Early Devonian volcanic facies, central Lachlan Orogen, New South Wales: implications for tectonic and metallogenic models

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ABSTRACT
The central Lachlan Orogen volcanic belt contains predominantly silicic and explosive eruptive products emplaced within elongate basins over an area ~350 km long and 20 km wide. The volcanic rocks are exposed in two parallel, south-southeast-trending belts between Cobar and Albury, NSW, and have S-, I- or A-type magmatic affinities. The southernmost sequences include subaerial rocks of the Gurragong Volcanics and Walleroobie Volcanics (herein renamed the Gurragong Group), and the newly described Culcairn Group. The Gurragong Group comprises crystal-rich Walleroobie Ignimbrite, lithic-rich Corella Ignimbrite, Mount Ariah Rhyolite coherent facies and newly recognised airfall Indarra Tuff. The Culcairn Group includes the Budgini and Wallandoon ignimbrites. The Budgini and Wallandoon ignimbrites, the Hadrells Hill Member hyaloclastite breccia and the Soldiers Quarry Member (coherent rhyodacite). The Wallandoon Ignimbrite is compositionally intermediate, metaluminous and amphibole-bearing. The volume estimate of southern pyroclastic units ranges from 15 to 75 km³ per succession. The northern volcanic successions include the Canbelego-Mineral Hill Volcanic Belt, Mount Hope Group and Ural Volcanics, all deposited in a shallow- to deep-marine environment during the Cobar Basin opening. The subaerial depositional environment of the southern volcanic successions, the proximity of exposed Silurian granitoid, and contact metamorphic overprint of the Devonian volcanic successions by contemporaneous intrusions implies the volcanic pile was thicker, and synchronous uplift was occurring. Variation in the aluminium saturation index from peraluminous to metaluminous, and a variation in high-field-strength elements in the almost exclusively felsic igneous rocks may reflect variation in the source rocks and temperature of partial melting. The resulting metallogenic patterns reflect these basement differences. Metals in the south resulted in intrusion-related Sn–W; in the north, the marine environment proximity to a major transcrustal structure and variation in the fertility of the lower crustal rocks led to the development of diverse mineral systems.

KEY POINTS
1. The central Lachlan Orogen Siluro-Devonian volcanic belt is predominantly silicic, containing explosive eruptive products emplaced within a series of elongate basins between Cobar and NSW.
2. The southernmost sequences, the Gurragong Group and the newly described Culcairn Group are subaerial; the northern sequences include the Canbelego-Mineral Hill Volcanic Belt, Mount Hope Group and Ural Volcanics and are wholly submarine.
3. Variations in the igneous rock chemistry and regional mineralisation reflect the variation in the basement source rocks, related fertility and associated structures.

Introduction
Siluro-Devonian volcanic rocks within the central Lachlan Orogen (CLO) are exposed in two parallel south-southeast-trending belts from just south of Cobar to just north of Albury (Figure 1). For ease of discussion, we divide the volcanic successions into northern and southern successions (Supplemental data, Table S1). The Geological Survey of New South Wales has recently engaged in numerous mapping and mineral assessment projects within the CLO, the most recent of which includes the East Riverina Mapping Project involving regional mapping between West Wyalong and Albury (e.g. Campbell, 2017; Eastlake, 2020; Gilmore, 2015;...
Volcanic successions within the southern CLO have been looked at as a part of the East Riverina Mapping Project and are the primary focus of this study. The southern successions include the Gurragong Volcanics and Walleroobie Volcanics, referred to herein as the Gurragong Group (see below; Tables S1 and S2), and previously unnamed volcanic rocks that crop out in the region (Adamson & Lowdon, 1966; Chappell et al., 1991; Tuckwell, 1976). We also identify new volcanic lithofacies that herein are collectively referred to as the Culcairn Group and include the Budginigi Ignimbrite and the Wallandoon Ignimbrite.

The northern volcanic successions of the CLO include volcanic sequences within the Canbelego-Mineral Hill Volcanic Belt (Kopyje Group), the Yarnel Volcanics (Ootha Group), the Mount Hope Volcanics (Mount Hope Group) and the Ural Volcanics (including the Shepherds Hill Volcanics; Rast Group; Table S1 and S2). Several volcanic sequences in the northern CLO, such as the Ural Volcanics and the Mount Hope Group, were initially interpreted to contain subaerial to shallow-water indicators (e.g. Pogson, 1967; Trigg, 1987). The presence of welding textures and airfall tuffs were used to support interpretations of widespread subaerial volcanism. However, focused volcanological studies have brought to light subaqueous features like quench textures, water-settled pumiceous facies, and interbedded sedimentary basin sequences (Bull, 2006; Bull & McPhie, 2006; Colquhoun et al., 2005; Simpson, 2015a, 2015b). The interpretation of a deep-marine (below storm-wave-base) depositional environment for these volcanic sequences, in conjunction with other data, has contributed to and confirmed the recognition of extensional backarc basins controlling Siluro-Devonian magmatism and related ore deposits (e.g. Cas, 1983; Downes et al., 2016; Fitzherbert et al., 2016; Glen et al., 1996).

Tectonic models of the Lachlan Orogen have predominantly focused on the deformation history of metasedimentary sequences (e.g. Chappell et al., 1988; Fergusson, 2017; Foster et al., 1999; Glen et al., 1996, 2012), but these models have under-utilised the depositional environment and chemical affinities of the Siluro-Devonian volcanic successions, as revealed by detailed facies mapping, to be important factors in unravelling the belt’s tectonic history. Similarly, the relationship of mineralisation to Lachlan Orogen volcanic successions has been poorly understood. Several ore-genesis models have been proposed within the tectonic framework of the CLO, and ideas have traditionally been split firmly between two camps—relatively local magmatic-related systems, or deep-fault transported metamorphic hydrothermal systems. Examples include Cu/Pb/Zn mineralisation of the Cobar Basin in the northern CLO, such as in situ, remobilised ca 420 Ma VMS, and intrusion-related systems (e.g. David, 2006; Edgecombe & Soininen, 2019); 415–400 Ma distal intrusion-related (including skarn; Fitzherbert et al., 2021) deposits; and 400–380 Ma inversion-related orogenic deposits (e.g. Lawrie & Hinman, 1998). In the southern CLO, where mineralised granites and volcanic facies are temporally and spatially related, the intrusion-related Sn–W systems have been relatively well constrained, although recent advancements in U–Pb dating of cassiterite have better defined the relationship between magmatism and mineralisation (e.g. Yuan et al., 2008; Zhang et al., 2017).

We present a more wholistic model for the evolution of the CLO directly relating temporal links between the volcanic successions of the southern and northern CLO,
volcanic facies distribution over the entire CLO, basement character over the CLO and the well-defined cycles of orogenesis for the Lachlan Orogen to contextualise the newly defined volcanic successions, and facies in relation to recent tectonic and metallogenic reconstructions.

Images of outcrops or hand samples, and photomicrographs, are included with the respective site, sample or thin-section number. The locations and associated metadata of the sites, samples or thin-sections may be found online in GSNSW Seamless Geology (Colquhoun et al., 2019).

Volcanic successions of the southern CLO

Gurragong Group

The Gurragong Volcanics, a formation initially described by Colquhoun et al. (2005) west of West Wyalong, extends for almost 25 km to just south of Ardelthan (Figure 1; Bull, 2015). Southeast of, but virtually continuous with the Gurragong Volcanics, volcanic rocks were identified and collectively named the Walleroobie Volcanics by Brunker and Offenberg (1970) and briefly described by Warren et al. (1995). Recent mapping increased the distribution of the volcanic succession, which crops out approximately 10 km north of Ardelthan, NSW and continues south-southeast for approximately 40 km (Figure 1; Bull & Blevin, 2016; Campbell, 2016; Trigg, 2016). Outcrops vary in thickness across the extent of the unit from 3 to 140 m.

Detailed investigations by the Geological Survey of NSW (e.g. Bull, 2015; Bull & Blevin, 2016; Campbell, 2016; Trigg, 2016) and work described in this study indicate that the Walleroobie Volcanics are indistinguishable from the Gurragong Volcanics. We, therefore, have combined the two coeval and texturally and compositionally similar formations and elevated them to group level as the Gurragong Group, and that group is subdivided into four formations: Walleroobie Ignimbrite, Corella Ignimbrite, Indarra Tuff and Mount Ariah Rhyolite (Figure 2; Table S2), all of which are summarised in Table S3 and briefly described below.

Walleroobie Ignimbrite

Characteristics of the Walleroobie Ignimbrite (Table S3) suggest that it represents a partially to densely welded crystal-rich pyroclastic density current deposit, or ignimbrite, that was emplaced in a subaerial environment. Evidence supporting this interpretation includes the presence of juvenile pyroclasts (crystals and pumice) (Fisher et al., 1993; Milner et al., 2003; Sparks et al., 1973), lithophysae and partial to dense welding textures. The crystals are generally fragmented, their abundances commonly >50%, and their size and spatial distributions are inconsistent. These characteristics are consistent with particulate concentration rather than representing phenocrysts in a formerly glassy groundmass (Figure 3; Druitt, 1998; Scarpati et al., 2020).

Pumice clasts are visible in non-metamorphosed exposures and tend to be plastically deformed, compacted, and ‘wispy’ in shape, suggesting hot emplacement and modification while still hot and malleable. The pumice is porphyritic to aphyrnic, reflecting similar phenocryst mineralogy as the crystals in the matrix. Furthermore, pumice clasts are indicators of explosive fragmentation when they are in the presence of other pyroclasts, and not associated with a vesicular margin of a lava or sill (Sparks et al., 1973; Wilson & Walker, 1982). Bubble-wall shards are by and large absent, except within an area east of Ardelthan where outcrops that contain partially welded bubble-wall shards can be found. In weakly metamorphosed examples, the groundmass exhibits banding and wrapping textures, devitrification textures and lithophysae after a volcanic glass (Figure 3). In particulate and fragmental rocks, the (formerly) glassy matrix can only be produced by welding glassy particles such as shards. Where banding and lithophysae are present and shards remain, the welding must have been moderate to dense (Breitkreuz, 2013; Quane & Russell 2005; Streck & Grunder, 1995).

