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Abstract

The Lachlan Fold Belt of southeastern Australia developed along the Panthalassan margin of East Gondwana. Major silicic igneous activity and active tectonics with extensional, strike-slip and contractional deformation have been related to a continental backarc setting with a convergent margin to the east. In the Early Silurian (Benambran Orogeny), tectonic development was controlled by one or more subduction zones involved in collision and accretion of the Ordovician Macquarie Arc. Thermal instability in the Late Silurian to Middle Devonian interval was promoted by the presence of one or more shallow subducted slabs in the upper mantle and resulted in widespread silicic igneous activity. Extension dominated the Late Silurian in New South Wales and parts of eastern Victoria and led to formation of several sedimentary basins. Alternating episodes of contraction and extension, along with dispersed strike-slip faulting particularly in eastern Victoria, occurred in the Early Devonian culminating in the Middle Devonian contractional Tabberabberan Orogeny. Contractional deformation in modern systems, such as the central Andes, is driven by advance of the overriding plate, with highest strain developed at locations distant from plate edges. In the Ordovician to Early Devonian, it is inferred that East Gondwana was advancing towards Panthalassa. Extensional activity in the Lachlan backarc, although minor in comparison to backarc basins in the western Pacific Ocean, was driven by limited but continuous rollback of the subduction hinge. Alternation of contraction and extension reflects the delicate balance between plate motions with rollback being overtaken by advance of the upper plate intermittently in the Early to Middle Devonian resulting in contractional deformation in an otherwise dominantly extensional regime. A modern system that shows comparable behaviour is East Asia where rollback is considered responsible for widespread sedimentary basin development and basin inversion reflects advance of blocks driven by compression related to the Indian collision.

Keywords

Lachlan Fold Belt, Late Silurian, Early to Middle Devonian, plate motion, extension, contractional deformation, convergence, GeoQUEST

Disciplines

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Plate driven extension and convergence along the East Gondwana active margin: Late Silurian–Middle Devonian tectonics of the Lachlan Fold Belt, southeastern Australia

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Running Title: Plate driven tectonics – Lachlan backarc

The Lachlan Fold Belt of southeastern Australia developed along the Panthalassan margin of East Gondwana. Major silicic igneous activity and active tectonics with extensional, strike-slip and contractional deformation have been related to a continental backarc setting with a convergent margin to the east. In the Early Silurian (Benambran Orogeny), tectonic development was controlled by one or more subduction zones involved in collision and accretion of the Ordovician Macquarie Arc. Thermal instability in the Late Silurian to Middle Devonian interval was promoted by the presence of one or more shallow subducted slabs in the upper mantle and resulted in widespread silicic igneous activity. Extension dominated the Late Silurian in New South Wales and parts of eastern Victoria and led to formation of several sedimentary basins. Alternating episodes of contraction and extension, along with dispersed strike-slip faulting particularly in eastern Victoria, occurred in the Early Devonian culminating in the Middle Devonian contractional Tabberabberan Orogeny. Contractional deformation in modern systems, such as the central Andes, is driven by advance of the overriding plate, with highest strain developed at locations distant from plate edges. In the Ordovician to Early Devonian, it is inferred that East Gondwana was advancing towards Panthalassa. Extensional activity in the Lachlan backarc, although minor in comparison to backarc basins in the western Pacific Ocean, was driven by limited but continuous rollback of the subduction hinge. Alternation of contraction and extension reflects the delicate balance between plate motions with rollback being overtaken by advance of the upper plate intermittently in the Early to Middle Devonian resulting in contractional deformation in an otherwise dominantly extensional regime. A modern system that shows comparable behaviour is East Asia where rollback is considered responsible for widespread sedimentary basin development and basin inversion reflects advance of blocks driven by compression related to the Indian collision.

KEY WORDS: Lachlan Fold Belt, Late Silurian, Early to Middle Devonian, plate motion, extension, contractional deformation, convergence.

INTRODUCTION

The Late Silurian to Middle Devonian tectonic development of the Lachlan Fold Belt in New South Wales and eastern Victoria is widely recognised as dominated by extensional tectonics with rifting, sedimentary basin development and abundant igneous activity in a largely continental setting. Overriding plate extension in backarc regions has been associated with either rollback or motion of the upper plate away from the trench at convergent margins

(“pullback”; Jarrard 1986; Heuret & Lallemand 2005; Heuret *et al.* 2007; Schellart 2008a, b; Schellart *et al.* 2008) and most authors have supported a backarc plate tectonic context for the Lachlan Fold Belt (Scheibner 1998; Collins 2002a, b; Glen 2005; Collins & Richards 2008; Kemp *et al.* 2009) although Powell (1984) argued for a transtensional setting.

