain of the Cadia Valley district, as expressed by faulting and fracturing which trends NW to WNW, and generally dips steeply to the SW. This structural grain has facilitated and localised the emplacement and elongation of the CIC, as well as strongly influencing the mineralising event, as is evidenced by the dominant orientation of mineralised sheeted veins at Cadia Hill, Cadia Quarry and Cadia East. On a broader scale, the mineralised corridor of the Cadia Valley District, as defined by the distribution of alteration and mineralisation that envelopes the string of ore deposits from Ridgeway to Cadia East, also parallels to this same structural trend. In addition, post-mineral faults, such as the PC40 which offsets the Big Cadia skarn (Fig. 5) and the Purple Faults which offset the North Fault at Ridgeway (Fig. 7), have the same NW- to WNW-orientation. Extension, that was orthogonal to this trend, accompanied the formation of sheeted veins (Holliday *et al.,* 2002; Wilson, *et al.,* 2003).

An additional, north-south striking, west dipping, set of post-Silurian faults, including the Cadiangullong and Gibb Faults, with west-over-east reverse movement, have dismembered and juxtaposed different parts of the Cadia hydrothermal system and orebodies. Specifically, the Cadia Quarry, Cadia Hill and Cadia East deposits have been telescoped together (Fig. 6), while the lower sections of the Forest Reefs Volcanics have been faulted over upper lithofacies of the same sequence to the east. These faults represent the northern extremity of the regional Werribee Fault system (Holliday *et al.,* 2002, Wilson *et al.,* 2003).

Petrology & Geochemistry of the Cadia Intrusive Complex

Holliday *et al.,* (2002) reported on a petrographic and geochemical study of 53 drill core and outcrop samples collected from different parts of the Cadia Intrusive Complex (CIC). Additional descriptions from the Ridgeway intrusives were contributed from work by Wilson *et al.,* (2003).

These reports show that the mafic phases of the main CIC are composed of 1-4 mm laths of euhedral plagioclase, 2-3 mm calcic pyroxenes and magnetite, all of which are partially or wholly enclosed by larger alkali feldspar crystals. Apatite and magmatic titanite are also present. Magmatic biotite is usually altered to secondary chlorite, epidote and titanite, while amphibole has been replaced by pyroxene. There are petrographic characteristics indicating both pyroxene and plagioclase accumulation and modestly developed layering (Holliday *et al.,* 2002) .

With increasing differentiation of the magma and transition from the mafic to felsic phases, the pyroxene abundance decreases and magmatic amphibole appears, while the alkali feldspar:plagioclase ratio increases, but not systematically. The grain size of the rock decreases from coarse equigranular to medium grained, with the accompanying appearance of porphyritic orthoclase and lesser plagioclase in the monzonites and quartz-monzonites. The monzonites are salmon pink to green in hand specimen, with phenocrysts up to 20 mm across of pink orthoclase within a seriate textured groundmass of plagioclase and mafics. With the exception of thin (generally <200 mm thick) syenogranite-aplite dykes, there are no crosscutting relationships observed in the main CIC (Holliday *et al.,* 2002).

At the physically separated and smaller intrusive complex at Ridgeway, the earliest phase is an equigranular monzodiorite, comprising an equigranular mass of intergrown plagioclase, orthoclase and clinopyroxene, minor biotite and magnetite with accessory apatite and titanite. The monzodiorite at Ridgeway was succeeded by three groups of monzonite intrusions (early-, inter- and late-mineral), all of which are post-monzodiorite. The early-mineral monzonite is typically green to dark green, characterised by the presence of rare orthoclase phenocrysts in a fine grained, highly altered groundmass, although all primary igneous textures have been obliterated by intense actinolite-magnetite-biotite (calc-potassic) alteration. This phase hosts the most densely developed quartz vein stockwork and highest gold-copper grades. The inter- and late-mineral monzonites are compositionally and texturally similar, but are more fractionated than the early-mineral phase. They are pale pink to cream, with abundant plagioclase, and lesser orthoclase and chlorite altered clinopyroxene phenocrysts, in an orthoclase rich groundmass, with accessory and trace magnetite, biotite, quartz, apatite and zircon. In contrast to the main CIC, multiple intrusion and mineralising phases are indicated by the truncation of intrusive contacts and veins within the smaller Ridgeway intrusive (Wilson *et al.,* 2003).

Holliday *et al.,* (2002) considered that early magmatic biotite, replacement of pyroxene by amphibole and the occurrence of aplites, pegmatites and vapour cavities filled by interstitial melts are all consistent with rapid build up of water within the melt during differentiation.

Holliday *et al.,* (2002) reported that petrographic and textural evidence indicate that the CIC crystallised under strongly oxidising conditions. The more mafic units contain 1 to 2 modal percent early crystallised magnetite, while magmatic biotite has high Mg/(Mg+Fe) ratios of 0.59 to 0.65. They also noted that whole rock Fe_2O_3/FeO ratios are elevated in the range 1.0 to 1.5, which they say are typical of intermediate igneous complexes associated with porphyry style mineralisation.

A series of analyses reported by Holliday *et al.,* (2002) shows SiO_2 values in the CIC range from 48 to 65%, with the more mafic end monzodiorites and diorites varying from 48 to 54%, while the mafic monzonites extend from 52 to 54% and the monzonites contain 58 to 65% SiO_2. The CIC is characterised by high (3.5 to 6.5%) K_2O, falling within the shoshonite field on K_2O-SiO_2 diagrams, while the complex exhibits a well defined trend from trachybasalt to trachyte fields on the alkali-SiO_2 diagrams with 5 to 11% K_2O+Na_2O. In addition, the molecular K/Na ratio for all unaltered samples is >1, i.e. they are potassic (Müller and Groves, 1995). Holliday *et al.,* (2002) also note that the high alkalis to SiO_2 ratio allows the CIC to be defined as *alkalic* (after MacDonald and Katsura, 1964).

Holliday *et al.,* (2002) also stated that calculated CIPW normative proportions for the CIC range from olivine normative (quartz saturated) to quartz normative (silica over-saturated). The absence of a strongly alkaline or peralkaline character is confirmed by the petrographic absence of late interstitial magmatic quartz throughout the