A variety of lithic clasts are locally present (<5%) (Bull & Blevin, 2016; Campbell, 2016), which also implies a pyroclastic origin. The clast types include cognate clasts porphyritic and aphyrnic felsic coherent clasts that are similar in phenocryst size and mineralogy to the host volcaniclastic matrix. Such felsic volcanic rock fragments are interpreted...
Figure 3. (a–d) Gurragong Group, Ardlethan area. (a) Rounded and jointed outcrop. Hammer handle is 50 cm. (b) Hand sample showing the crystal-rich texture of the unit. The spaced crystals and presence of pink feldspars make this unit appear similar to be a fine-grained porphyritic or sub-equigranular coherent rhyolite. (c) Photomicrograph showing the closely packed, angular and variable grainsize of the crystals. G, garnet; K, clay-altered K-feldspar; P, sericite-altered plagioclase. Plane-polarised light. Scale bar is 1 mm. (d) Photomicrograph showing welding. Densely welded formerly glass shards wrap around altered biotite and quartz crystals and crystal fragments. Plane-polarised light. Scale bar is 1 mm. (e–h) Walleroobie Ignimbrite, Ardlethan–Barmedman area. (e) Plane-polarised light image showing garnet ('G'). Biotite, pale to dark brown, totals about 5%. Note the large size variation and the angular, broken morphology of most crystals. The speckled texture of the matrix is granoblastic recrystallisation, indicating the rock has been contact metamorphosed. The scale bar is 1 mm. Thin-
to be from a similar source as the ignimbrite, like the vent or underlying coherent facies. Accidental granite and meta-
sandstone fragments are also common. The granitic frag-
ments are somewhat fluidal in shape and have indistinct
margins, such as the aligned inclusions just north of
Ardlethan (Figure 4a, b; Bull, 2015). These clasts appear
to have been included in and in equilibrium with the melt.
The meta-sandstone clasts are biotite-rich, schistose and
weakly foliated, and ± sillimanite- and cordierite-bearing.
Owing to their angular shapes, these clasts are interpreted
to have been incorporated from the basement during trans-
port of the pyroclastic density current. Where modal
lithic clast content is >5%, the crystal-rich facies is corre-
lated with the informal lithic ignimbrite unit (Dgsi) of
Colquhoun et al. (2005) and upgraded to Corella Ignimbrite
(described below). A high concentration of these clasts
likely represents the base of the ignimbrite (Walker, 1972;
Wilson & Walker, 1982).

A pyroclastic origin for the Walleroobie Ignimbrite is
also suggested by the presence of banded, wrapping tex-
tures that reflect the heating, dense welding and rheomor-
phic flow of formerly glassy pyroclasts, and the presence
of lithophysae and spherulites indicate crystallisation of dense
glass. Although entire cooling units or large portions of
pyroclastic density current deposits may not be welded,
the presence of textures that indicate a formerly dense
glassy matrix in a particulate, or clastic, rock cannot be
explained other than by welding.

The majority of the Walleroobie Ignimbrite from north
to southeast of Ardlethan exhibits evidence of secondary
recrystallisation, including granoblastic texture and grain-
size coarsening of the quartzo-feldspathic matrix (Figure
3f). These textures have not been described in crystal-rich
ignimbrites elsewhere. Given the proximity of these rocks
to younger intrusions, a sharp gradient to unrecrystallised
Walleroobie Ignimbrite and a lack of foliation, these tex-
tures suggest the rocks have been contact metamor-
phosed. In many cases, the recrystallisation has obliterated
any primary matrix textures such as welding, or formerly
glassy fragments such as pumice clasts. A Bouguer gravity
image over the area suggests a large intrusion underlying
the majority of the Gurragong Group (Figure 5). An exception
is on either side of the Newell Highway, east of
Ardlethan, where neither units of the Walleroobie
Ignimbrite nor the Mount Ariah Rhyolite (see below) exhibit
granoblastic textures. These textures are significant with
respect to the unit’s relationship to the contemporaneous
intrusions in the region, as discussed below.

A previously described porphyritic intrusion at and
around the Ardlethan Mine informally called the ‘garnet
quartz–feldspar porphyry’ (GQFP) unit (Paterson, 1976; Ren,
1989), is indistinguishable from the Walleroobie Ignimbrite
in the Gurragong Group (Figure 4c, d) (Bull, 2015; Bull &
Blevin, 2016; Trigg, 2016). The matrix exhibits granoblastic
texture and includes very fine-grained secondary biotite,
and overgrowths are present on quartz and feldspar crys-
tals indicating the unit has been contact metamorphosed.
Identification of the GQFP unit as an ignimbrite rather than
a porphyritic intrusion precludes the unit as a source of
mineralising fluids.

The Walleroobie Ignimbrite has recently yielded U–Pb
(SHRIMP) dates from magmatic zircon (and monazite) in
several locations (Bodorkos et al., 2013, 2018). East of the
Yalgogrin Range the unit yielded a U–Pb magmatic zircon
age of 415.4 ± 2.8 Ma (Bodorkos et al., 2018); just north of
the Ardlethan Mine an ignimbrite sample was dated to be
416.5 ± 2.4 Ma; at the Ardlethan Mine, the GQFP unit
yielded a date of 417.9 ± 2.3 Ma; and at Millbrae Quarry,
south side of Walleroobie Road, the ignimbrite was dated to
be 418.7 ± 1.8 Ma (Tables S1 and S4; Bodorkos et al., 2013).

Corella Ignimbrite

The Corella Ignimbrite is exposed east of Ardlethan, as well
as west of West Wyalong where it was the informal lithic
ignimbrite unit (Dgsi) within the Gurragong Volcanics
(Colquhoun et al., 2005) (Tables S1–S3). The unit is a clast-
and crystal-rich, variably welded volcaniclastic sandstone
that we interpret to be lithic-clast-rich ignimbrite
(Colquhoun et al., 2005; this study) (Figure 6a, b). These
rocks are similar in composition and crystal content to the
variably welded and pumice-bearing Walleroobie
Ignimbrite and include crystals, pumice clasts and bubble-
wall shards, but contain up to 40% angular accidental (or
possibly accessory) lithic clasts. The lithic fragments in the
unit west of West Wyalong include Ordovician quartzite
and slate in addition to a variety of porphyritic and aphyric
felsic volcanic clasts (Colquhoun et al., 2005). Within the
unit east of Ardlethan, the lithic clasts are predominantly
coherent rhyolite. The abundance of lithic clasts suggests
the formation represents an initial, vent-clearing explosive
deposit or the stratigraphically lowest in a succession that

Figure 3. (Continued)
section T089326. (f) The cross-polarised light image of a cordierite crystal (℃). The cordierite has tightly spaced parallel partings, typical of magmatic cordierite. Biotite and opaque (Fe-oxide) crystal clusters can be seen at either end of the cordierite. The matrix of the rock has a speckled granoblastic texture, typical of recrystallisation owing to contact metamorphism. Overgrowths, also owing to recrystallisation, can also be seen on the margins of the quartz and feldspar crys-
tals. Cross-polarised light. Thin-section T088274. (g) A porphyritic pumice lens is visible in the centre of this plane light photomicrograph. Very fine-grained secondary biotite, a result of contact metamorphism, is disseminated throughout the image and delineates margins of the pumice lens. Recrystallisation in this sample has not been so advanced as to obliterate the clast completely, however. The scale bar is 1 mm. Thin-section T088274. (h) Pumiceous clasts with wispy terminations (upper-centre and lower left), and welding bands are visible in this unmetamorphosed sample. Note the wrapping textures around crystals and small lenses of the slightly coarser-grained recrystallised glassy matrix. The small lenses likely represent small pumice clasts or recrystallised glassy vugs, such as lithophysae. Such textures suggest dense welding. Thin-section T089854.
picked up underlying lava or other bedrock fragments during transport. The Corella Ignimbrite west of West Wyalong yielded a U–Pb SHRIMP magmatic age of 417.9 ± 2.3 Ma (Table S4; Black, 2005).

Mount Ariah Rhyolite
Felsic coherent facies and associated autoclastic breccias within the Gurragong Group are collectively referred to as the Mount Ariah Rhyolite (Figure 2) and are characterised by porphyritic texture and similar phenocryst types and abundances. Phenocrysts include high modal quartz, lesser feldspar and biotite, and, commonly, trace amounts of primary garnet (Table S3). Additional phenocryst phases differ between the coherent units and may include cordierite, orthopyroxene or clinopyroxene. Accessory minerals (trace–2%) include fluorite, muscovite, zircon, and opaque minerals (predominantly non-magnetic). The groundmass in the felsic coherent units is generally a recrystallised mosaic of quartzo-feldspathic granophyric texture, locally perlitic and/or containing spherulites. Flow banding is common in the coherent facies, now defined by contrasting alteration products (e.g. bands of chlorite or iron oxide vs albite; or sericite + clay vs granophyric-textured recrystallised glass), probably after original variations in composition or spherulite contents that separated during lamellar flow. Geochemical analyses indicate the coherent units are predominantly rhyolites (see geochemical data below). Irregular quartz veinlets containing fluorite uncommonly occur in the felsic units.

Poor exposure makes it impossible to map most contacts and to estimate the size of each unit or body, but coherent rhyolite forms most exposures in the Yalgogrin Ranges north and select hills east of Ardlethan. There is substantial variability between felsic coherent units in terms of their geophysical signature and mineralogy. The coherent units east of Ardlethan are magnetite-bearing and anomalously high on aeromagnetic imagery (Figure 7). In contrast, the Rowallen rhyodacite exposed just approximately 5 km to the southwest of the
above coherent units contains fibrolite + spinel clasts, is magnetite-poor and overlies relatively weak total magnetic intensity (see below).

