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Abstract

The Ordovician Macquarie Arc is most widely exposed in the Lachlan Fold Belt of central New South Wales. Complex relationships between the arc and the Ordovician turbidite mega-fan are partly explained by anticlockwise rotation of the arc during the Ordovician. Thus, initially two lobes of the mega-fan formed to the north and south of the east-west trending arc, using present-day coordinates. The arc consists of the western Goonumbla-Trangie Volcanic Belt, replacing the inappropriate term Juneenarramine Volcanic Belt, and an eastern composite of the Molong, Rockley-Gulgong and Kiandra Volcanic Belts. These two major segments of the arc are separated by Ordovician quartz turbidites of the Kirribilli Formation and it is probable that the arc has been duplicated by a sinistral strike-slip fault. Eastonian palaeogeographic reconstruction of the eastern segment of the arc highlights a prominent limestone platform in the western Molong Volcanic Belt that grades eastwards into a realm of mainly deep-marine sedimentation and volcanic activity. By analogy with Guam in the western Pacific Ocean, the limestone platform is equated to a frontal arc ridge. This implies that the associated subduction zone was along the western side of the arc and not to the east, as in previous reconstructions. A wide zone of deformed Ordovician quartz turbidites, making up the Girilambone and Wagga-Omeo Zones west of the Macquarie Arc, is interpreted as a subduction complex that formed rapidly in the Late Ordovician. Flipping of the subduction zone was a relatively long event, inferred to have occurred during the latest Ordovician to early Silurian Benambran Orogeny. This was driven by collision of the subduction complex with northern continuations of the Stawell and Bendigo Zones, with a new west-dipping subduction zone forming to the east.

Keywords

Lachlan Fold Belt, Macquarie Arc, Ordovician, polarity reversal, subduction, GeoQUEST

Disciplines

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Tectonic evolution of the Ordovician Macquarie Arc, central New South Wales: arguments for subduction polarity and anticlockwise rotation

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Running Title: Tectonics of the Ordovician Macquarie Arc

The Ordovician Macquarie Arc is most widely exposed in the Lachlan Fold Belt of central New South Wales. Complex relationships between the arc and the Ordovician turbidite mega-fan are partly explained by anticlockwise rotation of the arc during the Ordovician. Thus, initially two lobes of the mega-fan formed to the north and south of the east-west trending arc, using present-day coordinates. The arc consists of the western Goonumbla-Trangie Volcanic Belt, replacing the inappropriate term Juneenarramine Volcanic Belt, and an eastern composite of the Molong, Rockley-Gulgong and Kiandra Volcanic Belts. These two major segments of the arc are separated by Ordovician quartz turbidites of the Kirribilli Formation and it is probable that the arc has been duplicated by a sinistral strike-slip fault. Eastonian palaeogeographic reconstruction of the eastern segment of the arc highlights a prominent limestone platform in the western Molong Volcanic Belt that grades eastwards into a realm of mainly deep-marine sedimentation and volcanic activity. By analogy with Guam in the western Pacific Ocean, the limestone platform is equated to a frontal arc ridge. This implies that the associated subduction zone was along the western side of the arc and not to the east, as in previous reconstructions. A wide zone of deformed Ordovician quartz turbidites, making up the Girilambone and Wagga-Omeo Zones west of the Macquarie Arc, is interpreted as a subduction complex that formed rapidly in the Late Ordovician. Flipping of the subduction zone was a relatively long event, inferred to have occurred during the latest Ordovician to early Silurian Benambran Orogeny. This was driven by collision of the subduction complex with northern continuations of the Stawell and Bendigo Zones, with a new west-dipping subduction zone forming to the east.

Key words: Lachlan Fold Belt, Macquarie Arc, Ordovician, polarity reversal, subduction.

INTRODUCTION

The Macquarie Arc is an assemblage of mainly mafic to intermediate volcanic rocks, abundant volcanoclastic rocks, interbedded limestone and chert, developed in central and eastern New South Wales and extending southwards into northeastern Victoria (Figure 1). Recently, the history of the arc has been divided into four main phases, each associated with igneous rocks of specific magmatic affinities including common high-K calc-alkaline and shoshonitic igneous rocks (Crawford *et al.* 2007a, b; Glen *et al.* 2007a; Percival & Glen 2007;

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Squire & Crawford 2007). Tectonic development of the arc has been related to a west-dipping subduction zone (Glen *et al.* 1998). A more complicated setting is recognised in the Late Ordovician to early Silurian interval, during cessation of arc activity in the Benambran Orogeny (Crawford *et al.* 2007a, b; Glen *et al.* 2007a; Percival & Glen 2007; Meffre *et al.* 2007; Squire & Crawford 2007).

A number of unresolved issues exist in relation to the tectonic development of the Ordovician Macquarie Arc and also the widespread Ordovician quartz turbidite successions (submarine mega-fan). The arc is commonly depicted as a northerly trending feature associated with a subduction zone to the east (Packham 1987; Glen *et al.* 1998, 2007a). However, numerous subduction zones have been proposed for the Ordovician in the Lachlan Fold Belt and it is far from clear how these subduction zones have interacted with the Macquarie Arc (Packham 1987; Foster & Gray 2000; Fergusson 2003; Fergusson & Frikken 2003). Pertinent to this issue is the relationship between the Macquarie Arc and the Ordovician mega-fan, which has been a major problem in geological mapping. Meffre *et al.* (2007) documented faulted contacts and inferred faulted contacts in some areas, such as in the Bara Creek area (Figure 1). They regarded the Macquarie Arc and Ordovician mega-fan as tectonostratigraphic terranes that formed distant from each other. Furthermore, Glen (2005) and Glen *et al.* (2007a) regarded parts of the Ordovician mega-fan as sub-terranes, and that these also developed widely apart in spite of the common geological history for much of the mega-fan. The most unusual aspect of the arc and mega-fan relationship is the development of Ordovician turbidites of the Kirribilli Formation between the arc successions of the Goonumbla-Trangie and Molong Volcanic Belts. This relationship implies major strike-slip offset of the arc as proposed by Packham (1987).

This paper presents an interpretation of the tectonic evolution of Ordovician rocks in the Lachlan Fold Belt based partly on a reassessment of the palaeogeography of the arc. Palaeogeographic reassessment is suggested especially for the Eastonian stage when a major limestone platform developed in the southwestern Molong Volcanic Belt (Webby 1976; Cas 1983; Powell 1984; Glen *et al.* 1998; Packham *et al.* 1999; Percival & Glen 2007). Present-day map patterns of the Macquarie Arc and Ordovician turbidite mega-fan are complex and inexplicable by any simple plate tectonic arrangement (Powell 1984; Wyborn 1992; Glen *et al.* 1998, 2007a; Foster & Gray 2000; Fergusson 2003; Gray & Foster 2004). The interpretation presented herein is based on three hypotheses: (1) the complexity apparent in the relationships between the arc and the submarine mega-fan is simplified by inferring anticlockwise rotation of the arc during the Ordovician, (2) the subduction zone related to the Macquarie Arc occurs along its western side rather than along the New South Wales south coast, and (3) as in other reconstructions the Macquarie Arc has been affected by substantial strike-slip displacement (Packham 1987; Glen *et al.* 2007a). Given the complexity of Lachlan Fold Belt geology, and the lack of palaeomagnetic constraints, none of these hypotheses is easily tested at the present time.

STRATIGRAPHIC FRAMEWORK OF THE MACQUARIE ARC

The Macquarie Arc is split into four volcanic belts (Glen *et al.* 1998; Crawford *et al.* 2007a): (a) the Junee-Narromine Volcanic Belt with a northward continuation defined by a prominent magnetic anomaly (Packham 1987), (b) the Molong Volcanic Belt that includes the most widespread exposure of the Macquarie Arc succession, (c) the Rockley-Gulgong Volcanic Belt, and (d) the Kiandra Volcanic Belt (Figure 1). The Junee-Narromine Volcanic Belt is the longest segment of the Macquarie Arc. It is inappropriately named as Junee is underlain by Silurian granite of the Wagga-Omeo Zone (Warren *et al.* 1995). Also Narromine is underlain

by quartz-rich turbidites of probable Ordovician age rather than mafic to intermediate volcanic and volcanoclastic rocks (Sherwin 1996). Therefore the Junee-Narromine Volcanic Belt is renamed herein the Goonumbla-Trangie Volcanic Belt.

Four phases of development are recognised for the Macquarie Arc (Crawford *et al.* 2007a; Percival & Glen 2007). Phase 1 units formed during Early Ordovician (ca 489–474 Ma) volcanic activity and deposition. They are restricted to the Goonumbla region west and northwest of Parkes, in the Goonumbla-Trangie Volcanic Belt, and the Bakers Swamp area, mid-way between Molong and Wellington, in the Molong Volcanic Belt (Figure 2). These units are characterised by mainly high-K calc-alkaline igneous rocks but include shoshonites (Glen *et al.* 2007b). Murray and Stewart (2001) also documented Early Ordovician chert in the southern Rockley-Gulgong Volcanic Belt that indicates deep-marine conditions and are overlain by undated mafic to intermediate volcanoclastic rocks. Meffre *et al.* (2007) and Percival and Glen (2007) suggested that these rocks are fault-bounded and part of the Ordovician quartz turbidite succession, in spite of the lack of quartz turbidites in the unit and its conformable upper contact as determined by the detailed mapping of Murray (2002). Other components of Phase 1 activity have been identified at Lake Cowal, and southwest of Narromine, but these areas lack age-specific fossils and/or radiometric ages of Early Ordovician age that confirm these correlations (Percival & Glen 2007).

