New lead isotopic and geochronologic constraints on mineralisation in the Macquarie Arc — insights from the Lake Cowal district, New South Wales

Abstract

The Macquarie Arc of eastern Australia hosts several large to world-class Au and Cu deposits, including Cadia and Northparkes. The Cowal district hosts the large Cowal gold mine (Endeavour 42) and other significant Au and Cu deposits including Endeavour (E)41, E43 and Marsden. We present 37 new lead isotope results, including 41 high-precision Pb isotope analyses for the Cowal district, nearly all of which plot within or close to the field for Ordovician porphyry copper–gold deposits of Carr et al. (1995). The data are also consistent with mantle-like lead in the Tasmanides, suggesting that magmas and mineralising fluids did not interact with contemporaneous siliciclastic sediments such as those of the Adaminaby or Girilambone groups. Data for individual deposits mostly have lead model ages consistent with independent age constraints on mineralisation, including a new Re–Os date on molybdenite of 458 ± 2 Ma for porphyry-like mineralisation at Milly Milly.

Results for Au-rich deposits in the Cowal district including E42 have discrete lead isotope signatures compared with porphyry-style copper–gold mineralisation. Overall, discrete lead isotope signatures associated with epithermal and/or mesothermal gold mineralisation at E41 and E42 suggest that a different and/or more intense mineralising event occurred compared with porphyry-style prospects, including E43, E39 and Milly Milly. The results support studies which suggest that mineralisation in the Lake Cowal district occurred in the Ordovician around 450–460 Ma and not during the ‘alkalic’ porphyry–epithermal gold–copper event associated with the world-class Cadia and Northparkes deposits (~436–443 Ma).

Decoy, the only VAMS-style prospect so far identified in the arc, has the least radiogenic lead isotope signature in the Lake Cowal district and is among the most primitive known to be associated with the Macquarie Arc — similar to that for Peak Hill and to some Cambrian MORB-like rocks. Such signatures may represent the substrate to the arc. We also report an unexpectedly young middle Silurian age by the Re–Os dating method, along with relatively evolved lead isotope signatures for the Trundle porphyry deposits southwest of Parkes. Overall, the data highlight lead isotopes as a useful exploration tool in the region.

Keywords: Macquarie Arc, Cowal district, Pb isotopes, Re–Os dating, arc substrate
Introduction

The Ordovician to early Silurian Macquarie Arc of eastern Australia is a volcanic-dominated terrane that hosts a range of deposit types including large to world-class porphyry Au–Cu systems such as Cadia and Northparkes (e.g. Cadia East, Cadia Hill, Ridgeway, Endeavour 22, Endeavour 26 North, Endeavour 27 and Endeavour 48), large gold-only systems including those in the Cowal district such as Endeavour (E)41, E42 and E46 and high sulfidation epithermal gold deposits at Gidginbung and Peak Hill.

In New South Wales the Ordovician to early Silurian Macquarie Arc-related gold–copper and gold-only systems account for over 61% of the state’s gold endowment (~1924 t of Au) and over 75% of the state’s copper endowment (~15.6 Mt of Cu — resources and past production, December 2014; refer to GSNSW MetIndEx Database). As a result, both company exploration and scientific research has been focussed on the porphyry-style systems, such as those at Cadia and Northparkes (see Heithersay et al. 1990; Heithersay & Walshe 1995; Blevin 2002; Holliday et al. 2002; Wilson et al. 2003; Cooke et al. 2007). By contrast, the larger deposits in the Cowal district including E42, otherwise known as the Cowal (or Lake Cowal) gold mine, along with E41 and E46, are of different style and tenor. These larger deposits are not porphyry-style but are: 1) gold dominant, with characteristics of epithermal gold deposits; 2) strongly structurally controlled by faults, shears, competency contrasts; and 3) are associated with rocks of low–medium-K calc-alkaline affinity (Blevin 2002; Crawford, Glen et al. 2007; Cooke & Fanning 2007). Endeavour 42 and E41 have been variously described as mesothermal (Miles & Brooker 1998) or as transitional between porphyry and low-sulfidation epithermal gold systems (Bywater et al. 2004; Henry et al. 2014).

The Cowal district (also known as Lake Cowal district or Cowal mining district) also hosts several porphyry-style mineralised zones including Marsden (the largest porphyry Cu–Au deposit in the district), E39, E43 and Milly Milly (see McInnes et al. 1998; Henry et al. 2014) and volcanic associated massive sulfide (VAMS) mineralisation such as the Decoy prospect. Crawford, Glen et al. (2007) and Crawford, Meffre et al. (2007) published U–Pb dating and geochemical evidence relating mostly to the nature of the host rocks, which are dominated by the Cowal Igneous Complex (Crawford, Cooke & Fanning 2007 — formerly termed the Lake Cowal Volcanic Complex by Raymond et al. 2000). Until recently, few attempts to directly date mineralisation have been successful and a comprehensive metallogenic study to constrain the
age of the ore forming events and the metal reservoirs of the district has yet to be undertaken, although new geological and timing constraints are available from Henry et al. (2014) and Zukowski et al. (2014). The focus of this paper is mineralisation in the Cowal district associated with the Ordovician to early Silurian Macquarie Arc. We present new lead isotope data for several deposits and prospects in that district that complements the existing Pb isotope dataset for the Ordovician to early Silurian Macquarie Arc. In addition, we present new Re–Os dating on molybdenite for the Milly Milly porphyry-style deposit that complements earlier studies by Henry et al. (2014) and Zukowski et al. (2014). It also provides independent constraints to the Pb isotope systematics for the Cowal district and more widely the Macquarie Arc. A limitation of the present study is that no suitable samples for Pb isotope analysis are available from the Marsden Cu–Au deposit.

The present study aims to: establish lead model ages for mineralisation, to better constrain the nature and timing of mineralisation in the Cowal district; identify potential reservoirs of lead as a proxy for copper and/or gold; to better constrain metallogenic events in the area; to compare the Cowal district with other parts of the Macquarie Arc and thereby improve the plumbotectonic model for the region. Finally, the possible substrate to the Macquarie Arc is discussed based on the Pb isotope data (see Forster et al. 2011; Huston et al. in review).

