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Chris L. Fergusson

University of Wollongong, cferguss@uow.edu.au

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Late Ordovician to mid-Silurian Benambran subduction zones in the Lachlan Orogen, southeastern Australia

Abstract

The Late Ordovician to early Silurian Benambran Orogeny had widespread effects in the Lachlan Orogen of southeastern Australia, including the Bendigo, Tabberabbera and Narooma zones. Much of the deformation in these zones has been attributed to formation of subduction complexes from accretion of Ordovician turbidites and has been a subject of ongoing controversy. The Narooma Zone subduction complex is more widely accepted because of the abundance of disrupted units, evidence for imbricated units and its metamorphic character. Imbricated and disrupted units consistent with a subduction accretion model also characterise the Tabberabbera Zone. A subduction complex model for the Bendigo Zone has been contested. Deep seismic profiles show a largely transparent upper crust down to ~18 km of inferred Ordovician turbidites with a layered middle to lower crust of mafic volcanic rocks as shown by the Heathcote Greenstone Belt being traced from the surface to the middle crust. During the Benambran Orogeny, the Bendigo Zone is interpreted as a rapidly formed mega-subduction complex with ~50 km crustal thickness. This is an exceptional thickness and much thicker than subduction complexes in Japan and the Barbados Accretionary Complex but more comparable with southeastern Alaska where the Chugach terrane (subduction complex) and underplated mafic igneous rocks have a present-day crustal thickness up to 30 km. Anomalous thick crust of the Bendigo Zone subduction complex is related to the huge volume of subduction inputs, with Cambrian fore-arc–backarc crust and the overlying thick Ordovician turbidite fan, resulting in a double décollement associated with the megathrust now represented by the Mount William Fault. The Benambran Orogeny is an example of widespread shortening reflecting rapidly initiated subduction zones with a short-lived history rather than long-lived subduction typical of the modern eastern Pacific Ocean.

Keywords

Lachlan Orogen, megathrust, Ordovician, orogeny, southeastern Australia, subduction

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Late Ordovician to mid-Silurian Benambran subduction zones in the Lachlan Orogen, southeastern Australia

C. L. FERGUSSON^{1*}

¹School of Earth & Environmental Sciences, University of Wollongong, NSW 2522, Australia

*cferguss@uow.edu.au

Running Title: Benambran subduction zones in the Lachlan Orogen

The Late Ordovician to early Silurian Benambran Orogeny had widespread effects in the Lachlan Orogen of southeastern Australia including the Bendigo, Tabberabbera and Narooma zones. Much of the deformation in these zones has been attributed to formation of subduction complexes from accretion of Ordovician turbidites and has been a subject of ongoing controversy. The Narooma Zone subduction complex is more widely accepted because of the abundance of disrupted units, evidence for imbricated units and its metamorphic character. Imbricated and disrupted units consistent with a subduction accretion model also characterise the Tabberabbera Zone. A subduction complex model for the Bendigo Zone has been contested. Deep seismic profiles show a largely transparent upper crust down to ~18 km of inferred Ordovician turbidites with a layered middle to lower crust of mafic volcanic rocks as shown by the Heathcote Greenstone Belt being traced from the surface to the middle crust. During the Benambran Orogeny, the Bendigo Zone is interpreted as a rapidly formed mega-subduction complex with ~50 km crustal thickness. This is an exceptional thickness and much thicker than subduction complexes in Japan and the Barbados Accretionary Complex but more comparable to southeastern Alaska where the Chugach terrane (subduction complex) and underplated mafic igneous rocks have a present-day crustal thickness up to 30 km. Anomalous thick crust of the Bendigo Zone subduction complex is related to the huge volume of subduction inputs, with Cambrian fore-arc–backarc crust and the overlying thick Ordovician turbidite fan, resulting in a double décollement associated with the megathrust now represented by the Mount William Fault. The Benambran Orogeny is an example of widespread shortening reflecting rapidly initiated subduction zones with a short-lived history rather than long-lived subduction typical of the modern eastern Pacific Ocean.

KEY WORDS: Lachlan Orogen, megathrust, Ordovician, orogeny, southeastern Australia, subduction

INTRODUCTION

In the Late Ordovician to early Silurian Benambran Orogeny, major shortening affected structural zones in the Lachlan Orogen of southeastern Australia with development of continental crustal thicknesses out of pre-existing oceanic regions (Powell 1983; Packham 1987; VandenBerg *et al.* 2000; Glen 2005, 2013). Many of the rocks involved in the orogeny are part of the widespread Ordovician quartz turbidite succession derived from Gondwana (Fergusson & Tye 1999; Fergusson *et al.* 2013) and thus recycling of older continental material has been significant in this continental growth (Armstrong 1991). Some newly extracted material from the mantle has been added to the crust as indicated by the Cambrian mafic igneous rocks that form basement to the Ordovician quartz turbidite succession (Crawford *et al.* 2003; Foster & Goscombe 2013). Seismic profiles from central Victoria support the inference that this new material makes up a significant part of the crust (Cayley *et al.* 2011). That the Benambran Orogeny has played a role in crustal development and the growth of Gondwana is non-controversial but the processes by which this has occurred is a much-debated issue.

One interpretation is that the Bendigo Zone (and the adjacent Stawell Zone) in western Victoria, the Tabberabbera Zone in eastern Victoria and the Narooma Zone along the New South Wales south coast formed as subduction complexes during the Benambran Orogeny (Gray & Foster 1997, 2004; Foster & Gray 2000). In this scenario, a number of subduction zones formed from subduction accretion of the widespread Ordovician quartz-turbidite succession with divergent double-subduction operating either side of the Melbourne Zone in central Victoria and a west-dipping subduction zone in the Narooma Zone. The idea of a subduction zone associated with the Narooma Zone has been widely argued in the literature (Powell 1983; Miller & Gray 1996, 1997; Offler *et al.* 1998a; Fergusson & Frikken 2003; Prendergast 2007; Prendergast *et al.* 2011, 2012) and has been challenged by Glen *et al.* (2004) and Glen (2013). Interpretations of divergent double-subduction in Victoria are also widely debated (Cayley *et al.* 2011; Glen 2013).