Phase 1 was followed by a hiatus of ca 10 million years in the Chewtonian to Early Darriwilian. This in turn was succeeded by widespread volcanic and volcanoclastic rocks of Phase 2 (ca 466 to 454 Ma) that developed across all four volcanic belts (Percival & Glen 2007). Phase 2 consisted mainly of high-K calc-alkaline volcanic rocks, with medium-K calc-alkaline rocks in the Cargo Volcanics (Crawford *et al.* 2007a; Simpson *et al.* 2007).

In comparison to the first two phases, Phases 3 and 4 (ca 457 to 438 Ma) are less clearly defined with different papers using the same terms but in slightly different contexts. Thus, Percival and Glen (2007, figure 2) show Phase 4 magmatism beginning at different times in different areas in the Eastonian to earliest Bolindian. Whereas Crawford *et al.* (2007b, figure 2) showed Phase 4 magmatism as occurring throughout the Eastonian in the eastern Molong Volcanic Belt and the Rockley-Gulgong Volcanic Belt. Phases 3 and 4 are overlapping partly because radiometric ages from a suite of medium-K calc-alkaline intrusive rocks, including those at Copper Hill north of Molong, span the Eastonian to earliest Llandovery interval (456 to 441 Ma, Crawford *et al.* 2007b). One reason given for separating these two phases is the development of the limestone platform in the southwestern Molong Volcanic Belt that includes thick limestone units around Cargo, Cliefden, and Molong. At least in this part of the Macquarie Arc, the limestone platform represents a major break in volcanism that has been correlated with emplacement of Phase 3 Copper Hill-type intrusions (Packham *et al.* 2003; Percival & Glen 2007).

Carr *et al.* (2003) found in the northern Gulgong-Rockley Volcanic Belt that the volcanism in the late Gisbornian to early Bolindian was predominantly shoshonitic. Furthermore some units (e.g. Burranah Formation) showed evidence of higher potassium contents than others, indicating regional diversity in chemical composition. It is clear from the correlation charts in Crawford *et al.* (2007b) that regional variation in geochemical character occurs across the Macquarie Arc, and therefore not too much emphasis should be placed on the geochemical significance of these so-called phases of magmatic activity (cf. Squire & Crawford 2007).

Relationship of the Macquarie Arc to the Ordovician mega-fan

The nature of the relationship between the Ordovician mega-fan and the intraoceanic Macquarie Arc remains an outstanding problem. It is difficult to explain the present-day relationships with Ordovician turbidites occurring west of the Macquarie Arc, in between the Goonumbla-Trangie and Molong Volcanic Belts in the Kirribilli Formation, south of both of the Molong and Rockley-Gulgong Volcanic Belts, and east of the Rockley-Gulgong Volcanic Belt (Figure 1). As pointed out by Meffre *et al.* (2007), these elements have distinctive compositional characteristics with no evidence for gradation between them. Glen (2005) and Meffre *et al.* (2007) argued that all contacts between these major units are significant faults, as was suggested in earlier papers by Packham (1987) and Fergusson and VandenBerg (1990). Due to incomplete exposure in areas, such as the Bara Creek area east of Mudgee and in the Oberon district, it has not been possible to demonstrate the existence of these major faults. Even if their existence is strongly suspected, no evidence has been presented to document the sense and amount of displacement on these inferred structures (cf. Fergusson & Colquhoun 1996; Meakin & Morgan 1999; Murray 2002; Meffre *et al.* 2007).

Both the southern Rockley-Gulgong and the southeastern Molong Volcanic Belts have an approximately east-west trending irregular contact with Ordovician quartz turbidites (Figure 1). The contact is problematic and has been regarded as a major fault by Glen and Wyborn (1997), Glen *et al.* (2002) and Meffre *et al.* (2007). The region is strongly affected by post-Benambran deformation (Murray 2002; Lennox *et al.* 2005). The lack of interfingering between these units is inconsistent with any suggestion that they developed in close proximity (Meffre *et al.* 2007). Age-specific fossils in the mega-fan units are mostly lacking immediately south of the contact, so that its full significance is difficult to evaluate. More detailed mapping is required although the generally low abundance of exposure will inhibit full resolution of the problem.

PALAEOGEOGRAPHY OF THE NORTHEASTERN LACHLAN FOLD BELT

Palaeogeography of the northeastern Lachlan Fold Belt is inferred from the present-day map distribution using the current stratigraphic scheme of the Macquarie Arc and the Ordovician turbidites (Figure 2; Colquhoun *et al.* 2005; Glen 2005; Percival & Glen 2007). Only the northeastern Lachlan Fold Belt, including the Goonumbla-Trangie, Molong and Rockley-Gulgong Volcanic Belts is considered, as this region includes most of the Macquarie Arc. The Kiandra Volcanic Belt is not included given its much narrower width (<10 km) than the other volcanic belts, which is probably due in part to thrusting of the Wagga-Omeo Zone from the west (VandenBerg *et al.* 2000). It is considered that the Molong and Rockley-Gulgong Volcanic Belts have developed substantially with their present arrangement without significant strike-slip displacement with respect to each other. These volcanic belts are only 10 km apart from each other southeast of Blayney and are not separated by strike-slip faults with documented major displacement (i.e. >10–20 km).

Macquarie Arc

Palaeogeography is shown for the Darriwilian-Gisbornian (466–454 Ma), Eastonian (454–449 Ma) and Bolindian (449–444 Ma) stages (Figure 2). Given the extent of younger rocks in the region and the lack of age constraints in some areas, only an outline of the palaeogeography is given. Even in modern island arcs details of stratigraphy and the succession of environments are limited, largely due to restricted island exposures along with few seismic sections controlled by widely spaced drill holes from the Ocean Drilling Program

and its precursors. Palaeogeography is most difficult to establish for the Goonumbla-Trangie Volcanic Belt as most of the succession is poorly exposed and lacks adequate age control, apart from the rocks west of Parkes (Simpson *et al.* 2005). Phase 1 units are only well dated at several sites and thus are too restricted to show meaningful palaeogeography.

The major facies subdivisions shown on Figure 2 are generalised for each interval and include:

- (1) volcanic-dominated units with lavas, shallow intrusions and hyaloclastites along with proximal volcanoclastic units formed in a marine setting usually including some shallow water depths — interpreted as volcanic centres such as submarine stratovolcanoes,
- (2) widespread *in situ* shallow marine limestone,
- (3) volcanoclastic dominated units with mudstone, sandstone and conglomerate but including some volcanic rocks and less substantial limestone lenses formed in shallow marine settings, and
- (4) volcanoclastic dominated units with mudstone, sandstone and conglomerate but including some volcanic rocks and usually chert formed in deep-marine settings.

The Darriwilian to Gisbornian palaeogeography has widespread volcanism with stratovolcanoes recognised in the Cargo Volcanics and potentially in the Walli Volcanics (Figure 2c; Simpson *et al.* 2007). Volcanic centres have also been recognised in the Fairbridge Volcanics north of Molong and to the north of Wellington (mapped as Oakdale Formation by Meakin & Morgan 1999, but referred to as the Cheesemans Creek Formation by Percival & Glen 2007). The age the volcanic centre north of Wellington is so poorly constrained that it is shown on all three palaeogeographic maps, even though it is most unlikely that this volcanic centre was active through 20 Ma of earth history (Figure 2). Deep marine conditions are inferred for the Oakdale Formation in the central eastern part of the Molong Volcanic Belt (Meakin & Morgan 1999). In the southern Molong Volcanic Belt, the Cargo and Walli Volcanics have probably developed to near shallow marine depths (Simpson *et al.* 2007). Further east, the Weemalla and Coombing Formation appear to be mainly relatively deep marine whereas the Blayney Volcanics are probably another volcanic centre in a shallow marine setting (Squire & McPhie 2007). No volcanic centres are recognised in the Rockley-Gulgong Volcanic Belt in the Darriwilian to Gisbornian, but lavas are interbedded with volcanoclastic turbidites, mudstone and chert indicating some volcanic activity in a deep marine setting (Meakin & Morgan 1999; Murray 2002). In the Goonumbla-Trangie Volcanic Belt, the palaeogeography west of Parkes consisted of a subsiding shelf with periodic influxes of volcanoclastic detritus and areas with rapid deepening; volcanic centres have not been identified in the succession but must have been nearby (Simpson *et al.* 2005). Small intrusions of Darriwilian to Gisbornian age have also been found in the Narromine and Cowal Igneous Complexes (Crawford *et al.* 2007c).