**Geological setting**

The Lachlan Orogen (formerly the Lachlan Fold Belt — Scheibner 1975) represents part of an extensive orogenic system — the Tasmanides (Scheibner & Basden 1996; Foster & Gray 2000; Glen 2005) — that developed during the Ordovician to the middle Carboniferous. This terrane is over 1000 km east–west, and has a roughly north–south strike for about 3000 km, extending along much of eastern Australia from Queensland to Tasmania. The orogen includes three major sub-provinces; the Western, Central and the Eastern subprovinces (see Glen 2005, 2013). The oldest known rocks in the Lachlan Orogen are the Precambrian to Cambrian MORB-like rocks best exposed in serpentinite belts (Cas 1983); the Ordovician siliciclastic turbidite sequences of the Girilambone, Adaminaby and Bendoc groups (Fergusson & Coney 1992), and the volcanic rocks and related units of the Ordovician to early Silurian Macquarie Arc (Glen, Meffre & Scott 2007; Glen, Crawford & Cooke 2007; Glen, Crawford et al. 2007; Glen 2013).

The Ordovician to early Silurian Macquarie Arc has been described and discussed by many workers (Owen & Wyborn 1979; Crawford, Meffre et al. 2007; Crawford, Cooke & Fanning 2007; Glen, Meffre & Scott 2007; Glen, Crawford & Cooke 2007; Glen, Crawford et al. 2007; Fergusson 2009; Glen, Quinn & Xiao 2011; Quinn et al. 2014). It consists of several belts of volcanic and volcanic-derived rocks, with Crawford, Cooke and Fanning (2007) defining four main phases of magmatism and related mineralisation over a period of about 38 Ma. The arc formed contemporaneously with the deposition of siliciclastic turbidite sequences that are now juxtaposed adjacent to it (Colquhoun & Fergusson 1999; Glen, Quinn & Xiao 2011).
The Macquarie Arc is unusual among intraoceanic arcs in that substrate sequences including ophiolites are largely absent. Furthermore, volcanic-derived sediments mostly do not intercalate with the siliciclastic turbidites, and black shale units that flank the terrane and accretionary complexes are absent (Glen et al. 2011). The nature of the substrate is also uncertain. Wyborn (1992) suggested that basement to the arc included Precambrian continental rocks whereas Crawford (2001) drew comparisons with the Mt Read Volcanics where such an association occurs. However, this is inconsistent with the available Pb isotope evidence (see Forster et al. 2011). Glen, Spencer et al. (2007) proposed an alternative model, based on the interpretation of seismic reflection data and structural studies, and suggested that Ordovician volcanic rocks may structurally underlie the terrane. Based on wide ranging evidence, Glen and co-workers (see Glen, Meffre & Scott 2007; Glen, Crawford & Cooke 2007; Glen, Crawford et al. 2007; Glen et al. 2011 and references therein) proposed that the Macquarie Arc formed as an intraoceanic volcanic arc that formed outboard of the proto-Pacific passive margin of Gondwana, with the arc being later disaggregated into four major belts that are preserved today (Figure 1). By contrast, Quinn et al. (2014; see also Glen et al. 2012) presented stratigraphic evidence in support of an alternative model whereby the volcanic sequences formed by rifting during the Ordovician within the already established continental margin.

Figure 2. Geological map of the Cowal district adapted after Raymond et al. (2000), Glen et al. (2006), Glen, Crawford, Percival and Barron (2007) and including interpretations of the geology of the Cowal Igneous complex by Henry et al. (2014). Major deposits and prospects discussed in the text are shown.
The Cowal district

The Cowal (Au–Cu) district lies within the Eastern Subprovince of the Lachlan Orogen, at the southern end of the Junee–Narramine Volcanic Belt of the Macquarie Arc. The Cowal district is approximately 40 km long and 15 km wide, lies between the Booberoi Fault and Marsden Thrust and has been previously informally termed the Cowal block. The Booberoi Fault and Marsden Thrust are terrane-scale faults that divide the Eastern and Central subprovinces of the Lachlan Orogen (Figures 1 & 2). The Cowal block is dominated by the Cowal Igneous Complex (see Glen et al. 2002) which was previously termed the Lake Cowal Volcanic Complex by Raymond et al. (2000). The Cowal Igneous Complex is characterised by Ordovician, subaqueous, volcano-sedimentary successions that have been intruded by diorite to granodiorite stocks and numerous dykes (Figure 2; Miles & Brooker 1998; McInnes et al. 1998; Crawford, Cooke & Fanning 2007). Most have low to medium K, calc-alkaline chemistry (Blevin 2002) which Crawford, Cooke and Fanning (2007) suggested is broadly consistent with subduction-related magmatism.

Attempts to date the rocks and to constrain the timing of hydrothermal mineralisation in the Cowal district have proven difficult. This is mainly due to a lack of zircons or multiple ages being obtained for xenocrystic

Figure 3. Time–space plot showing age constraints for the Cowal district. It includes references for original geochronological analysis and 206Pb/204Pb ratios for deposits, and the dated rock types where available.
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Application of high- and low-Pb isotope data to ore deposit studies

Using the principles of radioactive decay, Pb isotopes can be used to track the formation of geological terranes and mineralising events relative to the age and the initial isotopic composition of the Earth. These include known, homogeneous, crustal Pb reservoirs and primitive lithospheric mantle reservoirs. Geological studies involving Pb isotope data typically derive the ratio of radiogenic $^{206}$Pb (formed from the radioactive breakdown of $^{235}$U) to common lead ($^{204}$Pb), which relates to the age of the primitive Earth, and compare that ratio to $^{207}$Pb/$^{204}$Pb and $^{208}$Pb/$^{204}$Pb — where $^{207}$Pb is generated by radioactive decay of $^{238}$U, and $^{208}$Pb is the decay product of $^{232}$Th (Stacey & Kramers 1975). This enables the calculation of plumbotectonic models for specific terranes relative to $\mu$, or the initial calculated $^{238}$U/$^{204}$Pb value for a specific terrain (e.g. Stanton & Russel 1959).