Three examples of distinct coherent units include informal units referred to as the Mirrool rhyolite, Highview rhyolite, and Rowallen rhyodacite (Figure 7), and are described below.

**Mirrool rhyolite.** Exposed in a roadside rest area east of Ardlethan, near Beckom, the Mirrool rhyolite crops out as blasted boulders and small exposures (Bodorkos et al., 2016). The unit is porphyritic, including phenocrysts of up to 3 mm-diameter of quartz, plagioclase, K-feldspar, altered ferromagnesian minerals, and garnet (Figures 4d and 6c). Garnet totals <1%, is anhedral, fractured and rimmed by plagioclase. Apatite is commonly associated as inclusions or adjacent to many ferromagnesian phenocrysts and is present as long needles in the groundmass.

The ferromagnesian minerals in the Mirrool rhyolite are quite distinctive, ranging in size from 0.1 to 1 mm and, although generally replaced by opake minerals (ilmenite ± magnetite), they have morphologies ranging from diamond- to acicular- and prismatic-shaped crystals. This suggests that at least some of the crystals may have been amphibole, and some of the prismatic-shaped phenocrysts may have been biotite. Titanite is visible in places as an alteration phase, indicating the primary phases were titanium-rich, and the rock has an extremely high magnetic susceptibility (~1690 × 10⁻⁵ SI). The exposed rhyolite is on the southern end of a distinct magnetic anomaly (Figure 7).

**Highview rhyolite.** The Highview rhyolite crops out approximately 3 km southeast of the Mirrool rhyolite and at the southern end of the magnetic anomaly that is associated with the Mirrool rhyolite (Figures 7 and 8). Despite their proximity, the units differ in several ways. Most significantly, amphibole phenocrysts are absent in the Highview unit (Figure 8). In addition, the groundmass consists of relatively coarse-grained quartzo-feldspathic symplectite textures. Garnet phenocrysts contain multiple quartz inclusions (and are almost completely altered to biotite and chlorite). K-feldspar is present, although in sparse abundance (~1%), consistent with whole-rock chemical data indicating the unit is low-silica rhyolite.

**Rowallen rhyodacite.** A distinctive felsic coherent unit that crops out southwest of the Mirrool rhyolite (Figures 7 and 9), the Rowallen rhyodacite contains phenocrysts of 5% quartz, 5–7% plagioclase, 3–7% orthopyroxene, 1–2% biotite (some quite red), 2–3% garnet, and 5–7% of a needle-shaped, slightly purplish opaque mineral interpreted to be ilmenite. K-feldspar is absent suggesting rhyodacite (low-silica rhyolite) composition. Orthopyroxene is also locally associated with fine-grained plagioclase–ilmenite glomerophyric clusters, and here displays no edenite reaction rims in contact with the plagioclase–ilmenite (Figure 9a, b). In most cases, garnet is rimmed by plagioclase (albite?), although in one thin-section garnet is adjacent to and in textural equilibrium with orthopyroxene. Plagioclase crystals are zoned, and commonly resorbed.

In addition to the phenocrysts, the rhyolite contains wispy and somewhat fluidal clasts of meta-sedimentary rock comprising biotite, fibrolite, green spinel, and cordierite (locally altered to pineite) (Figure 9d–f). Sinusoidal bands resembling a kind of flow-band or rheomorphic flow are near meta-pelitic clast margins, and the groundmass contains quartzo-feldspathic micropoikilitic and granophyric recrystallisation textures.

Ages yielded from felsic coherent units in the Mount Ariah Rhyolite overlap with each other. Rhyolite from the Yalgogrin Ranges north of Ardlethan yielded a U–Pb SHRIMP zircon age of 419.0 ± 2.8 Ma; the rhyolite near Mirrool was dated at 418.3 ± 2.3 Ma; and a rhyolite autobreccia yielded an age of 418.1 ± 2.0 (Bodorkos et al., 2016, 2018) (Table S4). A U–Pb SHRIMP zircon age of 418.3 ± 2.3 was obtained from the previously informal garnet granite (Dsgg) unit within the Gurragong Volcanics (Black, 2005; Colquhoun et al., 2005).

**Indarra Tuff**

Indarra Tuff is a volumetrically minor facies that overlies coherent units 30–40 km north-northwest of Ardlethan (Figure 2). The unit is non- to densely welded, pumice- and shard-bearing,
crystal-poor to moderately crystal-rich, coherent rhyolite, volcaniclastic sandstone (Figures 2 and 10). On Kangaroo Hill, about 60 km north-northwest of Ardlethan (MGA Z55 475765.0 E, 6221820.7 N), the volcaniclastic sandstone drapes and infills between clasts in rhyolite autobreccia. Crystals within the unit consist of 0.2–2 mm angular and broken quartz, feldspar, and trace to 3% biotite. Quartz crystals are commonly embayed, and alkali feldspars locally exhibit microcline twinning (and altered to clay ± sericite). Biotite is common (altered to chlorite and opaque minerals), and the formerly glassy groundmass is recrystallised, but subsequently altered to clay, ± sericite and zeolites. The sandstone also contains sparse clasts of porphyritic or aphyric rhyolite.

Bubble-wall shards vary from somewhat annealed (sintered partially welded) to being densely welded (Figure 10c, d). Units are massive or may exhibit rare compaction laminations or bedding. A tectonic cleavage is variably detectible in these units, the best example of which is from atop Kangaroo Hill, where the rock exposures display steeply dipping foliation and have formed a series of ‘tombstone’ outcrops (Figure 10a).

**Gurragong Group correlations**

Mount Ariah Rhyolite unit ages correlate with those of the Walleroobie Ignimbrite and Corella Ignimbrite, suggesting they are contemporaneous (Table S4). The Mount Ariah felsic coherent units are also coeval with the garnet granite of Colquhoun et al. (2005). However, the garnet granite is interpreted to be a granitic intrusion, and we propose it to be separated from the Gurragong Group and named the Schillers Lane Granite.

**Culcairn Group**

Approximately 100 km south of the Gurragong Group (Figure 1), volcanic rocks were recognised by previous workers (Adamson & Lowdon, 1966; Chappell et al., 1991; Degeling, 1977; Hall & Whiting, 1957), but left undifferentiated and

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*Figure 6. (a, b) Corella Ignimbrite. Clasts of finely flow-banded (a; arrows) and perlitic rhyolite (b) in clast- and crystal-rich ignimbrite, east of Ardlethan. Thin-sections T090134, T090139. (c, d) Mirrool rhyolite. (c) The plane-polarised light image of the Mirrool rhyolite. Note K-feldspar (K), partially altered to brown clay, garnet (G) and opaque-altered ferromagnesian minerals (now Fe-oxide minerals). The scale bar is 1 mm. Thin-section T089358. (d) Cross-polarised light image of an amphibole pseudomorph now comprising opaques, likely a combination of magnetite and ilmenite. Note the titanite (T), a common secondary mineral after ilmenite. Thin-section T089358.*
Granite, Mullengandra Monzodiorite and the Koetong Granite (Figure 12; Bull, 2017). The unit contains 45–50%, 0.5–7 mm crystals that include euhedral and fragmented quartz, clay- and sericite-altered feldspar, biotite, garnet and possible cordierite. Lithic clasts are both aphyric and quartz-feldspar ± biotite-phryic. Also within the unit are chloride-altered, wispy compacted former vitriclasts, which we interpret to be former pumice clasts. Wrapping welding bands and discontinuous, attenuated recrystallised (microspherulitic) bands are suggestive of welding, and lithophyses are also visible in some samples. The high crystal density, welding bands and former vitriclasts suggest this unit is a welded ignimbrite.

Budginigi Ignimbrite on the east side of the Great Yambla Range was dated from U–Pb SHRIMP analysis of magmatic zircons to be 413.6 ± 2.2 Ma (Table S1; Bodorkos et al., 2021). The unit at Budginigi Hill was dated from U–Pb analyses of both zircon and monazite to be 415.0 ± 2.3 and 412.8 ± 3.5 Ma, respectively (Bodorkos et al., 2016).

A volumetrically minor volcaniclastic facies within the Budginigi Ignimbrite that directly underlies the unconformity on Hadrells Hill (Figure 11) is a crystal-rich, lithic-clast-bearing, pumice breccia that is up to ~5 m thick. On the south side of the hill, the unit contains up to 60% porphyritic and possibly spherulitic, chloritised clasts, from 0.1 mm to several centimetres in size that have curvilinear margins (Figure 12c, d). The cuspatel clasts are indicative of quench fragmentation, suggesting the deposition of a felsic coherent unit into a subaqueous environment. Many clasts are aligned and may reflect alteration after a compaction fabric and/or primary bedding. One clast captured in the thin-section is a reddish, Fe-oxide-altered crystal ignimbrite clast, which may represent a fragment of the underlying crystal-rich ignimbrite previously described (Figure 12d).

The Soldiers Quarry Member is a K-feldspar megacrystic, biotite-bearing porphyritic coherent rhyolite to rhyodacite (low-silica rhyolite) that we interpret to be a high-level, subvolcanic intrusion or a thick lava-flow or lava-dome deposit (Figure 13). Phenocrysts are evenly distributed and total approximately 35%. Trace amounts of angular to rounded 2–6 cm biotite to chloride-rich mafic lithic inclusions also occur within the rhyolite (Figure 13b). The groundmass of the rhyolite exhibits a recrystallised, granoblastic texture (Figure 13c), and there is also abundant fine-grained chloride, appearing to be alteration after secondary biotite. The granoblastic texture and occurrence of secondary biotite, in conjunction with overgrowths on phenocrysts, suggest the unit has been contact metamorphosed. The granoblastic texture in the groundmass of this rhyolite masks the primary crystallisation texture and creates a crystal-rich volcaniclastic appearance. However, the crystal distribution and contact relationships suggest a coherent body such as a high-level intrusion lava dome or thick lava-flow deposit. The Soldiers Quarry Member is similar in texture and composition to the Nyora Granite (Chappell et al., 1991; Colquhoun et al., 2005). Results from U–Pb SHRIMP
zircon analyses of the Soldiers Quarry Member give an age of 413.7 ± 1.7 Ma (Table S1; Bodorkos et al., 2021).