In the Eastonian, a limestone shelf developed in the southwestern part of the Molong Volcanic Belt (Figure 2d; Webby 1976; Powell 1984; Percival & Glen 2007). These limestone units indicate near continuous shallow marine sedimentation during much of the Eastonian, in contrast to evidence for scattered volcanism throughout the Gisbornian to Bolindian interval further east in the Molong and Rockley-Gulgong Volcanic Belts. The limestone shelf has an area of at least 80 x 20 km² with a gradual deepening to the east, as shown by eastward thinning of the Reedy Creek Limestone southeast of Molong (Raymond *et al.* 1998; Crawford *et al.* 2007b, figure 9). The full extent of shallow marine conditions is difficult to estimate due to incomplete exposure. Active volcanism seems to have occurred throughout the eastern part of the Molong-Rockley-Gulgong composite during the Eastonian with volcanic centres including the Blayney Volcanics, the Burranah Formation near Gulgong and tentatively the Oakdale Formation north of Wellington (Meakin & Morgan 1999; Squire & McPhie 2007). In the region south of Orange, a transition from a deeper marine to a

shallower marine setting has occurred (Squire & McPhie 2007). The palaeogeography is similar to that of island arcs that contain a frontal arc platform feature in the forearc with a submerged arc behind the platform (Karig 1974). A modern example of this arrangement is the Marianas Arc, with islands such as Guam and Saipan forming the frontal arc and submerged volcanoes of the active arc occurring to the west (Stern *et al.* 2003). The island of Guam has been a long-lived feature with limestone deposition from 32 to 13 Ma with no local volcanic activity in this interval (Meijer *et al.* 1983).

In the late Eastonian, the limestone shelf in the western Molong Volcanic Belt subsided with the development of widespread deep-marine environments, followed by renewed volcanism in the Bolindian (Figure 2e; Percival & Glen 2007). Volcanism was widespread throughout the Molong and Rockley-Gulgong Volcanic Belts and in the Goonumbla-Trangie Volcanic Belt to the northwest of Parkes, where the Wombin Volcanics indicate a very proximal setting to a volcanic centre (Simpson *et al.* 2005). Deeper water conditions appear to have prevailed generally throughout the Macquarie Arc in the Bolindian, with the exception of volcanic centres such as to the north of Wellington, north of Mudgee, south of Orange and northwest of Parkes (Figure 2e). Black shale deposition occurred along parts of the Goonumbla-Trangie Volcanic Belt in the Bolindian (Sherwin 1996; Percival & Glen 2007).

Ordovician quartz turbidites

In contrast to the Macquarie Arc, the palaeogeography of the Ordovician turbidite and black shale succession consisted of a submarine mega-fan extending from the Gondwana continental margin out into the palaeo-Pacific Ocean as far as 2000 km (Fergusson & Coney 1992a, b; Gray *et al.* 2006). Quartz turbidite deposition was not continuous across the whole mega-fan during the Early to Middle Ordovician interval. Bedded chert and black shale occur interbedded with the Ordovician turbidites and presumably reflect periods of sediment starvation on parts of the mega-fan (VandenBerg & Stewart 1992; Colquhoun *et al.* 2005). In the Narooma anticlinorium, on the south coast of New South Wales, an apparently continuous succession of Middle Cambrian to Eastonian age occurs and consists of chert and black mudstone, with no interbedded quartz turbidites (Glen *et al.* 2004). This succession has been interpreted as having formed on a separate oceanic plate from the submarine mega-fan (Glen *et al.* 2004). Alternatively, it may represent either the distal oceanic part or an elevated area of the sea floor, as part of the same plate containing the mega-fan.

In the Darriwilian to Gisbornian stages, quartz turbidite deposition waned and intervals dominated by chert formed widely in the succession (VandenBerg & Stewart 1992; Murray & Stewart 2001; Lyons & Percival 2002; Colquhoun *et al.* 2005). Turbidite deposition on the mega-fan was synchronous with the development of the Macquarie Arc in Phases 1 and 2, as well as continuing throughout the hiatus between them (Glen 2005; Percival & Glen 2007). By the beginning of the Eastonian, black shale deposition became widespread across the eastern parts of the mega-fan and quartz-rich Gondwana-derived sands almost ceased to be brought into the depositional environment (Figure 2). In the Bolindian, in northeastern Victoria and west of West Wyalong, renewed quartz-rich turbidites of the New Country Sandstone and Willandra Sandstone respectively, were deposited on these parts of the mega-fan (VandenBerg *et al.* 2000; Colquhoun *et al.* 2005).

TECTONIC EVOLUTION

Episodic calc-alkaline and shoshonitic igneous activity occurred throughout the Ordovician, associated with island chain and deep-marine environments, and is consistent with interpretation of the Macquarie Arc as a subduction-related island arc (Glen *et al.* 1998; Crawford *et al.* 2007b; Glen *et al.* 2007a, c; Percival & Glen 2007). In the reconstruction of the arc proposed herein, a composite fragment of the Molong, Rockley-Gulgong and Kiandra Volcanic Belts developed along strike to the south of the Goonumbra-Trangie Volcanic Belt in present-day coordinates (Figure 3). The Goonumbra-Trangie Volcanic Belt has subsequently been displaced by sinistral strike-slip movement along an inferred structure near the Kiandra-Narromine Structure of Packham (1987) in the Late Ordovician.

The configuration of the arc is commonly depicted as being elongate in a northerly direction relative to present-day coordinates (Figure 1), but the present-day northerly trends reflect multiple Palaeozoic orogenic events. Rotations of island arcs are relatively common in the Cenozoic history of the western Pacific Ocean as shown by the Izu-Bonin-Mariana, Luzon and east Philippine arcs (Hall 2002; Honza & Fujioka 2004). It is hypothesised herein that the arc was initially easterly trending with respect to present-day coordinates (Figure 3a). This allowed lobes of the Ordovician mega-fan to occur to the north (Wagga-Omeo and Girilambone Zones) and south (Bega Tract) of the arc, although they may well have been distant from the arc. During the Early to Middle Ordovician interval, anticlockwise rotation of the arc occurred, so that by the end of the Middle Ordovician large parts of the mega-fan were east of and behind the arc. Note that clockwise rotation of the arc is not feasible, as this would not account for the mega-fan engulfing the southern part of the arc.

It is suggested that the subduction zone lay to the west of the island arc in present-day coordinates and contrasts with the more usual interpretation that it lay to the east (Glen *et al.* 1998; Foster & Gray 2000). In the Early Ordovician, the island arc would have been distant from the Gondwana margin, which in the Australian sector was still an active margin (Foden *et al.* 2006). Continuous subduction and rotation in the Ordovician resulted in the arc approaching the Gondwana margin and coming into contact with the Ordovician turbidites of the Wagga-Omeo and Girilambone Zones. A substantial subduction complex formed along the western side of the island arc, made up of accreted Ordovician turbidites of the Girilambone Zone in the Late Ordovician. A modern analogue for this arrangement is the Barbados Ridge Complex developed adjacent to the Lesser Antilles island arc (Macdonald *et al.* 2000). This interpretation was given in Fergusson (2003) and Fergusson *et al.* (2005) but then the switch was from east-facing to west-facing subduction, an option also canvassed by Meffre *et al.* (2007), and no longer considered viable (see below).

Phase 2 volcanic activity was followed by the development of an inactive frontal arc in the southwestern Molong Volcanic Belt with the Eastonian limestone shelf existing for over 5 Ma (Figure 4). Frontal ridge features in forearc systems include Guam and Saipan in the Marianas Arc and the Bonin Ridge in the Izu-Bonin Arc (Karig 1974; Taylor 1992; Stern *et al.* 2003). These features have formed largely by intra-arc rifting (Karig 1974) and contrast with the New Hebrides Arc where the frontal ridge (Espiritu Santo Island) formed from the subduction of several ridges on the subducting plate (Meffre & Crawford 2001). The main axis of the Macquarie Arc continued to develop east of the Eastonian limestone shelf as shown by volcanism, albeit poorly dated, in the Blayney Volcanics, Oakdale Formation and more sporadically developed in the Rockley-Gulgong Volcanic Belt. The shelf is suggested to have formed as a result of subduction of a hypothetical ridge on the subducting sea floor rather than by rifting of the arc (cf. Glen *et al.* 1998; Meffre & Crawford 2001).

It may have been the initial collision of this hypothetical ridge with the arc that resulted in sinistral displacement of the arc. The location and overall displacement along the hypothetical strike-slip fault are not known with any certainty due to poor exposure and concealment by younger rocks overprinted by Devonian and Carboniferous deformation. Displacement along

this structure is needed to explain duplication of the arc and the present anomalous location of the Kirribilli Formation between the Goonumbla-Trangie and Molong Volcanic Belts (Packham 1987). No modern analogue of this feature is known although much smaller offsets of arc segments are characteristic of the Kuril and Aleutian Arcs (Kimura 1986; Geist *et al.* 1988). The significance of the Kirribilli Formation is also poorly understood. It was clearly part of the Ordovician mega-fan but it is not known if it was either (1) part of the Bega Tract in the backarc basin east of the Macquarie Arc, (2) part of the Wagga-Omeo and Girilambone Zones in the shrinking Wagga Marginal Sea that was being subducted, or (3) developed through the opening in the arc formed by the hypothetical strike-slip fault that enabled a new fan lobe to form east of and behind the Goonumbla-Trangie Volcanic Belt. Renewed widespread volcanism, mainly of shoshonitic affinity, followed in the Eastonian-Bolindian stages as the arc was undergoing further strike-slip faulting (Crawford *et al.* 2007b; Squire & Crawford 2007). This was accompanied by vast growth of the subduction complex to the west that continued into the early Silurian (Figure 3).