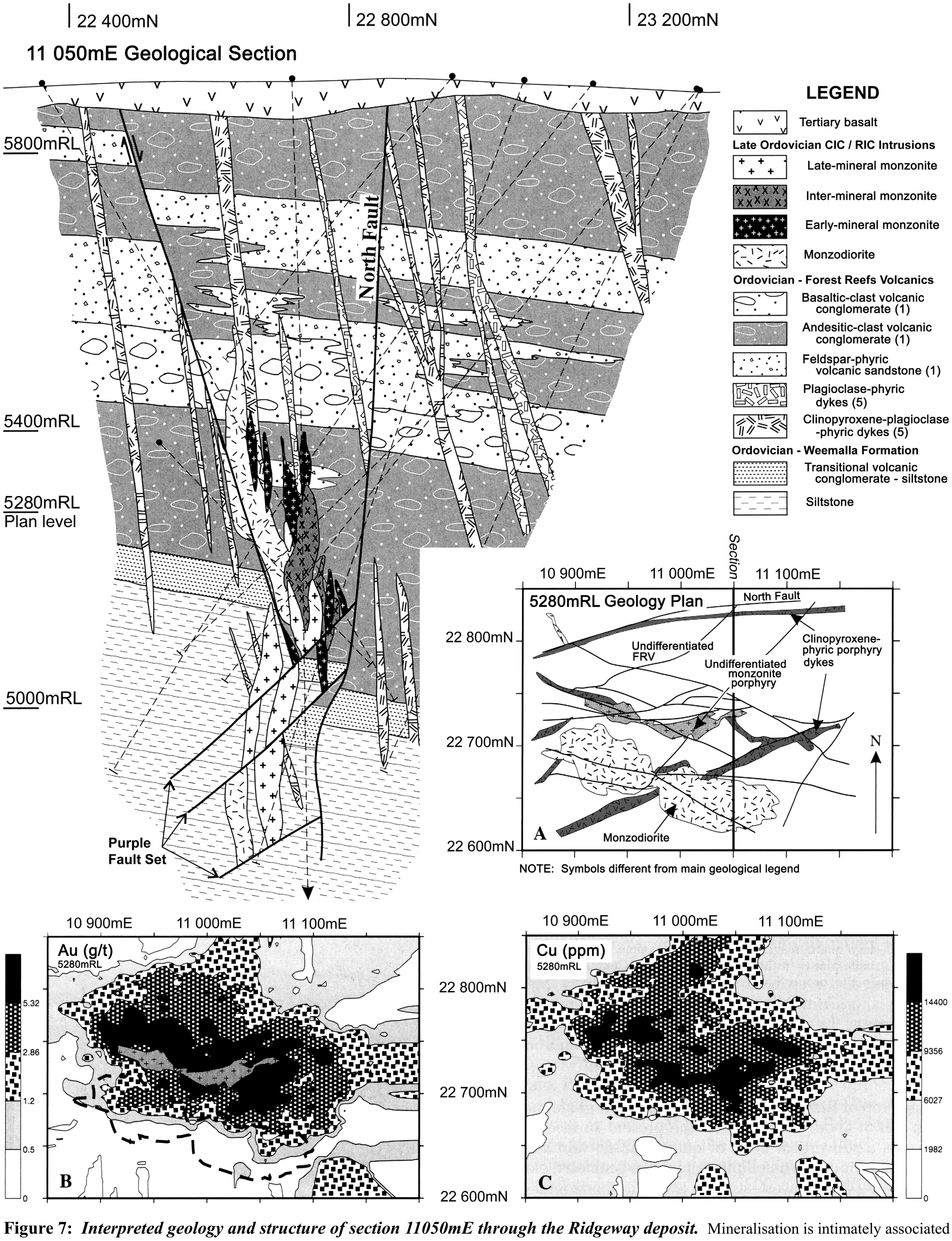


Figure 7: ***Interpreted geology and structure of section 11050mE through the Ridgeway deposit.*** Mineralisation is intimately associated with monzonite intrusions of the Ridgeway Intrusive Complex. Variations in stratigrahic thicknesses across the North Fault suggest it was in extension during deposition of at least part of the Forest Reefs Volcanics and may have influenced localisation of the Ridgeway Intrusive Complex. Numbers after the Forest Reefs Volcanics lithology in the legend refer to the lithofacies association discussed in the text. **Inset A -** ***Geology plan of the 5280mRL*** of the Ridgeway underground mine, showing the principal pyroxene porphyry dykes, the monzodiorite intrusion (pre- to early-mineral) and the un-differentiated monzonite porphyry complex (early- to late-mineral). The pyroxene porphyry dykes occupy ENE- and WNW-trending faults, the latter set possibly controlling the localisation of the monzodiorite and monzonite intrusions. **Inset B** - ***5280mRL gold grade*** - the monzodiorite intrusion (thick dashed line) is marginal to the main body of mineralisation, but the monzonite intrusive (grey polygon at the centre of the mineralisation) is partially coincident with the high-grade portion of the deposit. ***Inset C - 5280mRL copper grade*** - a close spatial association between Au, Cu and the monzonite intrusions is evident. The highest Au/Cu ratios are along the southern flank of the monzonite intrusion, where early-mineral monzonites have been logged. Abbreviations: FRV = Forest Reefs Volcanics. Contour intervals on insets B & C are at 75th, 90th, 95th, and 98th percentile values. *Modified from Wilson et al., 2003, Economic Geology, v98:8, p1642 Fig. 4 and p1645 Fig. 6.*

complex, the lack of "alkaline" chemical characteristics (eg. very high HFSE enrichments in elements such as Zr, Nb, etc.) and the absence of peralkaline minerals phases (eg. high Ti and/or sodic pyroxenes or amphiboles, etc.). Compositionally the complex conforms to the definition of shoshonite based on major element geochemistry and its modal mineralogy and textures. The CIC samples all fall within the shoshonite field on Ce/Yb-Ta/Yb and Th/Yb-Ta/Yb plots of Pierce (1982) and Müller *et al.,* (1992).

Mineralisation Styles & Deposits

The ore deposits and associated mineralisation in the Cadia Valley are spatially associated with high-K, alkalic affinity, shoshonitic, porphyritic monzonite to quartz-monzonite phases of the Cadia Igneous Complex (CIC). This mineralisation is interpreted to be genetically related to crystallisation of deeper portions of the CIC. The majority of the exposed porphyries of the complex and the adjacent wallrocks are hydrothermally altered and mineralised to some extent. This resultant alteration-mineralisation system defines a NW-trending mineralised corridor some 7 km long and up to 2 km in width, which has been intersected by drilling to a depth of more than 1600 m on the eastern end at Cadia East/Far East. The mineralised corridor embraces a string of elongate orebodies, both within the CIC and its hydrothermally altered wallrocks. The Ridgeway orebody to the NW is believed to have been emplaced at the deepest level in the porphyry system, and Cadia East, which is mainly in the wall rock of the CIC, at the shallowest (Holliday *et al.,* 2002).

Holliday *et al.,* (2002) have described six variations in the occurrence of ore and mineralisation within the Cadia-Ridgeway mineralised corridor, (Figs. 5 & 6) listed below from the deepest formed in the intrusive-hydrothermal system to the shallowest and from predominantly intrusion-hosted to predominantly wall rock volcanic-hosted:

i) intrusion- and wallrock volcanic-hosted stockwork quartz vein mineralisation at *Ridgeway,* closely associated with a separate intrusive plug of the CIC, developed at the base of the Forest Reefs Volcanics;
ii) intrusion-hosted, mainly sheeted quartz vein mineralisation at *Cadia Quarry*;
iii) intrusion- and wallrock volcanic-hosted, mainly sheeted quartz vein mineralisation at *Cadia Hill*;
iv) wallrock volcanic- and intrusion-hosted, mainly sheeted quartz vein mineralisation at *Cadia Far East (Cadia East Underground)*;
v) wallrock volcanic-hosted disseminated and sheeted quartz vein mineralisation at *Cadia East*; and
vi) iron rich skarns at *Big* and *Little Cadia,* hosted by wallrock calcareous volcanic sandstone at the top of the Forest Reefs Volcanics.

The following summarises the main ore deposits and corresponding mineralisation styles encountered to date within the Cadia-Ridgeway mineralised corridor.

Ridgeway

Ridgeway is a high grade gold-copper porphyry deposit. It is the deepest formed and highest grade of the four main deposits within the Cadia-Ridgeway mineralised corridor. It is also, at present, the most northwesterly of the economic resources that has been defined. Mineralisation and alteration are zoned around a small, vertically attenuated, alkalic intrusive complex of monzodioritic to quartz monzonitic composition that is part of the CIC, but some 500 m NW of exposures of the main CIC body, and concealed at a depth of 450 m below the present surface (Wilson *et al.,* 2003). At June 30 2003, the resource at Ridgeway amounted to 78 Mt @ 1.96 g/t Au, 0.67% Cu for a total of 149 tonnes (4.8 Moz) of contained gold (Newcrest Mining, 2003). The deposit is currently in production as an underground, sub-level cave mine.

Mineralisation and alteration at Ridgeway are hosted both by the intrusive complex and by the surrounding volcanics of the Forest Reefs Volcanics, at and just above, the contact with the underlying Weemalla Formation (Fig.7). Of the five main lithofacies of the Forest Reefs Volcanics, only lithofacies 1, 4 and 5 are represented at Ridgeway (described in *"Geological Setting"* above). Of these, lithofacies 1 is dominant, comprising massive bands that are >50 m thick of intercalated volcanic lithic conglomerates to breccias, and bedded volcanic sandstone. Clasts in the coarse units are well-rounded, clinopyroxene- and hornblende-phyric basaltic, to distinctly feldspar-phyric basaltic-andesites. They are supported by volcanic sandstones of the same composition as the clasts. Intercalated with these bands are packages up to 100 m thick of plagioclase, crystal-rich volcanic sandstones that may locally, but not commonly, show graded bedding on scales of metres to tens of metres. Lithofacies 4 is only a minor component at Ridgeway, where it comprises clinopyroxene-phyric basaltic to basaltic andesite flows. Lithofacies 5 is represented by a series of steeply north to NE dipping clinopyroxene-phyric basaltic to plagioclase-phyric andesitic dykes (Wilson *et al.,* 2003).

The Ridgeway Intrusive Complex is physically separated from, but is petrographically and compositionally identical to, and is believed to be connected at depth to, the main Cadia Igneous Complex (CIC). The top of the monzodioritic to monzonitic Ridgeway Intrusive Complex is 450 m below the present day surface. It comprises a thin, subvertical composite pipe, with a vertical extent in excess of 1 km, similar in size to those at Northparkes (described later in this paper). The earliest phase is an equigranular monzodiorite (described in the petrography section above) occurring as a WNW elongated, steep north dipping, 200x50x500 m body with an elliptical cross section, located on the southern margin of the Ridgeway orebody. In detail it occurs as two lobes, cut by the mineralisation, and is interpreted to be pre-mineral (Wilson *et al.,* 2003).

The main mineralisation at Ridgeway is spatially related to three groups of monzonite intrusions (early-, inter- and late-mineral), all of which are post-monzodiorite. They form an irregularly shaped composite plug with dimensions of 70x100x600, immediately to the north of the monzodiorite. The individual bodies of the composite mass having dimensions from metres to tens of metres horizontally and up to 200 m vertically. Multiple intrusion and mineralising phases are indicated by truncation of contacts and veins (Wilson *et al.,* 2003).

The most significant structure in the deposit area is the east to ENE trending, steeply south-dipping, North Fault, which appears to have been active during deposition of the Forest Reefs Volcanics and during intrusion. It bounds the northern margin of the orebody, although only minimal offset of the alteration envelope is indicated. Another fault set orientated NW to WNW and SW dipping, truncates both mineralisation and the intrusives of the Ridgeway Igneous Complex (Wilson *et al.,* 2003).

The top of the Ridgeway deposit (as defined by the 0.2 g/t Au cut-off) is some 500 m below the current surface. It takes the form of a subvertical, pipe like, quartz-sulphide vein stockwork body, with a WNW elongated axis and an elliptical 150x250 m horizontal shape which persists over a vertical interval of more than 600 m. Distinct styles of veining and alteration are related to each of the three monzonitic intrusive phases of the igneous complex. The metal grades and intensity of alteration decrease from the early- to the late-mineral phases of the intrusive (Wilson *et al.,* 2003).