**Wallandoon Ignimbrite**

Northwest of Albury and west of the Budginigi Ignimbrite, the Wallandoon Ignimbrite is exposed at the Wallandoon Trig site, Hurricane Hill Quarry and north of Doodle Comer Swamp Nature Reserve (Figure 11). The unit includes pumice-rich and pumice-poor facies; both are amphibole-bearing, crystal-rich, and are local with and without clear welding textures (Figure 14; Bull, 2017). On Wallandoon Hill, underlying the trig site, the unit contains approximately 5–7% wispy, compacted pumice clasts ranging from 2–15 cm long to 3–5 mm thick. Weathered surfaces on outcrops show the alignment of the compacted pumice clasts (Figure 14a).

The pumice-rich facies is composed of about 50% crystals of quartz, K-feldspar, plagioclase, clinopyroxene, orthopyroxene and hornblende. Pumice clasts are more intensely altered (chlorite–carbonate–epidote) than the ferromagnesian minerals or matrix. Lithic clasts total some 2–5% and comprise quartz–feldspar–amphibole porphyritic coherent rhyolite to rhyodacite. The matrix of the pumice breccia consists of clay-altered, devitrified and recrystallised glass and, locally, welding bands wrap around crystals (Figure 14). The Wallandoon Ignimbrite at and around Hurricane Hill Quarry has fewer pumice clasts and is more altered than at Wallandoon Hill. The unit is made up of about half crystals (45–50%), and contains clasts of possible granite and a dark, aphyric unit. Crystals are medium-grained (1–3 mm) and include approximately 10% quartz, 20% plagioclase and K-feldspar, minor biotite and chloride-altered amphibole, clinopyroxene and orthopyroxene. The rock also contains trace to 2% disseminated pyrite (±pyrrhotite) and is magnetic. Welding bands that wrap crystals are visible.

The abundance of crystals and the presence of pumice clasts and welding bands suggest that the unit is an ignimbrite. Flattened and aligned pumice clasts suggest the unit...
Figure 9. Rowallen rhyodacite. (a, b) Paired images were taken under plane-polarised (a) and cross-polarised (b) light of orthopyroxene phenocrysts (O). In (a), note the pink centre vs green rim pleochroism of the labelled phenocryst. Also note the dark green, fine-grained fibrous edenite (E) reaction rims on the margins of each orthopyroxene crystal. The prismatic opaque minerals are likely ilmenite. Note the lack of edenite reaction rim where orthopyroxene contacts plagioclase + biotite (arrow); the phenocrysts appear to be in equilibrium with the clusters, but not with the melt. The scale bar is 0.5 mm. Thin-section T089285. (c) The plane-polarised light image of garnet phenocryst. Note the reaction rim on the left side of the crystal comprising plagioclase, chlorite and very fine-grained biotite. Also, note the biotite and edenite rims around the orthopyroxene phenocryst on the right side of the garnet. The scale bar is 0.5 mm. Thin-section T089285. (d) Tightly folded flow banding is visible across the upper part of this plane-polarised image. Note the feathery sillimanite-rich clast rimmed by plagioclase (cl). The scale bar is 0.5 mm. Thin-section T089745. (e, f) Closer view in-plane- (e) and cross-polarised light (f) of meta-pelitic lithic clast visible in (d). Acicular fibrolite (sillimanite; S) crystals are intergrown with cordierite (C), and green/opaque spinel crystals (Sp). The scale bar is 0.5 mm. Thin-section T089745.
underwent compaction prior to lithification. A preliminary U–Pb SHRIMP date from magmatic zircon in the Wallandoon Ignimbrite on Wallandoon Hill yielded a date of 412.6 ± 2.5 Ma (Table S1; Bodorkos et al., 2021).

Southern CLO geochemistry

Southern volcanic successions: Gurragong and Culcairn groups

Geochemical data of southern volcanic successions of the CLO include analyses from the Gurragong and Culcairn groups (Bull, 2015, 2017; Bull & Blevin, 2016). The data are presented in Figure 15, grouped by geological unit and by facies (coherent vs volcaniclastic). A sample was deemed too altered to include for classification if it contained <2 or >5 wt% Na₂O and >5 wt% K₂O (n = 1 sample) after criteria from Large et al. (2001) for calc-alkaline rocks. Samples of volcaniclastic facies within this dataset are interpreted to be ignimbrites and thus represent syn-eruptive deposits. However, the loss of the small glassy fraction during explosive eruptions is problematic in interpreting ignimbrite geochemical data. Ancient successions are particularly difficult, since any elutriate fraction is not easily identified. Nonetheless, we have utilised the data and plotted them with the results from the coherent rocks for comparison and characterisation.

A compositional discrimination diagram of SiO₂ vs Nb/Y, modified after Winchester and Floyd (1977), confirms the majority of volcanic units are rhyolites or rhyodacites, owing to the high modal quartz contents (Figure 15). However, the amphibole-bearing Wallandoon Ignimbrite samples that contain 3–5% modal quartz plot as intermediate rocks and contain <65 wt% SiO₂. Intermediate to mafic whole-rock compositions are uncommon in the volcanic rocks that stretch from Mount Hope to Albury (Bull, 2015; Bull & Blevin, 2016; Bull & McPhie, 2006; Simpson, 2014). The remaining samples form moderately consistent fractionation trends with respect to most elements.
Figure 11. Culcairn Group (see Figure 1 for location). Budginigi Ignimbrite (BI) and Wallandoon Ignimbrite (WdI) are in violet. The majority of BI is a crystal-rich ignimbrite and includes the minor hyaloclastite pumice breccia Hadrells Hill Member at Hadrells Hill, and the Soldiers Quarry Member, a K-feldspar porphyritic coherent rhyolite east of and including Soldiers Hill Quarry. Stippled patterns are from NSW Seamless Geology (Colquhoun et al., 2016; Suppel & Gilligan, 1993). The main volcanic units of the Kopyje Group have been subdivided, from north to south, into the Florida, Babinda, Majuba, Mineral Hill and Yarnel volcanics (Ootha Group), with several smaller volcanic lithologies interfingering with Kopyje Group sedimentary packages (Table S1; Felton et al., 1985; Geological Survey of New South Wales, 1985; MacRae, 1988; Pogson, 1991). The sedimentary packages that host or are interbedded with the Kopyje and Ootha group volcanics include, from north to south; Meryula Formation, Baledmendum Formation, Mount Knobby Formation, Talingaboolba Formation and Mulguthrie Formation (Ootha Group). These sedimentary packages contain volcanic, biogenic and basement derived detritus, as well as rare in situ limestones (e.g. Rookery and White Tank limestones in the Meryula Formation, Boomerang Tank Limestone Member, Beloura Tank Limestone Member and unnamed limestone intersected in drill core beneath the Florida Volcanics (Fromager & Granger, 1975) in the Florida Volcanics (Fromager & Granger, 1975) in the Canbelego-Mineral Hill Volcanic Belt (including parts of the Kopyje and Ootha groups), the Ural Volcanics (part of the Rast Group) and the volcanic dominant Mount Hope Group (Figure 1; Table S1). Several small rhyolite sills or domes are also present within the deep-water sedimentary sequences of the Cobar Basin. The lower sequences of the Cobar Basin are also intruded by dykes/sills that have exploited major fault systems late in the basin rifting event. Several syn- and post-volcanic granitic intrusions locally intrude the volcanic and correlative/host sedimentary sequences, with the exception of the deep-water Cobar Basin sequences. Lithologies and available interpretations of the data and/or classification of the volcanic successions are summarised below.

**Volcanic lithologies, northern CLO**

The northern CLO volcanic successions are of particular interest and significance owing to their association with ore deposits within the Cobar Basin. Three broad zones of volcanic rocks are present and include, from east to west, the Canbelego-Mineral Hill Volcanic Belt (including parts of the Kopyje and Ootha groups), the Ural Volcanics (part of the Rast Group) and the volcanic dominant Mount Hope Group (Figure 1; Table S1). Several small rhyolite sills or domes are also present within the deep-water sedimentary sequences of the Cobar Basin. The lower sequences of the Cobar Basin are also intruded by dykes/sills that have exploited major fault systems late in the basin rifting event. Several syn- and post-volcanic granitic intrusions locally intrude the volcanic and correlative/host sedimentary sequences, with the exception of the deep-water Cobar Basin sequences. Lithologies and available interpretations of the data and/or classification of the volcanic successions are summarised below.

