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Ordovician Macquarie Arc and turbidite fan relationships, Lachlan Orogen, southeastern Australia: stratigraphic and tectonic problems

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Ordovician rocks of the Lachlan Orogen consist of two major associations, mafic to intermediate volcanic and volcaniclastic rocks (Macquarie Arc), which aerially comprise several north-south-trending belts, and the quartz-rich turbidite succession. Relationships between these associations are integral to resolving their tectonic settings and opinions range between contacts being major thrusts, combinations of various types of faults, and stratigraphic contacts with structural complications. Stratigraphic contacts between these associations are found with volcaniclastic-dominant units overlying quartz-turbidite units along the eastern boundary of the eastern volcanic belt and along the southern boundary of the central volcanic belt. Mixing between these major associations is limited and reflects waning quartzose turbidite deposition along a gently sloping sea floor not penetrating steeper volcaniclastic aprons that were developing around the growing volcanic centres formed during late Middle Ordovician to early Silurian Macquarie Arc igneous activity. An island arc setting has been most widely supported for the Macquarie Arc, but the identification and polarity of the associated subduction zone remain a contentious issue particularly for the Early Ordovician phase of igneous activity. The Macquarie Arc initiated within a Cambrian backarc formed by sea-floor spreading behind a boninitic island arc and presumably reflects a renewed response to regional convergence as subduction ceased along the Ross-Delamerian convergent boundary at the East Gondwana continental margin. An extensional episode accompanied initiation of the late Middle Ordovician expansion in island arc development. A SSE-dipping subduction zone is considered to have formed the Macquarie Arc and underwent anticlockwise rotation about an Euler pole at the western termination of the island arc. This resulted in widespread deformation west of the Macquarie Arc in the Benambran Orogeny and development of subduction along the eastern margin of the orogenic belt.

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Ordovician Macquarie Arc and turbidite fan relationships, Lachlan Orogen, southeastern Australia: stratigraphic and tectonic problems

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Running Title: Macquarie Arc – stratigraphic and tectonic problems

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Ordovician rocks of the Lachlan Orogen consist of two major associations, mafic to intermediate volcanic and volcaniclastic rocks (Macquarie Arc), which aerially comprises several north–south trending belts, and the quartz-rich turbidite succession. Relationships between these associations are integral to resolving their tectonic settings and opinions range between contacts being major thrusts, combinations of various types of faults, and stratigraphic contacts with structural complications. Stratigraphic contacts between these associations are found with volcaniclastic-dominant units overlying quartz turbidite units along the eastern boundary of the eastern volcanic belt and along the southern boundary of the central volcanic belt. Mixing between these major associations is limited and reflects waning quartzose turbidite deposition along a gently sloping seafloor not penetrating steeper volcaniclastic aprons which were developing around the growing volcanic centres formed during late Middle Ordovician to early Silurian Macquarie Arc igneous activity. An island arc setting has been most widely supported for the Macquarie Arc but the identification and polarity of the associated subduction zone remains a contentious issue particularly for the Early Ordovician phase of igneous activity. The Macquarie Arc initiated within a Cambrian backarc formed by seafloor spreading behind a boninitic island arc and presumably reflects a renewed response to regional convergence as subduction ceased along the Ross–Delamerian convergent boundary at the East Gondwana continental margin. An extensional episode accompanied initiation of the late Middle Ordovician expansion in island arc development. A SSE-dipping subduction zone is considered to have formed the Macquarie Arc and underwent anticlockwise rotation about an Euler pole at the western termination of the island arc. This resulted in widespread deformation west of the Macquarie Arc in the Benambran Orogeny and development of subduction along the eastern margin of the orogenic belt.

KEY WORDS: Lachlan Orogen, Macquarie Arc, Ordovician, Silurian, southeastern Australia, subduction, turbidites.

Introduction

Paleogeography is a major constraint in determination of ancient tectonic settings as illustrated by the review of Paleozoic plate tectonics by Domeier & Torsvik (2014). Additionally, the magmatic affinity for many mafic igneous assemblages on the basis of selected trace element geochemistry is also considered indicative of plate tectonic settings (Pearce, 1982, 2008). For the Ordovician – early Silurian Macquarie Arc assemblage of the eastern Lachlan Orogen in central and southern New South Wales and northeast Victoria (Figure 1), a subduction-related island arc tectonic setting has been based on both these criteria (Carr et al., 1996; Glen, Walshe, Barron, & Watkins, 1998; Glen, Percival, & Quinn, 2009; Crawford, Meffre, Squire, Barron, & Fallon, 2007a). An associated subduction zone has been proposed either to the west or east of the island arc, or some combination of both reflecting flipping of the subduction zone (Aitchison & Buckman, 2012; Glen et al., 1998, 2009; Fergusson, 2003, 2009, 2014; Meffre, Scott, Glen, & Squire, 2007). Alternatively, the Macquarie Arc succession has been related to an intraplate and/or backarc rift setting (Fergusson & Coney, 1992a, b; Glen, 2013; Quinn, Percival, Glen, & Xiao, 2014; Wyborn, 1992).

A significant issue relevant to tectonic setting has been the nature of relationships between the Macquarie Arc assemblage and the adjacent widely exposed Gondwana-derived Ordovician turbidite succession (Figure 1). These assemblages have a major compositional contrast as well as having overlapping ages. Many authors have noted the lack of facies interdigitation between these assemblages and this has been interpreted in different ways, some invoking the existence of numerous faulted contacts and/or questioning the nature and relative positions of the depositional systems themselves (e.g. Aitchison & Buckman, 2012; Quinn et al., 2014; Fergusson, Henderson, & Offler, 2016). Fault interpretations have included major overthrusting (Aitchison & Buckman, 2012; Fergusson & VandenBerg, 1990), major strike-slip dislocations (Packham, 1987), and a combination of various types of faults (Glen, Meffre, & Scott, 2007a; Meffre et al., 2007). Stratigraphic analysis of both the Ordovician mafic/intermediate volcanic and quartz turbidite successions has been hindered by the problem of discriminating between fossil-poor Ordovician and Silurian units (Percival, Quinn, & Glen, 2011). Some early Silurian units, for example the Kabadah Formation, are derived from multiple sources (Barron, Meffre, & Glen, 2007) whereas several Silurian units consist of thick quartz turbidite units (e.g. Cobbannah and Yalmy groups) which are difficult to distinguish from the Ordovician quartz turbidites.

Our aim is to review stratigraphic relationships between the Macquarie Arc assemblage, the Ordovician turbidite succession and relevant Silurian units, and thereby provide a basis for reassessment of the problematic tectonic setting of the Macquarie Arc. Relationships are most controversial for the eastern volcanic belt and adjacent Ordovician turbidites and are considered in more detail than for other parts of the Macquarie Arc. Data and interpretations have been presented over the last few years requiring revisions of previous tectonic models (Percival et al., 2011; Quinn et al., 2014; Thomas & Pogson, 2012). The importance of rifting has been highlighted in the model of Quinn et al. (2014), and is compatible with an island arc setting. The proposed existence of oroclines in the Lachlan Orogen of Victoria and southern New South Wales has a significant impact on the presumed arrangement of tectonic elements in the Ordovician (Cayley, 2015; Moresi, Betts, Miller, & Cayley, 2014; Musgrave, 2015). Understanding the tectonic context of Ordovician rocks of the Lachlan Orogen also requires consideration of the prior Cambrian tectonics and is enhanced using examples from appropriate modern settings (Fergusson, 2009).

Stratigraphic assemblages and relationships

Ordovician rocks of the Lachlan Orogen are split into two major associations: quartz-rich turbidites and the Macquarie Arc succession. The Macquarie Arc succession has four main belts of exposure (Figure 1) following the terminology of Glen et al. (1998): (1) the western volcanic belt (Junee–Narromine Volcanic Belt, also called the Goonumbla–Trangie volcanic belt by Fergusson, 2009), (2) the central volcanic belt (Molong Volcanic Belt), (3) the eastern volcanic belt (Rockley–Gulgong Volcanic Belt), and (4) the southern volcanic belt (Kiandra Volcanic Belt).

Considerable advances in the database of stratigraphic ages of Ordovician–Silurian units in the Lachlan Orogen have been made over the last 20–30 years reflecting widespread biostratigraphic age determinations of black shales and cherts (Fergusson & VandenBerg, 2003; Percival et al., 2011) as well as other biostratigraphic ages on the Macquarie Arc succession. A major increase in geochronological data has been developed with many new U–Pb zircon ages (Percival & Glen, 2007; Percival et al., 2011; Glen et al., 2011; Glen, Belousova, & Griffin, 2016; Wilson et al., 2007). Nevertheless there remain several units for which internal age control is either sparse, non-existent or contested and many age constraints have to be based on relationships with neighbouring units. The most significant examples of units with contested ages are the Kirribilli Formation and its equivalents in the Kirribilli Zone (Figure 1) and some of the units of the eastern volcanic zone in the Oberon district and north of Mudgee (Percival et al., 2011; Fergusson, 2014).

Faults have been widely inferred for contacts between the Ordovician turbidites and the Macquarie Arc succession. A weakness with studies that have emphasised the faulted nature of contacts has been that the type and orientation of faults are typically poorly documented. The question therefore remains as to the significance of these inferred faulted contacts. At one extreme, recognition of faulted contacts on the basis of "locally highly strained rocks" in combination with the sudden change in lithologies from the Macquarie Arc succession to the Ordovician turbidites is considered sufficient evidence to infer a major thrust sheet involving terrane displacement (Aitchison & Buckman, 2012; Fergusson & VandenBerg, 1990), i.e. an allochthon somewhat akin to the Samail ophiolite in Oman. In other accounts, complicated scenarios involving thrust and/or strike-slip faults in various combinations have been proposed (Glen et al., 2007a; Meffre et al., 2007; Packham, 1987). More recently, Percival et al. (2011) and Quinn et al. (2014) have suggested complicated fault systems in some regions but dominantly stratigraphic relationships between the successions elsewhere.

It is important to recognise that faults are abundant in the Lachlan Orogen, but for many areas are difficult to resolve due to paucity of exposure. In addition, uncertainty exists in documenting net slip and displacement history along faults which have no doubt been reactivated in the multi-phase tectonic history of the orogen. In many areas, rocks are highly deformed but as is well documented, deformation extends well beyond the contacts between the Ordovician units and also affects younger rocks. Faults with larger net slips are most readily recognised from stratigraphic offsets as is demonstrated by imbricate thrusting in Ordovician turbidites and black shale (Glen & VandenBerg, 1987; Fergusson & VandenBerg, 1990). Abundant faulting has also been mapped in some areas of the Macquarie Arc succession where marker horizons are plentiful (Simpson, Scott, Crawford, & Meffre, 2007; Squire & McPhie, 2007). Inferring significant offsets along faults on the basis of abrupt changes in lithology is less reliable than offsets determined on the basis of age discrepancies.

Ordovician turbidites

In Victoria and on the New South Wales South Coast, the basal Ordovician turbidite succession overlies bedded chert and underlying mafic volcanic rocks with a backarc magmatic affinity (Glen, 2013; Stokes, Fergusson, & Offler, 2015; VandenBerg et al., 2000). The basal Ordovician turbidites are Lancefieldian with the bulk of the succession deposited in the Lancefieldian to Darriwilian and locally into the Gisbornian (Figure 2). Thicknesses of the Ordovician turbidites are generally poorly constrained apart from in some well-dated sections (Figure 3) and are thought to be of the order of 2–3 km (Fergusson & VandenBerg, 2003; Thomas & Pogson, 2012). The succession contains some typically thin-bedded chert/siliceous mudstone horizons that are thickest in the uppermost part of the succession (Percival, 2012). Age control is provided by the ranges of various conodont index species in these cherts, but most age determinations are based on conodont assemblages of which some have durations of only 1 to 2 Ma (Percival, 2012; Quinn et al., 2014). Pre–Darriwilian cherts are typically <1–2 m thick, including the Mummel Chert Member in the Goulburn district. Darriwilian cherts include the Nattery Chert Member, locally up to 50 m thick (Figure 3a), and the equivalent Numeralla Chert Member considered to have a thickness of up to 100 m to the south of Canberra (Percival et al., 2011). Turbidite sedimentation continued sporadically during chert-dominated deposition with thin turbidites and intervals of turbidites interbedded within the chert/siliceous mudstone (Fergusson & Fanning, 2002; Thomas & Pogson, 2012,

p. 314–315). In some areas, for example east of Goulburn, turbidite deposition has continued to the top of the Gisbornian and contains thin interbeds of black shale, whereas in other sections the Gisbornian interval is dominated by black shale, including in eastern Victoria (Fergusson & VandenBerg, 2003; Thomas & Pogson, 2012).

Sections of black shale are widespread in the uppermost Middle to Upper Ordovician, and are particularly dominant in the Eastonian, with maximum thicknesses of 300–500 m (Fergusson & VandenBerg, 2003; Thomas & Pogson, 2012), indicating a maximum sedimentation rate of 100 m/Ma. It is possible that these thicknesses have been exaggerated by structural complications as detailed logging of the Warbisco Shale in Bungonia Creek, east of Goulburn, has determined a thickness of only 120 m for an Eastonian – early Bolindian section (Fergusson & Fanning, 2002), indicating a sedimentation rate of ~17 m/Ma. For the Nattery Chert Member a maximum sedimentation rate of the order of 15 m/Ma is calculated.

Widespread turbidite deposition resumed in the uppermost Ordovician with quartz turbidite units mapped in central and eastern New South Wales and eastern Victoria and most likely continued into the lower Silurian (Figure 2), although commonly the Silurian component of these units lack age-specific fossils (Colquhoun, Meakin & Cameron, 2005; Thomas & Pogson, 2012; VandenBerg et al., 2000). For example, the Cobbannah Group in eastern Victoria has no age-specific fossils and other units (e.g. the Yalmy Group) contain only rare early Silurian graptolites (VandenBerg et al., 2000).

Western volcanic belt

The western volcanic belt has an exposed length of over 250 km and is interpreted to extend northwards beyond the Queensland border (Figure 1), on the basis of significant magnetic and gravity features. Generally, exposure is sparse in the western volcanic belt with the succession well documented in the region west of Parkes and northwest of Forbes (Figure 4a) (Crawford , Cooke, & Fanning, 2007b; Glen, Spencer, Willmore, David, & Scott, 2007b; Glen, Crawford, Percival, & Barron, 2007c; Lyons, Raymond, & Duggan, 2000; Percival & Glen, 2007; Simpson, Cas, & Arundell, 2005). In addition an extensive literature exists on the associated ore deposits (e.g. Miles & Brooker, 1998). West of Parkes, the basal part of the succession consists of Lower Ordovician mafic-intermediate volcanic, volcaniclastic and fine-grained sedimentary rocks with monzonitic intrusions (Phase 1 of Percival & Glen, 2007). Phase 1 rocks are thought to be widely developed in the western volcanic belt, although age data in support of this is largely limited to the region west of Parkes (Crawford et al., 2007b; Glen et al., 2007c; Glen, Saeed, Quinn, & Griffin, 2011). The Phase 1 succession is overlain by the Phase 2 to 4 mafic-intermediate volcanic, volcaniclastic and sedimentary succession, including limestone beds, with ages from lower Darriwilian to Eastonian, and intrusions (Percival & Glen, 2007). An unconformity is inferred between Phases 1 and 2 (Simpson et al., 2005, p. 866), with a substantial hiatus of ~9 Ma (Figure 2) (Percival & Glen, 2007).

Limestone deposition associated with the Billabong Creek Limestone ranges from late Darriwilian (Da4) to early Eastonian (Ea2) but was not continuous with areas of non-exposure and the presence of interbedded siltstone and volcanic rocks (Pickett & Percival, 2001). The Billabong Creek Limestone is overlain by the Gunningbland Formation consisting of discontinuous limestone lenses interbedded with mudstone and volcanic sandstone (Figure 4a) (Percival & Glen, 2007). To the northeast these units are equivalent to the Goonumbla Volcanics consisting of limestone lenses/blocks, volcaniclastic rocks, mudstone, and abundant intrusions including trachyandesites associated with the overlying Wombin Volcanics (Simpson et al., 2005). In the Goonumbla Volcanics the oldest limestone is Middle Ordovician (Da2; Zhen & Pickett, 2008). Magmatic activity continued into the early Silurian as shown by U–Pb zircon ages as young as 437 ± 3 Ma on dykes (Lickfold, Cooke, Crawford, & Fanning, 2007).

The western boundary of the western volcanic belt has been considered to be a major west-dipping thrust based on interpretations and modelling of deep-seismic reflection profiles (lines 99AGS-L2 and 99AGS-L3, locations shown in Figure 5) with mid to lower crustal reflections of the Macquarie Arc dipping gently westward and underlying the highly deformed Ordovician turbidite succession of the Wagga and Girilambone groups (Glen et al., 2002, 2007b). In detail, relationships have been difficult to resolve as generally exposure is very poor and only limited surface structural data have been obtained. The map pattern of units is also indicated by aeromagnetic data particularly for covered Macquarie Arc units. In the north, the western boundary of the western volcanic belt was named the Tullamore Fault by Glen et al. (2007b). However, east of Fifield, slivers of poorly exposed Macquarie Arc succession occur west of the main part of the succession with interspersed Ordovician quartz turbidites (Sherwin, 1997) in the hanging wall of the Tullamore Fault. If these map relationships are correct they imply that a single major fault interpretation is over-simplified. A belt of Girilambone Group, located 40 km NNE of West Wyalong (Figure 1), is interpreted from seismic reflection line 99AGS-L2 as a shallow flat-lying thrust sheet overlying Silurian–Devonian sedimentary/volcanic rocks, granitic rocks and the Macquarie Arc succession at depth (Glen et al., 2002).