Early-mineral stage intrusion is accompanied by intense actinolite-magnetite-biotite (calc-potassic) alteration and up to four stages of high grade quartz-magnetite-sulphide veins, all of which contain abundant magnetite, actinolite and bornite with variable amounts of chlorite, biotite, chalcopyrite, pyrite, quartz and orthoclase. Bornite, which is the most abundant sulphide, correlates closely with gold. Magnetite dominates in the earliest vein stage, while in the last, chalcopyrite becomes more important. Some of these veins persist for up to 350 m outwards from the Ridgeway Igneous Complex (Wilson *et al.,* 2003).

Moderate- to weak-intensity potassic alteration as orthoclase-biotite ± magnetite accompanies both the inter- and late-mineral intrusions and is associated with chalcopyrite- and pyrite-rich quartz-orthoclase veining. The veining and alteration accompanying the inter-mineral phase intrusives is referred to as transitional-stage veining and transitional-stage alteration respectively. Transitional-stage alteration assemblages are characterised by orthoclase, biotite (mostly retrograde altered to chlorite) and magnetite with minor quartz, titanite and apatite. The transitional-stage veining occurs as up to 4 styles which contain variable amounts of magnetite, chalcopyrite and pyrite with quartz and orthoclase, while bornite is rare to absent. The late-mineral monzonite intrusives is accompanied by weak late-stage alteration, occurring as weak pervasive potassic (orthoclase) development around late-stage veins, and chlorite alteration of mafic components of the monzonite. The late-stage veins are characterised by pyrite ± chalcopyrite with fluorite, but no bornite or actinolite, and gangue progressing from quartz to sericite to chlorite-calcite from early to late phases (Wilson *et al.,* 2003).

Three discrete and partially zoned hydrothermal alteration suites are found on the periphery of the Ridgeway deposit, namely: i) an inner propylitic; ii) an outer propylitic; and iii) a sodic assemblage. These are peripheral to, and locally overprint, the potassic phase. Peripheral veins are characterised by epidote, prehnite, quartz and calcite in varying proportions with varying sulphides, depending on the position within the deposit. Some of the outer veins, up to 200 m beyond the inner propylitic zone, carry chlorite/calcite-sphalerite-chalcopyrite ± galena. Phyllic alteration is only found on the margins of late stage faults (Wilson *et al.,* 2003).

Cadia Hill

Cadia Hill was the first of the deposits to be mined on a large scale as part of the present Newcrest Mining Ltd Cadia Valley Operations. The ore grade mineralisation is predominantly hosted by a quartz monzonite porphyry phase of the CIC, although a small portion cuts a roof pendant of Forest Reefs Volcanics at the eastern end of the deposit (Holliday *et al.,* 2002). The total pre-mine resource at Cadia Hill was 352 Mt @ 0.63 g/t Au, 0.16% Cu for 221.3 tonnes of contained gold (Newcrest Mining, 1997). In June 2003, the remaining total measured + indicated + inferred resource was 260 Mt @ 0.70 g/t Au, 0.16% Cu for 180 tonnes of contained gold (Newcrest Mining, 2003). The deposit is currently being exploited via a large tonnage low grade open pit mine.

The Cadia Hill deposit is bounded on three sides by post-mineral faulting. To the west, a west-dipping reverse imbricate system, the Cadiangullong Fault (Figs. 5, 6 and 8), which encloses slivers of the Silurian Waugoola Group, truncates the ore and juxtaposes a block of quartz monzonite porphyry hosting the Cadia Quarry deposit over the Cadia Hill mineralisation. On its eastern margin, the quartz monzonite porphyry hosting the Cadia Hill deposit is thrust over Forest Reefs Volcanics carrying the Cadia East mineralisation, by the west dipping reverse Gibb Fault (Figs. 5 and 6) which has a displacement of at least 300 m. The northern side of the deposit is bounded by a NE-striking, steeply NW-dipping fault (Fig. 8). Fault dislocation is also evident within the deposit where disparate ore zones with varying metal ratios, grades and vein densities are juxtaposed across fault planes (Holliday *et al.,* 2002).

Mineralisation is present as chalcopyrite, native gold, lesser pyrite and bornite, which are disseminated within and immediately adjacent to the quartz-carbonate veins of a low density sheeted vein array (Fig. 8). This array forms a broadly tabular envelope that is approximately 300 m wide, dips SW at around 60° and strikes NW. The sheeted vein envelope persists over a length of some 900 m and to a depth of at least 800 m beneath the surface, although grades decrease below 600 m (Holliday *et al.,* 2002). Within the envelope, veins range from a millimetre to 10 centimetres in width with densities from 2 to 10 per metre, but locally in the core of the deposit may exceed 15 per metre (Newcrest Mining presentation). Gold grades can be broadly correlated with the intensity of chalcopyrite bearing veins, irrespective of the host lithology. In general, the higher copper grades are found in the core of the deposit where chalcopyrite dominates over pyrite. This zone is flanked by decreasing chalcopyrite:pyrite ratios, both outwards from the core and down dip/plunge. The chalcopyrite:pyrite ratio, however increases up dip and to the NW where zones carrying bornite become increasingly abundant. A higher grade copper zone is localised at the northwestern end of the deposit, with grades of up to 0.5% Cu being encountered in an interval where bornite and chalcopyrite occur as minor infill in a crackle brecciated quartz monzonite porphyry (Holliday *et al.,* 2002).

A pervasive, rarely texture destructive, propylitic alteration comprising a chlorite, albite, epidote and calcite assemblage is the most widespread overprint. The quartz monzonite porphyry has a pervasive pink colouration due to disseminated, sub-microscopic, hematite in both feldspar phenocrysts and in the groundmass, a feature common to the CIC in the Cadia Valley deposits. Potassic (orthoclase) alteration is manifested as narrow selvages to chalcopyrite and bornite bearing quartz veins and as ragged patches partially replacing some plagioclase phenocrysts and overprinting the earlier albite and chlorite phase and its associated magnetite veining. In addition, late- to post-mineral, milled, jigsaw-fit breccias have chlorite altered rock flour cement. Sericite-pyrite alteration, with localised sphalerite and galena is also found, in association with NW-striking late mineral faults, while weakly developed post-mineral crackle breccias have a laumontite-epidote-calcite-orthoclase ± fluorite cement and are found throughout the deposit (Holliday *et al.,* 2002).

Cadia Quarry

The Cadia Quarry deposit (now known as ***Cadia Extended***) lies in the hangingwall block of the west-dipping Cadiangullong reverse fault (Figs. 5 and 6) and is located immediately to the NW of the Cadia Hill pit. It is almost entirely hosted by quartz monzonite porphyry (Holliday *et al.,* 2002). The total pre-mine resource at Cadia Quarry was 40 Mt @ 0.40 g/t Au, 0.21% Cu for 16.0 tonnes of contained gold (Newcrest Mining, 2000). In June 2003 the remaining total measured + indicated + inferred resource was 50 Mt @ 0.40 g/t Au, 0.23% Cu for 21.8 tonnes of contained gold (Newcrest Mining, 2003). The deposit is currently being exploited via a high tonnage, low grade open pit, which is an extension of the Cadia Hill mine.

Mineralisation and alteration is largely similar to that described above for Cadia Hill. However, in addition to the sheeted quartz-carbonate vein mineralisation, there are locally high copper-molybdenum zones containing coarse grained chalcopyrite and molybdenite, which are intergrown with quartz-orthoclase-biotite-calcite-pyrite as cement in open space pegmatitic breccias within the host quartz monzonite porphyry. The breccias follow the NW- to NNW-structural grain of the Cadia district and take the form of elongate pipes/dykes up to 150 m long and 10 m wide, which persist to depths of as much as 500 m. The clasts within the breccias are strongly sericite altered quartz monzonite porphyry, while the pegmatitic textures and the mineralogy are suggestive of high temperature formation (Holliday *et al.,* 2002).

The Cadia Quarry mineralisation has a grade boundary to the west, where its tenor decreases to that of a geochemical anomaly which persists under cover for some 2 km to the west, to beyond the Ridgeway deposit. To the north, the deposit is terminated at the steep intrusive contact between the host quartz monzonite porphyry and the Forest Reefs Volcanics. This contact contains some localised, weakly gold-copper mineralised epidote-garnet-magnetite skarn. To the south, copper and gold grades gradually decrease as the quartz monzonite porphyry grades into a more mafic phase of the CIC (Holliday *et al.,* 2002).