Volcanic rocks of the Kopyje and southernmost Ootha groups form the Canbelego-Mineral Hill Volcanic Belt along the present-day northeastern margin of the Cobar Basin (Figure 16; Fitzherbert et al., 2016; Suppel & Gilligan, 1993). The main volcanic units of the Kopyje Group have been subdivided, from north to south, into the Florida, Babinda, Majuba, Mineral Hill and Yarnel volcanics (Ootha Group), with several smaller volcanic lithologies interfingering with Kopyje Group sedimentary packages (Table S1; Felton et al., 1985; Geological Survey of New South Wales, 1985; MacRae, 1988; Pogson, 1991). The sedimentary packages that host or are interbedded with the Kopyje and Ootha group volcanics include, from north to south; Meryula Formation, Baledmendum Formation, Mount Knobby Formation, Talingaboolba Formation and Mulguthrie Formation (Ootha Group). These sedimentary packages contain volcanic, biogenic and basement derived detritus, as well as rare in situ limestones (e.g. Rookery and White Tank limestones in the Meryula Formation, Boomerang Tank Limestone Member, Beloura Tank Limestone Member and unnamed limestone intersected in drill core beneath the Florida Volcanics (Fromager & Granger, 1975) in the Baledmendum Formation) and was deposited in a shallow-marine environment (Felton, 1981). Simpson (2015a) interpreted the main volcanic packages of the Kopyje Group as extensive submarine lava–sill complexes that range compositionally from dacite to rhyolite, and have associated autoclastic breccias, many of which are hyaloclastites.
Figure 12. Budginigi Ignimbrite southeast of the Great Yambla Range. (a) Crystal-rich ignimbrite in the foreground and Upper Devonian red beds in the background. The unconformity lies approximately across the middle of the image. Site ERIVKFB0303a. (b) Photomicrograph of crystal-rich, pumice-bearing ignimbrite. Fluidal-shaped, chloritic clast in centre is a pumice clast (p). Chlorite-altered biotite (B) are at the top of the image. Thin-section T090580. (c) An image taken of thin-section T090585 shows the curvilinear margins to the chloritic clasts, suggesting they are quench-fragmented formerly glassy clasts. The thin-section is 2.5 cm wide (vertical image dimension). (d) The plane light image of hyaloclastite breccia with Fe-oxide-altered welded crystal ignimbrite clast (cl). Chloritic fragments have curvilinear margins indicating they have been quench-fragmented. Porphyritic clasts are visible at the bottom and left sides of the image, and crystals are also present in the matrix. Thin-section T090585. (e, f) Budginigi Ignimbrite at Budginigi hills. (e) Shallow-dipping joints in the ignimbrite likely reflect bedding. Hammer is ~50 cm long. Site ERIVKFB0282b. (f) Budginigi Ignimbrite in cross-polarised light. Porphyritic rhyolite clasts are outlined in red lines; matrix crystals of quartz, feldspar, biotite and opaque minerals are angular and poorly sorted. The scale bar is 2 mm. Thin-section ERIVLMC0271_1X_2_XP.
(quench-fragmented breccia). Explosive volcanic deposits are also present and range from coarse- to very fine-grained volcaniclastic deposits. The location and nature of volcanic centres are undetermined, but textural evidence and facies relationships suggest the volcanogenic parts of the Baledmund Formation, Talingaboolba Formation and Yarnel Volcanics are deposited indicative of distal and/or waning volcanism. Such observations are consistent with these sequences being deposits in moderate to shallow (basin-margin) water, the eruption centres having been shallow subaqueous or coastal subaerial (Felton, 1981; Simpson, 2015a; Suppel & Gilligan, 1993).

Volcanic facies mapping and petrographic studies of the Mount Hope and Ural volcanic successions support models that indicate deposition to have been located within relatively small, narrow marine troughs (termed the Mount Hope and Rast troughs), which are part of the greater Cobar Superbasin (Figure 17; Table S1; Bull, 2006; Bull & McPhie, 2006; David, 2006; David & Glen, 2004; Glen et al., 1996; Pogson, 1967; Scheibner, 1987; Simpson, 2015b; Trigg, 1987; Walshe et al., 1995). The Ural Volcanics comprise felsic lava—sill complexes and minor submarine pyroclastic facies constructed over a 100 km north–south trend (Bull & McPhie, 2006; Colquhoun et al., 2005). Zircon U–Pb (SHRIMP) ages from the Ural Volcanics suggest submarine volcanism occurred between 413 and 412 Ma (Colquhoun et al., 2005; Downes et al., 2016). Younger magmatic U–Pb ages of about 409 Ma were obtained from zircons by Bull et al. (2008) using LA-ICP-MS, although larger uncertainties mean they fall within error of the SHRIMP ages. Older magmatic U–Pb ages from zircon obtained for the Ural Volcanics include 421 ± 2 Ma (LA-ICPMS, Bull et al., 2008), ca 420 Ma (preliminary, Bodorkos et al., unpub. data) and ca 425 Ma (Colquhoun et al., 2005), although the latter was suggested to be compromised by inherited zircon (Table S1).

Reconstruction of the evolution of the Ural Volcanics through a facies architecture study (Bull, 2006; Bull & McPhie, 2006) suggests that at least two eruptive centres produced a predominantly felsic sequence onto quartz turbidites and metamudstones of the Crossleys Tank Formation. Although both centres erupted coherent units (lavas and sills), one also erupted explosively, delivering pyroclastic products directly into the water via the eruption column and via high-particle concentration gravity currents.
Figure 14. Wallandoon Ignimbrite, pumice-rich facies. (a) Weathered outcrop showing preferentially eroded flattened pumice clasts (white arrows) to 15 cm long. Pen-magnet is 12 cm long. Site ERIVKFB0141c. (b) The left half of the image is a porphyritic rhyolite clast, right half is the host crystal-rich ignimbrite. Matrix ferromagnesian crystals include orthopyroxene (O) and clinopyroxene (C). Thin-section T090193. (c) Fluidal and wispy porphyritic pumice clast (p), and crystals (~ 50%) in clay-altered matrix with welding bands. Note kinked pyroxene crystal (Py) with the end slightly wrapped by fluidal pumice clast. Thin-section T089890. (d) Euhedral amphibole crystal in cross-polarised light. Thin-section T090071. (e) Despite the clay alteration of the matrix, bands wrapping crystals visible in this image suggest the unit has been welded. Thin-section T089890. (f) Facies north of Doodle Comer Swamp Nature Reserve. This unit is extremely sericite-altered, but quartz crystals (Q) and wispy to angular fragments are visible.
Figure 15. Plots of geochemical data of southern CLO volcanic rocks, were obtained during the East Riverina Mapping Project. Explanation of symbols is at the top. Abbreviations: ASI, Alumina Saturation Index; ME, moderately evolved; MO, moderately oxidised; MR, moderately reduced; SE, strongly evolved; SO, strongly oxidised; SR, strongly reduced; VSO, very strongly oxidised. Log(Fe₂O₃/FeO), and K/Rb plots modified after Blevin (2004). Compositional diagram Nb/Y vs SiO₂ after Winchester and Floyd (1977) shows felsic lithologies of the Gurragong Group (Mount Ariah Rhyolite and Walleroobie Ignimbrite). Wallandoon Ignimbrite samples are intermediate in composition.
Figure 16. Volcanic successions of the northern central Lachlan Orogen. Volcanic sequences are in brightened colours on the map and in bold labels in the reference. Modified after Fitzherbert et al. (2016).
Subvolcanic dacite intruded the volcanic pile late in the evolution of the succession. Identification of fossiliferous limestone interbedded with volcanic facies on the southern end of the Ural Ranges, and jasper-bearing black siltstone in the central depo-area also indicate deep-marine deposition, possibly shallowing to the south (Bull & McPhie, 2006; Colquhoun et al., 2005).

The Mount Hope Group volcanic sequences are separated from the Rast Group by shallow-water shelf sequences of the Walters Range Group and are described as relatively deep-water subaqueous dacite to rhyolite lavas and sills, primary explosive and reworked volcaniclastic deposits, and minor intermediate to mafic dykes and sills (Bull & McPhie, 2006; Pogson, 1967; Scheibner, 1987; Simpson, 2015b; Trigg, 1987). Zircon U–Pb (SHRIMP) ages from several coherent volcanic units within the Mount Hope Group suggest that submarine volcanism occurred between 423 and 419 Ma (Downes et al., 2016). Simpson (2015b) proposed multiple eruption centres produced a complex interbedded sequence of coherent and volcaniclastic facies that make up the Mount Hope Group (Figure 17b).

Several contemporaneous granites intrude the volcanic troughs. In the Mount Hope Trough these include the S-type, ca 423–422 Ma Gilgunnia and Mount Allen granites and the younger A-type, ca 415 Ma Boolabone Granite (Figures 17 and 18; MacRae, 1989; Scheibner, 1987), whereas in the Canbelego-Mineral Hill Volcanic Belt these include the ca 421–420 Ma Wilmatha, Mount Walton and Yellow Mountain granites, along with similar aged dacitic porphyry stocks (Table S1; Black, 2006). The youngest intrusive body to date is a small, ca 411 Ma hornblende-phyric body that intrudes the Meryula Formation east of Cobar township (Jones et al., 2020).

Small, isolated coherent rhyolite bodies and correlative shallow-level ‘porphyry’ intrusions occur at two stratigraphic levels within the siltstone-rich packages of the deep-water Cobar Basin (Figure 18). In the east, coherent, flow-banded rhyolite bodies (Perseverance and Peak rhyolites) are present at a complex faulted stratigraphic boundary between the Great Cobar Slate (siltstone-rich) and the Chesney Formation (sandstone-rich) of the Nurri Group. Subordinate volcanic-derived sandstone is also interbedded with the surrounding siltstone-rich sequences. The Stones Tank Tuff Member (immature volcaniclastic deposits and lesser coherent rhyolite; Felton, 1981) occurs at similar stratigraphic levels to the south and is interbedded with the siltstone-rich sequences of the lower Amphitheatre Group and upper Burthong Formation (shallow-water
equivalent of the Nurri Group). Zircon U–Pb (SHRIMP) ages for these rhyolites range from 423 to 419 Ma, which is consistent with the age of the lower Cobar Basin sequences elsewhere (Black, 2006; Downes et al., 2016; Jones et al., 2020). While the origin of the clastic beds is likely deep-water deposition with a potential eastly shelf source, the origin of the larger coherent rhyolite bodies has been disputed—being anything from allochthonous through to ocean floor lavas—but it is likely they are shallow-level sills; domes formed close to the sea floor within the deep-water sequences (Whittock, 2007). The contemporaneous porphyry stocks (e.g. Bee Porphyry) have been dated at ca 420–417 Ma (Black, 2006) and are hosted solely within the Chesney Formation of the Nurri Group.