No real consensus model exists for the Lachlan Orogen and the structures within it that have been produced by the Benambran Orogeny (VandenBerg *et al.* 2000; Gray & Foster 2004; Glen *et al.* 2007; Meffre *et al.* 2007; Aitchison & Buckman 2012; Foster & Goscombe 2013; Glen 2013). The aim of this paper is to reassess the role of subduction complexes played in the formation of continental crust proposed by Gray & Foster (1997) in the development of the Lachlan Orogen during the Late Ordovician to early Silurian Benambran Orogeny. A reassessment is required based on the seismic profiles from Victoria and the growing literature on subduction complexes in general. Comparisons are made between the inferred subduction complexes of the Lachlan Orogen and well-documented Cenozoic subduction complexes in Japan (including the Nankai Trough), the Barbados Accretionary Complex, the Rajang–Crocker subduction complex in Borneo, and the convergent margin in southeastern Alaska. The subduction complexes in Japan have previously been compared to those of the Lachlan Orogen and on this basis it has been argued that the Lachlan Orogen subduction complexes are invalid (Aitchison & Buckman 2012). The subduction complexes in the West Indies (Barbados) and in Borneo are considered suitable for comparison to those in the Lachlan Orogen as they are all dominated by quartz-rich turbidites. The subduction complex in southeast Alaska provides an example of a modern subduction zone with an exceptionally thick fore-arc crust as has been documented for the Bendigo Zone (see below). The Bengal Fan has also been considered analogous to the development of the Ordovician turbidite fan of the Lachlan Orogen (Fergusson & Coney 1992a). Reassessment of these inferred subduction complexes is warranted in light of the greater understanding of continental structure from seismic reflection and refraction profiles in

orogenic settings (Fuis *et al.* 2008; Ito *et al.* 2009). This paper mostly concentrates on the Bendigo Zone because this is the most controversial of these proposed subduction complexes yet I consider that the deep seismic profiles are most easily explained by the subduction complex model (cf. Cayley *et al.* 2011).

TECTONIC CONTEXT IN THE TASMANIDES AND LACHLAN OROGEN

In the early Paleozoic, Australia was part of Gondwana and the Tasmanides formed an evolving active continental margin. This is most clearly displayed in northeastern Australia where the Cambrian Delamerian Orogeny was followed in the Ordovician by extensional tectonics and arc to backarc igneous activity as represented in the Greenvale Province, Charters Towers Province, Anakie Province and inboard subsurface basement (Figure 1) (Fergusson & Henderson 2013). Backarc volcanic activity and sedimentation is documented in the Charters Towers Province with deposition of the Seventy Mile Range Group in the late Cambrian to early Ordovician (Henderson 1986). The volcanic succession in this province thins westward reflecting increasing distance away from a volcanic arc in the east (Henderson 1986). In the Broken River Province, quartz-rich turbidites of the Judea Formation formed at the early Paleozoic continental margin and were deformed in the early Silurian Benambran Orogeny caused by accretion of a late Ordovician island arc assemblage (Henderson *et al.* 2011). North and central Queensland are characterised by scattered to widespread silicic intrusions of early to late Paleozoic ages including the Pama and Kennedy igneous associations that are consistent with a long-lived backarc to arc setting (Glen 2013; Henderson *et al.* 2013). No fore-arc has been recognised associated with the Ordovician to early Silurian magmatic activity in northeastern Australia and either is in the subsurface or has been lost by tectonic erosion, a common process in active subduction zones (Stern 2011).

In southeastern Australia, an Ordovician to early Silurian tectonic setting has been difficult to resolve given the complicated geology of the Lachlan Orogen. A complex set of events involved island arc–passive margin collision and convergent margin settings in the middle to late Cambrian Delamerian Orogeny associated with destruction of the Neoproterozoic Gondwana passive margin (Li & Powell 2001; Cayley 2011; Gibson *et al.* 2011). In the late Cambrian and Ordovician, the Lachlan Orogen consisted of widespread quartzose to quartz-rich turbidites that extended from the Moyston Fault in the west to the east coast and formed part of a huge submarine fan developed on Cambrian pelagic and hemi-pelagic sedimentary rocks and underlying backarc, island arc and fore-arc crust (Fergusson & Coney 1992a; Crawford *et al.* 2003). These turbidites in eastern New South Wales and Victoria are associated with a thick upper horizon of graptolitic black shale and interlayered relatively thin horizons of bedded chert and are interpreted as reflecting deepening to the east consistent with available paleocurrent data (Powell 1983; Fergusson & Coney 1992a; VandenBerg *et al.* 2000). In eastern New South Wales and extending into northeastern Victoria, the Macquarie Arc consists of mafic to intermediate volcanic and volcanoclastic rocks, limestone and intrusions, with calcalkaline and shoshonitic magmatic signatures consistent with an island arc setting (Glen *et al.* 1998; Crawford *et al.* 2007). A major problem has been to explain how the island arc and the quartz turbidites developed in apparent proximity with the turbidites located west, south and east of the island arc as well as in between the western and eastern belts of the Macquarie Arc (Figures 1, 2; Meffre *et al.* 2007). Numerous attempts have been made to explain the complicated pattern including suggestions that: (1) the arc and quartz turbidite fan have developed largely as part of the Gondwana plate with quartz turbidites spilling into the trench and accreted to a subduction complex represented by the Narooma Zone (Powell 1983), (2) the Macquarie Arc is unrelated to subduction and represents intraplate igneous activity (Wyborn 1992; Glen 2013), (3) the Macquarie Arc is a huge allochthon

thrust over the quartz turbidites in a so-called island arc–passive margin collision (Aitchison & Buckman 2012), (4) large-scale displacements on strike-slip faults have resulted in the quartz turbidites being displaced to present locations east of the arc (Packham 1987; Glen *et al.* 2009), and (5) the arc–quartz turbidite relationships reflect counter-clockwise rotation of the Macquarie Arc accompanied by less significant strike-slip fault dislocation (Fergusson 2009).

The Benambran Orogeny in the Lachlan Orogen is marked by widespread effects including fold-thrust deformation in the Stawell, Bendigo, Tabberabbera, Wagga–Omeo, Girilambone and Narooma zones as well as distributed deformation in parts of the Macquarie Arc and in the Bungonia–Delegate Zone (Gray & Foster 2004; Glen *et al.* 2007). Two plutonic belts are associated with the Benambran Orogeny (Figure 3) as indicated by SHRIMP zircon ages (Ickert & Williams 2011). Both plutonic belts can be considered as magmatic arcs that are successors to the Macquarie Arc (Collins & Vernon 1992; Gray & Foster 1997; Collins & Hobbs 2001). It has been proposed that east-dipping subduction occurred along the western side of the Macquarie Arc (Glen *et al.* 2007; Meffre *et al.* 2007) with rapid development of a large subduction complex including the Girilambone, Wagga–Omeo and Tabberabbera zones (Fergusson 2003a, 2009; Fergusson *et al.* 2005). Westward migration of the Macquarie Arc was initially to the Fifield ultramafic–mafic complexes and then formed the NNW-trending plutonic rocks of the Wagga–Omeo Zone that were related to formation of the subduction complex in the Tabberabbera Zone (Collins & Vernon 1992; Collins & Hobbs 2001; Fergusson 2003a, 2009; Fergusson *et al.* 2005). The second Benambran plutonic belt includes the northerlytrending Berridale and Young batholiths and Collins & Hobbs (2001) related their development to the subduction complex of the Narooma Zone as a continuation of west-dipping subduction generating the Macquarie Arc.