The eastern boundary of the western volcanic belt is difficult to resolve due to the generally limited exposure. Quartz turbidites of the Kirribilli Formation and equivalents with associated Middle Ordovician cherts extend from Narromine south to Temora, a distance of over 250 km, and occur along the eastern side of the western volcanic belt (Figure 1). They have been regarded as being in contact along a major fault zone variously known as the Parkes Thrust and/or Parkes Fault Zone and has been modelled as a significant zone of west-dipping thrust faults (Glen et al., 2007b). This thrusting, if significant, must have postdated deposition of the synclinal mid Silurian Forbes Group and is probably largely of Middle Devonian age (Fergusson, 2017). These relationships are problematic and considered further in the section on Stratigraphic and Paleogeographic Problems below.

Central volcanic belt

The stratigraphy of the central volcanic belt has a similar Phase 1 assemblage to the western belt with volcanic and volcaniclastic rocks of the Mitchell Formation overlain by the Hensleigh Siltstone which contains Bendigonian graptolites (Percival et al., 2011). Phases 2 to 4 assemblages are well documented by Percival & Glen (2007) and Percival et al. (2011) and a representative stratigraphic column is given in Figure 4b. Phase 3 Eastonian limestones lens out eastwards into volcaniclastic and volcanic units (Pogson & Watkins, 1998). Volcanic centres are developed — for example the Cargo Volcanics was interpreted as part of a submarine stratovolcano (Simpson et al., 2007). Phase 4 magmatism continued into the early Silurian as shown by U–Pb zircon ages of 439–436 Ma from porphyry intrusions in the Cadia district 20 km southwest of Orange (Wilson et al., 2007).

West of the main outcrop of the central volcanic belt in the Cowra Trough (Figure 1) is the Kabadah Formation that has been considered at least partly of Ordovician age (Meakin & Morgan, 1999; Pogson & Watkins, 1998), but has been argued as Silurian by Percival & Quinn (2011) and Percival et al. (2011). The Kabadah Formation (Figure 5) contains early

Silurian graptolites, has abundant mafic volcaniclastic debris and a distinctive red-pink colour on RGB radiometric images (Meakin & Morgan, 1999). The petrology of the unit has been examined in detail by Barron et al. (2007) who documented ultramafic, granitic, metamorphic, and siliciclastic detrital fragments, indicative of mixed sources. They found locally common chromite and chlorite-altered ultramafic clasts from samples north of Yullundry. Minor S-type silicic volcanic rock fragments, volcanic quartz and garnet are restricted in distribution and recorded from only four samples in the Yullundry area and indicate overlap in age of the Kabadah Formation with at least early equivalents of the Canowindra Volcanics (Barron et al., 2007). The Kabadah Formation is at least partly equivalent to the Greengrove Formation and the overlying Kurrajong Park Formation of the lower Cudal Group that have Llandovery–Wenlock ages (Figure 6) and have a similar red-pink radiometric RGB colour to the Kabadah Formation (Pogson & Watkins, 1998). The Kabadah Formation is important as it has a mixed provenance, a feature missing from most Ordovician units, although the quantity of siliciclastic detritus within the unit is sparse even though it is widely distributed (Barron et al., 2007).

South of Orange in the Neville district, the Macquarie Arc assemblage is in contact with Ordovician turbidites and black shale and the contact has been considered faulted (Glen & Wyborn, 1997). Here, the feldspathic mudstone and volcaniclastic sandstone of the Coombing Formation of the Macquarie Arc is possibly Middle Ordovician from a sample with 467 ± 4 Ma detrital zircons (Meffre et al., 2007) and overlain by late Middle to Upper Ordovician units (Percival et al., 2011). Ordovician turbidites south of the Macquarie Arc assemblage include black shale markers but graptolites have not been found so the age of the succession is poorly constrained. The contact extends over 25 km in an east–west direction and a synclinal outlier of Coombing Formation apparently overlies the Adaminaby Group turbidites 6.5 km SSE of Neville and other outliers occur 25 km east of Cowra. In the Kempfield area and up to 10 km father north (Figure S1), Wyborn & Henderson (1996, p. 9) described a conformable contact between the Adaminaby Group and the overlying Coombing Formation, with fine-grained quartz sandstone beds occurring in the lower Coombing Formation. Farther to the south, 25 km northeast of Boorowa, the volcanic and volcaniclastic rocks of the Kenyu Formation have an age of latest Gisbornian to earliest Eastonian based on limestone blocks (Percival et al., 2008) and are considered to be in faulted contact with the Bendoc and Adaminaby groups to the east (Thomas & Pogson, 2012). Faulted relationships were also suggested by Meffre et al. (2007) for contacts between the southern central volcanic belt and the Ordovician turbidites based on development of foliations and multiple deformation structures. However, as they point out the Silurian granitic intrusions in this region are also strongly deformed and this deformation is widespread in the well-bedded Ordovician turbidites but dies out northwards into the more massive volcanic units of the southern Macquarie Arc.

Eastern volcanic belt

In contrast to the western and central volcanic belts, rocks of the eastern volcanic belt are of mostly deep-marine aspect and there have been fewer discoveries of age-specific fossils resulting in less certainty in age relationships. Percival et al. (2011, p. 26) questioned the extent of the Ordovician succession in the eastern volcanic belt and for the Gulgong–Dunedoo district they regarded that Ordovician limestones and volcaniclastic debris have been reworked into "Silurian deposits of the Hill End Trough". In the Gulgong district, the Burranah Formation contains a lower part with lavas and breccias, and an upper part with volcaniclastic rocks (Meakin & Morgan, 1999). The age of the Burranah Formation is constrained by Upper Ordovician limestone clasts providing a maximum age and an intrusive U–Pb zircon age for monzodiorite of 435 ± 5 Ma (Meakin & Morgan, 1999, p. 44), although this age was determined with the SL13 standard and could well be up to 2% older. It is possible that part of the succession may well continue into the lower Silurian.

East and southeast of Mudgee, the Coomber Formation consists dominantly of mudstone and mafic volcaniclastic sandstone but lacks age-diagnostic fossils (Meakin & Morgan, 1999). The Coomber Formation, in contrast to the Burranah and Tucklan formations, farther north is in contact with Ordovician quartz turbidites of the Adaminaby Group (Figures 7, 8). The quartz turbidites contain upper Middle Ordovician cherts (Fergusson & Colquhoun, 1996; Murray & Stewart, 2001; Stewart & Fergusson, 1995). The Coomber Formation is disconformably overlain by upper Silurian units (Meakin & Morgan, 1999). Meffre et al. (2007) inferred that the contact between the Adaminaby Group and Coomber Formation was faulted based on local outcrops with disrupted cherts and intensely deformed rocks. However, the sinuous map pattern of the contact between the Coomber Formation and Adaminaby Group (Figure 7) indicates that it is strongly folded, although it is probable that the contact is locally faulted accommodating the ductility contrast between the well-bedded Ordovician turbidites and the much more massive Coomber Formation. The discovery that a chert marker adjacent to the Mt Bara Thrust is the same age as chert 1.4 km farther west (Murray & Stewart, 2001) indicates additional structural complexities, including potential thrust faults and/or repetition by folding and reduces the inferred thickness of 1400 m for the Adaminaby Group (Figure 8) given by Fergusson & Colquhoun (1996).

In the Sofala district, the Sofala Volcanics include volcaniclastics, volcanics, chert, and limestone blocks with scarce fossils indicating a mainly Late Ordovician age for much of the succession (Pogson & Watkins, 1998). Several graptolite faunas have also been recovered from the Sofala Volcanics near Sofala (Cas, 1969; Packham, 1968) which suggest a Gisbornian–Darriwilian age (Pickett, 1978). Farther north, near Windamere Dam, Bolindian (Bo3) graptolites have been recovered from mudstones in the unit (Rickards, Wright, & Pemberton, 1998). Perkins, McDougall, & Walshe (1995) dated two samples in the Sofala Volcanics by Ar^{40}/Ar^{39}, yielding ages of 439 ± 1 Ma and 440 ± 1 Ma (middle Llandovery). These ages indicate a Llandovery age for the upper part of the Sofala Volcanics (Percival et al., 2011). Pickett, Sherwin, & Watkins (1996) recognised a Llandoverian unit (Pipers Flat Formation) beneath the Tanwarra Shale composed of thin bedded graptolitic shales with volcaniclastic sandstone, which accords with waning supply of detritus from the Macquarie Arc through this interval.

South of Palmers Oakey (Figure 9), the age of the upper part of the Sofala Volcanics is constrained by limestone blocks, and the conformably overlying middle Silurian Tanwarra Shale, as lower Silurian (Bischoff & Fergusson, 1982) confirming that at least part of the Sofala Volcanics continues into the early Silurian. East of Palmers Oakey, quartz-rich turbidites are widely developed along the upper Turon River and underlie mafic to intermediate volcaniclastic rocks of the Sofala Volcanics (Figure 9). These quartz-rich turbidites were mapped as the Ordovician Adaminaby Group by Watkins et al. (1997) and have also been recognised to the east of Capertee in an inlier in Airlie Creek (Figure 5). Chitinozoans have been extracted from samples collected at two sites within this rock package — one in Coolamigal Creek (Figure 9) and another in upper Airlie Creek (Figure 5) and have ages of Darriwilian to Bolindian and Darriwilian respectively (Fell, 1984). In the upper part of the quartz-rich turbidite unit, lenses of quartz-poor volcaniclastic turbidites occur. We have recalculated point-count data from Crook (1955) of both quartz-rich and quartz-poor sandstones to exclude matrix (Figure 10). Crook (1955) noted that the lithic sandstones contained abundant volcanic detritus and described the lithic fragments as being mainly “doleritic” with altered feldspar and probable augite. Minor quartz in these lithic sandstones is of volcanic and vein origin (Crook, 1955). Several lenses of lithofeldspathic turbidites were mapped by Fergusson (1979) within the quartz turbidites below the contact with the overlying Sofala Volcanics. One of the chitinozoan fossil localities of Fell (1984) is adjacent to one of these lenses indicating a Middle-Late Ordovician age (Figure 9). The contact mapped by Fergusson (1979) shown in Figure 9 is sinuous reflecting complicated refolding with two phases of folds identified as well as local poorly documented faults. This area was also briefly described by Meffre et al. (2007) who suggested that the quartz-rich turbidites were Silurian and unconformably overlie the Sofala Volcanics. They also indicated that the volcaniclastic marker(s) mapped by Crook (1955) and Fergusson (1979) contained quartz-rich volcaniclastics. While it is always difficult to be confident of relationships in these structurally complicated areas, the fossil evidence and the point count data of Crook (1955) support the interpretation given in Figure 9.

In the Oberon–Rockley region south of Bathurst (Figures 5, 11) there are important contact relationships between the Ordovician turbidites and the Macquarie Arc succession with scattered age control. Contact relationships have been interpreted in different ways by different authors (Percival et al., 2011). The map distribution of units is shown in broadly similar patterns by Fowler (1989), Stuart-Smith & Wallace (1997), Murray & Stewart (2001), Meffre (2003) and Meffre et al. (2007) but differ in detail. The geophysical data for the Oberon 1:100,000 geological sheet (Geological Survey of New South Wales, 2009a, b) is particularly useful in the northern part of the sheet but in the southern part many units have similar radiometric and magnetic patterns and are not easily distinguished. Unfortunately, mapping by Fowler (1987) preceded the collection of the geophysical data and these data were not available to Murray (2002).

The Macquarie Arc succession in the Oberon–Rockley region consists dominantly of deep-marine volcaniclastic rocks of the Triangle Formation and volcanics and volcaniclastics of the Rockley Volcanics. Mapping by Fowler (1989) showed that rapid facies variations occur between the lavas and associated coarse volcaniclastic detritus of the Rockley Volcanics and more distal slate and volcaniclastic sandstones of fringing apron deposits of the Triangle Formation. Ages have been documented from fossils by Fowler & Iwata (1995), Murray & Stewart (2001), Meffre (2003) and from detrital zircons by Glen et al. (2011, 2016). Locations of these ages are shown in Figure 11. Cherts occur in the succession south of

Rockley and east of the Native Dog Syncline and have mainly Darriwilian–Gisbornian ages apart from one Bendigonian chert unit and others that have a general Ordovician age (Fowler & Iwata, 1995; Murray & Stewart, 2001). It is not known if either the Bendigonian chert unit is separated from overlying volcaniclastic sedimentary rocks by a hiatus, as in the central and western volcanic belts, or if volcanic activity was locally active in the Chewtonian to Darriwilian (Figure 2). Two detrital zircon samples, both close to the contact with overlying Silurian rocks in the Native Dog Syncline, have a maximum age of 453 Ma (sample OR3) with the other sample OR2 having the youngest concordant zircon at 432 Ma so it is possible that at least locally the succession continues into the Silurian (Glen et al., 2011, 2016). Meffre (2003) mapped the Swatchfield Monzonite, with a U–Pb zircon age of 437 ± 8 Ma, as intrusive into the Macquarie Arc succession. These data support an Ordovician to early Silurian age of the Macquarie Arc succession in the Rockley district and in the belt along the eastern limb of the Native Dog Syncline (Figure 11). It has been suggested that some of these chert ages are not representative of the ages of adjacent volcanic/volcaniclastic units because of two reasons: (1) the samples come from “clasts in a younger matrix”, and (2) the ages are similar to those of the cherts in the Ordovician turbidites and derived from them by undocumented thrusting that has somehow separated the cherts from enclosing quartz turbidites and emplaced them in the volcanic/volcaniclastic rocks (Percival et al., 2011, p. 17–18). Both these explanations are considered ad hoc and undocumented; we regard them as unjustified. Certainly, parts of the succession do seem to extend into the early Silurian as has been documented in other parts of the Macquarie Arc succession.

Ordovician turbidites are widely developed between Oberon and Jaunter and in the core of the Rockley Anticline (Figure 11) where they are accompanied by common black shale considered part of the Bendoc Group but with no graptolites found to prove this. Contact relationships with the Macquarie Arc succession have been considered faulted (Meffre et al., 2007). The contact at and east from Oberon (Figures 11, S2) is particularly significant as here two sites in chert contain Darriwilian–Gisbornian conodonts within the Adaminaby Group and both are close to the contact with overlying mafic/intermediate volcanic/volcaniclastic rocks (Meffre, 2003). The contact is apparently folded although it has been suggested that it is a folded major fault in the Lachlan Transverse Zone (Glen in Pogson & Watkins, 1998; Glen & Walshe, 1998). On the Oberon sheet (Stuart-Smith & Wallace, 1997) a narrow band of black shale shown along the contact was considered an equivalent of the Bendoc Group although mapping by Meffre (2003) and Murray (2002) show that this unit is discontinuous.

In one road cutting southeast of Oberon, quartz turbidites dip and young away to the south from the contact indicating it is locally faulted (Glen in Pogson & Watkins, 1998), but mapping by Murray (2002) in other road cuttings show that elsewhere the quartz turbidites underlie a thin band of black shale and the overlying Macquarie Arc succession. Additionally, the Darriwilian–Gisbornian age of the chert samples near Oberon (Meffre, 2003) is consistent with the Macquarie Arc succession overlying the Adaminaby Group turbidites with the chert unit occurring high in the Lower to Middle Ordovician turbidite succession as found in the Goulburn region to the south (Figure 3b) (Thomas et al., 2013a, b). To the northeast of Oberon (Figures 11, S2), the Macquarie Arc succession is overlain by Silurian to Upper Devonian units consistent with a grossly concordant succession from the Ordovician upwards. Note the contacts of these units are overall east–west trending concordant with the underlying turbidite and Macquarie Arc succession contact.

In the Jaunter area (Figure 11), mafic volcaniclastics are overlain by a concordantly folded Silurian to Upper Devonian succession in a northeast–trending syncline of Carboniferous age. These mafic volcaniclastics overlie quartz turbidites that in the northeast Taralga sheet (Thomas et al., 2013a, b) are overlying Bendoc Group graptolitic black shale (C. L. Fergusson, unpub. data) and are therefore equivalent to the uppermost Ordovician Margules Group on the Goulburn sheet (Figure, 3b). South of Black Springs (Figure 11), Meffre (2003) mapped a highly folded contact with inferred Silurian quartz-rich siliciclastics overlying mafic volcanics/volcaniclastics of the Macquarie Arc succession (see also Meffre et al., 2007). On the Oberon sheet, the Silurian Campbells Formation includes both feldspathic and quartz sandstones (Wallace & Stuart-Smith, 1994) and overlies the Macquarie Arc succession including in the Oberon area and on the limbs of the Native Dog Syncline. These relationships are consistent with an Ordovician to early Silurian age for the Macquarie Arc succession in the Oberon region and local interdigitation of Silurian quartz-rich and volcaniclastic successions.