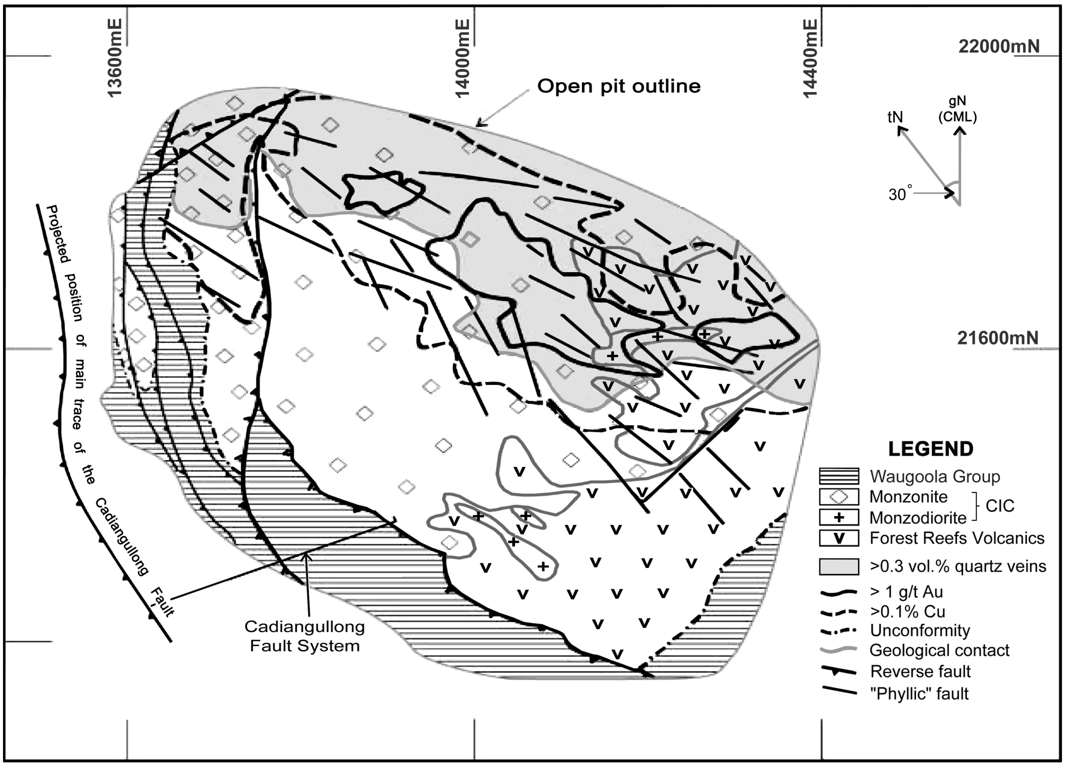


Figure 8: ***Simplified geology, grade, quartz vein intensity and structure of the Cadia Hill deposit,*** level plan at 5715mRL. Abbreviation: CIC = Cadia Intrusive Complex *Modified from Holliday et al., (2002).*

Cadia East & Cadia Far East

The Cadia East deposit and its continuation, Cadia Far East, extend SE to ESE over an interval of approximately 1.7 km in length, 300 m in width and at least 1600 m down dip, plunging to the SE. Inferred open pit resources at Cadia East in June 2004 were 300 Mt @ 0.46 g/t Au, 0.37% Cu for 134 tonnes of contained gold (Newcrest Mining, 2004). Cadia Far East (now Cadia East Underground) has a resource of 530 Mt @ 0.81 g/t Au, 0.33% Cu for 435 tonnes of contained gold (Newcrest Mining, 2004).

The composite deposit is hosted by a more than 2000 m thick, shallow to flat dipping sequence of the Forest Reefs Volcanics, comprising predominantly volcaniclastic breccias and conglomerates of lithofacies 1 (see *"Geological Setting"* above) and lesser pyroxene- and feldspar-phyric lavas of lithofacies 4. Minor monzodiorite to quartz monzonite stocks and dykes belonging to the CIC intrude these Forest Reefs Volcanics units, and in part host mineralisation at depth in Cadia Far East. The Ordovician rocks and the mineralisation are unconformably overlain by up to 200 m of the Silurian Waugoola Group (Holliday *et al.,* 2002).

Mineralisation occurs a two broad, overlapping zones, namely:

i) An upper zone of disseminated, copper dominant mineralisation within a 200 to 300 m thick, shallow dipping, unit of volcaniclastic breccia (lithofacies 1) where it is sandwiched between two coherent porphyritic volcanic bands (of lithofacies 4) - an upper feldspar porphyry and a lower pyroxene-phyric unit. This zone comprises the shallow western sections of the Cadia East open pit deposit. Within this zone, disseminated chalcopyrite-bornite forms a core zone, capped by chalcopyrite-pyrite mineralisation (Holliday *et al.,* 2002).

ii) A deeper, central gold rich zone with sheeted veins, which is localised around a core of steeply dipping sheeted quartz-calcite-bornite-chalcopyrite-molybdenite ± covellite ± magnetite veins. The highest grade gold is associated with the widest bornite-bearing veins, where native gold is commonly intergrown with bornite (Holliday *et al.,* 2002).

Elevated molybdenite levels are mostly associated with the upper disseminated copper zone, although molybdenum continues below this zone at depth, where it also occurs along both the hangingwall and footwall of the gold rich sheeted vein interval (Holliday *et al.,* 2002).

Three alteration styles and zones were recognised by Holliday *et al.,* (2002), as follows:

i) Intense silica-albite ± orthoclase ± tourmaline, with a late sericite-carbonate overprint. Pyrite and minor fluorite are observed, although no magnetite remains.

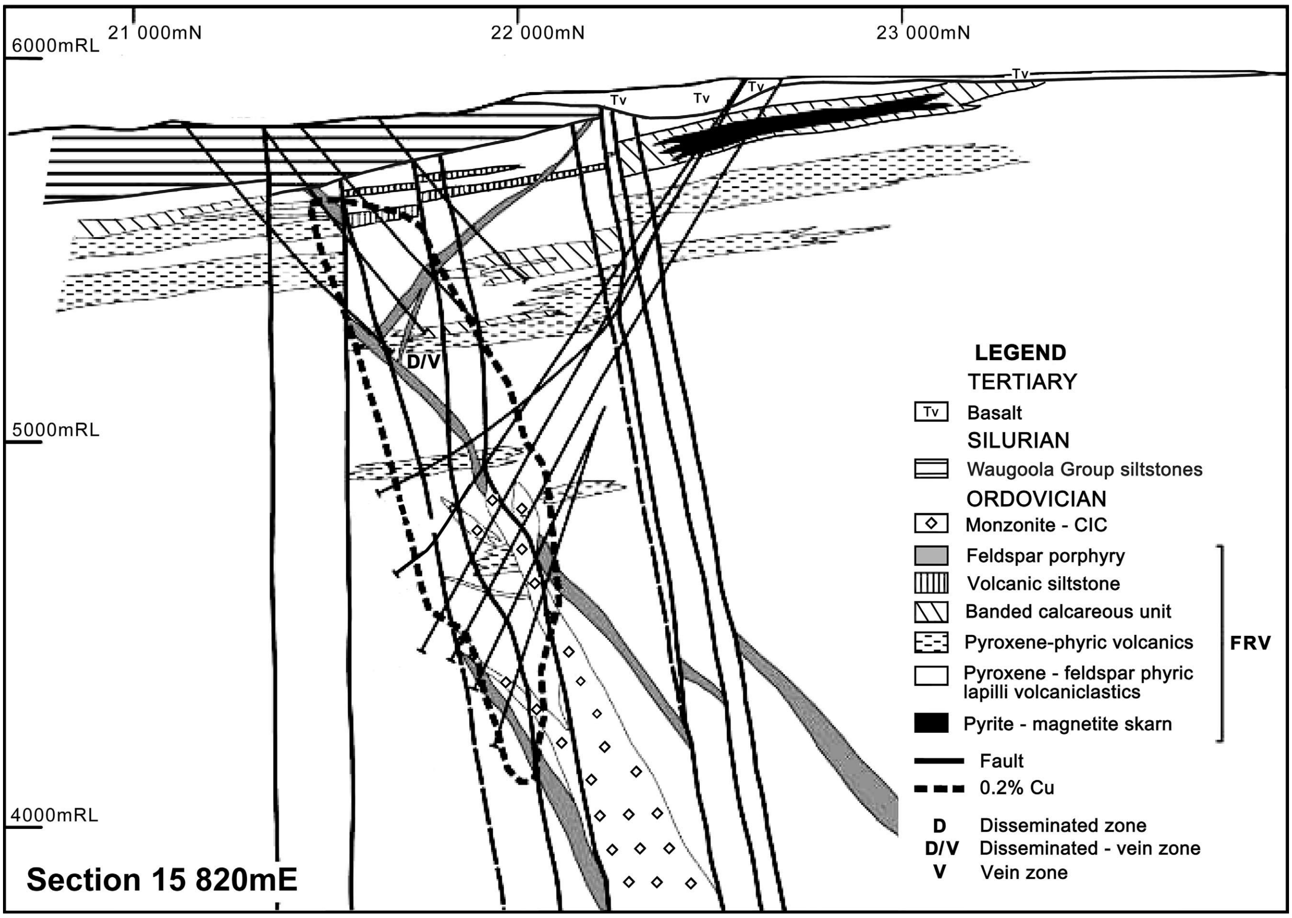


Figure 9: ***Interpreted geology and structure of the Cadia East deposit*** along section 15 820mE (see Fig. 5). The relative location of disseminated and vein-hosted copper mineralisation is also shown on the diagram. Abbreviation: CIC = Cadia Intrusive Complex, FRV = Forest Reefs Volcanics. *From Holliday et al., (2002).*

This zone forms a layer at shallower depths, that is semi-conformable with the Forest Reefs Volcanics stratigraphy, replacing more permeable volcaniclastic breccias. It is mainly the product of late sericite-carbonate and tourmaline overprinting of zone 2 type alteration and the destruction of magnetite. The upper disseminated copper rich mineralisation falls within this alteration zone.

ii) Moderate to intense, grey, silica-albite-orthoclase flooding with minor hematite staining. Hydrothermal magnetite is common and chlorite occurs as a late overprint. This style of alteration grades into an outer propylitic zone of chlorite-epidote ± actinolite ± calcite.

iii) Pervasive potassic alteration comprising albite-orthoclase-quartz-biotite-actinolite-epidote-magnetite with sulphides. Late chlorite is an overprint on biotite. Albite replaces magmatic plagioclase, while orthoclase occurs as an alteration selvage to mineralised veins. This zone occurs at greater depths, and overprints and passes out and upward into zone 2. The mineralised sheeted veins, particularly the gold rich zone, are accompanied by the most intense developments of this potassic zone, although the sheeted veins also persist into zone 2 alteration.