In the late Silurian to Middle Devonian the Lachlan Orogen was affected by extensional and compressional tectonics with widespread sedimentation and igneous activity and has been considered part of a Gondwana plate associated with a convergent margin to the east (Gray & Foster 2004; Glen 2005; Fergusson 2010).

BENAMBRAN SUBDUCTION ZONES

Stratigraphic, structural and metamorphic evidence for the three Benambran subduction complexes has been widely discussed and is summarised in Table 1. Detailed descriptions of the geology of these three zones are given elsewhere (Vandenberg *et al.* 2000; Gray & Foster 2004; Prendergast 2007; Cayley *et al.* 2011).

All three zones have a somewhat similar stratigraphic succession. A Cambrian oceanic igneous basement is overlain by bedded chert and mudstone of late Cambrian age and in turn overlain by the Lower to Middle Ordovician turbidite succession with less common Upper Ordovician black shale and turbidites. Inferred early Silurian turbidites occur in the Tabberabbera Zone and additionally the Narooma Zone contains an upper Cambrian to Upper Ordovician chert/mudstone unit (Narooma Chert) and the mudstone/clast-rich Bogolo Formation (Glen *et al.* 2004). Widespread development of a common stratigraphy and the extent of the succession across the whole Lachlan Orogen indicate that it formed a huge turbidite fan in an ocean basin, in part the Wagga marginal sea between the Gondwana continental margin and the Macquarie arc, and also extending beyond and partly enveloping the Macquarie Arc. During the Benambran Orogeny, the basin underwent massive shortening and is therefore a ‘remnant ocean basin’ using the terminology of Ingersoll *et al.* (1995, 2003). Criticisms of the subduction complex model such as given by Aitchison & Buckman (2012) and

Glen (2013) do not acknowledge the distinction between accretion of localised trench-wedge deposits and accretion of a widespread remnant ocean basin (see below).

Throughout most of the Lachlan Orogen, the structure of the Ordovician turbidite succession is characterised by strongly folded rocks with axial planar foliation and/or cleavage. In many areas stratigraphy is poorly understood because of the lack of marker horizons and age control. In the Bendigo Zone, the strongly folded rocks have widely spaced (5–10 km), steeply dipping, thrust faults as shown by stratigraphic repetition from graptolite ages within the turbidite succession (Gray & Willman 1991a, b; Willman 2007). Detailed structural studies for the Bendigo Zone have shown a total shortening of 66% (Gray *et al.* 2006). Fault imbrication is found in many parts of the Lachlan Orogen where stratigraphic successions are documented in Ordovician and Silurian deep-marine rocks and not just in the inferred subduction complexes (Bischoff & Prendergast 1987; Glen & VandenBerg 1987; Fergusson & VandenBerg 1990; Glen 1992; Glen *et al.* 2004; Colquhoun *et al.* 2005). In the Tabberabbera and Narooma zones, and elsewhere in the Lachlan Orogen, the Ordovician turbidites are multiply deformed with overprinting cleavages and/or foliations. *Mélanges* have been mapped widely in both the Tabberabbera and Narooma zones (Miller & Gray 1996, 1997; Watson & Gray 1999; Fergusson & Frikken 2003; Willman *et al.* 2005) but also elsewhere such as in the Bungonia–Delegate Zone (Fergusson & VandenBerg 1990).

Low-grade regional metamorphism is well documented for the Bendigo and Narooma zones (Table 1). Both zones are characterised by low geothermal gradients as expected of subduction complexes with burial of the order of 15 km achieved during the Benambran Orogeny (Offler *et al.* 1998a, b; Prendergast *et al.* 2012). Additionally, blueschist blocks are associated with the Cambrian greenstone belts at the margins of the Bendigo and Tabberabbera zones and a blueschist block in the Howqua River valley has an imprecise age of 450 ± 23 Ma consistent with subduction during the Benambran Orogeny (Spaggiari *et al.* 2002a, b).

Central Victoria deep seismic line and interpretation

Deep seismic lines across central Victoria (Figures 4, 5a) are particularly pertinent to the subduction complex interpretation of the Bendigo Zone (Willman *et al.* 2010; Cayley *et al.* 2011). A highlight of these data is that the Heathcote Greenstone Belt is traced from the surface down to the middle crust; this was also partially imaged in the shorter seismic lines of Gray *et al.* (1991). For the Bendigo Zone, the seismic profiles show an upper transparent crust down to depths of 18 km or less overlying a more reflective middle and lower crust. The upper crust is readily equated with the Ordovician turbidites. The reflective lower crust has been interpreted as mafic igneous rocks, which is apparent from the continuation of the Heathcote Greenstone Belt in the subsurface (Cayley *et al.* 2011). Recognition of listric faults throughout the profiles and repetition of oceanic crust along low-dipping crustal reflectors in the lower crust (Cayley *et al.* 2011) are less convincing interpretations, because of the weakly developed seismic reflectors in the upper crust and the uncertainty about the significance of seismic reflectors in the lower crust.

The seismic profiles show a present-day crustal thickness of ~40 km under the Bendigo Zone. Some idea of crustal thickness variations through time is constrained by metamorphic, structural and geochronological data. Metamorphic conditions for the exposed Ordovician rocks west of the Muckleford Fault indicate burial of ~15 km during the Benambran Orogeny (Offler *et al.* 1998b; Wilson *et al.* 2009). Thus at that time, it appears that the upper 30 km or so of the crust consisted of the deformed Ordovician turbidites. The structure of the rocks at the surface and common Lancefieldian turbidites in the hanging walls of thrust faults across the Bendigo Zone require

décollement with Ordovician turbidites detached from underlying Cambrian sedimentary rocks and the mafic igneous crust (Figure 6; Gray & Willman 1991a, p. 192). This is consistent with the separation of the crust into two main layers in the seismic profiles. Given a shortening of 66% with a structural thickness of 30 km, this indicates an initial stratigraphic thickness of 10 km, which is about double the estimate of Gray *et al.* (2006). Either structural complications involving undetected thrust duplication have occurred or stratigraphic thicknesses have been underestimated. Presently, the lower crust is ~25 km thick. Cayley *et al.* (2011) suggested that this lower crustal thickness formed in the Benambran Orogeny by duplication of mafic igneous crust. This overlooks probable addition of some mafic magma to the lower crust during the Early and Late Devonian igneous events in western Victoria. It is also conceivable that crustal shortening in the Silurian to Middle Devonian, especially in the Tabberabberan Orogeny, may also have caused some additional thickening of the lower crust. Thus the 25 km estimate for the thickness of the mafic lower crust formed in the Benambran Orogeny is probably overestimated but nevertheless a relatively thick mafic lower crust must have existed. A total crustal thickness of ~50 km during the Benambran Orogeny thus seems a reasonable estimate. Exposed Early Devonian intrusions formed at a depth of ~10 km implying ~5 km of erosion prior to emplacement, most of which must have been associated with the Benambran Orogeny (Offler *et al.* 1998b) and resulted in deposition of thick Silurian deposits of the western Melbourne Trough (Powell *et al.* 2003).