Lead isotope studies can also provide insights into ore genesis and can improve the understanding of metal sources including ‘model ages’ for groups of mineral deposits within a given terrane. Major magmatic and hydrothermal events typically result in the loss of $^{238}$U, $^{235}$U and $^{232}$Th and homogenise Pb isotope values unless overprinted by separate high-Pb events, or by the addition of radiogenic Pb (see Doe & Stacey 1974; Faure & Messing 2005). Cumming and Richards (1975) computed a Pb/Pb model age for Phanerozoic rocks of eastern Australia, which produced results very similar to independently obtained ages for ores containing crustal Pb. In a very important contribution, Gulson and Mizon (1979) used Pb isotopes to characterise deposits, including secondary ores, and related these to specific metallogenic districts and events. Carr et al. (1995) used Pb isotope ratio data for approximately 100 metallic mineralised zones/deposits to investigate the metallogenic evolution of the eastern Lachlan Orogen, including a number of systems associated with the Macquarie Arc. Those authors divided deposits according to whether Pb was derived from crustal or mantle reservoirs and suggested that there was mixing between the two reservoirs over time. Forster et al. (2011) highlighted that the Pb isotope signatures for Ordovician to early Silurian mineralisation of the Macquarie Arc indicate that mixing did not occur between reservoirs and that virtually all the Pb associated with the arc was mantle-like. This is consistent with an arc devoid of crustal-derived siliciclastic sediments prior to the Benambran Orogeny that commenced around 443 Ma (Percival & Glen 2007). Finally, Forster et al. (2011) noted correspondence the between Pb model ages and mineralisation ages based on independent constraints. Further, mineralised intrusions of the Macquarie Arc became more compositionally evolved over time based on higher $^{206}$Pb/$^{204}$Pb and age corrected $\varepsilon$Nd values (see also Wyborn & Sun 1993).

In studies using Pb isotope data, samples can be described as high- or low-lead. High lead samples generally contain galena, other Pb-rich minerals and/or have generally greater than ~700 ppm Pb (see Gulson 1986). For such samples there is generally...
insufficient $^{238}\text{U}$, $^{235}\text{U}$ and/or $^{232}\text{Th}$ to significantly change the initial Pb isotope ratios so the results would normally be considered to preserve an ‘initial’ Pb isotope ratio. By contrast, for samples with low amounts of Pb the presence of $^{238}\text{U}$, $^{235}\text{U}$ and/or $^{232}\text{Th}$, even in small amounts, can significantly change the initial Pb isotope ratio. Therefore the addition of radiogenic Pb formed after mineral deposition, needs to be corrected for, by measuring and applying an appropriate correction for the contained U and Th.

**Sampling and analytical techniques**

Forty-four new samples from the Cowal district were analysed at the University of Melbourne, School of Earth Sciences. Seven other samples, including those by Forster et al. (2011), were analysed using mass spectrometry at the CSIRO Earth Science and Resource Engineering laboratories in Sydney (see Carr & Dean 1987; Carr et al. 1995 for methodologies). Errors, expressed as analytical precision, are shown in the upper left corner of all the Pb isotope diagrams as 95% confidence ellipses based on over 1400 analyses (Carr et al. 1995).

Samples included in the present study were sourced from drillcore except for a single hand sample of galena (from Trents Lode at E42). Sample preparation varied according to the nature of the sample and laboratory location. Samples prepared at the Geological Survey of New South Wales were drilled using a micro-drill under a binocular microscope, crushed and any magnetic material removed with a rare earth magnet. Samples prepared at the University of Melbourne. Thirty-nine of the analyses contained <700 ppm (700 000 ppb) Pb (see Table 1, p. 20) and are therefore considered ‘low-lead’ samples according to Gulson (1986). As noted above, this required that corrections be applied for $^{238}\text{U}$ and $^{232}\text{Th}$. The corrections were applied based on their total U–Th–Pb concentrations and calculated parent/daughter ratios. The calculations included $^{238}\text{U}$/204Pb (or $\mu$) and $^{232}\text{Th}$/204Pb. The greater these values, the greater the variance between the observed and corrected values and the greater the error inherent in these corrections.

The correlations of measured results (not accounting for internal errors) of $^{207}\text{Pb}/^{204}\text{Pb}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$ gave $r$ factors of 0.990 and 0.962 respectively. The samples also have correspondingly higher calculated $^{238}\text{U}$/204Pb and $^{232}\text{Th}$/204Pb ratios, indicating that these radiogenic results are from in situ radioactive decay of $^{238}\text{U}$ and $^{232}\text{Th}$. Therefore, these results (including nine from the Cowal district) were excluded from the dataset (see Forster & Maas 2015).

As part of the present study, a sample of molybdenite from the Milly Milly prospect was dated by the Re–Os method at the Australian National University, Research School of Earth Sciences (see Stein et al. 2001; Norman et al. 2004).

**Mineralisation and results**

The data in the present study from the Cowal district included 41 samples analysed at the University of Melbourne. Thirty-nine of the analyses contained <700 ppm (700 000 ppb) Pb (see Table 1, p. 20) and are therefore considered ‘low-lead’ samples according to Gulson (1986). As noted above, this required that corrections be applied for $^{238}\text{U}$ and $^{232}\text{Th}$. The corrections were applied based on their total U–Th–Pb concentrations and calculated parent/daughter ratios. The calculations included $^{238}\text{U}$/204Pb (or $\mu$) and $^{232}\text{Th}$/204Pb. The greater these values, the greater the variance between the observed and corrected values and the greater the error inherent in these corrections.

The corrections were for the contained $^{238}\text{U}$ and $^{232}\text{Th}$ in each sample assuming a geologically reasonable age of 450 Ma for the Cowal district samples (see previous dating studies by Perkins et al. 1995; Henry et al. 2014). As outlined above, less-radiogenic analyses were preferred as they were more likely to preserve initial Pb isotope ratios.
This procedure left 31 new Pb isotope analyses for the Cowal district which are included in Table 1, on Figure 4 and are discussed below. The analyses include; 1) a new sample of galena from E41; 2) a single result from Decoy that contains >1000 ppm Pb; and 3) twenty-nine results from low-lead samples from a range of sulfides, feldspars and rocks. The low-Pb results included 11 from three prospects (Decoy, Logjam and Eurowie) which have measured vs corrected $^{206}\text{Pb}/^{204}\text{Pb}$ that vary by $<0.05\%$, or less than the analytical error, and therefore reflect initial ratios. Seven high-Pb analyses by the CSIRO from E41, E42 and E46 were presented by Forster et al. (2011) and are included in Table 1. Mineralisation associated with the Ordovician to earliest Silurian Cowal district can mainly be grouped as structurally controlled or porphyry-related. Structurally controlled gold-dominant systems include E41, E42 (Cowal gold mine) and E46. Porphyry-related copper–gold systems include Marsden, E39, E43, Logjam and Milly Milly. We present data (roughly from north to south) to give a geographic context to each deposit. Interestingly, the initial $^{206}\text{Pb}/^{204}\text{Pb}$ for individual mineral systems roughly decreases southwards with the exception of the Decoy prospect, which is probably a VAMS system.