Cadia East and Cadia Far East have been dislocated by at least three significant fault zones. Reverse movement on the major NE-trending, west dipping, Gibb Fault truncates the mineralised system and juxtaposes the Cadia Hill deposit over the Cadia East mineralisation on its western margin. A second, un-named, east trending reverse fault with a steep north dip occurs around 1 km to the east of the Gibb Fault and has displaced mineralisation by at least 100 m. A third significant fault is the east trending Pyrite Fault Zone which lies parallel to the main mineralisation direction at Cadia Far East, and has both syn- and post-mineralisation movement as indicated by milled clasts of pyrite, quartz and carbonate within a locally sericitic fault gouge (Holliday *et al.,* 2002).

Cadia Skarns

Two gold-copper-hematite-magnetite skarns, Big Cadia (also previously known as Iron Duke) and Little Cadia, have long been known in the Cadia Valley. Prior to the discovery of Cadia Hill, Iron Duke (Big Cadia) had been by far the largest producer in the district, having yielded more than 100 000 t of secondary copper ore @ 5 to 7% Cu from underground operations from 1882 to 1898 and 1905 and 1917, and 1.5 Mt of iron ore @ approximately 50% Fe from 1918 to 1929 and 1941-1943 (Welsh, 1975). Based on drilling during the 1960's, there is an estimated potential of 30 Mt @ 0.4 g/t Au, 0.5% Cu for 12 tonnes of contained gold at Big Cadia and 8 Mt @ 0.3 g/t Au, 0.4% Cu for 2.4 tonnes of contained gold at Little Cadia (Holliday *et al.,* 2002).

Big Cadia lies about 100 m north of the drill intersected contact of CIC monzonite and is some 200 m north of Cadia Quarry, while Little Cadia is some 800 m north of the Cadia Far East deposit (Holliday *et al.,* 2002) and 2 km SE of Big Cadia (Holliday *et al.,* 2002). Both skarn zones are around 1000 m long, 250 m wide and average 40 m thick, although in the centre of Big Cadia it reaches 70 m and is 50 to 85 m thick at Little Cadia. Weathering has resulted in the oxidation and slight secondary enrichment of each of the skarns (Welsh, 1975; Holliday *et al.,* 2002). Primary gold-copper mineralisation at both occurs in association with the hematite-magnetite skarn that formed in the impure bedded calcareous volcanic sandstones of lithofacies 2, at the top of the Forest Reefs Volcanics (see *"Geological Setting"* above). Elevated copper and gold grades are found in both the skarn and in a surrounding alteration envelope of epidote-quartz-actinolite-chlorite-sericite-calcite-rutile imposed on volcanic conglomerates of the underlying lithofacies 1 of the Forest Reefs Volcanics. Where best developed, the skarn comprises intergrowths of fine to coarse bladed hematite (partially replaced by magnetite) with interstitial calcite ± chlorite ± pyrite/chalcopyrite. Green (1999) presented mineralogic and isotopic evidence that suggested fluids infiltrated northwards from the CIC, along the volcaniclastic unit, to form Big Cadia. At Little Cadia many drill holes have intersected monzonite possibly belonging to the CIC below the skarn (Holliday *et al.,* 2002).

Endeavour Copper-Gold Deposits

Four economic porphyry copper-gold deposits have been delineated within the Goonumbla district, some 100 km WNW of Cadia. All lie within the Late Ordovician shoshonitic Goonumbla Igneous Complex of the Junee-Narromine Volcanic Belt and are the reserve base of the Northparkes mining operation (Figs. 2 and 4). They are the Endeavour 22, 26, 27 and 48 deposits, which together had a combined pre-production resource of 130.6 Mt @ 1.1% Cu, 0.5 g/t Au. Each is centred on a separate narrow, pipe-like shoshonitic, quartz monzonite porphyry intrusive complex.

Geological Setting

The Goonumbla Igneous Complex, which hosts the Endeavour deposits, is part of the Ordovician to Early Silurian Junee-Narromine Volcanic Belt, a remnant of the Macquarie Volcanic Arc. The complex is divided into two parts (see references in Lickfold et al., 2003), both products of the third pulse of arc volcanism, namely the:

Goonumbla Volcanics, which are 2500 to 4000 m thick and comprise a Middle to Late Ordovician sequence of coherent basaltic andesitic to trachyandesitic volcanic rocks, including lavas and shallow sills with peperitic margins, volcaniclastic rocks of similar composition, and minor intercalated limestones. A monzodiorite intrusion cutting the lower sections of the Goonumbla Volcanics has been dated at 450.8 ± 4.2 Ma.

Wombin Volcanics, which are 700 to 1000 m thick and of Late Ordovician age, are typically dark red hematite-dusted glassy lavas, ignimbrites, polymictic volcanic breccias and other volcanic sediments, with less abundant porphyritic trachyandesitic and flow banded trachytic lavas.

Basement to the Goonumbla Igneous Complex occurs a short distance to the south and consists of the Nelungaloo Volcanics overlain by the Early Ordovician Yarrimbah

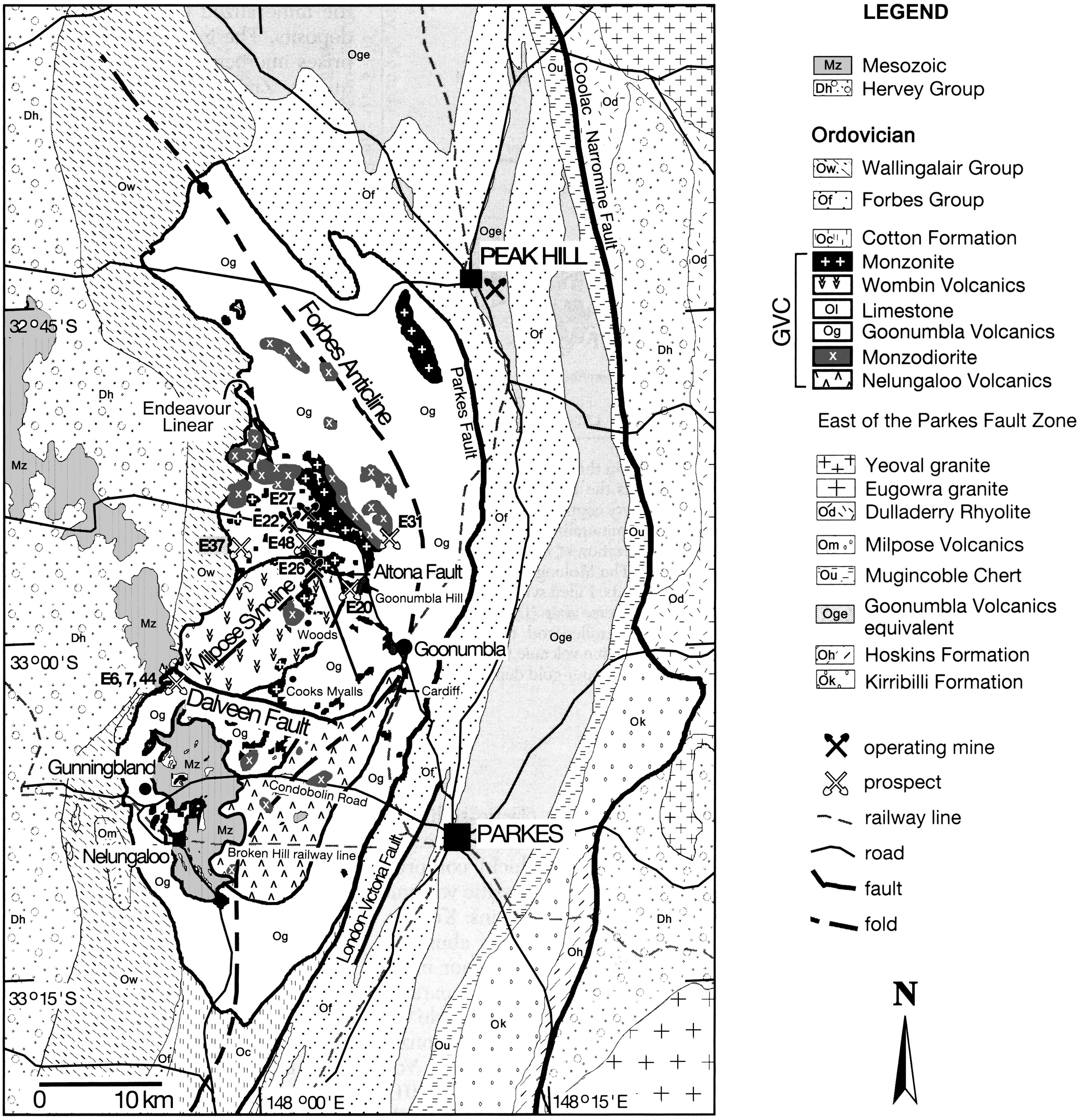


Figure 10: ***Local geology of the Goonumbla region.*** Abbreviations: GVC = Goonmubla Volcanic Complex; E22, E27, E28, E48, = Endeavour 22, 26, 27 and 48 respectively. *Modified from Lickfold et al., 2003, Economic Geology, v98:8, p1612 Fig. 5; (after Heithersay et al., 1990 and Heithersay and Walshe, 1995).*

Formation. These two units are manifestations of pulse 1 of arc magmatism and consist of andesitic lavas and volcaniclastic sedimentary rocks overlain by an upward fining-sequence of volcanic-derived conglomerate, sandstone and siltstone.