COMPARATIVE ANALYSIS

The following examples are picked to highlight aspects of the interpretation of Late Ordovician to early Silurian subduction zones within the Lachlan Orogen (see Introduction).

Southwest Japan and Nankai Trough

A crustal section, based on surface geology, showing subduction complex units in southwest Japan was compared with the Lachlan Orogen of central and western Victoria by Fergusson (2003a, figure 6) and is also shown interpreted from deep seismic data in both regions (Figure 5). It is clear that there are significant differences between the crustal structure of southwest Japan and the Bendigo Zone and other differences have also been emphasised by Aitchison & Buckman (2012) and Glen (2013). Subduction complexes such as those in southwest Japan, and also in part of the presently active Nankai Accretionary Complex, formed by accretion of relatively thin successions of oceanic pelagic units and trench-wedge turbidites. This results in an outward younging of sedimentary units in the direction of accretion as shown in Aitchison & Buckman (2012, figure 2) and widely recognised in subduction complexes where trench-wedge deposits are accreted (Kusky *et al.* 2013), such as in the New England Orogen (Cawood 1982; Fergusson 1984). Detailed seismic reflection data from the Nankai Trough show that the accretionary prism has a maximum thickness <10 km (Moore *et al.* 2009). In the outer zone of southwest Japan, three subduction complexes (North Shimanto Belt, South Shimanto Belt, Nankai Accretionary Prism) have been stacked in addition to the underlying subducting oceanic crust to form the present-day crustal thickness of ~30 km (Figure 5b; Ito *et al.* 2009). This contrasts to the Bendigo Zone where the crustal thickness (~40 km) largely reflects the single Benambran accretionary episode with metamorphic characteristics discussed above showing a crustal thickness as much as 50 km. This value is about 5 times thicker than individual subduction complexes in southwest Japan. Although the modern Nankai Trough is usually considered a sediment-rich subduction zone (Moore *et al.* 2001), in fact the sedimentary succession is generally <2 km with a significant thickness from the Shikoku Basin succession on the subducting Philippine Sea Plate (Ike *et al.* 2008). Thus it seems that accretion of trench-wedge deposits and relatively thin

subducting plate successions are unlikely to produce crustal thicknesses >10 km without some stacking occurring.

Much has also been made of the quartz-rich composition of the Ordovician turbidites that differ from lithofeldspathic sandstones (Aitchison & Buckman 2012) as documented from the Nankai Trough and found in some subduction complexes (Dickinson & Suczek 1979; Marsaglia *et al.* 1992). The problem with this argument is that it requires that all turbidites accreted to subduction complexes represent trench-wedge deposits derived from the adjacent magmatic arc. Modern systems such as the Nankai Trough, however, have complex sediment distributary systems reflecting rapidly changing tectonics. Thus the present turbidite trench-wedge of black volcanic-rich late Pleistocene sand documented at deep-sea drilling sites in the western Nankai Trough are derived from the eastern part of the system and reflect uplift and erosion of the Izu–Honshu collision zone including volcanic rocks of the uplifted Izu Island Arc and active volcanoes such as Mt Fuji (Underwood *et al.* 1993; Fergusson 2003b). No magmatic arc is presently active in southwest Japan in contrast to abundant volcanoes of the neighbouring Izu Island Arc and Honshu Arc in northeast Japan and Kyushu (Figure 7). Thus the volcanoclastic sediments in the western Nankai Trough are derived from an adjacent arc–island arc collision zone and not related to the volcanism caused by subduction of the Philippine Sea plate.

In the western Nankai Trough, Miocene turbidites are part of the Shikoku Basin succession of the subducting Philippine Sea plate, and have been widely mapped from seismic reflection profiles (Ike *et al.* 2008) and drilled in the western Nankai Trough (Site 1177; Moore *et al.* 2001) and the eastern Nankai Trough (Sites C0011 and C0012; Underwood *et al.* 2010; Expedition 333 Scientists 2012). These turbidites have been described from Site 1177 and consist of quartz-rich and sedimenticlastic sandstones (Fergusson 2003b). U–Pb zircon ages from these sands suggest wide-ranging sources including the Yangtze craton (Clift *et al.* 2013). The Shimanto Belt subduction complexes in southwest Japan do not solely consist of lithofeldspathic sandstones but contain a range of sandstone compositions including relatively quartz-rich sandstones reflecting derivation from the Asian landmass (Taira *et al.* 1982).

In summary, subduction complexes in Japan are not considered a suitable analogue for the inferred subduction complexes of the Lachlan Orogen given that in Japan mostly relatively thin trench-wedge and underlying oceanic plate facies (<2 km thickness in total) have been accreted to form overall relatively thin crustal layers (<10 m thick).

Bengal Fan

The Bengal Fan has previously been used as an analogue for the Ordovician turbidite succession of the Lachlan Orogen (Fergusson & Coney 1992a). The Bengal Fan is the world's largest turbidite fan with dimensions of 3000 x 1000 km² (Curry 1994) and is an example of a remnant ocean basin (Ingersoll *et al.* 1995, 2003). It has been suggested that part of the Bengal Fan has been accreted to a subduction complex in western Myanmar that continues southwards to the islands neighbouring Sumatra (Curry *et al.* 1982). This has been disputed for western Myanmar by Mitchell (1993), but provenance data from Neogene turbidites in western Myanmar are consistent with this suggestion (Allen *et al.* 2008). An impressive feature of the Bengal Fan is its huge volume as shown by sediment isopachs with an estimated >20 km thickness in the inner portion of the fan (Figure 8) (Curry 1991). Sediment thicknesses >5 km extend over 1000 km from the source Bangladesh Bengal Basin (Figure 8) and thicknesses >2.5 km are as far as 2500 km from source.