The Benambran Orogeny, in the Late Ordovician to early Silurian interval, has two main components: the first component accounts for the widespread deformation related to development of the subduction complex west of the arc (i.e. formation of the Girilambone and Wagga-Omeo Zones) and the second component reflects more widespread early Silurian deformation (VandenBerg *et al.* 2000; Collins & Hobbs 2001; Glen *et al.* 2007a). In the Llandovery, the volcanic arc jumped westward and formed the Fifield suite of ultramafic-mafic complexes (Barron *et al.* 2007; Glen *et al.* 2007a) and the granitic plutons of the Wagga-Omeo Zone. Fergusson (2003) regarded the Wagga-Omeo Zone as analogous to the Ryoke metamorphic belt of southwest Japan, which is a magmatic arc with high temperature low pressure metamorphism and associated plutonic rocks developed in subduction complex rocks (Nakajima 1994). Deformation migrated to the southwest with continuing accretion of the Ordovician mega-fan and also early Silurian turbidites to form the Tabberabbera Zone (Foster & Gray 2000; Collins & Hobbs 2001; Fergusson 2003).

Further south in central Victoria a realm of deep marine sedimentation (the Melbourne Trough) reflecting a remnant part of the closing Wagga Marginal Sea remained in existence until it was destroyed in the Middle Devonian Tabberabberan Orogeny (VandenBerg *et al.* 2000). A Late Ordovician subduction zone was postulated east of the Cambrian island arc of the eastern Melbourne Zone and this system subsequently collided with the Tabberabbera Zone in the Llandovery, jamming and terminating subduction in both systems (Figure 3b–d; Fergusson 2003). This arrangement is based on the evidence for Late Ordovician accretion east of the Cambrian island arc in the Howqua River Zone summarised by Fergusson (2003). Spaggiari *et al.* (2004) insisted that early Silurian accretion in the Tabberabbera Zone was somehow consistent with the older accretion event further to the west.

Termination of the east-dipping subduction system in the central Lachlan Fold Belt occurred around the Llandovery-Wenlock boundary. In central New South Wales failure of the subduction zone was presumably caused by collision of the Wagga-Omeo and Tabberabbera Zones with the east-facing system represented by the Stawell and Bendigo Zones (Figure 1; Foster & Gray 2000; Fergusson 2003; Gray & Foster 2004). This collision zone is poorly understood as it is overlain by the thick Darling Basin succession and also obscured by igneous rocks of the Hay-Booligal Zone (Figure 1; Hallet *et al.* 2005). Deformation in the latest Ordovician and early Silurian is widespread throughout the eastern Lachlan Fold Belt (Fergusson & Coney 1992b; Glen *et al.* 2007a). Termination of the west-facing Macquarie Arc system was caused by collision with elements to the west (Figure 3e).

It has been considered that an Ordovician subduction zone, developed on the south coast of New South Wales, was related to the Macquarie Arc (Packham 1987; Miller & Gray 1996, 1997; Foster & Gray 2000; Fergusson & Frikken 2003). An apparently near-continuous

Middle Cambrian to Late Ordovician sedimentary succession was involved in the subduction complex on the south coast of New South Wales (Bischoff & Prendergast 1987; Glen *et al.* 2004). $^{40}\text{Ar}/^{39}\text{Ar}$ ages of 445–450 Ma for mica crystallisation, at Narooma and Bermagui, indicate that metamorphism, associated with the developing subduction complex, formed by this time and are about the same age as the youngest fossils at the top of the sedimentary succession (Offler *et al.* 1998). It is suggested here that this subduction zone was initiated in the latest Ordovician by polarity reversal, as a result of collisions in the central Lachlan Fold Belt (see above). Although this subduction zone has previously been related to the Macquarie Arc, this is not viable as the so-called forearc of the Macquarie Arc is anomalously wide in its undeformed state. Much of the deformation in this region (the Bega Tract on Figure 1) occurred in the Silurian to Carboniferous (Fergusson & VandenBerg 1990; Fergusson & Coney 1992b; Glen 1992) and the width of this belt prior to deformation would have been as much as several hundred kilometres, far too wide for a normal arc-trench gap (Figure 3d). Subduction must have begun in the latest Ordovician prior to westward migration of Macquarie Arc magmatism. The lack of any magmatism associated with the newly formed subduction zone on the New South Wales south coast in the Llandoverly implies a low rate of subduction. Using a convergence rate of 10 mm a^{-1} only several hundred kilometres or so of subduction would have occurred during the latest Ordovician to early Silurian interval. This would have been sufficient to explain metamorphism in the shallow levels of the subduction zone and rapid development of the subduction complex. Igneous flare-up in the mid Silurian to Early Devonian eastern Lachlan Fold Belt is probably related to continuing subduction along this zone as it retreated eastwards (Collins 1998, 2002).

Polarity reversal from a subduction zone west of the Macquarie Arc to one to the east was a long-lived event occurring in the latest Ordovician to end of the Llandoverly (i.e. ca 15 Ma). This is puzzling and in marked contrast to the geologically much more rapid polarity reversals that have occurred in the western Pacific Ocean (Hall 2002). One explanation is that the collisions in the central Lachlan Fold Belt were relatively “soft” with subduction complex terranes, dominated by the deformed Ordovician mega-fan, colliding and moulding to each other over a long period. West of the Macquarie Arc, igneous rocks of the Wagga-Omeo Zone and the Fifield ultramafic and mafic plutonic complexes formed as the early Silurian west-facing arc migrated westward during the soft collisions, prior to complete shut-down of the east-dipping subduction zone (Fergusson *et al.* 2005; Barron *et al.* 2007; Glen *et al.* 2007a). The slowing of plate motions caused by these collisions triggered a new subduction zone to the east although for the Llandoverly, subduction remained slow until cessation of subduction to the west. Note that the subducting slabs in the upper lithosphere between the western and eastern subduction systems had to remain distant from each other to allow their unhindered descent into the mantle (Figure 5).

DISCUSSION

Polarity of the island arc

In the western Pacific Ocean, most Cenozoic subduction zones face east and it usually requires special circumstances for a subduction zone to face towards the continent (Karig 1974). For example, the New Hebrides and Solomon Arcs face southwest as a result of a polarity reversal following collision of the Ontong Java Plateau with the northeast-facing Solomon Arc (Hall 2002). Previous reconstructions show that the Macquarie Arc faced eastwards (Powell 1984; Packham 1987; Glen *et al.* 1998; 2007a). Nevertheless, a west-facing polarity for the development of the Macquarie Arc with respect to present-day

coordinates is argued here for two main reasons. Firstly, it explains why no interaction occurred between the Ordovician quartz turbidites and the Macquarie Arc in the Early to early Middle Ordovician west of the arc. Secondly, it eliminates a polarity reversal from east to west-facing in the Middle to Late Ordovician for which no explanation is apparent.

Late Early Cambrian to Late Cambrian rocks of the southern Lachlan Fold Belt and the New England Fold Belt include widespread rocks of juvenile island arc affinity, with boninites and tholeiitic basalts (Peel Fault, Aitchison & Ireland 1995; Bendigo and Tabberabbera Zones; Crawford *et al.* 2003) and some island arc calc-alkaline rocks (e.g. eastern Melbourne Zone; VandenBerg *et al.* 2000). Although the arrangement and even the number of island arcs are unknown, it was clear that prior to the Ordovician, a complex configuration of island arcs must have existed in the ancient Pacific Ocean. Given this circumstance, it is conceivable that the Macquarie Arc developed with a continent-facing polarity.

A characteristic feature of many island arcs is that they are associated with extensional events including backarc and even forearc spreading (Hamilton 1995; Stern *et al.* 2003). For an east-facing arc, the backarc (Wagga marginal sea) would have been expanding at various stages throughout the Ordovician, and the Ordovician turbidites would have had to keep flooding a greater region as the source Gondwana margin mountain chain was being worn away (Fergusson & Tye 1999). This difficulty is eliminated with a west-facing arc as the Ordovician turbidites would have been effectively impounded in a contracting marginal sea, as its sea floor was being subducted eastwards under the Macquarie Arc (Figure 3). Interaction between the Macquarie Arc and the Ordovician turbidites must have happened by the end of the Ordovician, which can most easily be explained by westward facing of the arc (Meffre *et al.* 2007, figure 10g).