Lickfold *et al.,* (2003) quoted Simpson *et al.,* (2000) as having interpreted the Goonumbla and Wombin Volcanics as a 'several kilometre' thick subaqueous volcaniclastic apron that formed on the flanks of a shallow marine, to possibly sub-aerial, largely Late Ordovician strato-volcano. They argue that the ignimbrites and trachytic lavas indicate voluminous explosive eruptions and sector collapse on the subaerial sections of the volcano.

Both the Goonumbla and Wombin Volcanics have been intruded by numerous monzonite and quartz monzonite bodies, including the mineralised quartz monzonite porphyry pipes associated with the Endeavour ore deposits. These intrusions typically have a microcrystalline to aphanitic, dark red K feldspar + quartz groundmass. Dating of two samples of zircon from quartz monzonite porphyries 3 km apart (see Lickfold *et al.,* 2003 for details), yielded ages of 439.1 ± 4.5 Ma and 438.9 ± 4.7 Ma respectively, and dating of white mica alteration from Endeavour 26 returned an age of 439.2 ± 1.4 Ma (Perkins *et al.,* 1990), suggesting the quartz monzonite porphyries and alteration are essentially coeval. Other age data confirm this hypothesis (Lickfold *et al.,* 2003).

Pre- and syn-mineralisation brittle structures are interpreted to have localised the emplacement of intrusives, including the NNW-trending Endeavour Linear, as well as several other NW- and NE-trending fracture sets. Minor brittle movement on certain post quartz monzonite porphyry structures resulted in mostly small-scale disruption and some dislocation of the Endeavour mineralisation (Lickfold *et al.,* 2003).

Intrusives

Lickfold *et al.,* (2003) described the Endeavour deposits as being concentrically zoned, cylindrical bodies of quartz-sulphide stockwork veining centred on pipe-like, multiphase, quartz monzonite porphyry complexes. These intrusive bodies have lateral dimensions in the order of 50 to 150 m and a minimum vertical extent of 600 to 900 m (Fig. 11). The associated ore zones are up to 400 m in diameter based on a 0.5% Cu equivalent cutoff.

The quartz monzonite porphyry (QMP) intrusions in all four Endeavour deposits have ubiquitous phenocrysts of plagioclase and K feldspar, the former typically rimmed by fine-grained, anhedral K feldspar. Primary and secondary magnetite are found in all of the intrusive phases, where the primary phenocrysts are distinguished from the secondary specks by their large (>50 µm) euhedral shape. Similarly, both primary and secondary biotite are also present in all intrusive phases. Apatite, sphene and lesser zircon are accessory micro-phenocrysts in most intrusions (Lickfold *et al.,* 2003).

Lickfold *et al.,* (2003) have recognised and described at least nine intrusive phases within the complexes that are associated with the Endeavour deposits, divided into pre-, early-, syn-, late- and post-mineral intrusions, as detailed below.

Pre-mineral Intrusions - represented by an *equigranular monzodiorite* which is found at deeper than 1300 m beneath the surface at Endeavour 26 and in outcrop 500 to 1000 m to the north. It contains 10 to 20% mafic minerals, including, in decreasing order of abundance: augite, biotite, magnetite and hornblende. K feldspar is intergrown with quartz, while rarely, primary(?) anhydrite is interstitial to plagioclase phenocrysts. No primary disseminated sulphides or quartz-sulphide veins are recorded within this lithology, although sericitised clasts of it are found in the biotite quartz monzonite (Lickfold *et al.,* 2003).

Early-mineral Intrusions - which are *biotite quartz monzonites* (BQM) that are found adjacent to, or beneath, each of the four deposits at depths of more than 650 m below surface. They are commonly brick red in colour, medium- to coarse-grained, and equigranular to semi-porphyritic, with 1 to 2 mm euhedral plagioclase, K feldspar and biotite crystals, and interstitial, fine-grained granular subhedral K feldspar, anhedral quartz and minor (<1%) anhydrite. Blebs of disseminated bornite, chalcopyrite and rarely chalcocite are found within the BQM at Endeavour 26, 27 and 48, as are minor 2 to 5 mm thick, straight walled quartz-sulphide veins with K feldspar ± biotite selvages.

The first of the three varieties of QMP that comprise the 50 to 200 m diameter complexes central to each if the Endeavour deposits are the early, volumetrically minor *biotite quartz monzonite porphyry* (B–QMP) intrusions. They comprise un-crowded (20 to 30% phenocrysts) to crowded (50 to 60% phenocrysts) porphyritic rocks containing plagioclase, K feldspar, biotite, augite and magnetite phenocrysts in an aphanitic to fine-grained granular groundmass of K feldspar and quartz, typically with around 5% quartz. Fine (10 to 50 µm) copper sulphides (~1%) are disseminated through the groundmass with coarse (11 to 80 mm) clots of bornite and chalcopyrite and minor (usually <1%) bornite-quartz veins in some deposits.

Syn-mineral Intrusions - primarily represented by *K feldspar quartz monzonite porphyry* intrusions (K-QMP, the second of the QMP phases), ranging in colour from pale to salmon pink to dark orange-red. It occurs in the central parts of the QMP complexes at all four Endeavour deposits and is volumetrically the most abundant phase. The hydrothermal alteration zones and high-grade ore at each deposit are centred on, and most intensely developed within, the K-QMP and the immediately adjacent volcanic rocks. Disseminated sulphides generally account for about 2%, and stockwork veins 5 to 20%, of the volume of the K-QMP respectively, although the density of veining diminishes in intensity with distance from the outer margin of the intrusive. K-QMP intrusions have an uncrowded porphyritic texture with 30 to 40% phenocrysts of plagioclase, K feldspar and minor (<2%) magnetite +biotite +hornblende, set in a mainly aphanitic K feldspar-quartz groundmass.

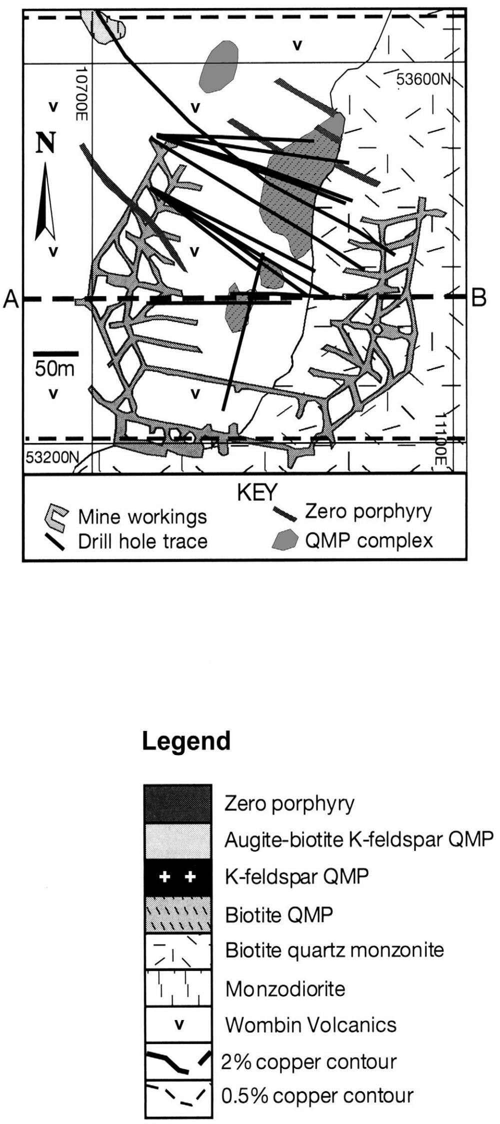
Late-mineral Intrusions - represented by dark orange-red *augite-biotite-K feldspar quartz monzonite porphyry* intrusions (KA-QMP, the third of the QMP phases) are found over much of the vertical extent of the four deposits, close to both the syn-mineral K-QMP and the following late-mineral B-QMP (see below). The KA-QMP intrusions are volumetrically the second most abundant intrusive phase and have a markedly diminished level of associated alteration and copper-gold mineralisation compared to the K-QMP. In addition, veins within K-QMP intrusions are truncated at the mutual contacts with KA-QMP. Certain of the KA-QMP examples contain xenoliths of volcanic rocks that have truncated quartz veins and clasts of the K-QMP phase. The KA-QMP intrusions are uncrowded to crowded porphyries with plagioclase, K feldspar and minor augite +biotite +magnetite +hornblende phenocrysts set in a fine-grained groundmass ranging from 10 to 50%, averaging 30 to 40% quartz. Bornite and chalcopyrite comprise up to 1% as disseminations through the groundmass. Mineralised quartz veins, with or without central K feldspar cores, locally comprise 5 to 10% of the KA-QMP in all four deposits.