In the central Cobar Basin coherent porphyritic rhyolite bodies occur at a higher stratigraphic level in the deep-water basin sequences as isolated bodies (Shuttleton Rhyolite Member and unnamed rhyolite encountered in drill core at the Wirlong prospect) within the sandstone-rich Shume Formation or intercalated with distinctive limestone-rich mass flow horizons within the Shume Formation (Figure 18; Mallee Bull prospect; Brown et al., 2013; Edgecombe & Soininen, 2019). Zircon U–Pb (SHRIMP) age dates for these rhyolite bodies range between 422 and 419 Ma (Jones et al., 2020). The Shume Formation is interpreted to represent the boundary between the rift and sag phases of the deep-water Cobar Basin (Glen, 1994). Interestingly, the correlative Biddabirra Formation on the northern deep-water Cobar Basin hosts allochthonous limestone blocks of suggested Pragian age (410–407 Ma; Mathieson et al., 2016) providing a maximum age for the rift-to-sag transition in the Cobar Basin, although the time–space plots of Glen et al. (1985) and MacRae (1989) suggest that some diachronity in the transition to sag phase deposition in the eastern vs western deep-water Cobar Basin. Ebach (2002) assigned trilobite fauna from the Biddabirra Formation to a Lower Devonian (Lockhovian–Pragian) age, although the author suggests the fauna are consistent with a Lockhovian age. Again, the relationship of the isolated volcanic rocks to the deep-water basin sedimentary rocks has been conjectured, and allochthonous (outrunner and olistolithic) or shallow-level syn-depositional sill origin suggested. However, recent work has favoured an allochthonous origin, likely sourced from the Mount Hope Trough to the east (Brown et al., 2013; Chapman, 2012; Jones et al., 2020). An allochthonous origin may explain the apparent diachronity in the onset of sag phase sedimentation across the Cobar Basin and potentially the ca 10–15 Ma mismatch between the paleontological determinations and the U–Pb geochronology, suggesting that a mixed source from the shelf to the west and/or either emergent or uplifted parts of the Mount Hope Group. Unfortunately, the mismatch between different paleontological determinations and U–Pb geochronology means there is still some degree of ambiguity around the relationship of central Cobar Basin rhyolite bodies and their host deep-water sequences.

No large intrusive bodies have been observed to intrude the deep-water sedimentary sequences of the Cobar Basin, although a number of small fault-focused, I- and A-type, ca 415 Ma dykes have intruded basement beneath the basin as well as intruding parallel to the Rookery Fault within the shallow-water sequences of the Mouramba Group (temporal equivalent of the Nurri Group in the north). Several moderate
to large intrusions have been inferred to have intruded immediately beneath or within the lower Cobar Basin sequences based on geophysical interpretation and mineral system studies (Fitzherbert et al., 2021; Fitzherbert & Downes, 2020; Ford et al., 2020; Forster & Seccombe, 1999).

**Northern volcanic successions—S-, I- and A-type classification**

**Northern Cobar Basin**

The time-space relationships of the northern volcanic succession are depicted in Figure 18.

**Florida Volcanics and Baledmund Formation.** The Florida Volcanics has a U–Pb SHRIMP age for magmatic zircons of 421.7 ± 2.3 Ma (Black, 2005), and more recent dating of the Baledmund Formation yielded an age of 419.3 ± 2.8 Ma (Table S1; Bodorkos et al., 2015). Simpson (2015b) interpreted the Baledmund Formation volcanic deposits to represent the distal deposits of coherent and volcaniclastic facies of the Florida Volcanics. Those deposits contain pseudomorphs of probable amphibole phenocrysts and crystals, which we suggest are indicative of metaluminous (‘I-type’) classification (Blevin, 2004; Blevin & Jones, 2004), although Chappell et al. (1991) classified the Florida Volcanics as peraluminous (‘S-type’).

**Shallow-level intrusions of the northeast Cobar Basin**

(Perseverance rhyolite, Bee Porphyry, Stones Tank rhyolite; dacitic sills). The Perseverance rhyolite is a subvolcanic to extrusive, rhyolite complex comprising coherent rhyolite and volcaniclastic facies that include welded and non-welded tuffs or ignimbrite, hyaloclastite breccia and peperite and volcaniclastic facies that include welded and non-welded, rhyolite complex comprising coherent rhyolite and dacitic sills). (Perseverance rhyolite, Bee Porphyry, Stones Tank rhyolite to extrusive, rhyolite complex comprising coherent rhyolite and dacitic sills). (Perseverance rhyolite, Bee Porphyry, Stones Tank rhyolite; dacitic sills).

**Mount Hope and Rast troughs**

**Mount Hope Group volcanic rocks.** The Mount Hope Group is interpreted to represent deep-marine lava domes, volcaniclastic aprons and pyroclastic deposits (Bull, 2006; Simpson, 2015b). Multiple volcanic centres were postulated by Simpson (2015b), based on interpretations of proximal and distal volcanic facies and on spatially associated and differing compositional variations within the Mount Hope volcanic rocks. Although limited initial chemical analyses indicated an A-type affiliation for some of the Mount Hope volcanic rocks (Bull et al., 2008), subsequent interpretations suggest at least some of the deposits (e.g. Mount Halfway, Nombiginni and Regina volcanics) are peraluminous and have an S-type affinity (Downes et al., 2016) or early eruptive products an I-type affinity (e.g. Mt. Kennan Volcanics; David, 2006).

**Ural Volcanics.** Major- and trace-element data for the Ural Volcanics (including Mount Hope Volcanics samples) indicate that the rocks are weakly peraluminous (ACNK 1.0–1.1) and sub-alkaline. The Ga/Al ratio is >2.5 and Ga/Al vs Nb data for the Ural Volcanics plot in A-type field (Bull, 2006; Bull et al., 2008). In addition, the data show decreasing P2O5 with increasing SiO2, low CaO + Fe2O3 and high Zr. These data and the variably high K, Zr, Nb and Y contents are consistent with A-type affinities.

**Discussion**

**Facies interpretations and implications for the Southern CLO—pyroclastic deposits**

The high concentration of crystals within a welded, banded matrix suggests the crystal-rich volcaniclastic sandstone units in the Gurragong and Culcairn groups are subaerial but are not welded ash-fall deposits. Concentrated crystals and sparse ash require a transport and depositional mechanisms that force winnowing of small, light particles and concentration of denser pyroclasts (crystals, lithic clasts), such as deposition from a pyroclastic density current (Walker, 1972). The minimal presence of spatially associated non-welded facies (excepting the pumice-rich Indarra Tuff facies) is likely in large part due to the rapid distribution of ash from wind and subsequent erosion, resulting in a lack of preservation.

Within the limited outcrops remaining there is generally a lack of discernible internal stratification or grading, with
two notable exceptions: within the Wallandoon Ignimbrite where large, compacted pumice clasts provide a subhorizontal stratification; and consistent, subhorizontal joints within the crystal-rich facies on Big Budginigi Hill that suggest flow laminae or weak bedding. Massive to weakly stratified units are common in moderate- to large-volume pyroclastic density deposits.

The exposures of the variably welded ignimbrites are vestiges of what must have been thick pyroclastic-flow deposits. The remaining Gurragong Group outcrops indicate that the crystal-rich facies form a south-southeast-trending lobate package at least \( \sim 200 \text{ km}^2 \), and the remnant, exposed thickness, presuming it is relatively flat-lying, ranges from 3 to 140 m. The facies east of Ardlethan forms a series of exposures over a south-southeast-trending area of approximately 155 \( \text{ km}^2 \), and in the Milbrae (formerly Walleroobie) Quarry the unit is exposed for \( \sim 50 \text{ m} \) vertically, suggesting a primary thickness perhaps twice that. Using an average thickness range of 50–100 m, an approximate minimum volume of the Walleroobie Ignimbrite is 18–35 \( \text{ km}^3 \).

Similarly, \( \sim 100 \text{ km} \) to the south, the variably welded Budginigi Ignimbrite has an exposed thickness of up to 200 m, and the Wallandoon Ignimbrite is 60–100 m thick. Collectively the units form two large lobes about 198 and 600 \( \text{ km}^2 \), respectively. If we use an average thickness range of 100 m, therefore, the average minimum volume of pyroclastic units in the southern CLO volcanic belt is roughly estimated to range from 15 to 75 \( \text{ km}^3 \) for each, the Budginigi and Wallandoon ignimbrites. This volume estimates, in conjunction with the crystal-rich, massive and, at least in part densely welded nature to the facies imply they represent subaerial, relatively distal pyroclastic density current deposits (ignimbrites). Such fairly large-volume (i.e. \( \geq 25 \text{ km}^3 \)) crystal-rich ignimbrite facies are common in Australia (e.g. McPhie, 1983, 1984; White & McPhie, 1996; Wyborn et al., 1981). In contrast, a volume estimate for the deep marine Ural Volcanics explosive products is about 3 \( \text{ km}^3 \) (Bull & McPhie, 2006).

The southern CLO deposits are most likely the result of large-scale column collapse-induced, rather than dome-collapse-induced, pyroclastic density currents due primarily to their moderately high volume. Dome-collapse ignimbrites also tend to contain abundant, predominantly monomictic, dense coherent clasts (e.g. Calder et al., 2000). The mixed nature and low relative abundance (\(<10\%\)) of lithic clasts within local areas of the Walleroobie Ignimbrite suggest they are accidental clasts picked up from the substrate rather than dense fragments from a dome-collapse density current (Bryan et al., 1998; Gardner et al., 1994) and may represent a proximal or even intra-caldera lag-breccia facies (Druitt & Bacon, 1986).