Southern volcanic belt

The southern volcanic belt is developed in southeast New South Wales with a smaller extent in adjacent northeast Victoria (Figures , 1, 12). The volcanic/volcaniclastic succession of the Kiandra Group has Gisbornian chert and Middle to Late Ordovician graptolites in siltstone (Meffre et al., 2007). A conformable and gradational contact has been mapped between the

Nine Mile Volcanics of the eastern part of the Kiandra Group and the underlying Ordovician quartz turbidites (Owen & Wyborn, 1979). This relationship was disputed by Meffre et al. (2007) who regarded the contact between these units as faulted with strike-slip and dip-slip offsets, but the faulting post-dated Late Silurian granite. Additional work by Quinn & Glen (2009) and Quinn et al. (2014) showed a middle to late Darriwilian transition between the Ordovician turbidites and overlying Kiandra Group based on conodonts from cherts; note that the locations (i.e. grid references) of these chert ages were not given. They showed that rare volcaniclastic beds are interbedded with quartzites of the upper chert-bearing part of the quartz turbidite succession and also include debris flow deposits with chert clasts and volcaniclastic beds with mixed volcanic and siliciclastic provenance. This transition was interpreted to show that the decreasing quartz turbidite deposition in the late Middle Ordovician was reflected in chert deposition (Figures 2, 3) and coincided with initiation of Phase 2 volcanism in the Macquarie Arc (Quinn et al., 2014). Quinn & Glen (2009) recorded widespread sheared and disrupted rocks as found by Meffre et al. (2007), but the important point was that the transition was based on conodont ages in chert, even though latter deformation resulted in local faulting and sheared rocks. In northeast Victoria, probable Gisbornian cherts have been found associated with mafic volcaniclastic sandstones, andesitic volcanics and interbedded quartz-sandstone turbidites at the southern end of the southern volcanic belt (Allen, 1988; Orth et al., 1995), consistent with the relationships documented farther north.

Owen & Wyborn (1979) mapped the Gooandra Volcanics, which they considered fault-bounded and distinct from the shoshonitic Nine Mile Volcanics because of their tholeiitic affinity (Wyborn, 1992). This unit does not appear on the map of the same area of Quinn et al. (2014) although Owen & Wyborn (1979) gave many details supporting the development of a distinctive volcanic succession west of the main outcrop belt of the Nine Mile Volcanics. The Gooandra Volcanics contain no age-specific fossils but have been mapped over a wider distribution along the Gilmore Fault to the northwest by Stuart-Smith (1991). The age of these rocks is unresolved but their tholeiitic affinity is consistent with other units of MORB-like affinity to the northwest (Wyborn, 1992).

Kirribilli Formation, Jindalee Group and equivalent units

The Kirribilli Formation consists of a turbidite succession with poly-deformed quartz-rich sandstones interbedded with mudstones, which is typical of the Ordovician turbidites (Lyons et al., 2000; Meffre et al., 2007). The unit is associated with the Mugincoble and Hoskins cherts that are both upper Middle Ordovician (Percival et al., 2011) and therefore the Kirribilli Formation is most likely Ordovician. However, this inference has been challenged by Percival et al. (2011, p. 20) who suggested that the “isolated chert units may represent a series of blocks redeposited into younger sediments”. They also claimed that dating of detrital zircons from the Kirribilli Formation “indicates a probable Silurian age” (cited as Quinn et al., unpubl. in Percival et al., 2011). However, the association of upper Middle Ordovician bedded chert units and quartz turbidites is widely developed in the Lachlan Orogen and it seems opportunistic to question relationships only for units that cause paleogeographic problems (see below). The suggestion that the cherts are allochthonous blocks in a younger matrix is considered unlikely given that no conglomerates/breccias with chert fragments have been found in these units, but are known from the nearby mid Silurian Forbes Group (Lyons et al., 2000). It is concluded that the Kirribilli Formation is probably largely Ordovician, although the stratigraphic context of the Kirribilli Formation is poorly documented and it is not clear if the unit is conformable either above or below or even interbedded with the Mugincoble and Hoskins cherts. The connection between the latest Ordovician to Lower Silurian black shale of the Cotton Formation and the Kirribilli Formation is also poorly documented as quartz-rich sandstone turbidite layers have been documented in the eastern and northern parts of the Cotton Formation (Meffre et al., 2007; Sherwin, 1996).

Equivalent units to the Kirribilli Formation on the Cootamundra 1:250,000 geological sheet (Figure 12) include the Bribbaree, Bronxhome, and Trigalong formations (Warren et al., 1995, 1996). The Flint Hill Chert Member of the Bribbaree Formation has four localities where conodonts indicate general upper Middle to Late Ordovician/Ordovician ages and two additional samples have late Darriwilian conodonts (Percival, 2007). As for the Kirribilli Formation it has been argued by Percival et al. (2011) that these cherts are blocks “redeposited into younger sediments” but we consider this unlikely (see below).

The Jindalee Group (Figure 12) has an assemblage of altered ultramafic and mafic igneous rocks and associated metamorphic and sedimentary rocks including chert and pelitic rocks (Warren et al., 1995). Cherts in the unit are of late Darriwilian to earliest Gisbornian age and considered to slightly postdate the upper Middle Ordovician cherts of the Ordovician turbidite succession (Lyons & Percival, 2002; Quinn et al., 2014). Again, Percival et al. (2011) and Quinn et al. (2014) proposed that these cherts, associated harzburgite and gabbro were “blocks” redeposited into Silurian–Devonian units. However, these authors noted that the association of chert and ultramafic/mafic blocks in younger units still provides an age constraint on the formation of ophiolitic fragments in this part of the Lachlan Orogen. Mafic igneous rocks in the Jindalee Group are tholeiitic and considered MORB-like (Warren et al., 1995), and include the Brangan Volcanics which is associated with the Hoskins Chert and Kirribilli Formation (Lyons et al., 2000).

Stratigraphic and Paleogeographic Problems

Paleogeography provides a fundamental constraint on tectonic reconstructions and has formed the basis for tectonic reconstructions of the Macquarie Arc and quartz turbidite successions (Cas, 1983; Cas et al., 1980; Powell, 1983; 1984; Fergusson, 2009; Glen et al., 1998). The Ordovician paleogeography of the Lachlan Orogen is constrained by the quartz turbidites that form part of a widespread deep-sea turbidite fan considered comparable to the modern-day Bengal fan (Fergusson & Coney, 1992a). The Macquarie Arc represents several linear belts of mafic to intermediate volcanic/volcaniclastic rocks with the widespread development of shallow marine limestone in the western and especially the western part of the central volcanic belt indicating several island volcanic chains (Figure 13). The western and central volcanic belts have strikingly similar magmatic and depositional histories (Percival & Glen, 2007). This paleogeography is widely supported in the older literature (Webby, 1976; Cas, 1983; Cas et al., 1980; Powell, 1983, 1984). How these volcanic chains relate to each other and the adjacent Ordovician quartz turbidite succession is a significant paleogeographic problem and has had an over-bearing influence on stratigraphic and structural interpretations.

The major paleogeographic problems are: (1) the distribution of Ordovician turbidites with significant components east, southeast and south of the eastern volcanic belt, south of the central volcanic belt, and most confusingly an apparently long relatively narrow tract between the western and central volcanic belts (Figure 1), (2) the lack of facies interdigitation between the Macquarie Arc succession and the Ordovician turbidites especially where they are in contact, and (3) a lack of evidence for provenance mixing between the distinct sources of the intraoceanic volcanoes and Gondwana for the Macquarie Arc succession and the Ordovician turbidites respectively. These issues are reassessed and discussed with reference to modern and appropriate ancient settings.

The first issue has presented a road block to determining the nature of relationships between the Macquarie Arc succession and the Ordovician turbidites. Numerous hypothetical arrangements of suspect terranes have been proposed involving considerable translations along various faults to explain the present distribution. In the first significant attempt to resolve this issue, Packham (1987) hypothesized an arrangement with significant sinistral strike-slip duplication of the volcanic chains in the early Silurian and placed all the Ordovician turbidites in a backarc setting as part of the Wagga Marginal Sea. This model was not supported as evidence for the existence of the requisite major strike-slip faults was not forthcoming. In a subsequent account, Fergusson & VandenBerg (1990) inferred that the western, central and eastern volcanic belts, but not the southern volcanic belt, were part of a major allochthon (the so-called Parkes terrane) thrust over the Ordovician turbidites with the contact strongly folded by Carboniferous deformation. In subsequent work, this concept was discarded and the paleogeography interpreted as the volcanic chains forming topographic features in the eastern part of a Bengal-sized turbidite submarine fan (Fergusson & Coney, 1992a, b; Fergusson & Tye, 1999).

Various continental margin terranes, combinations of strike-slip faults and thrust faults were considered in reconstructions by Glen (2005) and Glen et al. (2007a, 2009). These all involve long-distance displacement of part of the Ordovician quartz turbidite submarine fan from a location adjacent to Antarctica to an outboard location in contact with the eastern part of the Macquarie Arc succession. This was inferred to have accompanied northward strike-slip removal of an eastern forearc basin and subduction zone (Glen et al., 2007a). In a subsequent reconstruction, the subduction-related setting of the Macquarie Arc was abandoned and a new interpretation presented that the Macquarie Arc formed along a volcanic rift in the Ordovician submarine turbidite fan (Glen, 2013; Quinn et al., 2014). These papers no longer supported large displacements along faulted contacts and even recognized that some contacts were stratigraphic between the Ordovician turbidites and Macquarie Arc succession.

Aitchison & Buckman (2012) interpreted the Macquarie Arc as an allochthon thrust from east to west over the passive margin Ordovician turbidites during the Late Ordovician to early

Silurian Benambran Orogeny so that all contacts between them are faulted. Based on present-day extent this would imply considerable horizontal displacement (>300 km). This suggestion was proposed as the best possible explanation for the lack of facies interdigitation and provenance mixing between these disparate units but unlike other models involving fault displacements (Glen et al., 2007a; Meffre et al., 2007) gave no structural evidence and essentially proposed a hypothetical structure to resolve the stratigraphic problems.

Attempts to solve the paleogeographic problems by resorting to either ad hoc structures or complicated fault-based reconstructions proposed by numerous authors are considered by us as unlikely to determine the issue. Additionally, resolving these paleogeographic problems by claiming dated cherts are clasts in younger units should be supported by documentation to support these contentions as has been undertaken for allochthonous limestones in parts of the Lachlan Orogen (Conaghan et al., 1976). In this context it is notable that Quinn et al. (2014) documented chert clasts in an inferred debris flow at the top of the transition between the Ordovician turbidites and the overlying Kiandra Group yet still regarded other cherts that had been dated within the succession as conformable chert horizons within the units. This approach contrasts with the claims by these authors for the Kirribilli Formation and particularly for cherts in the Oberon district, where to the southeast of Oberon the succession resembles the gross relationships in the southern volcanic belt.

A major issue with the distribution of Ordovician units highlighted by the palaeogeographic maps (Figure 13) is how did the Ordovician turbidites manage to get around the southern, central and eastern volcanic belts of the Macquarie Arc? At least partly, this enigma is stratigraphic in origin. The oldest parts of the Macquarie Arc succession of the Lancefieldian – early Bendigonian Phase 1 are thought to be relatively widespread in the western volcanic belt (Percival & Glen, 2007) but extend no farther south than Temora (Figure 1). In contrast, Phase 1 units are only recognised in a relatively small part of the central volcanic belt mid-way between Orange and Wellington (Percival & Glen, 2007) and only in the limited amount of chert southwest of Oberon (Murray & Stewart, 2001). Darriwilian to early Silurian Phase 2 to 4 units dominate the central, eastern and southern volcanic belts and their timing broadly coincides with a marked reduction of turbidite deposition in the Ordovician turbidite submarine fan (Quinn et al., 2014). This relationship is consistent with mapping and age constraints from the Mudgee–Lue district, the Palmers Oakey – upper Turon River area and the Oberon area where Phases 2 to 4 of the Macquarie Arc succession overlies the Ordovician turbidites (Figures 7, 9, 11). So the relationships reflect rapid expansion of volcanic activity coinciding with a reduction in quartzose turbidite deposition. However, turbidite deposition did continue in parts of the submarine fan to the Gisbornian–Eastonian boundary as to the east of Goulburn (Fergusson & VandenBerg, 1990; Fergusson & Fanning, 2002) thus substantially overlapping with Phase 2 volcanism of the Macquarie Arc, but these units are not found anywhere in contact with each other.

The Kirribilli Formation and equivalents lying between the western and central volcanic belts is a paleogeographic conundrum and thus the incentive to revise the age of these units to Silurian (see above). Their ages are no better known than Middle to Late Ordovician and therefore overlap with Phases 2 to 4 volcanism of the Macquarie Arc. Fergusson (2009) explained the conundrum by inferring sinistral strike-slip dislocation of the western and central volcanic belts which also account for the apparent disruption of these belts. No more reason exists to support this strike-slip offset than other fault explanations including thrusting associated with the Parkes Fault Zone and major overthrusting from east to west (Aitchison & Buckman, 2012; Meffre et al., 2007).

No pre-Darriwilian chert ages have been found in the Kirribilli Formation and its equivalents and it is possible that they reflect a younger phase of turbidite deposition in an extensional trough developed in the Macquarie Arc (Lyons & Percival, 2002). “Extensional collapse” in the late Darriwilian was hypothesised by Quinn et al. (2014) to account for emplacement of harzburgite and associated MORB-like volcanism preserved in the Cootamundra region as well as debris flow deposition in the Snowy Mountains. We are puzzled as to why these authors have referred to this event as extensional collapse, given the widespread deep-marine sedimentation that prevailed at this time, but we concur that significant regional extension in the Darriwilian provides a viable model for development of the Jindalee Group and its associated ultramafic rocks. We agree that extensional rendering around this time would also explain rifting of the western and central volcanic belts and we suggest that this also accounts for deposition of the Kirribilli Formation in the intervening trough as initially proposed by Lyons & Percival (2002). More broadly this drawn out extensional episode also corresponds to initiation of the dominant Phases 2 to 4 volcanism of the Macquarie Arc (Quinn et al., 2014).

The lack of facies interdigitation between the Macquarie Arc succession and the Ordovician turbidites has long been recognised as a problematic feature of stratigraphic relationships in the Lachlan Orogen. It seems that the expectation is that some sort of facies mixing should be evident at the contacts between these units. For example, facies mixing has been documented at the transition between craton-derived siliciclastics and orogen-derived lithic detritus in the upper Sydney Basin succession (Conaghan et al., 1982; Cowan, 1993). However, the fluvial environments of the upper Sydney Basin succession allow the possibility for reworking and interdigitation of these different sourced units whereas in a deep-marine setting facies deposition is much more controlled by sediment pathways and bathymetry (Fergusson et al., 2017). In a deep-marine setting, it is difficult to envisage how the quartz turbidites that formed on a gently sloping sea floor could have penetrated the steeper volcaniclastic aprons associated with the Macquarie Arc. Thus the different sourced units tend not to show facies interdigitation but rather discrete stratigraphic contacts are observed as one distinct source is displaced by another which is what is observed in different parts of the Lachlan Orogen, described as provenance switching by Colquhoun, Fergusson, & Tye (1999).

Provenance mixing is seen in relatively few units in the Ordovician of the Lachlan Orogen. This is not unexpected as it is hard to imagine a situation where deep-marine turbidites derived from a dominant cratonic source could somehow intermix with volcaniclastic detritus derived from the submarine and relatively restricted island sources in an intraoceanic setting. Some quartzose detritus has been documented in the late Darriwilian to Bolindian of the central volcanic belt but all the quartz is of hydrothermal and/or volcanic origin of local derivation and therefore does not represent provenance mixing (Packham, Keene, & Barron, 2003). Nevertheless reports of provenance mixing between these disparate sources have been documented. The most puzzling example is a sample of the Mitchell Formation, a mafic volcaniclastic Phase 1 unit, with many zircons which have a detrital age spectrum distinctive of the Ordovician turbidites (Glen et al., 2011, 2016). In contrast fine-grained Phase 1 units including the Hensleigh Siltstone and Yarrimbah Formation have samples with fewer zircons but do include inherited zircons with one sample containing six Archean ages (Glen et al., 2011). Ancient, including Archean and Paleoproterozoic, zircons have been found in modern island arcs including in East Java, Vanuatu and the Solomon Islands (Buys, Spandler, Holm, & Richards, 2014; Smyth, Hamilton, Hall, & Kinny, 2007; Tapster, Roberts, Petterson, Saunders, & Naden, 2014). These zircons have been considered to have been sourced from a deeply buried continental block within these island arcs. The detrital zircon spectrum from the Mitchell Formation has been attributed to either mixing of volcaniclastic sediments with Ordovician quartz turbidites or erosion of the quartz turbidites (Glen et al., 2016, p. 1389–1390). If mixing had occurred it is puzzling as why so much detrital zircon was incorporated into the volcaniclastic sediment yet the quartz content of these rocks remained low (Glen et al., 2011). The second suggestion needs more explanation, but it should be noted that the chert breccias in the southern volcanic belt documented by Quinn et al. (2014) were cited by Glen et al. (2016) as support for redeposition. An example of this style of redeposition has also been documented from the Shoalhaven River Gorge where angular chert fragments are contained in quartz sandstone turbidites overlying bedded chert and reflect intraformational reworking by mass flow deposition on the submarine fan (Fergusson & Fanning, 2002, figure 6d).