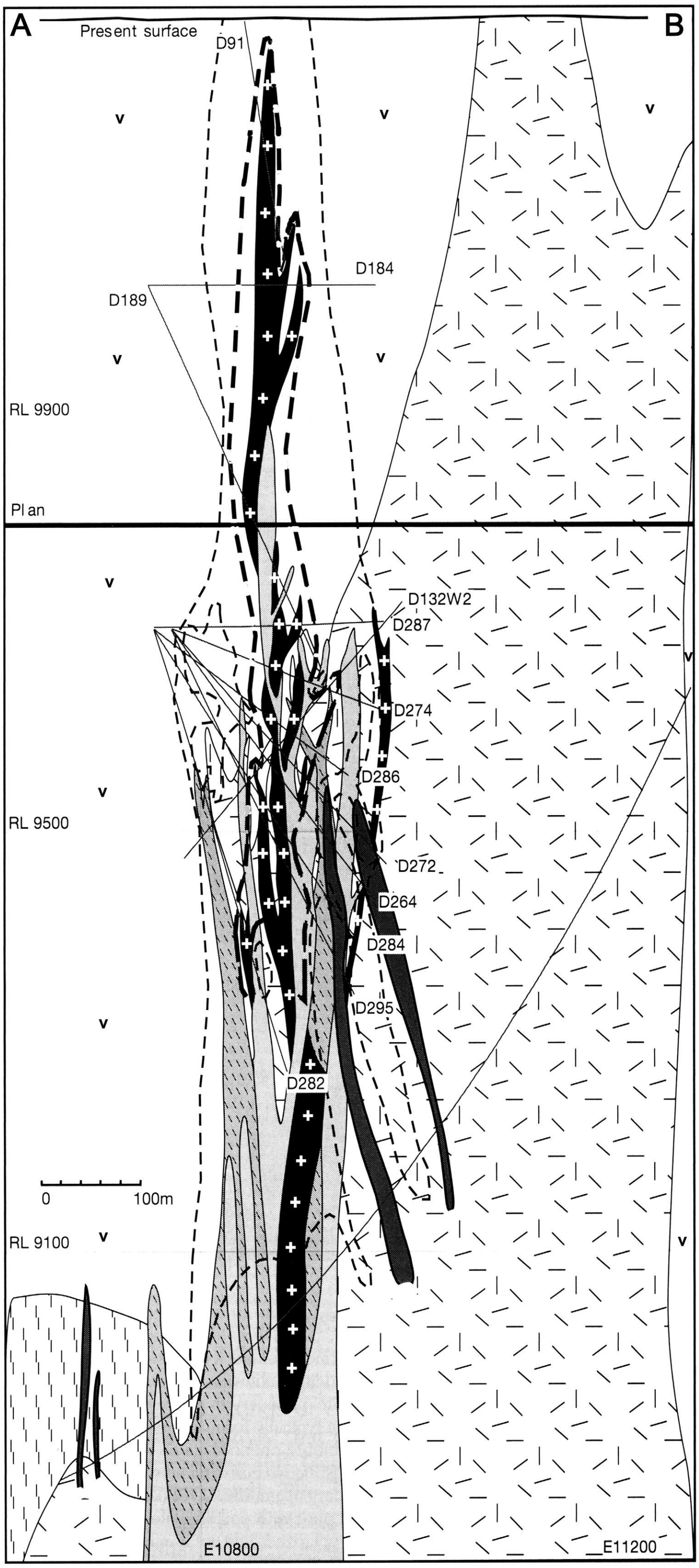
A second, but late-mineral phase of the *biotite quartz monzonite porphyry* (B-QMP), which followed the KA-QMP, is texturally and geochemically indistinguishable from the early-mineral intrusive with the same designation, although a late mineral timing is indicated by vein truncation where it cuts the K-QMP at Endeavour 22 and 26. At Endeavour 27 however, this latter intrusive phase is only found outside of the complex.

Post-mineral Intrusions - are present in volumetrically minor amounts and include dykes of *basaltic trachyandesite, mafic monzonite porphyry* and *basalt*. The most significant of these are the "Zero Porphyry" dykes, so named because of their very low ('zero') metal contents. These brownish-red, crowded (40 to 50%) porphyries contain K feldspar, augite +biotite +hornblende and anhydrite phenocrysts in an aphanitic groundmass of predominantly (~95%) K feldspar. Where trachyandesite dykes are present, they occur at the edges of the Zero Porphyries.

Several basaltic dykes around 1 m thick were emplaced at some of the deposits. The exact age of these dykes is unknown, although some may have intruded the porphyry complexes during the waning stages of volcanism associated with the Goonumbla Volcanic Complex: others may be Tertiary in age.

Figure 11: *Interpreted east-west section through the Endeavour 26 deposit at Northparkes.* *Modified from Lickfold et al., 2003, Economic Geology, v98:8, p1613 Fig. 6.*





Mineralisation & Alteration

Hydrothermal alteration and mineralisation at each of the four Endeavour deposits are centred on the QMP intrusive pipes and generally do not persist beyond 750 m from the margins of the intrusive complexes into the surrounding volcanic rocks (Lickfold *et al.,* 2003).

The sulphides in each of the mineralisation stages of the Endeavour ore deposits, as described below, are zoned outwards from the cores of the QMP intrusive complexes. They grade from proximal bornite-rich zones, to intervals with equal amounts of bornite and chalcopyrite, to chalcopyrite-dominant, to distal pyrite-dominated assemblages. Gold is typically present as <25 µm inclusions along fractures within bornite grains, along bornite grain boundaries, and on rare occasions, as inclusions in chalcocite. Silver is also found in association with bornite, with average grades of between 3 and 4 g/t in each of the four deposits. Bornite and chalcocite are intergrown where they are found together, while chalcopyrite occurs either along fractures and cleavage planes within bornite, or as mutual intergrowths where the two minerals coexist. Minor tellurides, selenides, tennantite-tetrahedrite and enargite are found as inclusions in bornite and chalcopyrite, as intergrowths in bornite, and less commonly in chalcopyrite and chalcocite. In the main stage veining, bornite and chalcopyrite are intergrown with anhydrite. Bornite also occurs as clots in the B-QMP, K-QMP and KA-QMP at each of the Endeavour deposits, generally accounting for <1% of the total sulphides. These clots are spherical to irregular in shape and contain ~98% bornite, with only traces of the other sulphides and silicates. They have no obvious connection with veining and occur in rocks that have been overprinted by K silicate alteration only; sericite alteration assemblages are absent (Lickfold *et al.,* 2003).

Lickfold *et al.,* (2003), and authors cited therein, noted that alteration assemblages are generally both discontinuous and non-symmetrical, and vary from deposit to deposit due to the multiplicity and geometry of intrusion and alteration/ mineralisation. They also point out that while the pattern at each deposit is therefore unique, there are common features that have combined to produce the overall result, as summarised below.

Pre-mineral Stage - an early halo of vein-like K feldspar +quartz dykes containing weak copper mineralisation appears to predate early K-silicate alteration and possibly to have been related to the BQM intrusions. Pre-mineral weak to intense alteration occurs mainly in the volcanic wall rocks and BQM intrusions and comprises albitisation and sericitisation of plagioclase and K feldspar, as well as alteration of magmatic magnetite to chlorite +quartz +carbonate ± fluorite.

Early Stage alteration and mineralisation, which followed the pre-mineral stage, resulted in the formation of 50-200 m wide alteration aureoles around all four of the QMP complexes central to the Endeavour deposits. These aureoles contain moderate to intense biotite-magnetite and K feldspar alteration and abundant quartz-sulphide veins at their cores, and grade outwards to epidote-bearing propylitic alteration at Endeavour 48. Inwards, towards the core of the deposits, there is a transition from biotite +magnetite to K feldspar, characterised by K feldspar ± anhydrite ± magnetite alteration assemblages, hematite dusting of the wall rocks, and irregular discontinuous veins of quartz +K feldspar, ± biotite ± chalcopyrire ± bornite ± magnetite ± anhydrite ± calcite. This alteration assemblage and veining is interpreted to have accompanied the early-mineral B-QMP intrusions.

Transitional Stage, unidirectional solidification textures (continuous to discontinuous alternating bands of comb quartz and aplite porphyry containing disseminated sulphides and occasional, plagioclase and/or K feldspar phenocrysts) and related anisotropic textures (such as miarolitic cavities, spherical aggregates of quartz and K feldspar) occur in both the K-QMP and KA-QMP phases. They have been interpreted to have accompanied each phase as discrete "magmatic to hydrothermal" transition episodes.