**Structurally controlled mineralisation within the ‘gold corridor’ (E40, E41, E42 and E46)**

Several mineralised zones lie along a north–south-trending, structurally deformed belt that is 6 km long by 2 km wide (the ‘gold corridor’) located on the western margin of the Cowal Igneous Complex (Miles & Brooker 1998; McInnes et al. 1998; Zukowski et al. 2014; Henry et al. 2014). From north to south they include E46, E42 and E41 (Figure 2). All are controlled by faults and shears and are located along the margin of an elongate northerly trending diorite sill — the Muddy Lake Diorite (Miles & Brooker 1998).

**E42 and E46**

The geology and mineralisation at E42 (Cowal gold mine) has been described by several workers including Miles and Brooker (1998), McInnes et al. (1998), Zukowski et al. (2014) and Henry et al. (2014) and is summarised below. The mine is hosted by a sequence including lower and upper volcaniclastic units that were tilted and subsequently intruded by a series of dykes and sills. These intrusions include at least four sets of dykes. In general dykes of mafic to intermediate composition pre-date mineralisation, whereas two sets of intermediate dykes post-date mineralisation (Henry et al. 2014; Zukowski et al. 2014). The deposit consists of gold-rich quartz–carbonate–pyrite–base-metal sulfide veins associated with sericite–carbonate–pyrite alteration. Less commonly, gold occurs with pyrite stringers and disseminations, shear-hosted chlorite–carbonate veins and shear-hosted quartz–carbonate–sulfide veins. Several stages of alteration have been identified at E42, with the post-mineralisation stage being pervasive adularia–silica alteration. Henry et al. (2014) classifies E42 as a deep epithermal deposit but notes that there are many features common to structurally controlled rather than intrusion-related deposits. However, earlier workers (e.g. Miles & Brooker 1998; McInnes et al. 1998) described many features of the deposit as being characteristic of mesothermal and orogenic gold systems.
To the north of E42 is the E46 zone, which may represent the northerly extension of E42. The geological setting for both is similar, being hosted by the same sequence, with a similar series of late dykes and sills. The gold mineralisation is associated with dilatant quartz–carbonate–sulfide (base-metal) veins at the faulted contact between the diorite sills and volcaniclastic and coherent volcanic rocks — analogous to those at E42. Barrick Limited (2010) interpreted the deposit as being located towards the base of the volcaniclastic sequence which is exposed at E42.

Dating of the gold mineralisation event at E42/ E46 has so far been problematic, with the timing of mineralisation being constrained by a range of dates. These include K–Ar dates on hornblende of 456 ± 5 Ma for the host diorite (Perkins et al. 1995; Bastrakov 2000) and 447 Ma ± 7.0 Ma for a cross-cutting vesicular dyke (Miles & Brooker 1998). In addition, a U–Pb SHRIMP age for monazite from a post-mineralisation diorite dyke that cuts the Cowal fault yielded 450.3 ± 1.3 Ma (Henry et al. 2014; see also Strickland 2005) (Figure 3).

Four high-Pb analyses from E42 and E46 are available, along with four new high-precision low-Pb results from key rock types at E42 that are associated with mineralisation (Table 1). The high-Pb results average 206\(^{\text{Pb}}/204\(^{\text{Pb}} = 17.968\), 207\(^{\text{Pb}}/204\(^{\text{Pb}} = 15.466\) and 208\(^{\text{Pb}}/204\(^{\text{Pb}} = 37.593\) and are within analytical error of five previous results from the CSIRO database and thus were ascribed to the homogeneous population Group CwA by Forster et al. (2011 — Group CwA1 on Figure 5). Low-Pb results (corrected for \(238\text{U}\) and 232\(^{\text{Th}}\)) average 206\(^{\text{Pb}}/204\(^{\text{Pb}} = 17.968\), 207\(^{\text{Pb}}/204\(^{\text{Pb}} = 15.454\) and 208\(^{\text{Pb}}/204\(^{\text{Pb}} = 37.688\) (see also discussion of E41 below) and define a tight group within analytical error of the CSIRO data (Group CwA2). The corrected low-Pb results, which include the vesicular dyke, are more variable and include higher 208\(^{\text{Pb}}/204\(^{\text{Pb}}\), largely due to the greater error inherent in \(^{208}\text{Pb}\). Nonetheless, they are distributed about the mean of high-Pb results that define Group CwA.

The E41 deposit occurs to the south of E42 and consists of two mineralised zones separated by the deposit scale Cowal Fault (Figure 2). The deposit has a total combined resource of 12.6 Mt @ 1.6 ppm Au. Like E42, mineralisation occurs near the margin of the Muddy Lake Diorite, which intrudes the volcaniclastic sequence along with numerous sills, dykes and stocks (informally termed the E41 intrusive complex). At E41, the major vein/mineralisation stages include early quartz–pyrite ± calcite ± adularia ± chloride veins, and later carbonate–base-metal sulfide veins (calcite, ankerite, quartz, pyrite, sphalerite, galena, chalcopyrite, silver tellurides, arsenopyrite) with associated apatite, hematite, illite–muscovite and chloride alteration. Late quartz–sulfide breccias contain colloform vein textures, chalcedony and adularia. The mineralisation is associated with intrusive phases including dykelets, and vein and alteration assemblages that are characteristic of both porphyry and low to intermediate sulfidation epithermal deposits. These features led Zukowski (2010) and Zukowski et al. (2014) to suggest that the deposit was a deeply emplaced epithermal gold–base-metal deposit with a structural overprint that had been unroofed during
the mineralising event. The maximum age of E41 is constrained by a U–Pb age of 465 ± 5.2 Ma for the host Muddy Lake Diorite and of 458.5 ± 5.2 Ma for a pre-mineralisation mafic monzonite intrusion emplaced after tilting (Zukowski et al. 2014).