Other samples of Middle to Late Ordovician volcaniclastic rocks have common detrital zircons with dominant ages similar to those of the surrounding rocks and with only a few pre-Ordovician zircons (Glen et al., 2011, 2016). This is consistent with the geochemistry and primitive ε_{Nd} values of the Macquarie Arc rocks reflecting their intraoceanic arc setting (Crawford et al., 2007a) and also extension and crustal thinning (see above). A sample from the Rockley Volcanics (sample OR2) also has common detrital zircon with an age spectrum typical of the Ordovician quartz turbidites and is potentially early Silurian (Glen et al., 2016), but its composition was not described. If it is quartz-poor volcaniclastic sandstone, as is typical of the Rockley Volcanics, then it also possibly reflects provenance mixing although again it is puzzling as to why this is only indicated by the detrital zircon. Apart from limited provenance mixing in the Kabadah Formation, it seems that provenance mixing between these diverse sources has not occurred and that the changes in provenance seen in different units reflects provenance switching with no mixing of the style documented in the upper Sydney Basin succession (see above). It is conceivable that the ancient detrital zircons in samples from the Mitchell Formation and Rockley Volcanics are not a reflection of provenance mixing at all but the result of contamination of igneous rocks from a buried crustal source as proposed for ancient zircons in some modern island arcs (see above). Given the unusual abundance of zircon in the Mitchell Formation sample and its remarkable similarity to the detrital zircon spectrums of the Ordovician turbidites (Glen et al., 2011) more sampling of the Mitchell Formation is required to confirm this result.

Tectonic Interpretation

It is apparent from the recent literature that the tectonics of the Ordovician is still a much discussed and somewhat perplexing issue (Fergusson, 2014; Glen, 2013; Moresi et al., 2014; Packham & Hubble, 2016; Quinn et al., 2014). The Macquarie Arc has been interpreted as an island arc based on both palaeogeographic and geochemical grounds (Blevin, 2002; Carr et al., 1996; Crawford et al., 2007; Fergusson, 2009; Glen et al., 1998, 2007b). This is also consistent with the abundance of intrusive porphyry Cu–Au mineralization associated with the Macquarie Arc (Wilson et al., 2007). Our tectonic interpretation considers the Cambrian tectonic setting, then the Macquarie Arc in the context of island arc development, and finally the more problematic issue of identifying the polarity of the arc through time.

Cambrian tectonic context

A feature of the early Cambrian of the Tasmanides is the linear remnants of boninitic volcanics developed on either side of the Melbourne Zone, a belt defined by samples dredged from the New South Wales South Coast continental slope, a belt along the Peel Fault in the New England Orogen and scattered fragments regarded as an allochthon in Tasmania (Cayley, 2011; Crawford & Berry, 1992; Glen, 2013; Packham & Hubble, 2016). Connections between these belts and fragments have been reconstructed in different ways including discrete island arcs formed during eastwards rollback (Glen, 2013). An alternative suggestion is that Ordovician turbidites and the Cambrian greenstone belts of central Victoria are duplicated by the Riverina and Tambo hinges of the Lachlan Orocline (Figure 1) as shown by Cayley (2015), Moresi et al. (2014) and Musgrave (2015). The dredged samples of boninites from the New South Wales South Coast continental slope (Packham & Hubble, 2016) provide additional evidence supporting the development of the Tambo Hinge with the Tabberabbera Zone connected to the Canberra and Narooma zones consistent with the oroclines of Cayley (2015) as discussed in Fergusson (2017, p. 33). These boninitic volcanics formed at 520–510 Ma (Packham & Hubble, 2016), apart from samples along the Peel Fault that have an age of ~530 Ma (Aitchison & Ireland, 1995). A simple interpretation is that the units from the southern New England Orogen and the Lachlan Orogen formed part of a single infant island arc, now appear widely separated due to oroclinal folding, which developed in an intraoceanic setting (Figure 14). The Cambrian boninitic rocks reflect initiation of a subduction zone, a so-called infant arc of Stern & Bloomer (1992). Given that the boninitic ophiolites of western Tasmania have formed in the same 520–510 Ma interval the simplest explanation is that they are part of a single Cambrian arc (Cayley, 2011; Corbett et al., 2014). The Tasmanian ophiolites were emplaced as an allochthon soon after they formed in contrast to the Cambrian boninitic units in Victoria and offshore New South Wales South Coast that were deformed in the Benambran and subsequent orogenies (Packham & Hubble, 2016; VandenBerg et al., 2000). Ophiolite emplacement in Tasmania indicates that the polarity of the Cambrian arc was west-facing as shown in Figure 14. Collision of the arc with the VanDieland continental fragment terminated subduction east of VanDieland (Cayley, 2011) and following a modern example (see below) we suggest that it caused subduction reversal farther north. VanDieland is a continental fragment incorporating Tasmania, adjacent oceanic continental fragments and the Selwyn Block of central Victoria (Cayley, 2011). A similar reversal of polarity of a subduction zone associated with collision occurred when the Ontong Java Plateau collided with the Vityaz Trench in the Miocene (Crawford, Meffre, & Symonds, 2003).

Continuing subduction and rollback along the northern, still active segment of the Cambrian arc which is now east-facing generated a large backarc basin with sea floor spreading dated at around 502 Ma (Figure 15) based on the age of the Dookie gabbro (Spaggiari, Gray, & Foster, 2003) and considered equivalent to the tholeiitic basalts of the Howqua River (Packham & Hubble, 2016). The western side of the backarc basin, which most likely included pre-existing oceanic crust that predated the infant arc development, was subducted along the active margin of East Gondwana associated with the magmatic arc in western Victoria, western New South Wales and the following Delamerian Orogeny (Figure 15) (Cayley, 2011; Greenfield et al., 2011). Timing of initiation of this subduction and associated Andean margin is poorly constrained in southeast Australia, but is thought to be as early as 580 Ma in the Transantarctic Mountains of East Antarctica (Goodge et al., 2004). Gondwana-derived mid to late Cambrian turbidites were deposited in the southwestern part of the backarc basin (Figure 15) now preserved in the Stawell Zone of western Victoria as an accretionary complex formed during the west-dipping Delamerian subduction (Cayley, 2011). Basement of the Stawell Zone had formed by backarc sea-floor spreading in the early Cambrian (Squire, Wilson, Dugdale, Jupp, & Kaufman, 2006).

Cessation of subduction and backarc spreading in the mid-Cambrian resulted in the infant arc and adjoining backarc basin being joined to a greater paleo-Pacific plate to the southeast.

Locking of the backarc basin, boninitic arc and paleo-Pacific plate are associated with increased convergence along the Delamerian Andean margin. Strangely, subduction seems to have ceased soon after in southeastern Australia but continued in Northern Victoria Land as shown by eastward accretionary growth of the Robertson Bay Terrane from ~495 Ma to 450 Ma (Figures 16, 17) (Dallmeyer & Wright, 1992).

Overall, subduction seems to have involved several relatively short-lived episodes along various plate boundaries with a rapidly formed backarc basin. The overall history is unique but its complexity resembles modern-day plate interactions of the western Pacific Ocean, particularly the eastern Indonesian region and the Philippine Sea plate (Gaina & Müller, 2007; Hall, 2002; Zahirovic, Seton, & Müller, 2014).

The development of a single boninitic arc in the early Cambrian incorporating the greenstone belts of central Victoria (Heathcote Greenstone belt and Howqua River belt, Figure 1) and the boninites dredged from the continental slope east of the New South Wales South Coast has implications for two significant related issues in the Cambrian and Ordovician geology of southeastern Australia. These issues are the arrangement of Cambrian boninites and backarc basin basalts in relation to the Riverina and Tambo hinges of the Lachlan Orocline and the nature of the basement of the widespread Ordovician quartz turbidites. In the Heathcote Greenstone Belt the boninites are developed in a belt east of the backarc basin basalts (VandenBerg et al. 2000), whereas in the Howqua River belt the boninites are found west of the backarc basin basalts (Spaggiari, Gray, & Foster, 2004). On the New South Wales South Coast backarc basin basalts are found at Melville Point (Figure 1) (Stokes, Fergusson, & Offler, 2015) and boninites are dredged from the continental slope to the east (Packham & Hubble, 2016). Thus the pattern on the New South Wales South Coast and continental slope is similar to that in the Heathcote Greenstone Belt but opposite to that of the Howqua River belt and was considered evidence for the Lachlan Orocline of Cayley (2015) by Fergusson (2017, p. 33). Our interpretation is that the backarc basin basalts form basement to the Ordovician turbidites as documented in the Heathcote Greenstone Belt, Howqua River belt and at Melville Point (Stokes et al., 2015; VandenBerg et al., 2000) as was also argued by Packham & Hubble (2016). The boninitic volcanics form a distinct island arc that persisted as a topographic ridge adjacent to the basin containing the Ordovician quartz turbidites and did not form basement to them as given in other models (e.g. Fergusson & Coney, 1992a, b; Glen, 2013).

Backarc Basin, Island Arc Development and Rifting

After the main phase of the Delamerian Orogeny, the Gondwana-derived turbidites were deposited widely across the backarc basin in the Early to Middle Ordovician (Figure 16). A possibility is that parts of the backarc basin inundated by the turbidites underwent additional episodes of sea-floor spreading although the only evidence for this is the geochemistry of cherts that indicate a greater oceanic affinity over time consistent with widening of the basin (Bruce & Percival, 2014). Unfolding the Lachlan Orocline (Figure 1) significantly affects the geometry of the Ordovician turbidite fan (Moresi et al., 2014). For example, it had been considered as forming a major submarine fan almost as wide as it was long (Fergusson & Coney, 1992a). Instead, it could well have been much more elongate infilling and following the inactive Delamerian trench in the west with a lobe extending south of the developing Macquarie Arc (Fergusson, 2009).

The context for formation of the Macquarie Arc was a broad backarc basin bounded by inactive subduction zones (Figure 16). It is unclear why subduction would have initiated in the midst of this backarc basin. In reconstructions of the western Pacific (e.g. Crawford et al., 2003; Hall, 2002; Zahirovic et al., 2014) many subduction zones seem to form by subduction reversal during island arc collisions. Also island arcs migrate and duplicate by backarc spreading largely driven by rollback. A possibility is that the Macquarie Arc was induced by convergence across the backarc basin and formed along an older weak boundary within it, e.g. an earlier rifted part of a remnant island arc. Orientation of the island arc was of course unknown in the Early Ordovician and following Fergusson (2009) we show it had a high-angle to the Gondwana margin as this geometry allows turbidite deposition on both sides of the developing island arc (Figure 16). As discussed in Fergusson (2009) several island arcs in the western Pacific have undergone major rotations during their development, including the Izu-Bonin-Marianas island arc and the New Hebrides island arc, as suggested for the Macquarie Arc. Polarity of the Macquarie Arc is considered below.

Development of the island arc is readily divided into two major episodes. In the first episode (Phase 1 of Percival & Glen, 2007), at 485 to 475 Ma (Figure 16) igneous activity was probably widespread in the western volcanic belt but is poorly preserved in the central and eastern volcanic belts and is unlikely in the southern volcanic belt. Phase 1 was followed by a hiatus of ~9 Ma prior to the dominant episode of island arc activity in Phases 2 to 4 of Percival & Glen (2007) that lasted from ~465 Ma into the early Silurian up until 435 Ma (Figure 17). Island arc development in this second episode was initiated by rapid rollback on the accompanying subduction zone as shown by the extensional rendering of the island arc in the Darriwilian (Quinn et al., 2014). Extension (Figure 17) is considered responsible for separation of the western and central volcanic belts as postulated by Glen et al. (2007a) but also emplaced ultramafic rocks and generated MORB volcanic activity of the Jindalee Group (Quinn et al., 2014) and Gooandra Volcanics (Wyborn, 1992). Rifting is also shown by development of the Kirribilli Formation with the Mugincoble and Hoskins chert members of late Middle Ordovician age that are also associated with MORB volcanics (Lyons et al., 2000; Warren et al., 1995). Deep-marine pelagic to hemi-pelagic deposition of these cherts between the western and eastern volcanic belts is evidence for the extent of this rifting.

Widespread development of the island arc in Phase 2 (Figure 17) resulted in build-up of volcaniclastic sedimentary wedges that displaced and stratigraphically overlay the Ordovician quartz turbidites at the same time as turbidite deposition was waning on the turbidite fan especially for the southern and eastern margins of the central and eastern volcanic belts. Widespread development of black shale deposition on the Ordovician turbidite fan in the Late Ordovician is consistent with this and may reflect higher sea levels in the Eastonian and Bolindian (Munnecke, Calner, Harper, & Thomas, 2010). Turbidite deposition continued through much of the Late Ordovician in the southeast part of the Bendigo Zone and indicates that the massive Gondwana sediment source was still operative as is also shown by continuing thick quartz turbidite deposition in uppermost Ordovician to lower Silurian turbidites in eastern Victoria (VandenBerg et al., 2000). Although higher sea levels in the Late Ordovician may have contributed to the reduction in turbidite deposition across the turbidite fan it is also likely that sediment was diverted by the re-initiation of subduction along the extinct Delamerian subduction zone resulting in accretionary growth of the Stawell and Bendigo zones from about 455 Ma onwards (Gray & Foster, 2004). It is unclear how this subduction zone continues northwards but our preference is that it is connected to the Tabberabbera and Narooma zones around the Lachlan Orocline which developed in the Benambran Orogeny (Figures 17, 18).

Polarity of the Island Arc

A common suggestion for the polarity of the Macquarie Arc is that it was east-facing (i.e. a west-dipping slab) throughout its history consistent with subsequent tectonic development of the Lachlan Orogen (Glen et al., 1998; Glen, 2005; Scheibner & Basden, 1998). More complicated models with double divergent subduction were devised to explain the high shortening in deep-marine turbidites and the opposed vergences of the Bendigo and Tabberabbera zones on either side of the Melbourne Zone and associated rare high-P metamorphic rocks in the Late Ordovician to early Silurian (Gray & Foster, 1997; Spaggiari, Gray, & Foster, 2002). Additionally the east-facing Macquarie Arc has been considered associated with the Narooma Accretionary Complex on the New South Wales South Coast (Miller & Gray, 1996, 1997). Development of the Tabberabbera Zone subduction was related by Fergusson (2003, 2014) to east-dipping subduction along the western side of the Macquarie Arc that also accounted for the strong deformation in the Ordovician turbidites of the Girilambone and Wagga–Omeo zones in contrast to the weak Benambran deformation of the Macquarie Arc.

In the reconstruction of Fergusson (2009) polarity of the Macquarie Arc is shown for Phase 1 activity as facing northwards and changing gradually to the west as the arc rotated anticlockwise around an Euler Pole located near its western terminus. This geometry would imply active extension was occurring southwest of this pole. Similar plate boundary geometry occurs on the northwest boundary of the Caroline plate in the western Pacific Ocean north of West Papua, south of Palau (Bird, 2003). For Phase 1 igneous activity in the Macquarie Arc, the location of the subduction is not clear as no evidence remains to uniquely locate it. The simplest assumption following from its later location (Figure 17) would be that the arc faced to the NNW with a SSE-dipping subducting slab. A difficulty with analyzing long-lived island arcs in the ancient record is that subduction processes operate in the longer term to remove evidence of subduction polarity. The dominant process in subduction zones is subduction erosion rather than subduction accretion (Stern, 2011) and thus forearcs can be lost over time resulting in much reduced forearc widths and the loss of potential subduction polarity indicators including high-P metamorphic rocks, subduction complexes and forearc basins.

In the late Middle Ordovician, the polarity of the Macquarie Arc seems more reliable given the strongly deformed Lower to Middle Ordovician turbidites of the Girilambone Zone which were interpreted as a subduction complex by Scheibner & Basden (1998) and supported by

Fergusson, Fanning, Phillips, & Ackerman (2005). Later deformation and metamorphism in the early Silurian part of the Benambran Orogeny has resulted in juxtaposition of the Girilambone Zone subduction complex and volcanic arc, although as noted above the nature of the contact relationship is ambiguous in some areas. In contrast farther south in the Wagga–Omeo Zone, the succession extends into the uppermost Ordovician (Colquhoun, Meakin, & Cameron, 2005) indicating accretion of the turbidite succession was no earlier than this. Arguments over the accretionary development or otherwise have been widely canvassed in the literature (e.g. Fergusson, 2014; Glen, 2013; Gray & Foster, 2004) and need not be repeated here. The point is just reiterated that the widespread deformation involving deep-marine turbidites in the Late Ordovician to early Silurian is most easily accommodated in a subduction complex setting. More recently, Packham & Hubble (2016) have argued that the Narooma Accretionary Complex is a fold-thrust belt developed along the eastern side of their "Albury-Bega basin". If the setting is considered a fold-thrust belt, as suggested by Packham & Hubble (2016), then this still requires some sort of plate convergence as was also argued by Glen et al. (2004) for formation of the Narooma Accretionary Complex. Alternative explanations to subduction complexes either seem to involve producing reconstructions that mirror subduction complex interpretations (e.g. Glen, Stewart, & Percival, 2004, specifically see their figure 9), or solely attribute the deformation to the "Benambran Orogeny" as if this somehow provides a tectonic explanation (e.g. Glen, 2013, p. 335) or simply just ignoring it (Quinn et al., 2014). We are struck that the Benambran Orogeny has widespread effects in Ordovician turbidites within the Bendigo, Tabberabbera, Narooma, Girilambone and Wagga–Omeo zones yet had minimal to almost no effects in much of the volcanic arc which was still active with continuing sedimentation (e.g. the Kabadah Formation) and also presumably thermally weakened given that it was still active into the early Silurian. The Macquarie Arc was most active in the Late Ordovician to early Silurian overlapping with the Benambran Orogeny and therefore susceptible to convergent deformation. In contrast, the oceanic backarc crust of the Ordovician turbidites had formed in the early Cambrian and had at least 50 Ma of thermal cooling and associated lithospheric strengthening prior to the Benambran Orogeny. We therefore favor subduction accretion as the preferred model for causing deformation both west and east of the Macquarie Arc in the Ordovician turbidites of the Girilambone, Wagga–Omeo, Tabberabbera and Narooma zones (Fergusson, 2014).