Main Stage M1 and M2 veins, associated with the K-QMP and KA-QMP intrusives respectively, were responsible for the main episodes of mineralisation in the Endeavour deposits. The bulk of the sulphide mineralisation in all four deposits occurs in the M1 veins, which vary in character with time. Early M1 veins have K feldspar halos, while those emplaced later are fringed by sericite-hematite. Early *M1a veins* and veinlets are thin (<10 mm) and comprise quartz + sulphide + K feldspar ± anhydrite ± calcite ± apatite ± rutile with thin (<5 mm) quartz-K feldspar selvages. The *M1b stockwork or sheeted veins*, which are characteristically linear and vary from 5 to 20 mm in thickness, comprise quartz + sulphide ± anhydrite + carbonate + K feldspar, enclosed by a halo of pervasive, locally mottled, sericite + quartz ± hematite alteration. Minor tetrahedrite-tennantite, covellite, chalcocite, tellurides and/or lead selenides are also found within these veins. M1b veins contain the bulk of the sulphides in the Endeavour deposits. The *M1c veins* comprise milky quartz +chalcopyrite>bornite +calcite which are found ~50 m outboard of the QMP complexes in volcanic wall rocks; they are characterised by higher calcite and lower quartz, and are enriched in chalcopyrite and bornite compared to M1b veins.

The *M2a and M2b stage veins* are associated with the KA-QMP intrusive phase in each of the Endeavour deposits and are broadly similar to M1a and M1b, although the M2a and M2b veins carry more chalcopyrite than bornite.

Late Stage mineralisation and alteration are represented by three sericite alteration assemblages and associated veining, although only one, L1, is strongly mineralised. *L1* alteration comprises intense to moderate, pervasive quartz + sericite + carbonate ± hematite replacement of feldspar phenocrysts and groundmass to produce a fine-grained mass that preserves the original texture of the host and is best developed in the K-QMP and KA-QMP intrusions in the core of the Endeavour deposits. Chalcopyrite and minor bornite are disseminated in the

Deposit	Host intrusion	Coeval volcanics	Ore- related alteration	Sulphide zonation - from core	Quartz stockwork	Au (t)	Au/ Cu (g/ t:%)	Abundant magnetite	References
Ajax-Ajax, British Columbia, Canada	Diorite, monzodiorite	Yes	Albite- diopside-epidote	Chalcopyrite- pyrite	No	31	0.6: 1	No	Ross *et al.,* 1995, Dawson *et al.,* 1991
Copper Mountain, Ingerbelle & Similkameen, British Columbia, Canada	Diorite- monzonite- syenite	No	(i) Albite- diopside-epidote- calcite; (2) Orthoclase- biotite- epidote- magnetite	Bornite-chalcopyrite → chalcopyrite- pyrite	No	55	0.36: 1	No	Dawson *et al.,* 1991 Stanley *et al.,* 1995
Galore Creek, Stikine, British Columbia, Canada	Syenite	Yes	Garnet- biotite-orthoclase- anhydrite	Chalcopyrite-bornite → pyrite	No	164	0.76: 1	Yes	Enns *et al.,* 1995
Mount Milligan, British Columbia, Canada	Monzonite, diorite	Yes	Biotite- magnetite-orthoclase	Chalcopyrite-bornite → pyrite	No	205	2.2: 1	Yes	Sketchley *et al.,* 1995, Dawson *et al.,* 1991
Mount Polley, Caribou Bell, British Columbia, Canada	Diorite- monzonite	Yes	Orthoclase- diopside- actinolite- magnetite-biotite	Chalcopyrite-bornite → pyrite	No	88	1.3: 1	Yes	Fraser *et al.,* 1995
Red Chris, British Columbia, Canada	Monzonite, quartz monzodiorite	No	Orthoclase- albite-quartz- magnetite-biotite	Chalcopyrite-bornite → pyrite	Yes	141	0.77: 1	No	Newell and Peatfield, 1995; Baker *et al.,* 1997
Skouries, Greece	Monzonite, syenite	No	Biotite- magnetite-orthoclase- quartz	Bornite → chalcopyrite → pyrite	Yes	>250	1.3: 1	Yes	Tobey *et al.,* 1998; Kroll *et al.,* 2002
Dinkidi, Philippines	Quartz-monzonite, syenite	Yes	(1) Orthoclase- actinolite- magnetite; (2) sericite-carbonate	Bornite-chalcopyrite → chalcopyrite-pyrite	Yes	132	2.4: 1	Yes	Wolfe *et al.,* 1999
Endeavour 26, NewSouth Wales, Australia	Quartz monzonite	Yes	Orthoclase- biotite-quartz- magnetite	Bornite → chalcopyrite → pyrite	Yes	65	0.45: 1	Yes	Heithersay and Walshe, 1995; Lickfold *et al.,* 2003
Cadia Hill, Cadia Quarry, Cadia East, &	Quartz monzonite	Yes	Orthoclase- quartz- calcite- biotite	Chalcopyrite → pyrite	Yes	639	3.8: 1	No	Newcrest Mining., 1997, 2003, 2004
Ridgeway, New South Wales, Australia	Monzodiorite, quartz monzonite	Yes	Actinolite- biotite- magnetite- quartz	Bornite chalcopyrite → pyrite	Yes	149	3.2: 1	Yes	Newcrest Mining., 2003

Table modified and updated after Sillitoe, 2000 and Wilson *et al.,* 2003

Table 2: ***Comparison of the principal features of alkalic gold-copper porphyry deposits***

altered matrix of these intrusive complexes at Endeavour 22, 26 and 27, while chalcocite + bornite + tennantite-tetrahedrite are evenly distributed in the similarly altered groundmass at Endeavour 48. Away from the pervasive alteration, L1 quartz + carbonate + sericite + chalcopyrite and/or pyrite veins are distinguished from other veins by their sericite-carbonate-pyrite selvages.

Late stage *L2* alteration takes the form of fracture- and fault-controlled sericite (phyllic) assemblages that contain sericite + carbonate + quartz + pyrite ± anhydrite.

L3 veins are less abundant and comprises carbonate + sericite + quartz + gypsum +/or anhydrite + base metal sulphides ± fluorite, with selvages of the same non-metallic minerals. The base metal sulphides vary widely in quantity and type and are mainly pyrite ± sphalerite ± galena ± chalcopyrite.

Post-mineral alteration takes the form of weak to moderate propylitic alteration, where feldspars and mafic minerals have been selectively replaced by carbonate ± hematite ± pyrite. This alteration episode overprinted the "Zero Porphyry" dykes.

Conditions of Deposition

Lickfold *et al.,* (2003) reported microthermometric analyses of fluid inclusions from early-, transitional-, main- and late-stage veins indicating that the Endeavour deposits were formed at depths between 1000 and 1700 m below the palaeosurface, where lithostatic pressure regimes prevailed during early- to main-stages, and near hydrostatic during late-stage events. They note that the data suggest the early-, transitional- and main-stages were subjected to high-temperature (460 to 550˚C) magmatic-hydrothermal fluids with salinities of ~55 to 60 wt percent NaCl ± KCl equivalent. Although the late stage fluids were cooler (350 to 450˚C) and less saline (~40 wt % NaCl equiv.), their compositions are consistent with magmatic-hydrothermal origins. They conclude that the Endeavour porphyry deposits are representative of the orthomagmatic end member of the porphyry continuum.

Comparison of Alkalic Deposits

Wilson *et al.,* (2003) observed that the Ridgeway deposit in the Cadia district, and by association, the other shoshonite-related ore deposits in the Cadia district and the Endeavour group, have features that are distinctive of alkalic porphyry gold-copper deposits (Table 2). Gold and copper in such deposits are typically associated with alteration assemblages rich in calcic, potassic or sodic hydrothermal minerals (Lang *et al.,* 1995b). Similar calc-potassic assemblages occur at Dinkidi in the Philippines (Wolfe *et al.,* 1999), and sodic alteration similar to that at Cadia-Ridgeway occurs in association with mineralisation at Ajax and Afton in Canada (Ross *et al.,* 1995). The lack of pervasive phyllic alteration at Ridgeway is also characteristic of alkalic porphyry deposits globally (Lang *et al.,* 1995a). One of the main differences between the deposits of the Macquarie Arc and those of British Columbia (Canada) is the presence of abundant quartz veins in the former and the correspondence between the density of veining and the gold and copper grades. Mineralised fractures in the Canadian deposits are characteristically devoid of quartz (Lang *et al.,* 1995b). The Red Chris alkalic porphyry deposit in northwestern British Columbia is an exception, with mineralisation being hosted by quartz-rich stockworks, while sericitic alteration is also widespread (Baker *et al.,* 1997). Based on these features and on the whole rock geochemistry of the related intrusions, Baker *et al.,* (1997) suggest that Red Chris is transitional between calc-alkalic and alkalic end members of porphyry-style deposits, a position Wilson *et al.,* (2003) suggest may be the case at Cadia Ridgeway and Endeavour. All of the discussion above is drawn directly from Wilson *et al.,* (2003).

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