The predominantly felsic composition of the ignimbrites suggests that these would have been highly explosive eruptions (i.e. plinian to subplinian) and likely caldera-related. Small thicknesses and the moderately large areal extent of the deposits (tens of kilometres) may suggest they are caldera outflow facies. However, the lack of non-welded facies suggests large stratigraphic thicknesses have been lost to erosion, which may suggest that the deposits are the welded remnants of a thick intra-caldera pile. The lack of internal structure and of additional facies, and the presence of the Corella Ignimbrite lithic-rich breccia could support an intra-caldera context for these deposits.

The Walleroobie Ignimbrite contains what appear to be S-type granitic clasts that are of varying sizes and in places appear to have been disaggregated. The granitic clasts have no reaction rim and seem to be in equilibrium with the melt. Two implications follow: the volcanic melt is either sourced from such granitic rocks, or the melts have picked up granitic clasts early enough in the melt transport to partly disassemble them, as well as lengthen and align them within the flow. The best example of this is on Bolero Mountain within the Walleroobie Ignimbrite (Figure 4a, b), but similar textures may be found in the southern Walleroobie Ignimbrite such as in Milbrae Quarry. Meta-sedimentary lithic clasts within the ignimbrite, however, are consistently angular and considered accidental.

**Associated intrusions and contact metamorphism of volcanic facies**

Walleroobie Ignimbrite exposures exhibit granoblastic textures east and south of the Yalgogrin Ranges to Ardlethan, and southeast through Milbrae Quarry (Figure 5). Soldiers Quarry Member of the Budginigi Ignimbrite also exhibits granoblastic recrystallisation, including secondary biotite. These contact metamorphic textures suggest a high-level, high-temperature pluton intruded post volcanism under a large portion of an area between West Wyalong to the southeast of Ardlethan.

Bouger gravity data over the East Riverina study area between West Wyalong and Albury show coincident relative low gravity response beneath the majority of the Gurragong Group (Figure 5). This low gravity response coincides well with the full extent of the Gurragong Group and includes the contemporaneous Ardlethan Granite (Duca) (414.7 ± 2.3 Ma; Bodorkos et al., 2013), the Sprots Tank Granite (Skos) north of Ardlethan, and the Bungambil Granite southeast of Ardlethan (Figure 18) (Bodorkos et al., 2021; Colquhoun et al., 2019; Trigg, 2016). Interestingly, the Gurragong Group units that form hills between the Newell Highway and the Mirool Road, northeast of Ardlethan, are not underlain by a low relative gravity anomaly and are not contact metamorphosed.

The scale of contact metamorphic recrystallisation in the peraluminous Walleroobie Ignimbrite implies reheating by a large, relatively hot intrusion, possibly reflected in the extensive low gravity anomaly underlying most of Gurragong Group exposures. Limited exposures restrict us from better knowledge of contact relationships between the volcanic facies and intrusions, except in drill core and mine exposures.
at the Ardlethan Mine. In this context, the Walleroobie Ignumbrite (formerly the ‘GQF Porphyry’ unit in the Ardlethan Mine area) was intruded by the Ardlethan Granite, which itself is cross-cut by the Yithan Porphyry (formerly the ‘Mine Porphyry’) (Bull & Blevin, 2016; Ren, 1989; Ren et al., 1995). The Yithan Porphyry has been dated at \( 412.0 \pm 1.9 \text{ Ma} \) (‘Cassiterite porphyry’, Bodorkos et al., 2013). Recent sampling suggests it is a metaluminous I-type intrusion.

Metaluminous, I-type magmas are characterised by greater degrees of fractionation and higher oxidation states than S-type, peraluminous magmas, and thus are associated with higher magmatic temperatures than S-type intrusions (Blevin & Chappell, 1992, 1995). The peraluminous, S-type Walleroobie Ignumbrite would likely, then, have been recrystallised not by an intrusion of similar composition like the contemporaneous Ardlethan Granite, but perhaps by a large, unexposed I-type intrusion that is reflected in the large gravity low underlying the Gurragong Group volcanic sequences.

The gravity response underlying the granoblastic Soldiers Quarry Member is only moderately low; lower relative gravity responses are 10–15 km to the west, under the metaluminous I-type Jindera Granite (407–403 Ma; Bodorkos et al., 2021; Bull, 2017), and slightly lower responses to the east under the Black Rock, Ralvona, Woomargama and similar granites (429–428 Ma; Bodorkos et al., 2015; Bull, 2017; Campbell, 2018). The Wallandoon Ignumbrite, which comprises extensive, highly magnetic metaluminous I-type deposits, is notably not underlain by a low gravity response, suggesting the source for the extrusive rocks is not necessarily reflected in a large underlying intrusion.

**Level of emplacement**

In the southern CLO, Gurragong and Culcairn group volcanic units directly (disconformably) overlie not only Ordovician meta-sandstone of the Ordovician Adaminaby Group, but also upper Silurian granitoids, such as the Sprys Tank Granite at the Ardlethan Mine (428.1 ± 2.8 Ma called the ‘Mine granite’ in Bodorkos et al., 2013), Wantabadgery Granite east of the southern Walleroobie Ignumbrite (431.3 ± 4.1 Ma, Ickert & Williams, 2011), and the Mount Royal Granite at and near the Hickory Hill mine, west of the Wallandoon Ignumbrite (430.5 ± 3.4 Ma, Waltenberg et al., 2019). These relationships imply not only rapid uplift and erosion of basement and upper Silurian granites prior to Siluro-Devonian eruptions, but also very high levels of emplacement for those ca 430 Ma granites.

In fact, there are a remarkable number of examples in the CLO where volcanic facies are spatially and chemically associated with contemporaneous granitic intrusions. Such examples include the Nymagee felsic dykes, Blind Calf dyke swarm and the Mineral Hill Volcanics; the Yellow Mountain Granite and the Majuba Volcanics; the Mount Allen, Boolahbone and Gilgunnia granites and the Mount Hope Group; the Nyora, Ardlethan, Beckom South, Yarranjerry, Boblegibgie, granites associated with the Gurragong Group (Black, 2007; Bodorkos et al., 2016; Downes et al., 2016; Fitzherbert et al., 2016, 2019). Close depositional contacts of ignimbrites and coeval intrusions imply high-level emplacement of these ca 415 Ma intrusions; granites virtually intruding their ‘own’ volcanic pile or at least similarly sourced eruptive products.

**Tectonic control on the CLO volcanic belt**

Previous workers have recognised post-compressional marine rift basins that formed during deformation cycles in the Lachlan Orogen, and the importance of those basins being the focus for magmatism and related ore deposits (e.g., Bierlein et al., 2002; Glen, 1995; Glen et al., 1996; Gray & Gregory, 2003; Perkins et al., 1994; Scheibner, 1973). Structures driving the opening of the Cobar Basin and the volcanogenic Rast and Mount Hope troughs during the Tabberabberan Cycle (433–380 Ma) controlled magmatic activity and mineralising fluids in the basins owing to maximum northeast–southwest-oriented extension that resulted in sinistral transtension (Collins & Richards, 2008; Foster et al., 1999; Glen, 1990, 2005; Glen et al., 1985). These troughs have controlled and confined the eruptive products, and the underlying structures have been the focus of ongoing deformation as well as intrusive activity and periodic mineralisation at ca 420 Ma, 415–410 Ma, 405–395 Ma, and 390–380 Ma (Figure 19; see Fitzherbert et al., 2019 for details of direct dating of mineralisation; Fitzherbert et al., 2016; Perkins et al., 1994; Solomon & Groves, 1994). In the Cobar Basin, primary, marine volcanic deposits are associated with shelf deposits on the basin margins and approximately coeval felsic dykes that intruded volcanic facies (e.g., Kopyje Group; Simpson, 2015a; Downes et al., 2016). Contact metamorphic aureoles and related mineralisation suggest larger scale intrusions at depth and ongoing mineralisation during basin rifting (Fitzherbert et al., 2016, 2017, 2019; Leverett et al., 2005). The Mount Hope and Ural volcanic successions provide evidence for multiple volcanic centres within deep marine (central basin) settings that include explosive and effusive eruptions associated with shallow-level intrusions (Bull, 2006; Bull & McPhie, 2006; Colquhoun et al., 2005; Simpson, 2005b). The southern CLO, subaerial volcanic successions, newly described here, are generally contemporaneous with the marine volcanic belts in the Cobar, Rast and Mount Hope depocentres, and we suggest that these were similarly controlled by extensional tectonics. The subaerial depositional environment of the southern volcanic successions suggests less subsidence than their northern siblings.

The changing volcanic facies and thus interpreted paleogeography from south to north during the Siluro-Devonian can be thought of in terms of the recent tectonic reinvigoration of the Lachlan Orogen as an oroclinal system developed through the southern accretion of the Vandieland microcontinent during the Ordovician, and its effects on the development of the successor Siluro-Devonian
subduction system (e.g. Cayley, 2015; Cayley et al., 2012; Huston et al., 2015, 2016; Moresi et al., 2014). In this model, the prior embedment of the Vandieland microcontinent in the southern Lachlan Orogen created south-to-north asymmetry and a retreating west-dipping slab responsible for the development of the Siluro-Devonian backarc systems (Cayley, 2015; Collins, 2002). As depicted in Figure 20 the microcontinent is envisaged to have pinned the southern end of the retreating slab, while the northern parts of the slab were uncongested and in free-rollback within an enforced transtensional environment associated with large-scale strike-slip faulting (Cayley, 2015; Moresi et al., 2014). The asymmetry generated by this model elegantly explains the paleogeographic transition of a subaerial terrestrial environment for the southern CLO volcanic belt, to the contemporaneous development of the northern CLO volcanic belt within the moderate- to deep-water, transtensional backarc rift Cobar Basin (Figure 20). Basement composition played a vital part in the changing genetic character of the CLO volcanic rocks within this asymmetric tectonic environment. The interplay between tectonic evolution and basement composition imparted control on the associated Siluro-Devonian metallogeny of the region and is discussed below.