A major polarity switch occurred in the Benambran Orogeny with the establishment of a subduction zone in the Narooma Zone (Fergusson, 2009, 2014) and follows on from earlier arguments presented by Miller & Gray (1996, 1997), Gray & Foster (1997, 2004), and more recently by Prendergast (2007). The timing of the initiation of subduction in the Narooma Zone is poorly constrained, as Ar-Ar ages (~440 Ma, Gray & Foster, 2004) are associated with metamorphism that only developed after substantial growth of a wedge of deformed turbidites. Overlap must have occurred in terms of subduction timing and uncertainty remains about the extent of this overlap. In the reconstruction shown in Figure 18 as argued by Fergusson (2014), following Collins & Hobbs (2001) and consistent with abundant new U–Pb zircon ages on granites (e.g. Ickert & Williams, 2011), two magmatic arcs formed in the early Silurian associated with these two subduction zones. These features have to be considered in relation to formation of the Riverina and Tambo hinges of the Lachlan Orocline (Figure 1) (Cayley, 2015; Moresi et al., 2014; Musgrave, 2015). In the reconstructions given here (Figures 17, 18) we suggest that the west-facing Macquarie Arc collided with the eastern margin of East Gondwana and resulted in widespread Benambran effects found in northwest New South Wales (Greenfield et al., 2011) and in parts of central and north Queensland (the Benambran reworked zone of Fergusson & Henderson, 2013). In the Late Ordovician, subduction initiated southeast of the Macquarie Arc resulting in the accretionary complex of the Narooma Zone and was effectively connected to the southwest with the Tabberabbera and Bendigo zones as subduction was gradually terminated west of the Macquarie Arc in central-western New South Wales. Indentation from the south by VanDieland resulted in development of the oroclines (Moresi et al., 2014). These authors opted for a late Silurian timing for most of the oroclinal development associated with rollback and formation of the Darling Basin in central-western New South Wales but detailed arguments in support of this timing have not yet been published. Our preference is that a significant component of the oroclinal folding took place in the Benambran Orogeny and was accommodated by subduction at that time, but remains contentious pending publication of a full reconstruction of events associated with orocline development in the southern Lachlan Orogen by Ross Cayley.

Conclusions

The Macquarie Arc has two main episodes of magmatic activity (simplified from Percival & Glen, 2007): (1) their Phase 1 in the Early Ordovician, and (2) their Phases 2 to 4 in the late Middle Ordovician into early Silurian, separated from the earlier episode by a hiatus of 9 Ma. As argued by Quinn et al. (2014) initiation of the second episode of igneous activity was accompanied by a major extensional event associated with emplacement of ultramafic rocks, MORB volcanism and chert deposition of the Jindalee Group and equivalent units and resulted in separation of the western, central and southern volcanic belts (Glen et al., 2007a).

The nature of contacts between the Macquarie Arc succession and the Ordovician quartz turbidite and black shale succession that is widely developed throughout the Lachlan Orogen remains unresolved. We suggest that too much emphasis has been placed on faulting along these contacts rather than taking into account gross relationships that in some areas have Macquarie Arc units conformably overlying quartz turbidites especially along the eastern side of the eastern volcanic belt and also at the southern end of the central belt. This is shown by the sinuous nature of contacts consistent with folding, although local faults undoubtedly occur and these relationships reflect the ductility contrast between the well-bedded turbidite succession and the massive volcanic/volcaniclastic succession of the Macquarie Arc. Lack of interdigitation between these major associations reflects: (1) a stratigraphic relationship with Macquarie Arc expansion in the late Middle Ordovician coinciding with a reduction in sediment supply to the Gondwana-derived turbidite fan, and (2) overwhelming of the Gondwana-source by influx of sediment from the Macquarie Arc.

The Macquarie Arc and Ordovician turbidites developed overlying a Cambrian backarc formed by seafloor spreading west of an east-facing boninitic arc whose polarity had flipped from west-facing as a result of collision with VanDieland. Why subduction was initiated in this backarc basin is problematic; the backarc basin in the Early Ordovician came under general convergence as a result of cessation of subduction along the Ross-Delamerian Andean convergent boundary and possibly resulted in initiation of subduction along a relict remnant arc within the backarc basin. Formation of the new arc at a high-angle to the former active East Gondwana margin allowed turbidite sedimentation on both sides of the arc but the polarity in the Early Ordovician remains unknown. After an interval of inactivity with either no or very slow subduction, the inner backarc basin was closed as the arc rotated about an Euler pole at its western termination resulting in collision of the Girilambone Zone with the eastern margin of Gondwana. These events were accompanied by initiation of a new subduction zone to the east of the arc and development of the Narooma Accretionary Complex. The Benambran Orogeny reflects these events, which explains why the thermally weakened Macquarie Arc was only weakly affected.

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Figure Captions

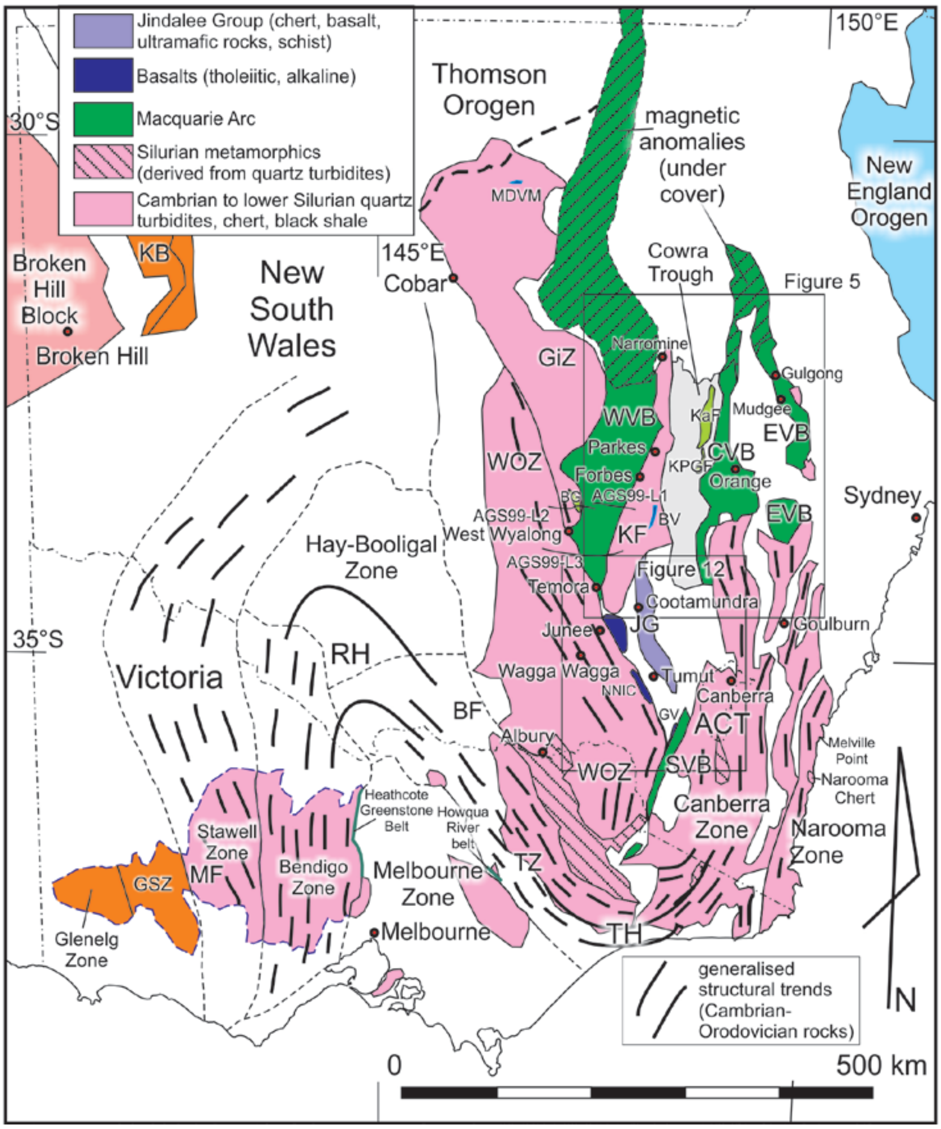

Figure 1. Map of southeastern Australia with the distribution of the Macquarie Arc and Ordovician turbidite successions. Structural trends are shown for Cambrian–Ordovician rocks and are based on field measurements portrayed on geological maps and magnetic data (magnetic data from Geoscience Australia, map compiled from digital data in Raymond et al., 2007a, b). Structural trends in the Lachlan Orogen in Victoria and southern New South Wales outline the Lachlan Orocline with the western Riverina Hinge and the eastern Tambo Hinge (names formalised by Musgrave, 2015). Northern continuation of the Macquarie Arc is under

cover and inferred from magnetic data. Locations of deep seismic lines for central New South Wales are shown (Glen et al., 2002). Abbreviations: ACT–Australian Capital Territory, BF–Bootheragandra Fault, BG–Burcher Greywacke, BV–Brangan Volcanics, CVB–central volcanic belt, EVB–eastern volcanic belt, GiZ–Girilambone Zone, GSZ–Grampians–Stavely Zone, GV–Gooandra Volcanics, JG–Jindalee Group, KaF–Kabadah Formation, KB–Koonenberry Belt, KF–Kirribilli Formation, KPGF–Kurrajong Park and Greengrove formations, MDVM–Mount Dijou Volcanic Member, MF–Moyston Fault, NNIC–Nacka Nacka Igneous Complex, RH–Riverina Hinge of the Lachlan Orocline, SVB–southern volcanic belt, TH–Tambo Hinge of the Lachlan Orocline, TZ–Tabberabbera Zone, WOZ–Wagga–Omeo Zone, WVB–western volcanic belt.

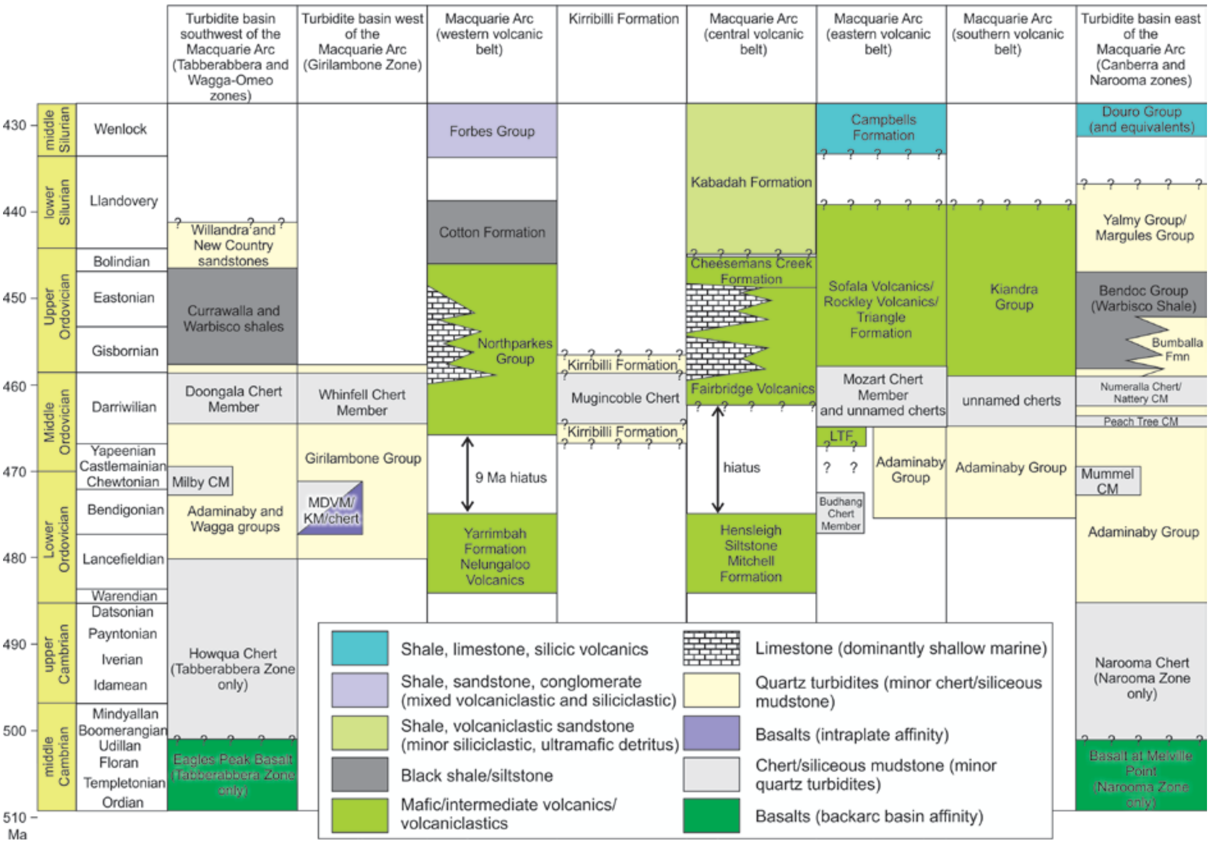

Figure 2. Time-space plot showing representative columns for the Ordovician turbidites, Macquarie Arc succession and lower to mid Silurian units in the eastern Lachlan Orogen using the timescale of the International Commission on Stratigraphy (Cohen, Finney, Gibbard, & Fan, 2013, updated) with eastern Australian Ordovician stages (e.g. Percival et al., 2011). Abbreviations: CM–Chert Member; LTF–Lower Triangle Formation, KM–Kaiwilta Member, MDVM–Mount Dijou Volcanic Member.

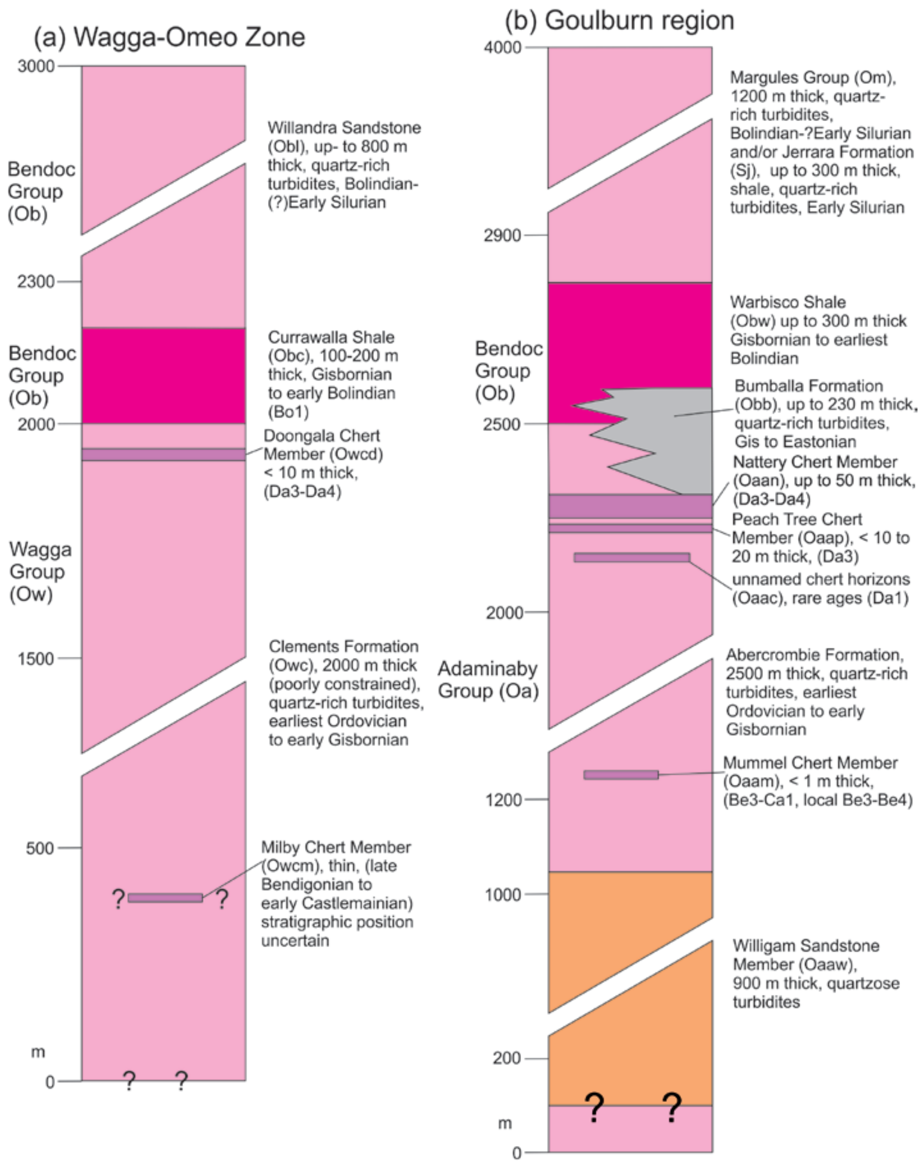

Figure 3. Simplified stratigraphic columns for the Ordovician – early Silurian turbidite succession. Note the truncated scale for the thickest units and that the thicknesses of the chert members have been exaggerated. (a) Wagga–Omeo Zone region, west of West Wyalong, compiled from data in Colquhoun et al. (2005). (b) Goulburn region, compiled from data in Thomas & Pogson (2012). Ages of cherts have been determined by Percival (in Thomas & Pogson, 2012).