For E41, four analyses for galena (Forster et al. 2011) and two corrected low-Pb results are available. They average $^{206}\text{Pb}/^{204}\text{Pb} = 17.988$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.459$ and $^{208}\text{Pb}/^{204}\text{Pb} = 37.681$ and have slightly greater variance than data for E42 and E46. Two high-Pb and one corrected result from a low-Pb sample of the monzonite that intrudes the Muddy Lake Diorite are conspicuously more radiogenic than the remaining samples which plot within Group CwA2 along with results from E42 and E46 (Figure 5).

**Porphyry-associated mineralisation**

The Cowal district hosts several porphyry-style prospects, some of which also have epithermal characteristics. These include E39, E43, Logiam and Milly Milly (Figure 2). They are associated with monzodiorite, monzonite and granodiorite intrusions of predominantly medium-K calc-alkaline affinity that are not strictly porphyries, but are associated with holocrystalline intrusive rocks (Miles & Brooker 1998; Blevin 2002; Crawford, Cooke & Fanning 2007; Zukowski et al. 2014).

**Eurowie**

The Eurowie prospect is the most southerly of a series of gold–copper occurrences within the Wyrra district (see Figure 2). The host rocks at the prospect include coherent diorite to monzodiorite and bedded variably calcareous volcaniclastic units of calc-alkaline affinity which are intruded by mafic feldspar porphyry and diorite dykes. Gold mineralisation is associated with widespread silica–illite–pyrite alteration which grades to a deeper potassic K-feldspar–biotite–magnetite and hematite alteration that appears to be fault and breccia controlled (this study).

Eight new corrected initial ratio Pb isotope results for mineralised veins from Eurowie are the most radiogenic for the Cowal district overall, averaging $^{206}\text{Pb}/^{204}\text{Pb} = 18.019$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.468$ and $^{208}\text{Pb}/^{204}\text{Pb} = 37.729$ (Table 1). All but one corrected result from sulfides and feldspars are within analytical error of measured values. Sulfides and feldspars are grouped separately on Figure 6 (Groups EuA and EuB), with the sulfides being more radiogenic. These minerals were sampled from an amphibole–chlorite–calcite–feldspar vein with a magnetite selvage (see Figure 7). Other corrected results for the sulfide-bearing host rocks from Eurowie prospect (five Wyrra samples) were more variable due to the greater inherent error (especially for $^{208}\text{Pb}$) given the samples’ higher U/Pb and Th/Pb.

**E43**

Vein- and breccia-hosted chalcopyrite±bornite-bearing mineralisation at E43 is spatially associated with a series of early and syn-mineralisation porphyry intrusions that include diorite and granodiorite. Quartz dacite along with aplite and pyroxene-phycy dykes are also closely spatially and temporally associated with the sulfides (Zukowski 2009). Sulfide (chalcopyrite±pyrite) filled fractures are generally sparse, discontinuous and are associated with a
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The age of 463.5 ± 2.1 Ma by the Re–Os method on molybdenite (H. Stein, Research School of Earth Sciences, Australian National University, unpublished data) was also reported by Bissig et al. (2008). As part of the present study feldspar from a quartz dacite was analysed for a Pb isotope signature (Table 1). The corrected data plot at \( ^{206}\text{Pb} / ^{204}\text{Pb} = 17.906, ^{207}\text{Pb} / ^{204}\text{Pb} = 15.453, ^{208}\text{Pb} / ^{204}\text{Pb} = 37.652 \) and is one of the least evolved results for porphyry-related mineralisation identified in the present study.

Logjam

Porphyry-style copper–gold mineralisation at the Logjam prospect 12 km southeast of E42 (Figure 2) and involves potassic alteration (biotite, magnetite and K-feldspar). The veining is generally weaker than at several other porphyry prospects in the area, with a pervasive chlorite alteration predominant. Three analyses were undertaken as part of the present study (Table 1, Figure 6). Two samples of galena from a zone that assayed 1160 ppm Pb yielded corrected results which plotted within error (\( ^{206}\text{Pb} / ^{204}\text{Pb} = 18.000, ^{207}\text{Pb} / ^{204}\text{Pb} = 15.456 \) and \( ^{208}\text{Pb} / ^{204}\text{Pb} = 37.541 \)). In addition, a single analysis of galena from an altered and veined breccia clast in a rock flour matrix gave corrected and measured values within analytical error (measured \( ^{206}\text{Pb} / ^{204}\text{Pb} = 17.917, ^{207}\text{Pb} / ^{204}\text{Pb} = 15.455 \) and \( ^{208}\text{Pb} / ^{204}\text{Pb} = 37.547 \)).

Milly Milly and E39

Although about 10 km apart, the E39 and Milly Milly copper–gold prospects are both porphyry-like and have similar features. Milly Milly is associated with diorite to monzodiorite and granodiorite stocks whereas E39 is entirely hosted by granodiorite, possibly suggesting that Milly Milly represents a shallower equivalent of E39 (see McInnes 2010).

E39

Miles and Brooker (1998) noted that the E39 copper–gold system (Figure 2) is a large, low-grade system developed entirely within the granodiorite. At E39, early potassic alteration is overprinted by a later sericitic alteration assemblage that is closely associated with quartz–carbonate–chlorite±tourmaline–chalcopyrite–bornite±molybdenite veins (Miles & Brooker 1998) with sulfides, chlorite and epidote developed after ferromagnesian sites in alteration haloes. Highest copper and gold grades coincide with the steeply dipping sheeted veins. Previous dating at E39 has failed to resolve the timing of mineralisation (see Figure 3). Perkins et al. (1995) dated a diorite porphyry from near E39 at ~457 ± 5 Ma (K–Ar on hornblende). However, dating of the same sample of the host granodiorite gave ages of 465.7 ± 1 Ma

Figure 7. Photograph of diamond drillcore from drillhole WYD003 (441.5 m depth) showing amphibole–chlorite–calcite–feldspar–pyrite–chalcopyrite vein with a magnetite selvage. The drillcore was sampled for Pb isotopes on individual grains of chalcopyrite and feldspar. Cal = calcite, Py = pyrite, Mt = magnetite, Fld = feldspar. Coin is 19 mm diameter.
and 450.9 ± 4.5 Ma using 40Ar/39Ar and U–Pb SHRIMP methods respectively (Figure 3, Perkins et al. 1995; Crawford, Cooke & Fanning 2007). Dating of sericite from the ore zone yielded a signiﬁcantly younger age of 439.6 ± 1.1 Ma (Perkins et al. 1995).