Igneous activity and tectonics

Relationships between phases of igneous activity and tectonics in Cenozoic island arcs are not necessarily straightforward. For example, the Izu-Bonin-Mariana arc has developed over nearly 50 Ma of continuing subduction with major changes in volcanic activity through that time, including an early phase of widespread juvenile arc development with common boninitic-tholeiitic volcanism, followed by calc-alkaline and some local shoshonitic volcanic activity along a single volcanic chain, with several episodes of rifting and related volcanism, including silicic igneous activity (Bloomer *et al.* 1995; Fryer 1996; Stern *et al.* 2003). Igneous activity within the Macquarie Arc has been dominated by calc-alkaline and shoshonitic magmatism with mafic to intermediate compositions (Crawford *et al.* 2007b). An unusual feature of the Macquarie Arc is the abundance of K-rich volcanism, not only in Phase 4 but also in Phases 1 and 2, and is in contrast with the dominant styles of low-K volcanism in most island arcs (Leat & Larter 2003). Phase 3 calc-alkaline dacite and silicic intrusive rocks are relatively small-volume and their abundance is much less than high-Si volcanic rocks associated with rifting in parts of some modern island arcs, such as in the Sumisu Rift of the Izu Arc (Marsaglia *et al.* 1995; Leat & Larter 2003). Similar high-Si rocks also occur in ancient arcs such the Middle Devonian succession at Mt Morgan in central Queensland (Murray & Blake 2005). Rift-related mafic volcanic rocks have not been identified within the present bounds of the Macquarie Arc, as occur in the Devonian Tamworth Group of the southern New England Fold Belt (Offler & Gamble 2002).

Tholeiitic mafic volcanic rocks occur along the Gilmore Fault in southern New South Wales with occurrences elsewhere including the Jindalee Group, the basement to the Tumut Basin (Figure 1; Wyborn 1992; Meffre *et al.* 2007). The origin of these rocks is problematic

as their ages and relationships are poorly known, apart from in the Jindalee Group where they are associated with cherts of Darriwilian-Gisbornian age (Lyons & Percival 2002). It has been suggested that these rocks formed in an extensional event associated with the Macquarie Arc (Lyons & Percival 2002). These rocks are developed adjacent to the line of the offset of the Macquarie Arc and are consistent with extensional segmentation of the arc at around the Middle to Late Ordovician boundary, prior to sinistral offset of the Macquarie Arc (Figure 3b, c). It is conceivable that these rocks have been displaced along the strike-slip fault offsetting the arc, so it is not clear if they formed either in a forearc or backarc rift location relative to the Macquarie Arc.

Terranes and displacements

Glen *et al.* (2007a) and Meffre *et al.* (2007) regarded the Macquarie Arc and the Ordovician quartz turbidite succession (their Adaminaby Superterrane) as two tectonostratigraphic terranes. They argued that the contacts between the Macquarie Arc succession and the Ordovician quartz turbidites are major faults, even though in some areas evidence for significant faulting is lacking, such as in the Bara Creek and Oberon areas (Fergusson & Colquhoun 1996; Meakin & Morgan 1999; Murray 2002). Recognition of these elements as tectonostratigraphic terranes is certainly appropriate, but the relationship between these terranes during the Ordovician remains unresolved.

In an earlier reconstruction, Packham (1987) suggested duplication of several segments of the Macquarie Arc by sinistral strike-slip movement along several inferred major faults, including the Kiandra-Narromine Structure. In another reconstruction, the effects of substantial east-west shortening were removed, particularly from the Ordovician turbidite successions (Fergusson & Coney 1992b) and this approach was also undertaken with considerable refinement for western and central Victoria (Gray *et al.* 2006). Several reconstructions of the Macquarie Arc were proposed, after removal of the effects of younger folding, inferred extension and reversal of duplication along inferred strike-slip faults by Glen *et al.* (2007a).

Glen (2005) argued that parts of the mega-fan, which is recognised as having a common depositional history, also formed widely apart. Thus he portrayed the Ordovician turbidites of the Bega Tract as having had substantial strike-slip displacement, with derivation from an initial site of deposition outboard of the Gondwana margin of the Transantarctic Mountains of North and South Victoria Land. In contrast, widespread development of Ordovician turbidites of the Bega Tract, including the northward continuation to the Bara Creek area, is explained herein by inferred anticlockwise rotation of the arc. These relationships between the Macquarie Arc and the northern Bega Tract are enigmatic and difficult to interpret. Tectonic models of the Ordovician history of the Lachlan Fold Belt are based either on the inference of large-scale strike-slip displacements along faults to account for palaeogeographic anomalies (Packham 1987; VandenBerg *et al.* 2000; Glen 2005; Glen *et al.* 2007a) or relate most of the palaeogeographic complexity to substantial east-west contraction (Foster & Gray 2000; Fergusson 2003). In the model of VandenBerg *et al.* (2000) and Willman *et al.* (2002) much emphasis has been placed on major dextral strike-slip displacement along the eastern margin of the Melbourne Zone to account for palaeogeographic differences between the Melbourne and Tabberabbera Zones. The problem with this model is that no evidence for major dextral displacements has been identified along the extension of the proposed fault in western New South Wales where considerable new magnetic and gravity data has been obtained (e.g. Hallet *et al.* 2005). Aspects of both approaches are combined in this analysis with more emphasis on

east-west contraction that accompanied collapse of the mega-fan during the Benambran Orogeny than strike-slip faulting.

The arc was presumably bounded to the south (west) by a transform fault (Figure 3a–c) as occurs in the Mariana, Scotia and Lesser Antilles arcs. In this case, turbidity currents have been able to flow around the end of the arc and into the backarc basin. In an analogous way, turbidites and drift derived from the South Island of New Zealand are deposited in the Kermadec Trench by a number of routes, including one over 4500 km long (Carter *et al.* 1996; Glen *et al.* 1998).

Eastonian limestone shelf

The Eastonian limestone shelf has been recognised as a significant feature of the Ordovician palaeogeography (Packham *et al.* 1999; Percival & Glen 2007). Glen *et al.* (1998) suggested that subduction of a seamount caused a hiatus in volcanism and was followed by subsidence with limestone deposition. Uplift caused by collision with topographic features on the subducting plate is shown by development of a long-lived shelf on Espiritu Santo in the New Hebrides (Meffre & Crawford 2001). For this model to work it makes more sense that the Macquarie Arc faced west rather than east as outlined above (Figure 4). Packham *et al.* (1999, p. 1) noted the contrast between the limestone shelf and the deep-water Macquarie Arc succession to the east and recognised two major provinces that “were juxtaposed in latest Ordovician to earliest Silurian time along a major discontinuity”. In the region south of Orange, a discontinuity occurs between these provinces, but further to the north near Molong the Reedy Creek Limestone lenses out to the southeast, implying a gradational relationship between shallow and deep marine successions (Figure 2a; Raymond *et al.* 1998; Crawford *et al.* 2007b). Percival and Glen (2007) suggested that formation of the limestone shelf was caused by uplift associated with intrusion of the widespread but small-volume Phase 3 Copper Hill-type intrusions and this view was widely supported in the Crawford *et al.* (2007a) volume. These intrusions have small areas but are scattered over a large region and it is unclear as to why they would have only developed uplift over a relatively small part of the arc (Figure 2e).

CONCLUSIONS

Several issues related to the tectonic interpretation of Ordovician rocks in the Lachlan Fold Belt are problematic including the polarity of the arc, the complicated map pattern of the mega-fan and the island arc, and the apparent offset of the western part of the island arc. The interpretation presented here is that the Macquarie Arc was originally at a high angle to the Gondwana margin, which enabled lobes of the Ordovician mega-fan to occur on both sides of the arc. In the reconstruction proposed here, the arc was west-facing rather than east-facing with respect to present-day coordinates and reversal of subduction polarity occurred in the Late Ordovician to early Silurian Benambran Orogeny. This was as a result of collision between the subduction complex west of the Macquarie Arc and northern continuations of the Stawell and Bendigo Zones in western New South Wales. Development of a new subduction zone to the east of the Macquarie Arc enigmatically overlapped with continuing subduction to the west, by as much as 20 million years. The Eastonian limestone shelf of the southwestern Molong Volcanic Belt is interpreted as a frontal ridge feature that developed west of the main island arc volcanoes further east. The Molong, Rockley-Gulgong and Kiandra Volcanic Belts form part of the island arc that has been displaced by Late Ordovician sinistral strike-slip

along a hypothetical strike-slip fault, from a location south of the Goonumbla-Trangie Volcanic Belt (new name to replace the Junee-Narromine Volcanic Belt), modifying the reconstruction of Packham (1987) and Glen *et al.* (2007a). The Macquarie Arc is an atypical arc, as shown by the abundance of high-K magmatism and the lack of extensional events associated with sea floor spreading that is so characteristic of most island arcs.