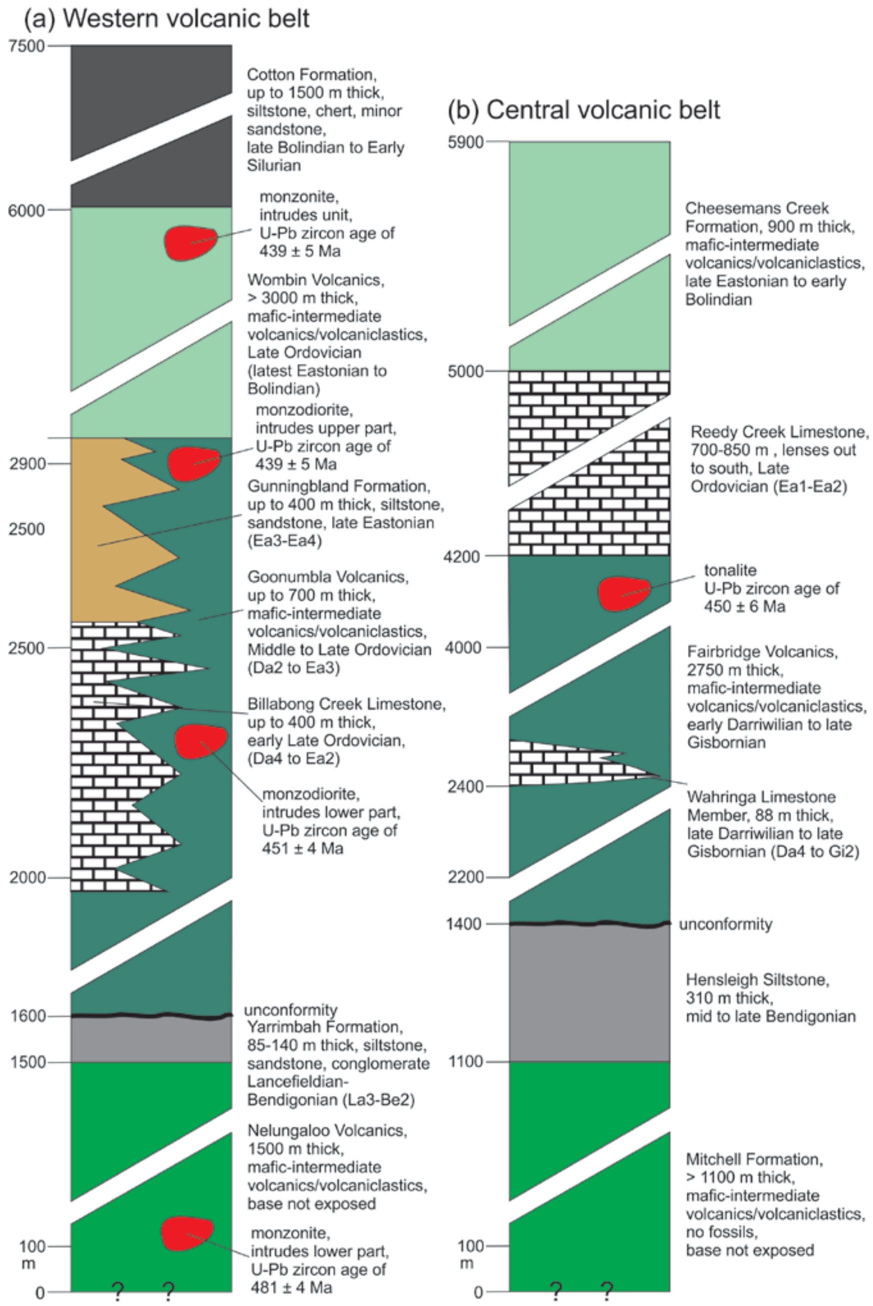

Figure 4. Representative stratigraphic columns for the Macquarie Arc. Note the truncated scale for the thickest units. (a) Western volcanic belt in the region west of Parkes compiled from numerous sources (Glen et al., 2007b; Lyons et al., 2000; Pickett & Percival, 2001; Simpson et al., 2005; Zhen & Pickett, 2008). Radiometric ages are all U–Pb zircon ages from Butera, Williams, Blevin, & Simpson (2001) with the age for the monzonite in the lower Nelungaloo Volcanics reassessed by I. Williams (in Simpson et al., 2005). (b) Central volcanic belt north of Orange, compiled from numerous sources (Crawford et al., 2007a; Percival & Glen, 2007; Percival et al., 2011). The radiometric age of the tonalite north of Molong was cited in Percival & Glen (2007).

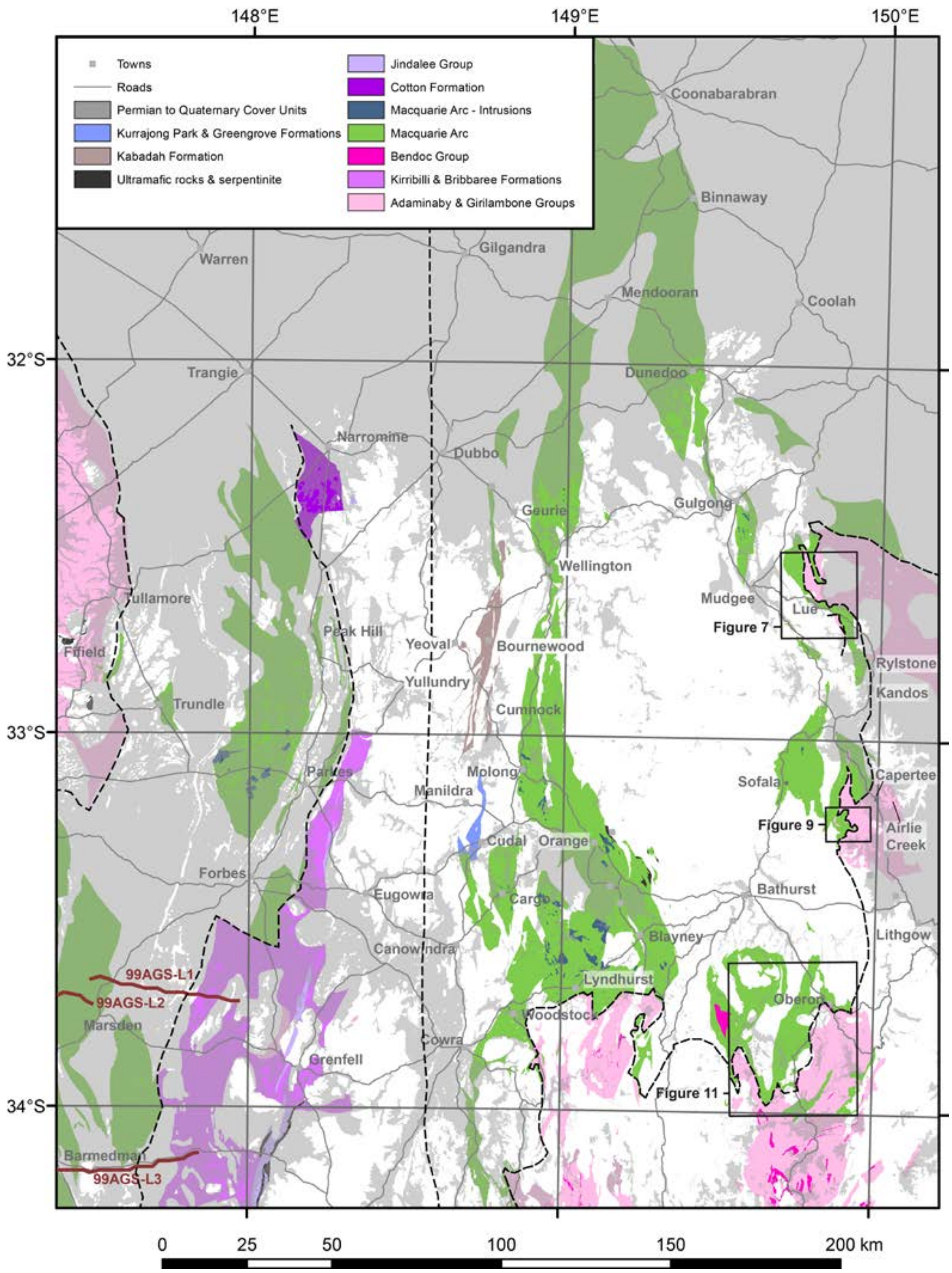

Figure 5. Ordovician and related lower Silurian units including the widespread volcanics/volcaniclastics of the Macquarie Arc succession in the northern Lachlan Orogen modified from the digital maps of Colquhoun et al. (2015, 2017). Location of seismic lines 99AGS-L1, 99AGS-L2 and 99AGS-L3 also shown (from Glen et al., 2002). Dashed black lines show inferred/known boundaries between the Ordovician turbidites and the Macquarie Arc succession.

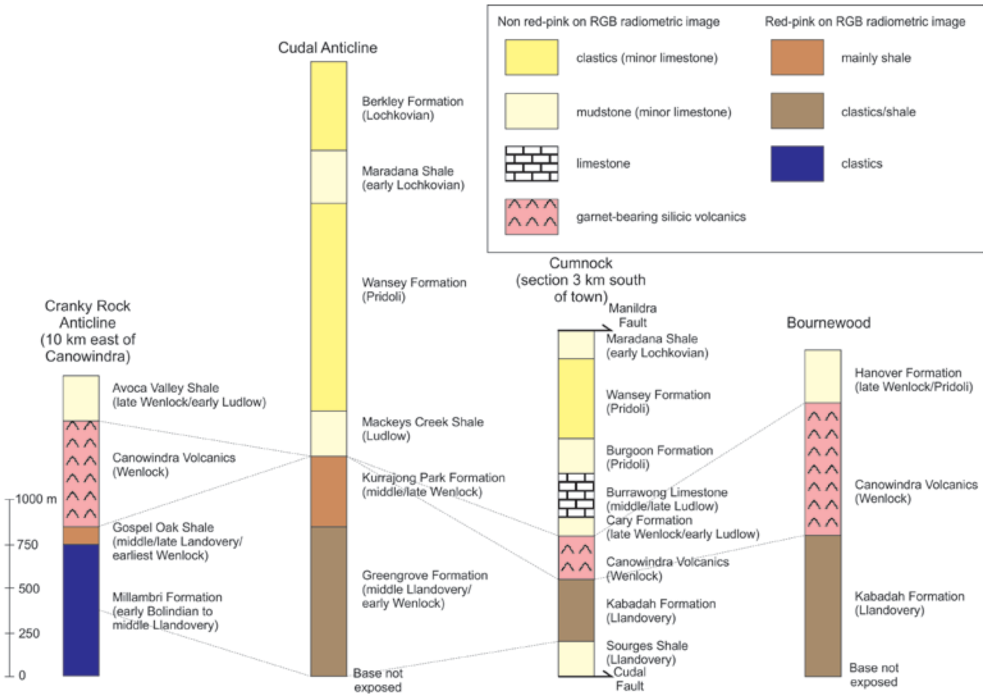

Figure 6. Stratigraphic diagram for Ordovician to earliest Devonian units of the Cowra Trough showing inferred relationships between the clastic wedge of mainly volcaniclastic rocks of the Kabadah Formation, related units (red-pink on RGB radiometric image, Geological Survey of New South Wales, 2009a) and relationships with other units. Thicknesses determined from: (1) a cross section drawn along the axial trace of the Cranky Rock Anticline from the Cowra 1:100,000 geological map (Krynen & Moffitt, 1997) and data in Ryall (1965), (2) cross section CD on the Molong 1:100,000 geological map (Krynen, Morgan, Scott, Raymond, & Warren, 1997) for the Cudal Anticline southeast of Manildra, (3) an east–west cross section drawn 3 km south of Cumnock from data on the Wellington 1:100,000 geological map (Scott et al., 1999), and (4) estimates given in Meakin & Morgan (1999). Ages of units are given in Pogson & Watkins (1998) and Meakin & Morgan (1999).

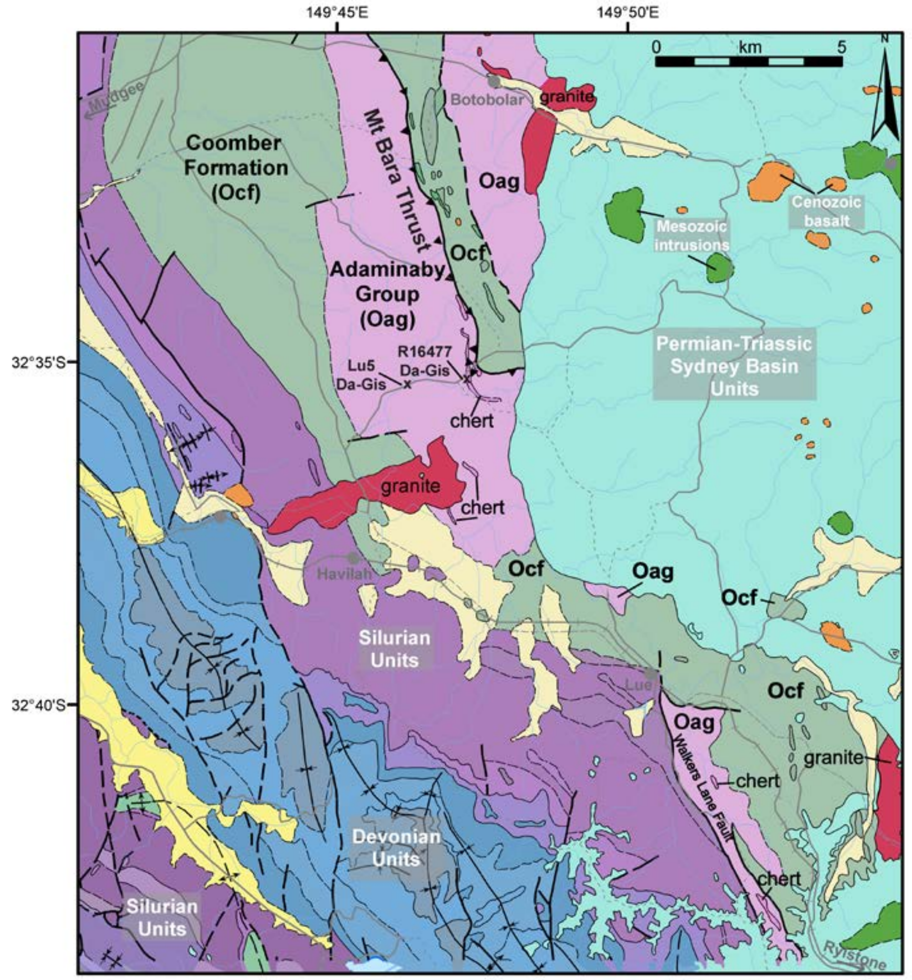

Figure 7. Map of the Adaminaby Group and Coomber Formation southeast of Mudgee (see Figure 5 for location). Fossil ages of chert are shown (Murray & Stewart, 2001; Stewart & Fergusson, 1995). The map is modified from the digital maps of Colquhoun et al. (2015, 2017). The granites are Carboniferous. Abbreviation: Da-Gis – Darriwilian-Gisbornian.

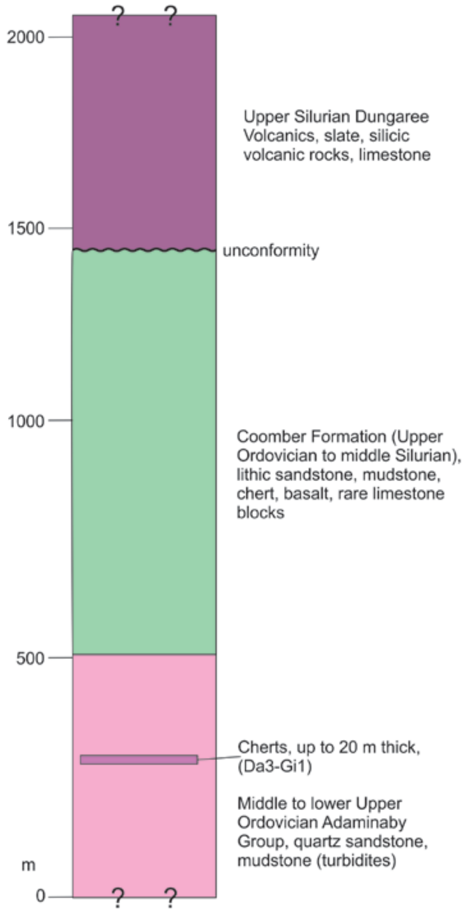

Figure 8. Stratigraphic column for Ordovician to Silurian units to the southeast of Mudgee. Modified from figure 2c in Fergusson & Colquhoun (1996) and taking into account the reduced thickness of the Adaminaby Group given that Darriwilian–Gisbornian chert is documented at different structural levels in the unit (see Figure 7) indicated by a new fossil age for chert west of the Mt Bara Thrust (Murray & Stewart, 2001, figure 9).