Two Pb isotope results for feldspars from a diorite porphyry dyke and the host granodiorite at E39 are more radiogenic and less radiogenic respectively than group CwA1, for high-Pb results for the ‘gold corridor’ (Table 1, Figures 3 and 5).

**Milly Milly**

The Milly Milly copper–gold porphyry system is about 10 km south-southwest of E39 and has mineralisation associated with probable diorite to monzodiorite and granodiorite stocks. Early potassic alteration at Milly Milly is overprinted by a sericitic alteration assemblage that is very similar to that at E39.

Dating of molybdenite from an equigranular monzonite segregation within monzodiorite at Milly Milly gave an age of 458 ± 2.0 Ma using the Re–Os technique. The sample was from diamond drillhole MMD003 (142.2 m depth). The Re content (377 ppm) of the dated sample is low compared with other porphyry systems in the Macquarie Arc, suggesting a different magma source and/or degree of fractionation of the progenitor intrusion (M. Norman pers. comm. 2012).

A single Pb isotope analysis of molybdenite-rich sulfides from the dated sample gave a result that lies outside the normal range related to the Macquarie Arc (206Pb/204Pb = 21.236, 207Pb/204Pb = 15.790, 208Pb/204Pb = 39.304) and probably does not represent initial Pb isotope ratios.

**Other**

The Decoy copper–gold–zinc prospect lies within a magnetic low about 1.5–2 km wide and is located just to the north of E35 (Figure 2). The mineralisation is hosted by mafic to intermediate trachyandesite, hyaloclastite volcanioclastic breccia, sandstone and mudstone units within a southeast-striking graben-structure that together indicate deposition in a submarine environment (McInnes 2008). The mineralisation is copper–gold–zinc-rich and is anomalous in arsenic, barium and cobalt. Although disrupted by faulting, the zinc-rich mineralisation grades inwards and downwards to a chalcopyrite-rich zone. The zone includes a massive chalcopyrite–pyrite-rich lens with >80% sulfides from altered host rock. Chalcopyrite and pyrite stringers are present beneath the highest grade zones (including 26 m @ 1.38 g/t Au and 0.49% Cu), with chalcopyrite observed to replace fractured pyrite. Decoy is also strongly zoned, with sulfide-rich zones grading outwards and upwards to chlorite–pyrite–chalcopyrite-rich alteration and peripheral silica–sericite–pyrite alteration. These features led Gemmel (2010) to suggest that Decoy has a VAMS association.

Five high-precision Pb isotope analyses are available for Decoy (Table 1). Two of the three samples contained visible galena. Four of the five analyses plot in a tight group, almost within analytical error (Figure 8). Measured results average 206Pb/204Pb = 17.711, 207Pb/204Pb = 15.430 and 208Pb/204Pb = 37.323, whereas corrected results plot in a tight group (Group DcA

**Figure 8.** Plumbotectonic models for a) 206Pb/204Pb vs 207Pb/204Pb and b) 206Pb/204Pb vs 208Pb/204Pb for the Lachlan Orogen by Carr et al. (1995). Summary Pb isotope data for the Cowal district and other deposits discussed in the text are superimposed. The model shows the average fields for groups of deposits associated with major groups of rocks and tectonic events of the Lachlan Orogen. Radiogenic results with 206Pb/204Pb >18.3 are not shown.
— average = $^{206}\text{Pb}/^{204}\text{Pb} = 17.678$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.428$
and $^{208}\text{Pb}/^{204}\text{Pb} = 37.360$. As the age of the Decoy prospect is unknown, the same correction of 450 Ma was applied for Decoy as for other deposits. However, given the low U/Pb ratios, varying the age corrections even by 100 Ma has negligible effect. All results are slightly enriched in $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{207}\text{Pb}/^{204}\text{Pb}$ compared with the Ordovician copper–gold field on the plumbotectonic model of Carr et al. (1995).

**Discussion**

New high precision Pb isotope data from the Cowal district mostly form shallow positive arrays on $^{208}\text{Pb}/^{204}\text{Pb}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{207}\text{Pb}/^{204}\text{Pb}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$ plots. They closely conform to the mantle growth curve2 of Carr et al. (1995), strongly suggesting mantle-like, or unevolved sources of lead. Such values are typical of mineralisation associated with the Ordovician to early Silurian volcanic rocks of the Macquarie Arc and have been used to define the field for Ordovician porphyry-related copper–gold mineralisation by Carr et al. (1995). The new Pb isotope data are also consistent with those for mantle-like reservoirs including Pacific MORB (Hanan & Graham 1996; Saal et al. 1998). Overall, the data support previous interpretations by Carr et al. (1995) and Forster et al. (2011), who found no evidence for lead with elevated $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{206}\text{Pb}/^{204}\text{Pb}$ that is characteristic of crustal Pb reservoirs known in the Lachlan Orogen prior to the Benambran Orogeny.