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REFERENCES

- Aitchison J. C. & Ireland T. R. 1995. Age profile of ophiolitic rocks across the Late Palaeozoic New England Orogen, New South Wales: implications for tectonic models. *Australian Journal of Earth Sciences* **42**, 11–23.
- Barron L. M., Meffre S. & Glen R. A. 2007. Arc and mantle detritus in the post-collisional, Lower Silurian Kabadah Formation, Lachlan Orogen, New South Wales. *Australian Journal of Earth Sciences* **54**, 353–362.
- Bischoff G. C. O. & Prendergast E. I. 1987. Newly discovered Middle and Late Cambrian fossils from the Wagonga Beds of New South Wales, Australia. *Neues Jahrbuch für Geologie und Palaontologie* **175**, 39–64.
- Bloomer S. H., Taylor B., MacLeod C. J., Stern R. J., Fryer P., Hawkins J. W. and Johnson L. 1995. Early arc volcanism and the ophiolite problem: a perspective from drilling in the Western Pacific. In: Taylor B. and Natland J. (eds), *Active margins and marginal basins of the Western Pacific*, pp. 1–30. American Geophysical Union, Geophysical Monograph 88.
- Carr P. F., Fergusson C. L., Pemberton J. W., Colquhoun G. P., Murray S. I. and Watkins J. 2003. Late Ordovician island arc volcanic rocks, northern Capertee Zone, Lachlan Fold Belt, New South Wales. *Australian Journal of Earth Sciences* **50**, 319–330.
- Carter L., Carter R. M., McCave I. N. and Gamble J. 1996. Regional sediment recycling in the abyssal Southwest Pacific Ocean. *Geology* **24**, 735–738.
- Cas R. A. F. 1983. A review of the palaeogeography of the Lachlan Fold Belt, southeastern Australia. *Special Publication of the Geological Society of Australia* **10**, 104 pp.
- Collins W. J. 1998. Evaluation of petrogenic models for the Lachlan Fold Belt granitoids: implications for crustal architecture and tectonic models. *Australian Journal of Earth Sciences* **45**, 483–500.
- Collins W. J. 2002. Nature of extensional orogens. *Tectonics* **21**, doi:10.1029/2000TC001272.
- Collins W. J. & Hobbs B. E. 2001. What caused the Early Silurian change from mafic to silicic (S-type) magmatism in the eastern Lachlan Fold Belt? *Australian Journal of Earth Sciences* **48**, 25–41.
- Colquhoun G. P., Meakin N. S. & Cameron R. G. 2005. *Cargelligo 1:250 000 Geological Sheet 3rd edition SI/55-6: Explanatory Notes*. Geological Survey of New South Wales, Sydney.
- Crawford A. J., Cayley R. A., Taylor D. H., Morand V. J., Gray C. M., Kemp A. I. S., Wohlt K. E., VandenBerg A. H. M., Moore D. H., Maher S., Direen N. G., Edwards J., Donaghy

- A. G., Anderson J. A. & Black L. P. 2003. Neoproterozoic and Cambrian continental rifting, continent-arc collision and post-collisional magmatism. In: Birch W. ed. *The Geology of Victoria*, pp. 73–93. Geological Society of Australia, Victorian Division.
- Crawford A. J., Glen R. A., Cooke D. R. & Percival I. G. (Guest Editors) 2007a. Geological evolution and metallogenesis of the Ordovician Macquarie Arc, Lachlan Orogen, New South Wales. *Australian Journal of Earth Sciences* **54**, 137–479.
- Crawford A. J., Meffre S., Squire R. J., Barron L. M. & Falloon T. J. 2007b. Middle and Late Ordovician magmatic evolution of the Macquarie Arc, Lachlan Orogen, New South Wales. *Australian Journal of Earth Sciences* **54**, 181–214.
- Crawford A. J., Cooke D. R. & Fanning C. M. 2007c. Geochemistry and age of magmatic rocks in the unexposed Narromine, Cowal and Fairholme Igneous Complexes in the Ordovician Macquarie Arc, New South Wales. *Australian Journal of Earth Sciences* **54**, 243–271.
- Fergusson C. L. 2003. Ordovician–Silurian accretion tectonics of the Lachlan Fold Belt, southeastern Australia. *Australian Journal of Earth Sciences* **50**, 475–490.
- Fergusson C. L. & Colquhoun G. P. 1996. Early Palaeozoic quartz turbidite fan and volcanoclastic apron, Mudgee district, northeastern Lachlan Fold Belt, New South Wales. *Australian Journal of Earth Sciences* **43**, 497–507.
- Fergusson C. L. & Coney P. J. 1992a. Implications of a Bengal Fan-type deposit in the Paleozoic Lachlan fold belt of southeastern Australia. *Geology* **20**, 1047–1049.
- Fergusson C. L. & Coney P. J. 1992b. Convergence and intraplate deformation in the Lachlan Fold Belt of southeastern Australia. *Tectonophysics* **214**, 417–439.
- Fergusson C. L., Fanning, C. M., Phillips D. & Ackerman B. R. 2005. Structure, detrital zircon U-Pb ages and $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology of the Early Palaeozoic Girilambone Group, central New South Wales: subduction, contraction and extension associated with the Benambran Orogeny. *Australian Journal of Earth Sciences* **52**, 137–159.
- Fergusson C. L. & Frikken P. 2003. Diapirism and structural thickening in an Early Palaeozoic subduction complex, southeastern New South Wales, Australia. *Journal of Structural Geology* **25**, 43–58.
- Fergusson C. L. & Tye S. C. 1999. Provenance of Early Palaeozoic sandstones, southeastern Australia, part 1: vertical changes through the Bengal fan-type deposit. *Sedimentary Geology* **125**, 135–151.
- Fergusson C. L. & VandenBerg A. H. M. 1990. Middle Palaeozoic thrusting in the eastern Lachlan Fold Belt, southeastern Australia. *Journal of Structural Geology* **12**, 577–589.
- Foden J., Elburg M. A., Dougherty-Page J. & Burtt A. 2006. The timing and duration of the Delamerian Orogeny: correlation with the Ross Orogen and implications for Gondwana assembly. *Journal of Geology* **114**, 189–210.
- Foster D. A. & Gray D. R. 2000. Evolution and structure of the Lachlan Fold belt (Orogen) of eastern Australia. *Annual Review of Earth and Planetary Sciences* **28**, 47–80.
- Fryer P. 1996. Evolution of the Mariana convergent plate margin system. *Reviews of Geophysics* **34**, 89–125.
- Geist E. L., Childs J. R. & Scholl D. W. 1988. The origin of summit basins of the Aleutian ridge: implications for block rotation of an arc massif. *Tectonics* **7**, 327–341.
- Glen R. A. 1992. Thrust, extensional and strike-slip tectonics in an evolving Palaeozoic orogen—a structural synthesis of the Lachlan Orogen of southeastern Australia. *Tectonophysics* **214**, 341–380.
- Glen R. A. 2005. The Tasmanides of eastern Australia. In: Vaughan A. P. M., Leat P. T. & Pankhurst R. J. eds. *Terrane Processes at the Margins of Gondwana*, pp. 23–96. Geological Society, London, Special Publications **246**.

- Glen R. A., Crawford A. J. & Cooke D. R. 2007c. Tectonic setting of porphyry Cu–Au mineralisation in the Ordovician – Early Silurian Macquarie Arc, eastern Lachlan Orogen, New South Wales. *Australian Journal of Earth Sciences* **54**, 465–479.
- Glen R. A., Crawford A. J., Percival I. G. & Barron L. M. 2007b. Early Ordovician development of the Macquarie Arc, Lachlan Orogen, New South Wales. *Australian Journal of Earth Sciences* **54**, 167–179.
- Glen R. A., Korsch R. J., Direen N. G., Jones L. E. A., Johnstone D. W., Lawrie K. C., Finlayson D. M. & Shaw R. D. 2002. Crustal structure of the Ordovician Macquarie Arc, eastern Lachlan Orogen, based on seismic reflection profiling. *Australian Journal of Earth Sciences* **49**, 323–348.
- Glen R. A., Meffre S. & Scott R. J. 2007a. Benambran Orogeny in the Eastern Lachlan Orogen, Australia. *Australian Journal of Earth Sciences* **54**, 385–415.
- Glen R. A., Stewart I. R. & Percival I. G. 2004. Narooma terrane: implications for the construction of the outboard part of the Lachlan Orogen. *Australian Journal of Earth Sciences* **51**, 859–884.
- Glen R. A., Walshe J. L., Barron L. M. & Watkins J. J. 1998. Ordovician convergent-margin volcanism and tectonism in the Lachlan sector of east Gondwana. *Geology* **26**, 751–754.
- Glen R. A. & Wyborn D. 1997. Inferred thrust imbrication, deformation gradients and the Lachlan Transverse Zone in the eastern belt of the Lachlan Orogen. *Australian Journal of Earth Sciences* **44**, 49–68.
- Gray D. R. & Foster D. A. 2004. Tectonic evolution of the Lachlan Orogen, southeast Australia: historical review, data synthesis and modern perspectives. *Australian Journal of Earth Sciences* **51**, 773–817.
- Gray D. R., Willman C. E. & Foster D. A. 2006. Crust restoration for the western Lachlan Orogen using the strain-reversal, area-balancing technique: implications for crustal components and original thicknesses. *Australian Journal of Earth Sciences* **53**, 329–341.
- Hall R. 2002. Cenozoic geological and plate tectonic evolution of SE Asia and the SW Pacific: computer-based reconstructions, models and animations. *Journal of Asian Earth Sciences* **20**, 353–431.
- Hallet M., Vassallo J., Glen R. & Webster S. 2005. Murray-Riverina region: an interpretation of bedrock Palaeozoic geology based on geophysical data. *Quarterly Notes of the Geological Survey of New South Wales* **118**, 1–16.
- Hamilton W. B. 1995. Subduction systems and magmatism. In: Smellie J. L. ed. *Volcanism Associated with Extension at Consuming Plate Margins*, pp. 3–28. Geological Society of London Special Publication **81**.
- Honza E. & Fujioka K. 2004. Formation of arcs and backarc basins inferred from the tectonic evolution of Southeast Asia since the Late Cretaceous. *Tectonophysics* **384**, 23–53.
- Karig D. E. 1974. Evolution of arc systems in the Western Pacific. *Annual Reviews of Earth and Planetary Sciences* **2**, 51–76.
- Kimura G. 1986. Oblique subduction and collision: forearc tectonics of the Kuril arc. *Geology* **14**, 404–407.
- Leat P. T. & Larter R. D. 2003. Intra-oceanic subduction systems: introduction. In: Larter R. D. & Leat P. T. eds. *Intra-oceanic subduction Systems: Tectonic and Magmatic Processes*, pp. 1–17. Geological Society of London, Special Publication **219**.
- Lennox P. G., Trzebski R., Armstrong R. & Siebel W. 2005. Structural evolution and granite chronology of the central Molong Zone, Eastern Lachlan Fold Belt, Australia. *Australian Journal of Earth Sciences* **52**, 79–99.