By contrast the Ordovician turbidite deposition of the Lachlan Orogen has been estimated to extend as far as 2000 km from the continental margin (Fergusson & Coney 1992a, b) with a history of deposition lasting from the late Cambrian to around the end of the Middle Ordovician with widespread mainly Upper Ordovician black shale deposited upon the turbidite fan throughout the eastern Lachlan Orogen (Fergusson & VandenBerg 2003; Percival *et al.* 2011). A thickness of ~4–5 km has been estimated for Ordovician turbidites of the Bendigo Zone where age control is widespread (Gray *et al.* 2006). From the crustal structure discussed above a thickness potentially as much as 10 km may apply for at least the western part of the Bendigo Zone where much of the succession is pre-Lancefieldian and lacks graptolite age control (VandenBerg *et al.* 2000). Presumably the Ordovician turbidites thin down-slope towards the east and northeast. The Selwyn Block represents a topographic barrier for turbidite deposition but nevertheless Ordovician turbidites have been deposited upon the Selwyn Block in the Mornington Peninsula 60 km south of Melbourne. Topographic barriers including a largely covered ridge at 85°E and the Ninetyeast Ridge also are present in the Bengal Fan and turbidite deposition has been thin or even absent from these features. Presumably thickness variations are also present in the Ordovician turbidite fan on topographic features such as the Selwyn Block and extinct Cambrian island arcs.

Sediment provenance of the Bengal Fan is poorly documented apart from at several deep-sea drilling sites at its southern extremity (Ingersoll & Suczek 1979). The source of the Bengal Fan is the Himalayan–Tibetan Orogenic Belt and sediments in adjacent foreland basins are predominantly quartzose detritus that plot in the recycled orogen field on a QFL plot with most of the lithic fraction being metamorphic fragments (Allen *et al.* 2008). This is somewhat similar to the Lachlan Ordovician turbidites (Fergusson & Tye 1999) apart from lower quartz contents in the Himalayan–Tibetan derived sediments. Accretion of Bengal Fan sediments to the western Neogene belt of the Indo–Burman Ranges is debated (see above). Nevertheless, the ultimate fate of oceanic regions is that they are subducted resulting in accretion of submarine fans as considered to be the case for the Ordovician turbidites of the Lachlan Orogen.

Borneo

An example of a relatively large accreted submarine fan dominated by quartz-rich turbidites is the Rajang–Crocker subduction complex of northern Borneo (Figure 9). This formed by subduction of the South China Sea and accretion of a huge turbidite fan resulting in a subduction complex over 400 km across (Hall 2002). The turbidite fan is of Eocene to early Miocene age and was considered derived from Indochina but detrital zircon ages indicate a source region including Cretaceous granites in western Borneo to the south of the accretionary margin (van Hattum *et al.* 2006). Imbrication, tight upright folds and mélange belts characterise the Rajang–Crocker subduction complex (Honza *et al.* 2000) and are similar to structural features of the Narooma and Tabberabbera zones (Table 1).

Barbados Accretionary Complex

A seismic profile across the Barbados Accretionary Complex at latitude 16°12'N shows a thickness of ~10 km (Westbrook *et al.* 1988), i.e. similar to that of the Nankai Trough Accretionary Prism. The Barbados Accretionary Complex is dominated by quartz-rich turbidites derived from South America via the Orinoco River and delta (Vebel 1985; Kasper & Larue 1986; Figure 10) and is similar in this respect to the Ordovician turbidites of the Lachlan Orogen. However the contrast in structural thickness of the Barbados Accretionary Complex to that of the Bendigo Zone suggests it is a poor analogue for this system.

Additionally, mud volcanism is widespread in the Barbados Accretionary Complex and is driven by presence of water with the mud being derived from numerous units (Deville *et al.* 2006). It has been suggested that mud diapirism is one mechanism that can account for *mélange* development with subsequent shortening resulting in flattening of mud diapirs and formation of a strong structural grain (Williams *et al.* 1984; Barber *et al.* 1986; Barber 2013). This explanation has been considered for the Bogolo Formation in the Narooma Zone with mud diapirs incorporating fragments derived from Ordovician Adaminaby Group turbidites that would account for the many rafted lenticular formerly bedded fragments observed in this unit (Figure 11a; Fergusson & Frikken 2003). Small-scale diapirs have been recognised by Prendergast (2007) but contacts between Bogolo Formation and other units in well exposed coastal outcrops south of Batemans Bay are all faulted (Fergusson & Frikken 2003). Cross-cutting contacts between greenstones and both the Bogolo Formation and Adaminaby Group are relatively common and formed early in the deformational history as they are overprinted by S_1 foliation and F_1 folds (Figure 11b). They have been interpreted as related to diapiric injection of clay-rich altered mafic volcanic rocks (Fergusson & Frikken 2003). It is also conceivable that some of the *mélange* belts within the Tabberabbera Zone are also related to mud diapirism although more work is needed to establish this. In contrast, the Bendigo Zone has no evidence for any mud diapirism.

Southeast Alaska

The convergent margin of southern Alaska reflects a long history of subduction with accretion of island arc terranes and associated subduction complexes (Plafker *et al.* 1994). Accretionary terranes of southeastern Alaska include Mesozoic to Cenozoic subduction complexes such as the Chugach and Prince William terranes that contain abundant lithic sandstone derived from neighbouring arc terranes as shown by detrital zircon ages (Bradley *et al.* 2009; Amato & Pavlis 2010). These sandstones are more typical of subduction complexes in contrast to the quartz-rich sandstones of the inferred Lachlan Orogen subduction complexes. Although there are numerous complexities associated with the geology of the Alaskan convergent margin, including the controversial role of terrane displacements and a tear in the subducting slab (Fuis *et al.* 2008), a comparison is made between the crustal structure of the Bendigo Zone and that of southeastern Alaska.

The crustal structure of southeastern Alaska is relatively well known from Trans-Alaska Crustal Transect (TACT) seismic and refraction profiles (Figures 5c, 12; Page *et al.* 1986; Fuis *et al.* 2008). A maximum crustal thickness of 55 km has been established from these data for the Peninsula terrane (a composite arc) with neighbouring Chugach and Prince William terranes (subduction complexes) underlain by crustal thicknesses up to 30 km. These accretionary terranes include abundant metamorphic rocks (with pressures of 2–4 kb; Hudson & Plafker 1982) and blueschist metamorphic rocks consistent with considerable erosion in addition to other exhumation processes (Plafker *et al.* 1994). This exceptional crustal thickness reflects underplated oceanic crust making up the lower crust (Figure 5c) including accretion of a potential oceanic plateau, the Yakutat Terrane (Fuis *et al.* 2008). Although the subduction complexes of southern Alaska have little in common with the Bendigo Zone Ordovician turbidites, a thick mafic lower crust is characteristic of both regions and at least demonstrates that exceptional crustal thicknesses are developed in subduction zones where conditions arise for the underplating of mafic crust. For the Bendigo Zone, an exceptional turbidite thickness overlying thick backarc basin and fore-arc crust has resulted in *décollement* and subsequent formation of a very thick crust in the relatively short Benambran Orogeny (*ca* 15 Ma). As in Alaska, subduction of thicker than normal oceanic crust, or in this case boninitic–tholeiitic island

arc crust and fore-arc crust, has resulted in underplating and accretion of mafic units at depth rather than their subduction.