New high precision data also corresponds well with lower precision CSIRO data (Table 1). Deviations toward more crustal values are greater for $^{208}\text{Pb}/^{204}\text{Pb}$, are associated with low-Pb samples, and can mostly be explained by the greater variability for $^{208}\text{Pb}$ and the greater error inherent in calculations of initial ratios from samples with low Pb and high U/Pb ratios. The data support the interpretation that a single, mantle-like reservoir was associated with most of the mineralisation in the Cowal district (see Forster et al. 2011). This implies that mixing with lead of higher $^{208}\text{Pb}$ and $^{207}\text{Pb}$ did not occur, and therefore, that the Pb reservoir(s) in the Cowal district formed independently from more ‘crustal’ Pb, according to the Pb isotope models applicable to the region (see Cumming & Richards 1975; Carr et al. 1995). The data do not support mixing between the mantle-like lead, and reservoirs with much higher or lower $^{232}\text{Th}/^{204}\text{Pb}$ and/or $^{238}\text{U}/^{204}\text{Pb}$ (µ). Rocks of the Macquarie arc and the Cowal district in particular have very low abundances of lead. Therefore, interaction between the mineralising fluids and more Pb-rich and more ‘crustal’ sources of lead (such as siliciclastic sedimentary rocks of the Adaminaby Group or Wagga Group) should have scavenged lead and produced higher $^{208}\text{Pb}/^{204}\text{Pb}$ and $^{207}\text{Pb}/^{204}\text{Pb}$ with deviations from the mantle array (see Glen et al. 2013; Bouse et al. 1999). An interpretation of predominantly mantle-like sources is also supported by the available whole-rock geochemical data for the Cowal district (Crawford, Meffre et al. 2007) and by regional eNd data (Wyborn & Sun 1993; Crawford, Cooke & Fanning 2007; Huston et al. in review; P. Blevin unpubl. data).

**Cowal ‘gold corridor’ (E40–E41–E42–E46)**

Structurally controlled mineralisation of deep epithermal to mesothermal style at E41 and at E42–E46 (the ‘gold corridor’) gave results consistent with mantle-like Pb as defined by existing models (Figures 8). Excluding three more radiogenic results for E41 (which are interpreted to not represent initial ratios) the results from mineralisation at E41, E42 and E46 deposits plot almost within analytical error as defined by Group CwA1 (average $^{206}\text{Pb}/^{204}\text{Pb} = 17.974$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.466$; corr = 0.87, $^{208}\text{Pb}/^{204}\text{Pb} = 36.623$, n = 6) (Figure 5). Furthermore, a very precise group (CwA2) is defined by six high-Pb samples from E41, E42 and E46 and one corrected result from a vesicular dyke at E42. Group CwA2 averages $^{206}\text{Pb}/^{204}\text{Pb} = 17.967$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.465$ and $^{208}\text{Pb}/^{204}\text{Pb} = 37.560$, with close correspondence for $^{206}\text{Pb}/^{204}\text{Pb}$ vs $^{208}\text{Pb}/^{204}$ and $^{207}\text{Pb}/^{204}\text{Pb}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$ compared to the Ordovician Macquarie Arc field of Carr et al. (1995) (Figure 5).

These results are consistent with a homogenous Pb reservoir that is associated with mineralisation (see Gulson et al. 1987). A single corrected result for a vesicular dyke dated at 447 ± 4 Ma by the U–Pb SHRIMP method on zircon, corresponds precisely with Group CwA. We propose a model whereby the unique signature reflects a homogenous lead reservoir which formed during the mineralising ‘gold corridor’ event, roughly synchronously with deformation and the emplacement of phryic dykes.

More radiogenic results for E41 plot on a shallow positive slope relative to Group CwA2. Figure 5b shows this trend as a secondary isochron forced through Group CwA, thus relating the more radiogenic results to that population (see also Carr et al. 1995, p. 1473).

These data are consistent with the complex paragenetic associations described by Zukowski et al. (2014) that suggest that mineralisation at E41 was associated with magmatic–hydrothermal processes, characteristic of porphyry and low-sulfidation epithermal-style mineralisation. By contrast, at E42 porphyry and epithermal features are less well-developed, with mineralisation associated with intense structural
dilatancy. The structural history included a second stage of gold mineralisation which marks a change from an extensional to a compressional structural regime during the formation of E42 (Henry et al. 2014).

**Porphyry-associated deposits**

All but one result for porphyry-style prospects (for which measured and corrected values are within analytical error) plot on a linear array and are within or slightly above the field for Ordovician copper–gold deposits on the plumbotectonic models of Carr et al. (1995). Despite the deviations toward more crustal values, $^{206}\text{Pb}/^{204}\text{Pb}$ vs $^{207}\text{Pb}/^{204}\text{Pb}$ ratios noted above and corrected results for whole-rock samples have quite similar average $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{207}\text{Pb}/^{204}\text{Pb}$ compared with the Eurowie prospect sulfides, and generally plot about results for the high-Pb samples from the Cowal district (Figure 6). We suggest that the porphyry deposits are related to a single, fundamental source of mantle-like lead that is typical of ore deposits associated with the Macquarie Arc. Major deviations from mantle values are interpreted to be mainly the result of calculations of initial ratios for low-Pb samples with high U/Pb and Th/Pb.

However, in detail, data for individual porphyry deposits plot in less well-defined groups compared with results from the ‘gold corridor’. The data for E39 and Logjam suggest that there was insufficient Pb and an absence of large-scale hydrothermal activity — resulting in an inhomogeneous Pb isotope signature compared to E41, E42 and E46.

**Regional comparisons**

The Pb isotope signatures for the Cowal district, supported by the age dating of intrusions and mineralisation now available, are distinct from the Pb isotope signatures associated with deposits at Cadia and in the Goonumbla district (Northparkes etc; see Figure 8; Carr et al. 1995; Forster et al. 2011).

Cadia and Northparkes deposits formed around 443–437 Ma, roughly coincident with the Benambran Orogeny (Figure 8, Forster et al. 2004; Glen, Meffre & Scott 2007; Glen, Crawford & Cooke 2007; Cooke et al. 2007; Percival & Glen 2007). The distinctly less radiogenic signatures in the Cowal district imply that the $^{40}\text{Ar}/^{39}\text{Ar}$ dates on sericite of 438.6 ± 0.5 Ma (Perkins 1993) and 437.6 ± 0.6 Ma (Perkins et al. 1995) from within the ore zone at the Cowal mine reflect metahydrothermal activity associated with the Benambran Orogeny, not the mineralising event associated with the ‘gold corridor’ which we interpret to have formed about 450–455 Ma. Furthermore, the almost unique Pb isotope signatures for economically significant gold mineralisation in the Cowal ‘gold corridor’ contrast with the disparate signatures of the synchronous to slightly older porphyry deposits (e.g. Milly Milly — 458 ± 2 Ma), all of which are sub-economic, highlighting Pb isotopes as a useful exploration tool in the region (see Gulson et al. 1987).