- Lyons P. & Percival I. G. 2002. Middle to Late Ordovician age for the Jindalee Group of the Lachlan Fold Belt, New South Wales: conodont evidence and some tectonic problems. *Australian Journal of Earth Sciences* **49**, 801–808.
- Macdonald R., Hawkesworth C. J. & Heath E. 2000. The Lesser Antilles volcanic chain: a study in arc volcanism. *Earth-Science Reviews* **49**, 1–76.
- Marsaglia K. M., Boggs S., Clift P., Seyedolali A. & Smith R. 1995. Sedimentation in western Pacific backarc basins: new insights from recent ODP drilling. *In*: Taylor B. and Natland J. eds. *Active margins and marginal basins of the Western Pacific*, pp. 291–314. American Geophysical Union, Geophysical Monograph **88**.
- Meakin N. S. & Morgan E. J. 1999. *Dubbo 1:250 000 Geological Sheet 2nd edition SI/55-4: Explanatory Notes*. Geological Survey of New South Wales, Sydney.
- Meffre S. & Crawford A. J. 2001. Collision tectonics in the New Hebrides arc (Vanuatu). *The Island Arc* **10**, 33–50.
- Meffre S., Scott R. J., Glen R. A. & Squire R. J. 2007. Re-evaluation of contact relationships between Ordovician volcanic belts and the quartz-rich turbidites of the Lachlan Orogen. *Australian Journal of Earth Sciences* **54**, 363–383.
- Meijer A., Reagan M., Ellis H., Shafiqullah M., Sutter J., Damon P. & Kling S. 1983. Chronology of volcanic events in the eastern Philippine Sea. *In*: Hayes D. E. ed. *The Tectonic Evolution of Southeast Asian Seas and Islands: Part 2*, pp. 349–359. American Geophysical Union, Geophysical Monograph **27**.
- Miller J. McL. & Gray D. R. 1996. Structural signature of sediment subduction – accretion in a Palaeozoic accretionary complex, southeastern Australia. *Journal of Structural Geology* **18**, 1245–1258.
- Miller J. McL. & Gray D. R. 1997. Subduction-related deformation and the Narooma Anticlinorium, eastern Lachlan Fold Belt. *Australian Journal of Earth Sciences* **44**, 237–251.
- Murray C. G. & Blake P. R. 2005. Geochemical discrimination of tectonic setting for Devonian basalts of the Yarrol Province of the New England Fold Belt, central coastal Queensland: an empirical approach. *Australian Journal of Earth Sciences* **52**, 993–1034.
- Murray S. I. 2002. Tectonic relationships between Ordovician sedimentary and volcanic successions of the Lachlan Fold Belt, Central/Southern Tablelands, New South Wales. Unpub. PhD thesis, University of Wollongong, Wollongong, New South Wales.
- Murray S. I. & Stewart I. R. 2001. Palaeogeographic significance of Ordovician conodonts in the Lachlan Fold Belt, southeastern Australia. *Historical Biology* **15**, 145–170.
- Nakajima T. 1994. The Ryoke plutonometamorphic belt: crustal section of the Cretaceous Eurasian continental margin. *Lithos* **33**, 51–66.
- Offler R. & Gamble J. 2002. Evolution of an intra-oceanic island arc during the Late Silurian to Late Devonian, New England Fold Belt. *Australian Journal of Earth Sciences* **49**, 349–366.
- Offler R., Miller J. McL., Gray D. R., Foster D. A. & Bale R. 1998. Crystallinity and b_0 spacing of K-white micas in a Paleozoic accretionary complex, eastern Australia: metamorphism, paleogeotherms, and structural style of an underplated sequence. *Journal of Geology* **106**, 495–509.
- Packham G. H. 1987. The eastern Lachlan Fold Belt of southeast Australia: a possible Late Ordovician to Early Devonian sinistral strike-slip regime. *In*: Leitch E. C. & Scheibner E. eds. *Terrane Accretion and Orogenic Belts*, pp. 67–82. American Geophysical Union, Geodynamics Series **19**.

- Packham G. H., Percival I. & Bischoff G. 1999. Age constraints on strata enclosing the Cadia and Junction Reefs ore deposits of central New South Wales, and tectonic implications. *Quarterly Notes of the Geological Survey of New South Wales* **110**, 1–12.
- Packham G. H., Keene J. B. & Barron L. M. 2003. Middle to early Late Ordovician hydrothermal veining in the Molong Volcanic Belt, northeastern Lachlan Fold Belt: sedimentological evidence. *Australian Journal of Earth Sciences* **540**, 257–269.
- Percival I. G. & Glen R. A. 2007. Ordovician to earliest Silurian history of the Macquarie Arc, Lachlan Orogen, New South Wales. *Australian Journal of Earth Sciences* **54**, 143–165.
- Pogson D. J. & Watkins J. J. 1998. *Bathurst 1:250 000 Geological Sheet SI/55-8: Explanatory Notes*. Geological Survey of New South Wales, Sydney.
- Powell C. McA. 1984. Ordovician to earliest Silurian: marginal sea and island arc; Silurian to mid-Devonian dextral transtensional margin; Late Devonian and Early Carboniferous: continental magmatic arc along the eastern edge of the Lachlan Fold Belt. In: Veevers J. J. ed. *Phanerozoic Earth History of Australia*, pp. 290–340. Oxford University Press, Oxford.
- Raymond O. L., Pogson D. J. et al. 1998. *Bathurst Geology Second Edition (1:250,000 geological map SI55-08)*. Australian Geological Survey Organisation, Canberra/Geological Survey of New South Wales, Sydney.
- Sherwin L. 1996. *Narromine 1:250 000 Geological Sheet SI/55-3: Explanatory Notes*. Geological Survey of New South Wales, Sydney.
- Simpson C. J., Cas R. A. F. & Arundell M. C. 2005. Volcanic evolution of a long-lived Ordovician island-arc province in the Parkes region of the Lachlan Fold Belt, southeastern Australia. *Australian Journal of Earth Sciences* **52**, 863–886.
- Simpson C. J., Scott R. J., Crawford A. J. & Meffre S. 2007. Volcanology, geochemistry and structure of the Ordovician Cargo Volcanics in the Cargo – Walli region, central New South Wales. *Australian Journal of Earth Sciences* **54**, 315–352.
- Spaggiari C. V., Gray D. R. & Foster D. A. 2004. Lachlan Orogen subduction-accretion systematics revisited. *Australian Journal of Earth Sciences* **51**, 549–553.
- Squire R. J. & Crawford A. J. 2007. Magmatic characteristics and geochronology of Ordovician igneous rocks from the Cadia – Neville region, New South Wales: implications for tectonic evolution. *Australian Journal of Earth Sciences* **54**, 293–314.
- Squire R. J. & McPhie J. 2007. Complex volcanic facies architecture of the Forest Reefs Volcanics near Cadia, New South Wales, associated with prolonged arc-related volcanism. *Australian Journal of Earth Sciences* **54**, 273–292.
- Stern R. J., Fouch M. J. & Klemperer S. L. 2003. An overview of the Izu-Bonin-Mariana subduction factory. In: Eiler J. & Hirschmann M. eds. *Inside the Subduction Factory*, pp. 175–222. American Geophysical Union, Geophysical Monograph **138**.
- Taylor B. 1992. Rifting and the volcanic-tectonic evolution of the Izu-Bonin-Mariana Arc. In: Taylor B., Fujioka K. et al. eds. *Proceedings of the Ocean Drilling Program, Scientific Results*, 126, pp. 627–651. Ocean Drilling Program, College Station, Texas.
- VandenBerg A. H. M. & Stewart I. R. 1992. Ordovician terranes of the southeastern Lachlan Fold Belt: stratigraphy, structure and palaeogeographic reconstruction. *Tectonophysics* **214**, 159–176.
- VandenBerg A. H. M., Willman C. E., Maher S., Simons B. A., Cayley R. A., Taylor D. H., Morand V. J., Moore D. H. & Radojkovic A. 2000. The Tasman Fold Belt System in Victoria. Geology and mineralisation of Proterozoic to Carboniferous rocks. *Geological Survey of Victoria Special Publication*.
- Warren A. Y. E., Gilligan L. B. & Raphael N. M. 1995. *Cootamundra 1:250 000 Geological Sheet SI/55-11: Explanatory Notes*. Geological Survey of New South Wales, Sydney.