It is also apparent that the subducted and accreted Yakutat terrane is not only associated with localised exceptional crustal thickness but is also spatially related to the northeastward termination of the Alaskan volcanic arc (triangles show active volcanoes in Figure 12). It is clear from cross sections across the Wadati-Benioff zone in southern Alaska (given on the foldout map in Fuis *et al.* 2008) that the underplated Yakutat Terrane is associated with a flat-slab region, which would account for the magmatic gap noted by Fuis *et al.* (2008). Perhaps a similar explanation also applies to the Bendigo Zone, with the subduction of thick crust being responsible for a flat-slab region generating a gap in the magmatic arc rather than the absence of magmatism reflecting the lack of subduction as favoured by Cayley *et al.* (2011).

DISCUSSION

Macquarie Arc and the problematic Kirribilli Zone

The Benambran Orogeny represents a culmination in tectonic activity in the Lachlan Orogen in the Late Ordovician to early Silurian and was associated with rapid crustal thickening. As argued by Gray & Foster (1997) and supported herein, it reflected development of short-lived subduction zones with accretion of the pre-existing thick Ordovician turbidite fan. The nature of the tectonic arrangement in the Early to Middle Ordovician preceding the Benambran Orogeny remains an unresolved matter. The Macquarie Arc is subduction-related as shown by its magmatic affinity (Glen *et al.* 1998). However, the polarity of the arc remains unresolved through time. Several authors have argued for a west-facing arc as opposed to an east-facing arc (Fergusson 2003a; Fergusson *et al.* 2005; Meffre *et al.* 2007; Aitchison & Buckman 2012). A more complicated model involving anticlockwise rotation of the Macquarie Arc was developed to account for the problematic relationships of Ordovician turbidites occurring on both sides of the arc (Fergusson 2009).

Ordovician turbidites and chert of the Kirribilli Zone lie between the western and eastern parts of the Macquarie Arc succession (Figures 1, 2) and present an obvious problem. An Ordovician age for these rocks has been queried by Percival *et al.* (2011) who suggested that the Ordovician turbidites are Silurian, based on unpublished zircon ages and on the unsupported idea that dated cherts associated with these units could be older blocks in a younger unit. The Ordovician age of these rocks was established by regional mapping using radiometric and aeromagnetic data and dating of associated chert units such as the Mugincoble Chert (Lyons *et al.* 2000), and therefore should be considered valid until detailed work is published that establishes this mapping is wrong. The model suggested by Lyons & Percival (2002) that Ordovician chert and turbidites of the Kirribilli Zone formed within a rift zone between the western and eastern parts of the Macquarie Arc provides the most reasonable explanation for these relationships and is preferable to speculation by Fergusson (2009) that offset along an unmapped strike-slip fault disrupted the paleogeography.

No straightforward resolution of the polarity of the Macquarie Arc is evident. The wide zone of Benambran deformation, including the Girilambone, Wagga–Omeo, and Tabberabbera zones (Figure 2), is consistent with the idea that these zones constituted a vast subduction complex formed in the Late Ordovician during east-dipping subduction along the western side of the Macquarie Arc (Fergusson 2003a, 2009; Fergusson *et al.* 2005). Thus the Girilambone Zone, previously considered by Scheibner & Basden (1998) as a likely subduction complex, formed in the early part of this subduction that subsequently migrated into the Wagga–Omeo and Tabberabbera zones. The

problem is that the Macquarie Arc disappears southwards. Fergusson (2009) explained this on an *ad hoc* basis by anticlockwise rotation about an Euler pole located in northeast Victoria. Alternatively, it has been argued that the Macquarie Arc is part of a huge allochthon thrust westwards over an Ordovician “passive margin succession” in an early Paleozoic island arc–passive margin collision (Aitchison & Buckman 2012). The main objections to this model are that: (1) it suggests that the Ordovician turbidites are part of a passive-margin succession even though they have well-documented boninitic basement in central Victoria (Crawford *et al.* 2003), (2) structural zonation in the Lachlan Orogen is almost completely ignored, and (3) evidence for major thrust displacements required have not been given (see Fergusson 2013 for further discussion of this model). In this allochthon model, the Kirribilli Zone represents a window through the thrust sheet but evidence for the contact being a regional-scale thrust fault with hundreds of kilometres of westward displacement has not been given.

Vice model for the Stawell and Bendigo zones

Two main models are presently argued for the interpretation of the significance of the Benambran Orogeny in the Stawell and Bendigo Zones: the subduction–accretion model as argued by Gray & Foster (2004) and the vice-like contraction model as presented by VandenBerg *et al.* (2000) and reiterated by Cayley (2011) and Cayley *et al.* (2011). Initially, the significance of $^{40}\text{Ar}/^{39}\text{Ar}$ ages across these zones was interpreted to indicate diachronous deformation consistent with eastward growth of a subduction complex (Foster *et al.* 1999; Foster & Gray 2000). Phillips *et al.* (2012) have emphasised that these $^{40}\text{Ar}/^{39}\text{Ar}$ ages indicate a general age of 445 Ma for deformation and metamorphism and that no diachronous deformation is recognisable. These ages would therefore seem to support the vice model. However, it is also conceivable that this general 445 Ma age reflects rapid development of a mega-subduction complex with widespread deformation culminating at this time. Given that in modern convergent settings, deformation in subduction zones and in foreland-fold and thrust belts is diachronous, it seems unlikely that deformation was completely synchronous everywhere in the Stawell and Bendigo zones during the Benambran Orogeny.

Does a suitable modern analogue for the vice model exist? Today along the convergent boundary west of Myanmar (Figure 8) ocean basins are closed by subduction of their oceanic lithosphere with closure of the Bay of Bengal and eventual accretion of the Bengal Fan. Nevertheless, multiphase long-wavelength folding of the Bengal Fan succession and underlying oceanic crust affects part of the Indian Ocean (Krishna *et al.* 2001). Does this provide an analogue for the Ballarat Zone? Shortening in the Indian Ocean is trivial by comparison with the Ballarat Zone and it is unclear what will happen in the future. One possibility is that this deformation may be a precursor to the development of a new convergent boundary as the northward motion of India is resisted by continuing continental collision (Stern 2004).