Mantle-like Pb isotopic signatures are almost ubiquitous for the Macquarie Arc (Wyborn & Sun 1993; Carr et al. 1995; Crawford, Meffre et al. 2007; Crawford, Cooke & Fanning 2007). By contrast, the Pb isotope signatures for many of the mineralisation styles (including porphyry-style deposits analogous to those at Cowal) that post-date the Benambran Orogeny, have either mixed signatures or crustal-dominant signatures (see Carr et al. 1995; Downes 2009). New Pb isotope data for the porphyry-style Trundle and Rose Hill prospects are a good example of this (see Figure 1, Figure 8 and Forster & Maas 2015). Both prospects are hosted by Late Ordovician volcanic rocks, are probably associated with quartz monzonite to quartz syenite stocks, and are in many respects analogous to systems such as E22 and E26 at Northparkes. However, recent dating suggests that the mineralisation at Trundle is Early Devonian in age (Re–Os age of 418.6 Ma ± 2 Ma on molybdenite from Trundle — D. Forster and M. Norman unpublished data). An Early Devonian age for mineralisation at Trundle is also supported by a Pb–Pb model age of ~396 Ma (Figure 8). The Pb isotope values for Rose Hill and Trundle have high $^{208}\text{Pb}/^{204}\text{Pb}$ and $^{207}\text{Pb}/^{204}\text{Pb}$ ratios that plot distinctly above the mantle-like field for Ordovician Cu–Au deposits of Carr et al. (1995). This indicates that mixing between mantle-like and crustal Pb reservoirs occurred after accretion of the Macquarie Arc along the eastern margin of Gondwana (see Glen 2013). The identification of such mixed signatures for deposits interpreted as being associated with the Ordovician to earliest Silurian Macquarie Arc is significant and emphasises the usefulness of Pb isotopes in discriminating between deposits formed as part of the arc and those formed as a result of later events.

**Decoy**

As well as being the first recognised VAMS-style copper–gold prospect associated with the Macquarie Arc, the Decoy prospect, which shares several characteristics with the nearby E35 prospect, has most un-radiogenic signature for deposits in the Cowal district and is the second most un-radiogenic known to be associated with the Macquarie Arc. The data for Decoy is analogous to that for Peak Hill, which has the most un-radiogenic mantle-like signature so far identified in the Macquarie Arc. Carr et al. (1995) used the data for Peak Hill to define the un-radiogenic
end member of the field for Ordovician copper–gold deposits associated with the Macquarie Arc. Like Peak Hill, Decoy may reflect lead being sourced from older, possible Cambrian or Early Ordovician MORB-like Pb reservoirs (see Forster et al. 2011) by deeply cycled seawater-rich fluids. Such an interpretation is supported by a lead model age of ~484 Ma for Decoy that is older than the age of the host rock sequence. The metal abundance for VAMS-type mineralisation reflects the metal endowment of the volume of the rock within the reaction zone that forms the source area to that zone/deposit (see Franklin et al. 2005). Given that units forming the Macquarie Arc have low to very low lead abundances, it is likely that deposits such as Decoy will also have low lead abundance but be enriched in a range of elements including copper, gold and zinc. Franklin et al. (2005) noted that VAMS-type systems associated with mafic-dominated sequences (such as the Macquarie Arc where siliciclastic sedimentary rocks are lacking) have average abundances of only 0.02% Pb but host average grades of 1.2% Cu, 0.84% Zn, 1.4 g/t Au and 10.62 g/t Ag. Such grades are analogous to Decoy, further supporting a VAMS association, although silver grades are mostly <5 g/t.

Implications for the substrate to the Macquarie Arc

The substrate to the Macquarie Arc is poorly exposed and largely speculative. It most likely consists of serpentinised MORB-like rocks of Cambrian age, but for the most part they are not in contact. Quinn et al. (2014) suggested that basement to the turbidite sequences that flank the Macquarie Arc includes MORB-like ophiolite units such as those near Kiandra and Tumut, but such rocks are not well exposed within the arc itself. Lead, and to an extent neodymium isotopes can fingerprint unexposed metal reservoirs (Gulson & Mizon 1979; Gulson 1986; Carr et al. 1995). Forster et al. (2011) and Huston et al. (in review) noted the unradiogenic and isotopically primitive, mantle-like source of lead in parts of the Macquarie Arc and suggested that the signatures reflect part of the poorly exposed substrate. Decoy and Peak Hill have similar lead isotope signatures to Cambrian MORB-like mafic and ultramafic rocks such as those near the Ponto mine. Lead isotope data for the Ponto mine, which is hosted by Cambrian sedimentary rocks (see Greenfield et al. 2010) in western New South Wales, are closely analogous to the data for Peak Hill and support the interpretation that Cambrian to Early Ordovician MORB-like units are present at Peak Hill and at Decoy. Such rocks could form a key component of the substrate to the Macquarie Arc. Given that isotopic data is a useful exploration tool in the region.

Conclusions

The lead signatures of the Cowal district suggest that lead and ore metals were sourced from mantle-dominated lead reservoirs. Structurally controlled epithermal and porphyry-style mineralisation in the district probably formed 465–450 Ma, significantly before the Cadia and Goonumbla (Northparkes) systems which formed ~440 Ma. The plumbotectonic model of Carr et al. (1995) applies to the Cowal district. However, higher 206Pb/204Pb ratios for individual deposits correspond with (younger) independent age constraints on mineralisation. We suggest that mineralisation of the Macquarie Arc was associated with one or more long-lived lead reservoirs that were not heterogeneous with respect to µ prior to the Benambran Orogeny, supporting previous interpretations by Forster et al. (2011). The unique lead signatures associated with major mineral districts compared with weaker mineralisation and more crustal or evolved signatures associated with unexpectedly young prospects such as Trundle, highlights that Pb isotope data is a useful exploration tool in the region. The mafic-hosted Decoy copper–zinc–gold VAMS-type prospect has a very non-radiogenic and possibly old lead isotope signature. This suggests that Cambrian to Early Ordovician MORB-like rocks form basement to parts of the Cowal district and younger mineralising events sourced metals from such a substrate. Additional dating to constrain the timing of mineralisation, as well as further high resolution Pb isotope, Nd isotope and O-Hf studies throughout the Macquarie Arc, would help to define the nature of the substrate to the arc and allow for more robust regional comparisons.

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For further details see Forster & Mao (2015).

* Eliminated results - Not initial ratios
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