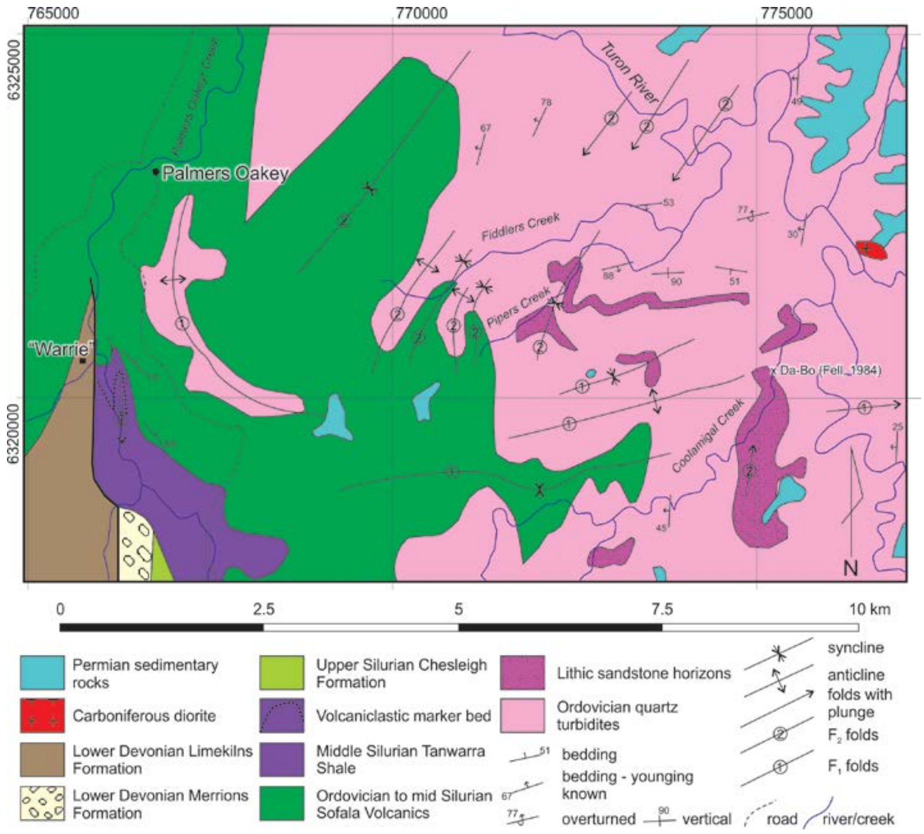

Figure 9. Geological map of the Palmers Oakey district and extending east to the upper Turon River (see Figure 5 for location). Compiled from Fergusson (1979) and a digital version of part of the Bathurst 1:100 000 geological map (Watkins et al., 1997). Fossil locality is a chitinozoan of Darriwilian to Bolindian age from Fell (1984) abbreviated as 'Da-Bo (Fell, 1984)' on map.

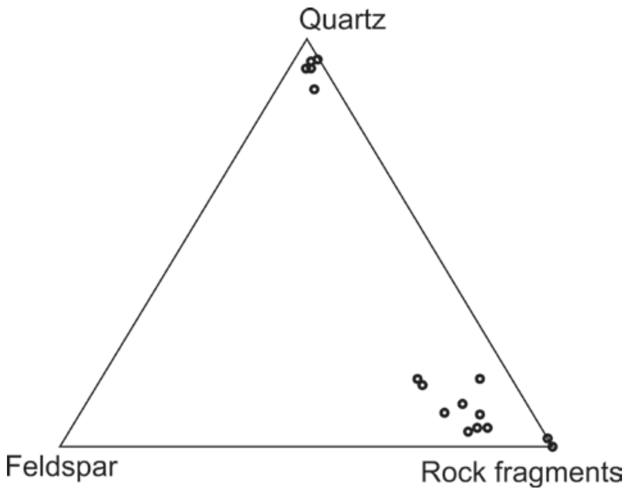

Figure 10. QFR triangular diagram showing recalculated point count data by us from 16 sandstone/conglomerate modes in lower Coolamigal Creek from Crook (1955). Quartz-rich samples are from the Ordovician turbidites whereas the lithic sandstones/conglomerate

samples are from the eastern band of lithic sandstone/conglomerate/mudstone in lower Coolamigal Creek.

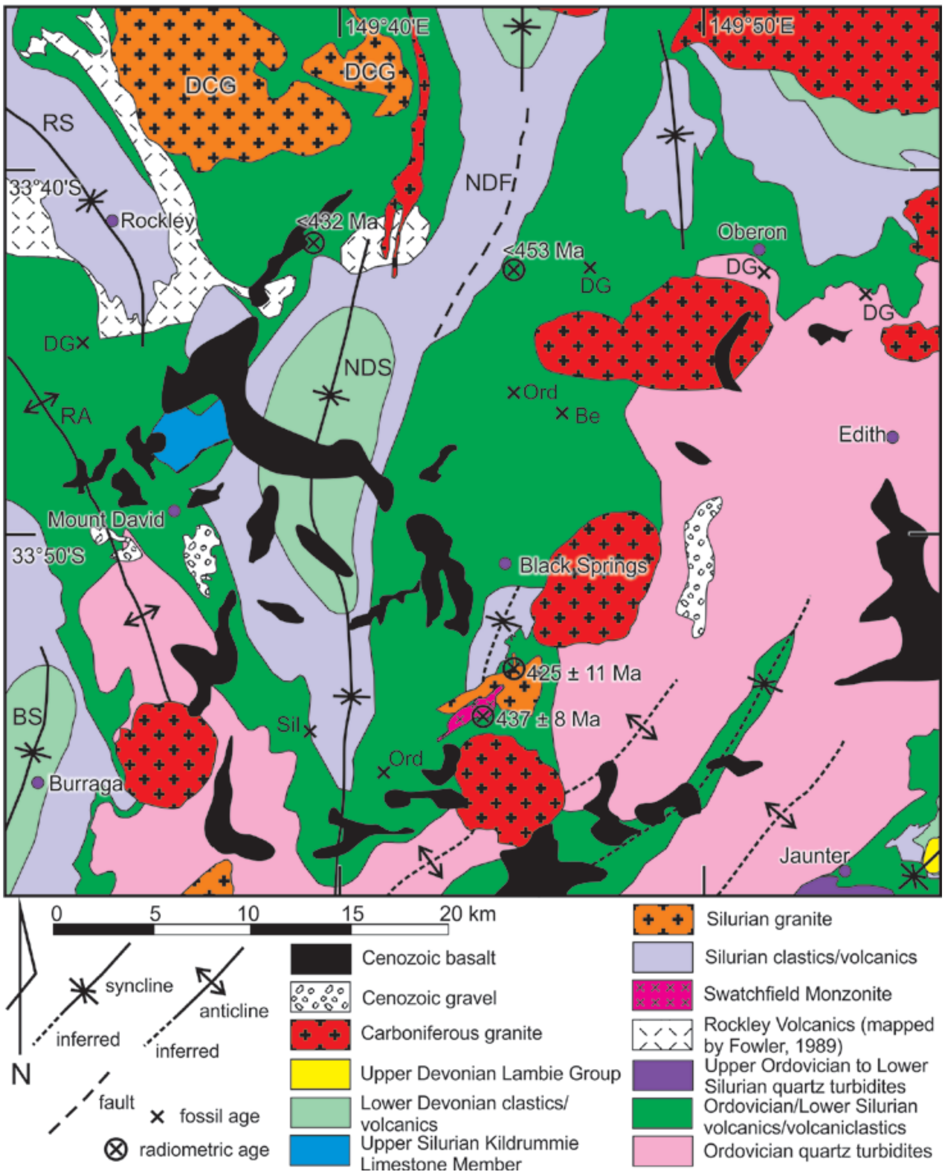

Figure 11. Simplified geological map of the Oberon district (see Figure 5 for location). Crosses show fossil localities for conodonts in chert from Fowler & Iwata (1995) for the locality south of Rockley, from Meffre (2003) for the two localities near Oberon, and from Murray & Stewart (2001) for all other localities, apart from the Silurian macrofossil locality (Pickett, 1973). Radiometric ages include two detrital zircon samples (youngest age given) from Glen et al. (2016) and two U–Pb zircon ages for plutonic rocks south of Black Springs from Meffre (2003). Abbreviations for fossil ages: Be–Bendigonian, DG–Darriwilian-Gisbornian, Ord–Ordovician, Sil–Silurian. Abbreviations for structures and units: BS–Burraga Syncline, DCG–Davies Creek Granite, NDF–Native Dog Fault, NDS–Native Dog

Syncline, RA–Rockley Anticline, RS–Rockley Syncline. Map modified from the digital copy of the Oberon 1:100,000 geological map (Stuart-Smith & Wallace, 1997) and taking into account mapping by Fowler (1989) and Meffre (2003). Inferred folds west of Jaunter are based on map pattern in an area of widespread Cenozoic cover. Extent of basalt and Cenozoic sediments has been either reduced or left off the map.

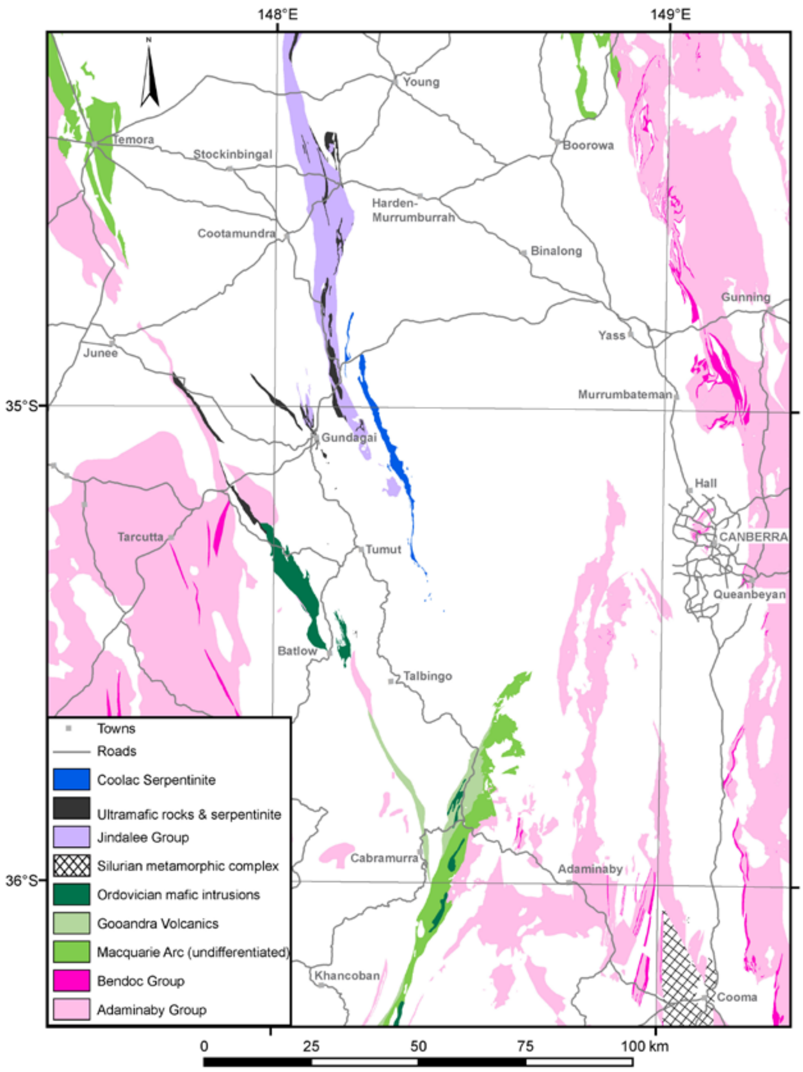

Figure 12. Ordovician and related units including volcanics/volcaniclastics of the Macquarie Arc succession of the southern Macquarie Arc in the Cootamundra–Kiandra region modified from the digital map of Colquhoun et al. (2017).

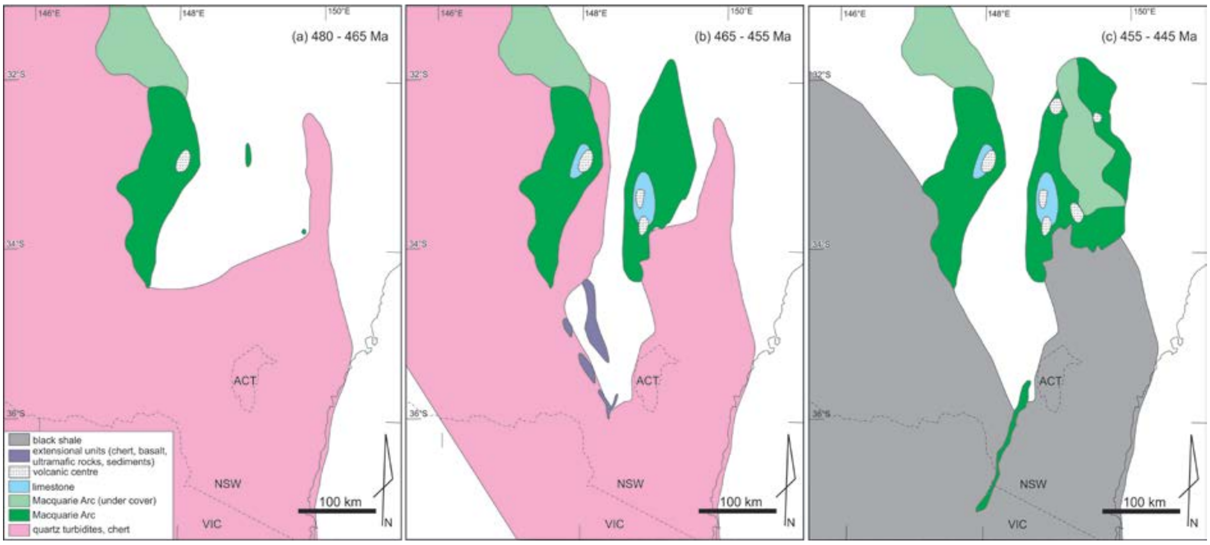

Figure 13. Ordovician paleogeography of the eastern Lachlan Orogen divided into three time slices based on the present distribution of units without undeforming the extent of units. Coastline, state (New South Wales and Victoria) and ACT (Australian Capital Territory) borders are given for reference. (a) Lancefieldian to early Darriwilian (480–465 Ma), (b) late Darriwilian to Gisbornian (465–455 Ma), and (c) Eastonian to Bolindian (455–445 Ma).

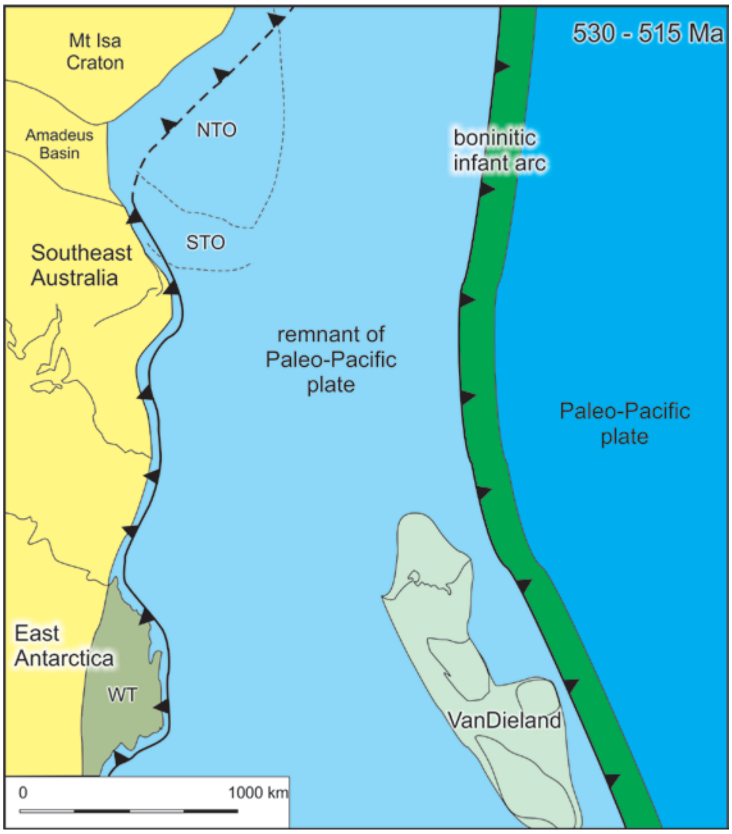

Figure 14. Reconstruction of the Cambrian boninitic island arc and backarc basin neighbouring East Gondwana in the middle Cambrian (~515 Ma). A single Cambrian boninitic arc with west-facing polarity is east of VanDieland and subsequently collided with

it (modified from Cayley, 2011). The boninitic arc is represented by boninites in the Heathcote Greenstone Belt, the Howqua River belt, the continental slope of the New South Wales South Coast, Tasmania and the southern New England Orogen (see text). Continental reconstruction with VanDieland geometry is after Müller et al. (2016) in preference to that used by Cayley (2011), also in Figures 15 to 18. Locations of the north Thomson Orogen (NTO) and south Thomson Orogen (STO) are indicated although these had not formed until ~495 Ma and ~440 Ma respectively (Fergusson & Henderson, 2015). Subduction zones are indicated by heavy black lines with triangles on the upper plate. Subduction zone southeast of the Mount Isa craton is inferred (shown by black dashed line).