**Or dovician basement, Siluro-Devonian volcanism and mineralisation in the CLO**

The CLO Siluro-Devonian volcanic belt and associated intrusions is one of the most extensive and voluminous volcano-plutonic complexes in Australia. Differences in the interpreted source (I-, A- and S-type magmatism) of the different volcanic successions of the CLO volcanic belt (Figure 19) coincide broadly with spatial variations in metallogeny (e.g. Cu–Au or Zn–Au or Pb–Zn–Ag or Sn–W-dominant); a time–space plot for basement and successor basin sequences, including the volcanic successions of the CLO is presented in Figure 18. These differences are in turn commensurate with variations in basement character along and across the belt (i.e. Blevin & Jones, 2004; Chappell et al., 1988) as well as influences stemming from variable tectonic regimes along the belt during the period of active volcanism. The northern volcanic successions straddle the boundary between two distinct packages (mostly separated by the Rookery Fault system) of craton-derived Ordovician turbidites that developed in a likely backarc setting (e.g. Gilmore et al., 2018). The Girilambone Group constitutes the eastern basement package (mostly east of the Rookery Fault; Figure 18) and is largely a sequence of monotonous siliciclastic turbidite, but here the Ordovician sequences include an upper, condensed package of Upper Ordovician black mudstone (Bendoc Group; Figure 18) and there is no contemporaneous mafic volcanism. The uppermost Silurian to Lower
Devonian Mount Hope and Rast troughs unconformably overlie the Ordovician Adaminaby/Bendoc groups sequences and are dominated by S- and A-type volcanism (Blevin & Jones, 2004). About 415 Ma the A-type Tarran Volcanics were intruded and erupted along with the Rookery Fault system immediately south of the Cobar Basin (Blevin & Jones, 2004). Isolated I-type rhyolite bodies (e.g. Peak Rhyolite: Figure 18) occur within the eastern deep-water Cobar Basin sequences and in conjunction with the I-type Siluro-Devonian Kopyje Group volcanic successions (e.g. Mineral Hill Volcanics and Majuba Volcanics; Figure 18), and also overlie a Girilambone Group basement. The southern CLO volcanic successions and intrusions are S-type dominant and have developed solely in and over the Adaminaby/Bendoc group basement (Figure 18). The character of the lower crust that melted to produce the volcanic and plutonic sequences that overlie these two Ordovician turbidite domains—S/A-type in the west and south, and I-type in the east (Blevin & Jones, 2004)—fundamentally varies, and these basement variations have strongly influenced the nature of the successor, Siluro-Devonian volcanic troughs/belts.

The strongly domanial inherited lower crust character not only had an overarching control on the genetic character of the CLO volcanic sequences but initiated a domino effect controlling the subsequent metallogeny within the successor basins that overlie these domains (see Blevin & Jones, 2004; Chappell et al., 1988; Huston et al., 2015, 2016). A fundamental metallogenic divide exists in the Cobar Basin (Figure 18), with Cu–Au VHMS mineralisation, hosted by Ordovician quartz-rich turbidites of the Girilambone Group, being concentrated in the northeastern basin and within the Canbelego-Mineral Hill Volcanic Belt, and even within the intervening basement (i.e. along with and east of the Rookery Fault). The metallogeny west of the Rookery Fault is blurred by the additional Pb–Zn–Ag fertility of the Cobar Basin sedimentary rocks and the position of the boundary between eastern Girilambone basement and Adaminaby/Bendoc group basement is obscured by the deep-water basin sequences in the north. Nevertheless, Blevin and Jones (2004) noted that the metallogeny of the eastern Cobar Basin and Canbelego-Mineral Hill Volcanic Belt is typical of I-type magmatic-hydrothermal associations, while the metallogeny of prospects associated in the Mount Hope and Rast troughs is more typical of A-type magmatic-hydrothermal associations. Deposits such as the Au–Zn-rich Hera orebody in the southeastern Cobar Basin may also fall into this A-type metal association and curiously occur directly above the Girilambone/Adaminaby basement divide, which has been exploited by A-type melts in this southern region. Even deposits such as the Pb–Zn-rich parts of the Mallee Bull orebody in the central Cobar Basin contain anomalous Sn, display inherited Pb isotopic composition consistent with the Ordovician basement (Downes & Poulson, 2018) and almost certainly overlie Adaminaby/Bendoc group basement. The
contemporaneous southern CLO volcanic rocks erupted exclusively over Adaminaby/Bendoc group basement and host predominantly Sn–W mineralisation; these deposits extend northward to just south of the Cobar Basin (e.g. Tallebung deposit). This mineralisation is thus related to lower crustal melting and concentration of Sn–W during S-type magmatism between ca 420 and 412 Ma.

VHMS and contemporaneous epithermal deposits are proposed to exist in the Mount Hope Group and the Canbelego–Mineral Hill Volcanic Belt (e.g. David, 2006; David & Glen, 2004; Edgecombe & Soininen, 2019), whereas in the deep-water sedimentary sequences massive sulfides are turbidite-hosted and have a strong spatial association with basin faults. Lawrie and Hinman (1998) proposed an orogenic base metal model for these deposits, whereby Cu–Au were leached from the fertile basalt-bearing Girilambone Group and its basement rocks during basin inversion and Pb–Zn–Ag-rich deposits originated from deep Cobar Basin aquifers during inversion. The latter is certainly true, but Fitzherbert et al. (2019, 2021) and Fitzherbert and Downes (2020) presented evidence for a likely pre-inversion magmatic character to the Cu–Au-rich eastern Cobar orebodies and dated the mineralising event to ca 414–408 Ma, which is ca 20 Myr years prior to the ca 390–380 Ma inversion of the Cobar Basin and ca 6–12 Myr younger than much of the inter- and intra-basin magmatism. However, A-type magmatism in the western basin and along the Rookery Fault occurred between 415 and 412 Ma (Boolabone Granite, Ural and Tarran volcanics) along with limited I-type magmatism to 411 Ma in the mineralised northeastern Cobar Basin. We propose the orogenic mineral system model is missing a key step in the metal fertility cycle, this being the further concentration of metals through melting of the fertile lower crust during the Cobar rifting event followed by magmatic transport to near depositional sites via major faults, and final concentration through magmatic crystallisation processes. The faults that control much of the mineralisation are transcrustal, and multiple mineralising events are possible during even small fault motions over the rifting period and potentially into the sag phase of the basin evolution. For syndepositional and basin inversion deposits the metal budget of the successor basin will contribute to the metallogeny. In the case of the Cobar, basin-derived Pb–Zn–Ag mineralisation also occurred during basin inversion, while many deposits along the major fault systems were remobilised and concentrated during inversion (Fitzherbert & Downes, 2020). Thus, the complex metallogeny and relatively large metal endowment of the Cobar Basin has resulted from a combination of enhanced lower crustal fertility, located over a major transcrustal structure(s) that divides two fundamentally different lower crustal domains, increased fertility through lower crustal melting and metal concentration through magmatic processes during successor basin formation and emplacement of the northern CLO volcanic belts. Inversion-related mineralisation further diversified and bolstered the metal endowment, no doubt benefiting from the new basin fertility and the two phases of magmatic metal enrichment that preceded.

As discussed in the previous section, the proposed tectonic regime during the Siluro-Devonian produced the terrestrial topography in the southern CLO and development of the transtensional marine Cobar rift basin in the north. Subaerial volcanism in the southern CLO occurred in combination with deposition broadly coincident with base ment-controlled S-type magmatism. The metal budget resulted in intrusion-related Sn–W as a viable mineralising system. In contrast, the northern CLO was a marine environment proximal to a major transcrustal structure. The fertility of the lower crustal rocks varied from west to east and led to the development of diverse mineral systems. This included rift-related VHMS, epithermal, skarn (Cu–Zn–Au) and intrusion-related deposits (Fitzherbert & Downes, 2020). Inversion generated new deposits from the newly developed basin and remobilised/concentrated older deposits, building and further diversifying the metal endowment in this region.

**Summary**

The CLO volcanic belt in NSW represents emplacement of predominantly silicic, explosive and effusive eruptive products within an approximately 350 km long, 20 km wide series of elongate basins from approximately 428 to 411 Ma. A coincident belt of contemporaneous granitic intrusions makes this one of the most extensive and voluminous volcano-plutonic complexes in Australia.

In the northern volcanic belt, the Cobar Basin and its broadly north–south-oriented volcanic sub-basins, such as the Rast and Mount Hope troughs, opened coeval to volcanic activity in the volcanic belt owing to sinistral transtension. These troughs have controlled and confined the eruptive products. We suggest the Gurragong and Culcairn groups’ subaerial pyroclastic deposits were similarly controlled by extensional tectonics. The subaerial depositional environment of the southern volcanic successions suggests the basins experienced less subsidence than their northern siblings, and the proximity of exposed Siluro-Devonian granites, and the contact metamorphic overprint by younger intrusions, imply shallow intrusion depths accompanied by uplift and erosion of the intrusions prior to and during rifting development.

The volcanic rocks produced in these extensional basins, rather than being bimodal are almost exclusively silicic. Despite being consistently felsic, there is a variation in the aluminium saturation index from peraluminous to metaluminous, and variation in high-field strength elements that may reflect variation in the source rocks and temperature of partial melting. These variations probably affected the associated mineralising fluids, resulting in metallogenic patterns that reflect these basement differences. The metal budget in the southern CLO resulted in intrusion-related
Sn–W as a viable mineralising system. In contrast, the northern CLO was a marine environment proximal to a major transcrustal structure. The fertility of the lower crustal rocks varied from west to east and led to the development of diverse mineral systems.

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No potential conflict of interest was reported by the authors.

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