Tabberabbera and Narooma zones

Of the three inferred subduction complexes argued by Gray & Foster (2004), the eastern-most Narooma Zone (also known as the Narooma Accretionary Complex) has been most widely supported in the literature. It was argued for by Powell (1983) with more detailed structural and metamorphic work presented by Miller & Gray (1996, 1997), Fergusson & Frikken (2003), Offler *et al.* (1998a), Prendergast (2007) and Prendergast *et al.* (2011, 2012). Alternatively, it has been argued by Glen *et al.* (2004) that the Narooma Zone was unrelated to subduction and formed in a transpressional transform setting (see Fergusson & Miller 2005 and Glen & Percival 2005 for Discussion and Reply on this topic). The original idea of a subduction complex in the Tabberabbera Zone is a radical

reinterpretation of Lachlan Orogen tectonics and indicates that a former plate boundary must have existed within the confines of the Lachlan Orogen rather than at its margin, which is the case for the Narooma Zone.

It is important to emphasise that structural features in these zones such as multiple deformation, fault imbrication and *mélange* development are not restricted to the Tabberabbera and Narooma zones but occur elsewhere in the Lachlan Orogen in deformed Ordovician rocks. For example, in the Bungonia–Delegate Zone in the Goulburn region all these features have been mapped in Ordovician rocks that were deformed in the Silurian to Early Devonian in a frontal arc setting (Fergusson & VandenBerg 1990). In this case, strain-rates and intense shortening have accounted for a similarity in structural style; the location of this deformation in an intra-arc setting rules out its interpretation as a subduction complex. The Narooma and Tabberabbera zones are aligned with Benambran plutonic belts considered to be related magmatic arcs (Collins & Vernon 1992; Gray & Foster 1997). In contrast, no magmatic arc is recognised for the Bendigo Zone except that on the scale of the Gondwanan margin where an Ordovician to early Silurian convergent margin is justified by the geology of north and central Queensland (Fergusson & Henderson 2013; Henderson *et al.* 2013) and indicates a magmatic gap west of the Bendigo Zone.

CONCLUSIONS

Benambran subduction complexes are recognised on the basis of discrete zones of deformation that are related to magmatic belts (Tabberabbera and Narooma zones) apart from the case of the Bendigo Zone, which must have formed adjacent to a magmatic gap in a convergent margin. Shortening within Ordovician turbidites outside of these zones, such as in the Bungonia–Delegate Zone, have many structural features in common with those of the inferred subduction complexes. This is not unexpected as high-strain rate deformation in any convergent-related setting is likely to produce a similar suite of structures. The inferred Benambran subduction complexes incorporate abundant deep-marine rocks and are most easily explained by deformation associated with a subduction zone. Thus to some extent the debate over inferred subduction complexes in the Lachlan Orogen may reflect differences of opinion over terminology, i.e. recognition that discrete fold-thrust belts dominated by turbidites are equated to subduction complexes. Where the structural zonation of the Lachlan Orogen is completely ignored then tectonic models are unlikely to provide much insight.

In the Bendigo Zone, the exceptional crustal thickness formed in the Benambran Orogeny was produced by great volumes of subduction inputs and has resulted in a tiered detachment with accretion of mafic crust as is thought to have occurred in southeast Alaska. In this scenario, the Mt William Fault as interpreted on the deep seismic line by Cayley *et al.* (2011) is an example of a reactivated megathrust (i.e. subduction zone).

This study has attempted to highlight aspects of comparable settings relevant to the inferred subduction complexes formed during the Late Ordovician to early Silurian Benambran Orogeny in the Lachlan Orogen. The abundance of Ordovician quartz-rich turbidites has been considered problematic for these inferred subduction complexes even though a comparable characteristic is present in subduction complexes such as in the West Indies and in Borneo. The presence of *mélanges* in the Tabberabbera and Narooma zones has been considered more in line with a subduction complex setting. I argue that the lack of these features in the Bendigo Zone is not caused by the absence of accretionary processes but rather reflects the large subduction zone inputs with the accretion of a thick turbidite submarine fan overlying an anomalously thick fore-arc igneous crust. In

the case of southeastern Alaska, underplating of a thickened oceanic crust has resulted in a flat slab and a magmatic gap, which may also be the situation for the Bendigo Zone.

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FIGURE CAPTIONS

- Figure 1** Map of the Tasman Orogenic System (Tasmanides) showing the main early Paleozoic elements of the Thomson and Lachlan orogens. The Tasmanides form the Australian part of the Gondwana–Pacific margin orogenic belt east of the Precambrian craton (gray shade and includes the Mt Isa craton, Curnamona craton and basement to the Delamerian Orogen) that makes up the western two-thirds of Australia. Modified from the Geoscience Australia digital Surface Geology of Australia 1:1,000,000 scale (Geoscience Australia 2010).
- Figure 2** Map of the Lachlan Orogen in New South Wales and Victoria showing three inferred subduction complexes outlined by dashed lines and structural zones. The original subduction complexes identified by Gray & Foster (1997) include (1) the Stawell and Bendigo zones, (2) the Tabberabbera Zone, and (3) the Narooma Zone. Modified from the Geoscience Australia digital Surface Geology of Australia 1:1,000,000 scale (Geoscience Australia 2010).

Figure 3 Map of the eastern Lachlan Orogen in New South Wales and Victoria showing distribution of plutonic rocks (red and crosses) and Ordovician quartz turbidites (yellow shade). U–Pb zircon ages for plutonic rocks are given in Ma (from Colquhoun *et al.* 2005; Kemp *et al.* 2005, 2006; Lennox *et al.* 2005; Ickert & Williams 2011). Dashed lines show axes of two early to mid-Silurian Benambran magmatic belts. Modified from the Geoscience Australia digital Surface Geology of Australia 1:1,000,000 scale (Geoscience Australia 2010).

Figure 4 Map of pre-Permian bedrock geology of central Victoria showing granites (red and crosses), sedimentary rocks (Cs–Cambrian turbidites of the Stawell Zone, Os–Ordovician turbidites of the Bendigo Zone, stipple pattern – undifferentiated rocks), Cambrian volcanic rocks (green v patterns). AF–Avoca Fault, MF–Muckleford Fault, HGB–Heathcote Greenstone Belt. Seismic lines from Cayley *et al.* (2011). Modified from Simons & Moore (2000, digital version).

Figure 5 Interpretations of crustal structure based on deep seismic reflection profiles with constraints from seismic refraction results for (b) and (c). (a) Interpretation of seismic lines across central Victoria modified from Cayley *et al.* (2011) and Willman *et al.* (2010). See Figure 4 for location of seismic lines. (b) Interpretation of seismic profile across southwest Japan modified from Ito *et al.* (2009). See Figure 7 for location of seismic line. (c) Interpretation of crustal profiles from the TACT lines in southeast Alaska modified from Fuis *et al.* (2008). See Figure 12 for location of seismic lines.

Figure 6 Idealised model of pre-Benambran stratigraphic succession of the Bendigo Zone showing thicknesses and shortening calculations constrained by metamorphic data (Offler *et al.* 1998b; Gray *et al.* 2006; Wilson *et al.* 2009). Dashed lines show locations of major décollement associated with development of a Benambran megathrust (subduction zone).