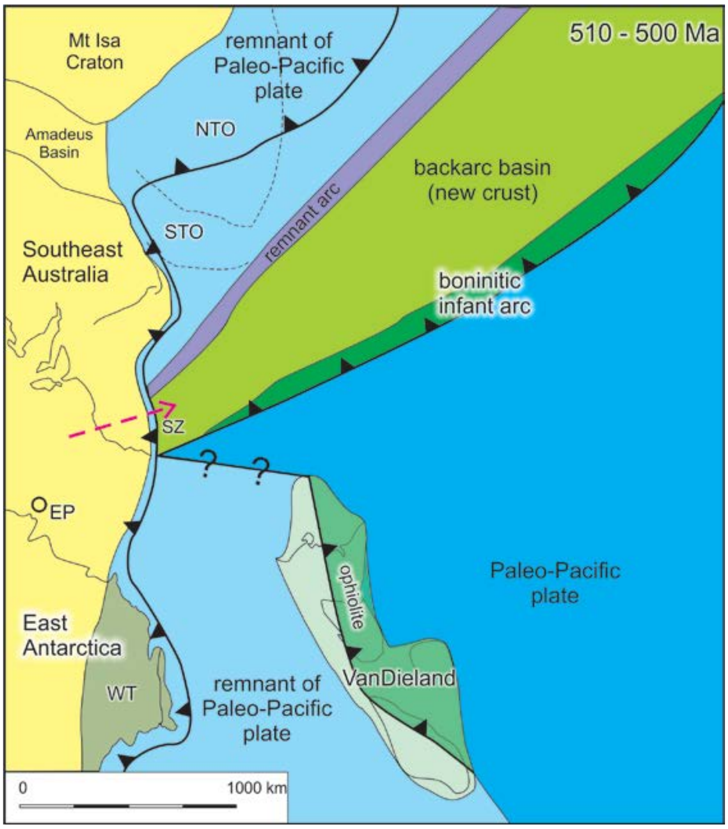

Figure 15. Reconstruction of the Cambrian arc following passive margin – island arc collision with VanDieland which caused switching of subduction polarity from an east-dipping to a northwest-dipping slab resulting in subduction of the Palaeo-Pacific plate with ongoing rollback rotating about an Euler Pole (EP) in the west and resulting in wedge-shaped backarc sea-floor spreading including formation of the basement to the Stawell Zone in western Victoria. The type of plate boundary between the northern end of the ophiolite sheet in Vandieland and the boninitic island arc is unknown. The Delamerian Orogeny along the East Gondwana Andean margin was promoted by subduction of the inferred remnant arc which

caused the Delamerian Orogeny. This event occurred later in the north Thomson Orogen than farther south (Fergusson & Henderson, 2015). Magenta dashed arrow shows sediment movement associated with deposition of late Cambrian turbidites of the Stawell Zone. Abbreviations: NTO–north Thomson Orogen, STO–south Thomson Orogen, SZ–Stawell Zone, WT–Wilson terrane.

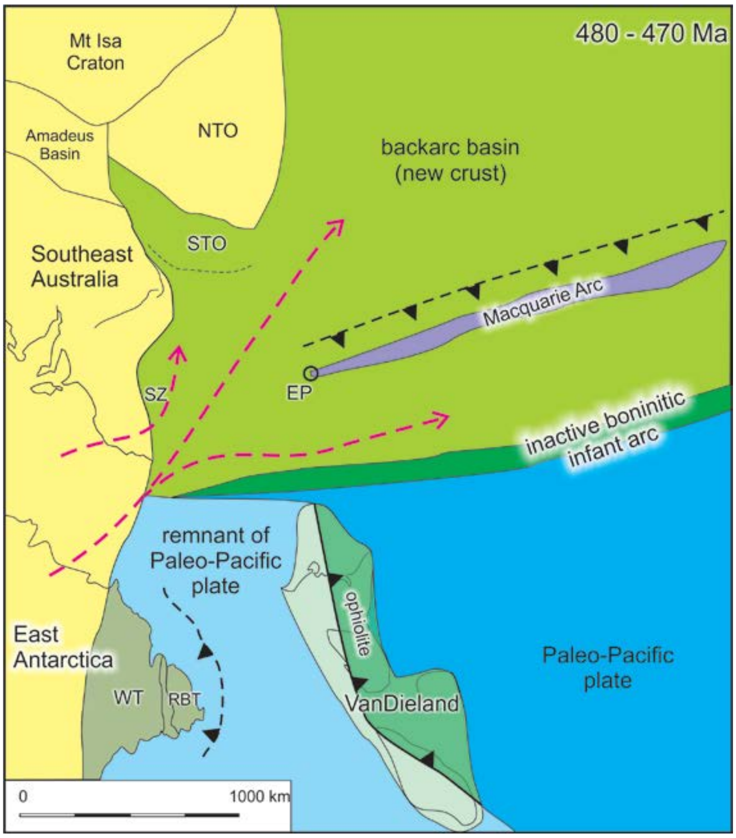

Figure 16. Early Ordovician reconstruction showing the newly initiated Macquarie Arc in the backarc basin that developed behind the Cambrian arc. Dashed arrows (magenta) show the sediment distributary system from East Gondwana into the submarine turbidites that formed on both sides of the Macquarie Arc (Fergusson, 2009). Polarity of the Macquarie Arc in this interval is not known and was possibly a SSE-dipping slab resulting in gradual closure of the northwestern part of the backarc basin by anticlockwise rotation about an Euler Pole (EP). This rotation also accounts for the southward disappearance of the Macquarie Arc as subduction rate decreases towards the Euler Pole. An incipient subduction zone (black dashed line with triangles on upper plate) is shown for the accretion of the Robertson Bay Terrane turbidites (Dallmeyer & Wright, 1992). Abbreviations: NTO–north Thomson Orogen, RBT–Robertson Bay terrane, STO–south Thomson Orogen, SZ–Stawell Zone, WT–Wilson terrane.

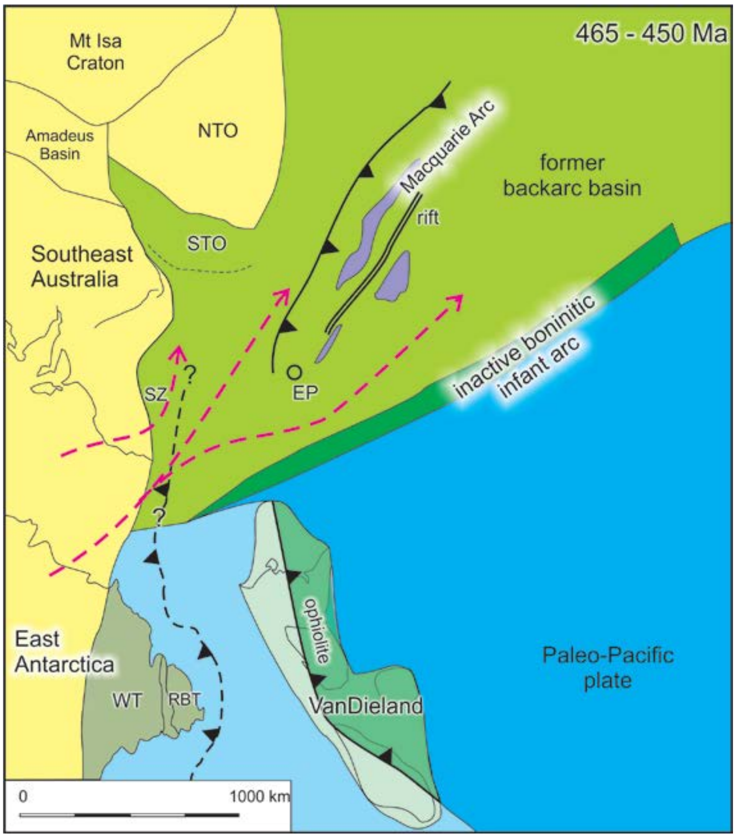

Figure 17. Middle to Late Ordovician reconstruction showing the Macquarie Arc during Phases 2–4 of Percival & Glen (2007). This was accompanied by extension resulting in formation of a trough between the western and central/eastern volcanic belts. Continuing motion around the Euler Pole in the south accounts for this rifting and as in Figure 16 is also consistent with the southward termination of the Macquarie Arc. Dashed magenta arrows show the sediment distributary system from East Gondwana into the submarine turbidites that formed on both sides of the Macquarie Arc (Fergusson, 2009). Polarity of the Macquarie Arc is shown by development of the Girilambone Zone subduction complex (see text) resulting in final closure of the backarc basin. The subduction zone off East Antarctica is based on Dallmeyer & Wright (1992) who document deformation in the Robertson Bay terrane up to 450 Ma, which therefore has minor overlap with the Benambran Orogeny in western Victoria (Cayley, 2011). Cayley (2011) noted the similarity between the Stawell and Bendigo zones to the Robertson Bay terrane and on this basis the subduction zone is tentatively continued farther north. The eastern Stawell Zone and the Bendigo Zone were affected by the late Ordovician to early Silurian Benambran Orogeny (Gray & Foster, 2004). This is thought to have been driven by west-dipping subduction and potentially this subduction zone could link with either the subduction zone west of the Macquarie Arc or with the developing subduction zone east of the Macquarie Arc in the (?)latest Ordovician. The latter idea is our preferred

option but awaits a more detailed assessment of tectonic events associated with formation of the Lachlan Orocline. Abbreviations: NTO–north Thomson Orogen, RBT–Robertson Bay terrane, STO–south Thomson Orogen, SZ–Stawell Zone, WT–Wilson terrane.

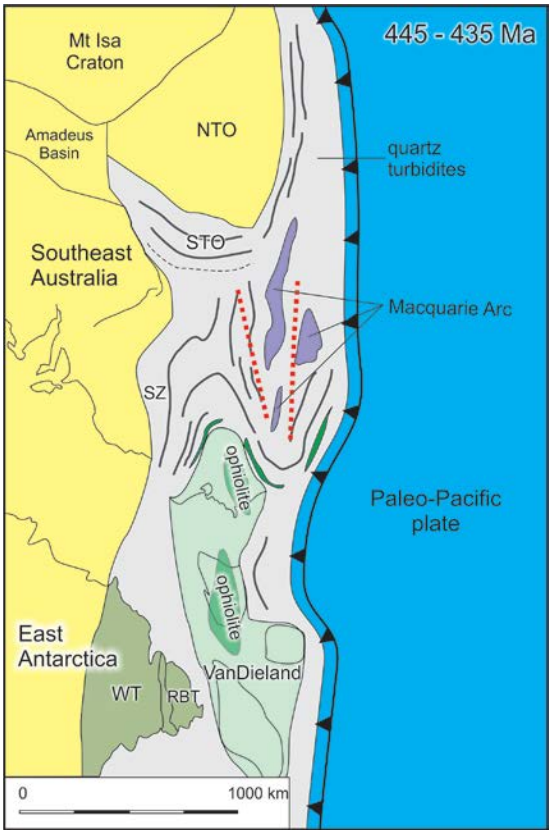

Figure 18. Early Silurian reconstruction highlighting the Macquarie Arc during the final phase of igneous activity at the height of the Benambran Orogeny. Dark gray lines show structural trends in interpreted subduction complex rocks. Red dotted thick line shows axes of two major plutonic belts related to oppositely dipping subduction zones (Collins & Hobbs, 2001; Fergusson, 2014). Development of the Lachlan Orocline in the southern Lachlan Orogen reflects indentation from the VanDieland continental fragment and according to Moresi et al. (2014) largely formed in the late Silurian to Early Devonian in contrast to the mainly Benambran timing indicated here. Abbreviations: NTO–north Thomson Orogen, RBT–Robertson Bay terrane, STO–south Thomson Orogen, SZ–Stawell Zone, WT–Wilson terrane.

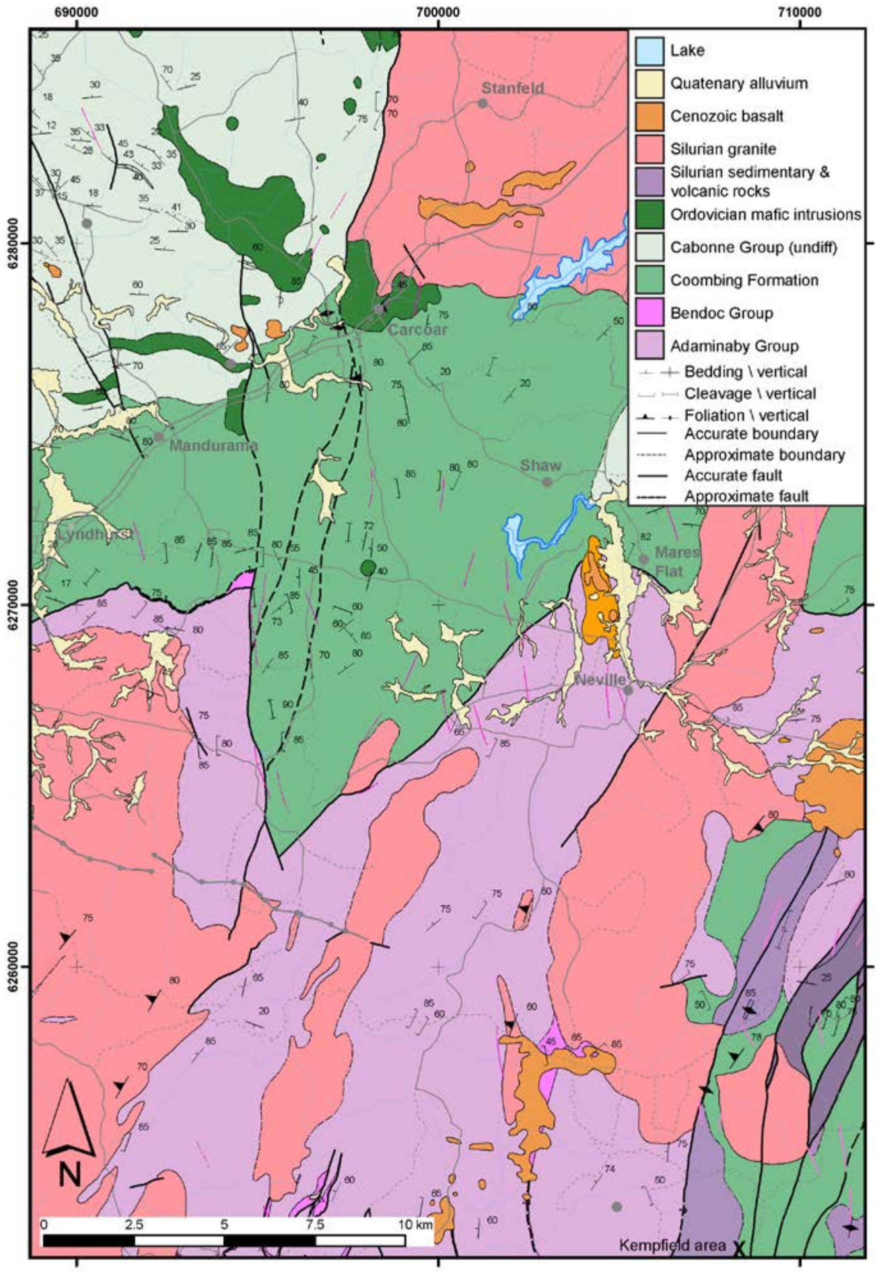

Figure S1. Part of the digital Blayney 1:100,000 geological map (Wyborn & Henderson, 1997) modified and reinterpreted by Colquhoun et al. (2017) showing the contact between the Ordovician turbidites and the Macquarie Arc succession. The Kempfield area is indicated where Wyborn & Henderson (1996) found a conformable boundary between the Ordovician turbidites and overlying Coombing Formation.

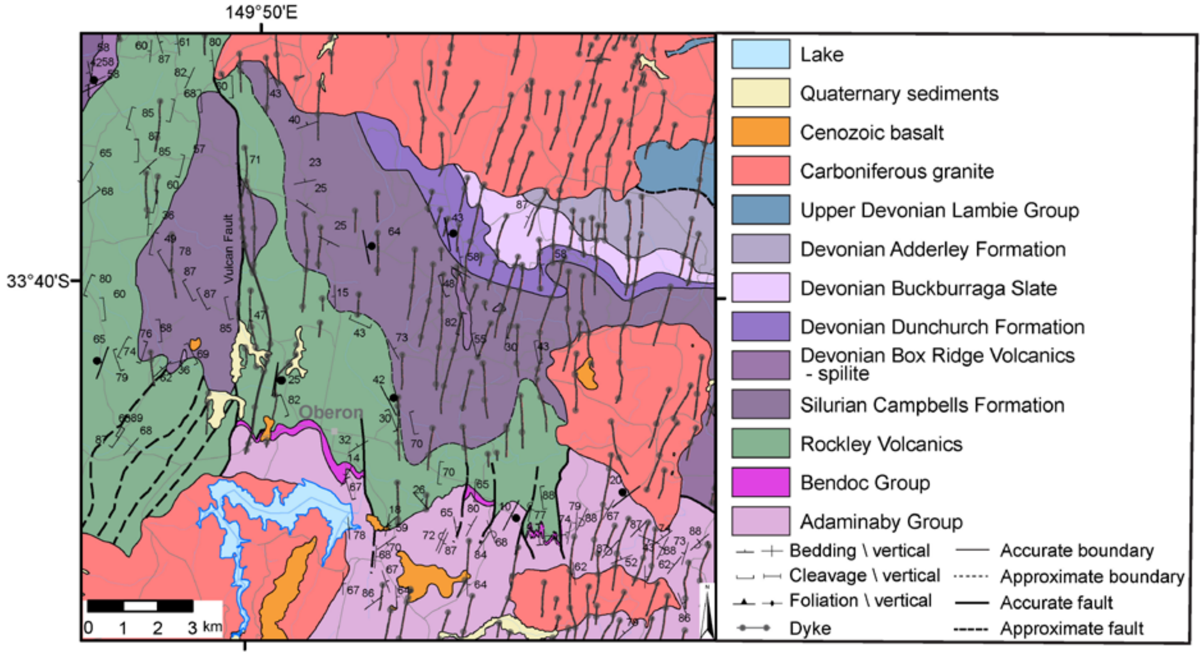

Figure S2. Part of the digital Oberon 1:100,000 geological map (Stuart-Smith & Wallace, 1997) modified and reinterpreted by Colquhoun et al. (2017) showing the contact between the Ordovician turbidites and the Macquarie Arc succession and the overlying units all with a general east–west trend.