- Webby B. D. 1976. The Ordovician System in south-eastern Australia. *In*: Bassett M. G. ed. *The Ordovician System*, pp. 417–446. Proceedings of a Palaeontological Association Symposium, University of Wales Press, Cardiff.
- Willman C. E., VandenBerg A. H. M. & Morand V. J. 2002. Evolution of the southeastern Lachlan Fold Belt in Victoria. *Australian Journal of Earth Sciences* **49**, 271–289.
- Wyborn D. 1992. The tectonic significance of Ordovician magmatism in the eastern Lachlan Fold Belt. *Tectonophysics* **214**, 177–192.

FIGURE CAPTIONS

Figure 1 Map of the Lachlan Fold Belt, southeastern Australian mainland, with the Macquarie Arc (dark shade), Ordovician submarine mega-fan (light shade) and metamorphic basement of the Delamerian Fold Belt (double-dash pattern). The Macquarie Arc is divided into the Goonumbla-Trangie Volcanic Belt (GTVB), Molong Volcanic Belt (MVB), Rockley-Gulgong Volcanic Belt (RGVB) and Kiandra Volcanic Belt (KVB). Abbreviations: AF = Avoca Fault, BT = Bancannia Trough, CT = Cowra Trough, GF = Gilmore Fault, GoF = Governor Fault, HFZ = Heathcote Fault Zone, KF = Kiewa Fault, KirF = Kirribilli Formation, KoF = Koonenberry Fault, KNS = Kiandra-Narromine Structure, MF = Moyston Fault, SRV = Snowy River Volcanics, Tv = Tholeiitic volcanics (Ordovician), WF = Wonnangatta Fault. Northern extensions of the Stawell, Bendigo and Tabberabbera Zones are from Hallet *et al.* (2005). Trend lines in the Thomson Fold Belt are from gravity and magnetic data from Geoscience Australia. Rectangle shows the location of Figure 2(a).

Figure 2 (a) Distribution of Eastonian limestones in the southern Molong Volcanic Belt. Abbreviations: BP = Bowan Park Limestone, Ca = Cargo Creek Limestone, C = Canomodine Limestone, Cl = Cliefden Limestone, RC = Regans Creek Limestone, ReC = Reedy Creek Limestone. Distribution of Ordovician volcanic units above and below the Eastonian limestone is shown along with undifferentiated succession south of Orange. (b) Key to symbols in (c) to (e). (c) – (e) Palaeogeography of the Macquarie Arc for the Late Ordovician rocks of the northeastern Lachlan Fold Belt. Dashed lines show extent of Goonumbla-Trangie Volcanic Belt (GTVB) and western boundary of the Molong Volcanic Belt (MVB) and the southern boundaries of the Molong and Rockley-Gulgong Volcanic Belts (RGVB). Volcanic centres include: Blayney Volcanics (B), Burranah Formation (Bu), Cargo Volcanics (C), Fairbridge Volcanics (F), Oakdale Formation (O) north of Wellington (note age is unclear), Walli Volcanics (W), Wombin Volcanics (Wo) (Pogson & Watkins 1998; Meakin & Morgan 1999; Percival & Glen 2007; Simpson *et al.* 2005, 2007; Squire & McPhie 2007). Selected radiometric ages: (c) U-Pb zircon ages of the Narromine Igneous Complex (463–459 Ma) and Cowal Igneous Complex (466–456 Ma) from Crawford *et al.* (2007c), Coombing Formation detrital zircons south of Orange (467 ± 4 Ma) from Meffre *et al.* (2007), (d) U-Pb zircon age of monzodiorite northwest of Parkes (451 ± 4 Ma) from Simpson *et al.* (2005), an unpublished U-Pb zircon age of the Copper Hill intrusion north of Molong (450 ± 6 Ma) quoted in Percival and Glen (2007), detrital zircons from sandstone at the base of the Eastonian limestone south of Molong (453 ± 4 Ma) from Simpson *et al.* (2007), and (e) unpublished U-Pb zircon ages from the Gidginbung Volcanics southeast of West Wyalong (439–436 Ma) quoted in Percival and Glen (2007), a U-Pb zircon age of granodiorite northeast of West Wyalong (447 ± 7 Ma) and U-Pb zircon ages from granodiorite and dacite of the Narromine Igneous Complex southwest of Narromine (449–441 Ma) from Crawford *et al.* (2007c), U-Pb zircon age of monzonite from northwest of Parkes (439 ± 5 Ma) from Simpson *et al.* (2005), K-Ar ages from igneous rocks at Copper Hill north of Molong

(449–446 Ma), U-Pb zircon ages of intrusions from Cadia south of Orange (439–437 Ma), $^{40}\text{Ar}/^{39}\text{Ar}$ ages for intrusions in the Sofala Volcanics south of Mudgee (440–439 Ma) and an intrusion in the Burranah Formation north of Mudgee (435 ± 5 Ma), a U-Pb zircon age from the Swatchfield Monzonite south of Bathurst (437 ± 8 Ma) all from Percival and Glen (2007 and references therein).

Figure 3 Tectonic reconstructions showing evolution of the Lachlan Fold Belt for the Ordovician to Llandovery interval with coastline of southeast Australia and eastern boundaries of the Delamerian (DFB) and Thomson Fold Belts (TFB) for reference. Mega-fan is shaded (BT = Bega Tract, BZ = Bendigo Zone, GZ = Girilambone Zone, MZ = Melbourne Zone, SZ = Stawell Zone, TZ = Tabberabbera Zone, WOZ = Wagga-Omeo Zone) and Macquarie Arc (GTVB = Goonumbra-Trangie Volcanic Belt, MVB = Molong Volcanic Belt, KVB = Kiandra Volcanic Belt, RGVB = Rockley-Gulgong Volcanic Belt) drawn in pre-deformed state based on estimates of shortening in Fergusson and Coney (1992b) and Gray *et al.* (2006). Offset of Macquarie Arc modified from Packham (1987). Extinct island arc is the Cambrian island arc developed in the eastern Melbourne Zone. Abbreviations: M = Melbourne, NA = Narooma anticlinorium, S = Sydney. (a) Early Ordovician at 480 Ma. Rotation of the Macquarie Arc and trench is shown by dashed lines and arrows. (b) Earliest Late Ordovician (Gisbornian) at 460 Ma. Reactivation(?) of Cambrian subduction zone east of Cambrian volcanic rocks in eastern Melbourne Zone with continuing rotation of the Macquarie Arc. (c) Mid Late Ordovician (Eastonian) at 452 Ma. Subduction of submarine ridge west of the Macquarie Arc may have initiated strike-slip fault obliquely across the arc. (d) Latest Late Ordovician (Bolindian) at 445 Ma. Continued strike-slip offset of the arc accompanied by growth of subduction complex in the mega-fan west of the arc and initiation of a new subduction zone in the eastern Bega Tract. (e) Llandovery at 435 Ma. Continuing subduction and collision has resulted in a much reduced extent of the mega-fan. Post-mid Silurian shortening will eventually result in tectonic elements being displaced westward to their present locations (Figure 1).

Figure 4 (a) Cross section of the New Hebrides arc across Santo Espirito (from $166^{\circ}19'3''\text{E}$, $15^{\circ}33'37''\text{S}$ to $168^{\circ}30'47''\text{E}$, $15^{\circ}14'41''\text{S}$); limestone shelf from Meffre and Crawford (2001). (b) Cross section of the Marianas arc across Guam (from $144^{\circ}9'18''\text{E}$, $13^{\circ}44'26''\text{N}$ to $146^{\circ}16'5''\text{E}$, $12^{\circ}54'27''\text{N}$); limestone shelf from Meijer *et al.* (1983). Note that this cross section is from a southeast (left) to northwest (right) direction to enable comparison with the other cross sections. (c) West-east cross section drawn for the Eastonian across the Molong and Rockley-Gulgong Volcanic Belts of the Macquarie Arc at the latitude of Bathurst (33.4°S). Effects of post-Ordovician deformation have been removed. Same scale and vertical exaggeration ($V/H = 5$) is used in all cross sections.

Figure 5 West-east cross section at around 35°S (present-day coordinates) of the co-existing two subduction zone systems of the central and eastern Lachlan Fold Belt towards the end of the Llandovery (modified from Fergusson 2003, figure 5). Macquarie Arc is simplified and includes the western and eastern volcanic belts and some Ordovician turbidites. *SL* = sea level. Horizontal scale = vertical scale.

Figure 1.

Figure 2.

Figure 3.

Figure 4.

Figure 5.