Figure 7 Map of the Japan region showing topography from ETOPO1 (Amante & Eakins 2009), locations of volcanoes, the 1 km sediment isopach in the Nankai Trough (from Ike *et al.* 2008) and location of seismic line for which an interpretation of crustal structure is given in Figure 5b (after Ito *et al.* 2009).

Figure 8 Map of the Bay of Bengal and surrounding regions showing topography from ETOPO1 (Amante & Eakins 2009), locations of volcanoes, sediment isopachs in the Bengal Fan (white lines, from Curray *et al.* 2003) and earthquake epicentres (moment magnitude > 5 for the period 1975–2011, obtained from the USGS earthquake catalogue, <http://earthquake.usgs.gov/regional/neic/>).

Figure 9 Map of northern Borneo and surrounding regions showing topography from ETOPO1 (Amante & Eakins 2009), locations of volcanoes, location of northwest (NW) Borneo Fold and Thrust Belt from Morley *et al.* (2011, figure 4) and location of the Rajang–Crocker subduction complex from van Hattum *et al.* (2006, figure 1).

Figure 10 Map of the West Indies region and northern part of South America showing topography from ETOPO1 (Amante & Eakins 2009), locations of volcanoes, sediment isopachs (white lines, from Whittaker *et al.* 2013), and locations of mapped mud volcanoes (from Deville *et al.* 2006). Note the distribution of mapped mud volcanoes in

the Barbados Accretionary Complex reflects the extent of detailed bathymetric surveys; in most of the complex mud volcano distribution is unknown.

Figure 11 (a) Fragment of quartz sandstone derived from broken turbidite sandstone bed from the Adaminaby Group (northern headland of Malua Bay). Long axis of fragment lies in S_1 foliation plane. (b) Greenstone crosscutting *mélange* derived from the Adaminaby Group (southern side of Burrewarra Point headland). S_1 foliation is parallel to axial planes of small F_1 folds in the contacts of the injection feature and also parallel to long axes of fragments in *mélange*.

Figure 12 Map of southeast Alaska showing topography from ETOPO1 (Amante & Eakins 2009), locations of volcanoes, earthquake epicentres (moment magnitude > 5 for the period 1975–2011, obtained from the USGS earthquake catalogue, <http://earthquake.usgs.gov/regional/neic/>), the Yakutat Terrane and TACT profile lines (modified from Fuis *et al.* 2008).

Table 1 Characteristics of the Bendigo, Tabberabbera and Narooma zones.

Figure 1.

Figure 2.

Figure 3.

Figure 4.

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Figure 6.

Figure 7.

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Figure 10.

Figure 11.

Figure 12.

Table 1.

Structural Zone	Bendigo Zone	Tabberabbera Zone	Narooma Zone
Stratigraphy	Cambrian boninitic and tholeiitic volcanic and volcanoclastic rocks, shale, chert in the hanging wall of the Mt William Fault at the eastern boundary of the zone; Early to Middle Ordovician quartz turbidite succession with abundant thin black shales, graptolites indicate Lancefieldian to Darriwilian ages; a Late Ordovician turbidite unit in the southeast; unfossiliferous turbidites of pre-Lancefieldian age are widespread in the west (VandenBerg et al. 2000)	Cambrian boninitic and tholeiitic volcanic and volcanoclastic rocks, shale, chert in the Howqua River, Dookie; ultramafic rocks and Cambrian limestone in the Dolodrook River; Early to Middle Ordovician quartz turbidite succession with widespread thin chert layers and rare black shale, Late Ordovician black shale; Early Silurian(?) quartz turbidite succession (VandenBerg et al. 2000)	Cambrian ocean island basalts, shallow marine limestone; bedded chert and mudstone of Cambrian to Late Ordovician age; Early to Middle Ordovician quartz turbidite succession, Late Ordovician black shale; lithofeldspathic turbidites (age unknown); pebbly mudstone, olistostrome(?), mélangé (Bischoff & Prendergast 1987; Miller & Gray 1996; Fergusson & Friksen 2003; Glen et al. 2004; Prendergast & Offler 2012)
Structure	Northerly trending tight to isoclinal folds with widely spaced (up to 10 km) imbricate thrust faults verging eastwards, with 66% or more shortening, single axial planar cleavage, tectonic mélangé along Heathcote Greenstone Belt along eastern boundary (Gray & Willman 1991a, b; VandenBerg et al. 2000)	Tight to isoclinal folds affect bedding-parallel foliation, associated thrust faults verge southwest, widespread zones of tectonic mélangé along faults such as the Wonnangatta Fault and faults associated with Cambrian igneous rocks; Benambran structures are overprinted by widespread multiple deformation (VandenBerg et al. 2000, 2004; Watson & Gray 2001; Spaggiari et al. 2003a, b, c, 2004a, b; Willman et al. 2005)	Tight to isoclinal folds affect bedding-parallel foliation and associated thrust faults that verge eastwards and locally westwards, zones of tectonic mélangé and fault breccia; evidence of deformation of unlithified rocks with mud injections; Benambran structures are overprinted by widespread multiple deformation (Bischoff & Prendergast 1987; Miller & Gray 1996, 1997; Fergusson & Friksen 2003; Glen et al. 2004; Prendergast 2007)
Metamorphism	Epizonal metamorphism west of Whitelaw fault; 15 km depth of burial west of Muckleford Fault during Benambran Orogeny, geothermal gradient of 26°/km; at time of Early Devonian intrusions a depth of burial of 9-10 km is indicated; anchizone metamorphism east of the Whitelaw Fault; burial to 10 km depth for rocks east of the Muckleford Fault in the Benambran Orogeny; rare blueschist blocks in the Heathcote Greenstone Belt (Offler et al. 1998b; Spaggiari et al. 2002a, b; Wilson et al. 2009)	Regional low-grade metamorphism, has not been studied in detail apart from blueschist blocks in the Howqua River which had burial depths of 21-27 km; adjoining low-grade phyllites had burial depths of 10-12 km (Spaggiari et al. 2002a, b)	Epizonal metamorphism with burial depth of 15 km in the Benambran Orogeny, geothermal gradient of 20°/km; burial depth of 11 km during intrusion of Early Devonian plutons (Offler et al. 1998a; Prendergast et al. 2011, 2012)
Magmatic arc	None	Wagga-Omeo Zone NNW-trending belt of plutonic rocks 436 to 420 Ma (Gray & Foster 1997; Collins & Hobbs 2001; Colquhoun et al. 2005; Ickert & Williams 2011)	Berridale and Young batholiths (western Bungonia-Delegate Zone) 436 to 420 Ma (Collins & Hobbs 2001; Lennox et al. 2005; Kemp et al. 2005, 2006; Ickert & Williams 2011)