One puzzling aspect of the Lachlan Fold Belt is alternation between extensional and convergent tectonics which has been difficult to account for in a backarc setting. Widespread contractional deformation is evident especially in the Early to Middle Devonian (Fergusson & Coney 1992; Glen 1992, 2005). Collins (2002a, b) and Collins & Richards (2008) attributed this “tectonic switching” to an overall extensional backarc temporally affected by subduction of topographic features on the underriding plate that caused contractional deformation in parts of the weak backarc. However, contractional deformation in modern systems, such as the central Andes, is driven by advance of the overriding plate and a location distant from plate edges rather than subduction of topographic features (Schellart 2008a). In contrast to Collins (2002a, b), VandenBerg (2003, p. 155) suggested that alternating contractional and extensional episodes could be explained by the interplay between roll-back and convergence so that extension occurred when roll-back exceeded convergence and vice-versa.

This paper examines the Late Silurian to Middle Devonian interval of the Lachlan Fold Belt concentrating on the most widespread exposures of extensional basins in New South Wales. Alternation of extensional and convergent tectonics is placed in a plate tectonic context. This interval followed the complicated Ordovician to Early Silurian history where an island arc (Macquarie Arc) formed mainly in the New South Wales portion of the Lachlan Fold Belt and the Ordovician turbidite megafan was deposited and widely deformed in the Late Ordovician to Early Silurian Benambran Orogeny (Glen 2005). The context of the Late Silurian–Middle Devonian Lachlan Fold Belt as part of the East Gondwana margin is examined with reference to the Tasman Orogenic Zone (Tasmanides, Figure 1). Causes of strain in the overriding plate are considered in the light of the growing literature on this topic. For the mid-Paleozoic tectonics of the Lachlan Fold Belt, no single modern analogue is considered appropriate and constraints are discussed from various modern continental convergent margins. A more detailed comparison is made with East Asia where Cenozoic extensional and contractional deformation has occurred (Morley 2001, 2002, 2009; Schellart & Lister 2005).

Basin evolution is illustrated by cross sections of representative areas that portray undeformed stratigraphic relationships, facies and thicknesses compiled from the literature and geological maps with an emphasis on the most well developed extensional features, especially those in the New South Wales part of the Lachlan Fold Belt (Figures 2–5). Stratigraphic time-space diagrams of the Lachlan Fold Belt are given in Scheibner & Veevers (2000) and Glen (2005) and a summary time-space diagram for the Silurian–Middle Devonian interval is given in Figure 6. Much new information has been published on the stratigraphy and depositional setting particularly by state geological surveys and Geoscience Australia with age control provided by many new fossil ages and new SHRIMP U–Pb ages in unpublished reports (Black 2005, 2006). In this account the Silurian and Devonian timescales of Kaufmann (2006) and Pogson (2009) are followed. Pogson (2009, figure 1) shows the Silurian with an “Early” subdivision containing the Llandovery and Wenlock stages and a “Late” subdivision with the Ludlow and Pridoli stages. This nomenclature is followed herein.

LATE SILURIAN TO MIDDLE DEVONIAN EXTENSIONAL BASIN DEVELOPMENT IN NEW SOUTH WALES AND EASTERN VICTORIA (NEWELL BASIN)

Numerous sedimentary basins characterise the Late Silurian to Middle Devonian interval in the eastern Lachlan Fold Belt, particularly in New South Wales (Cas 1983; Powell 1984), although basin recognition is constrained by contractional and strike-slip deformation which has obscured the original basin geometry, with uplift having caused erosion and loss of records. A useful approach for the eastern Lachlan Fold Belt was adopted by Kemežys (1978) who suggested that in the Silurian a single basin, the Newell Basin, formed east of the Wagga–Omeo Zone although in some areas it extends into the Wagga–Omeo Zone (Figures 1, 2). The advantage of this term is that it recognises that Silurian deposition was widespread across the region and not restricted to distinct basins. The present-day outcrop pattern has large areas of Ordovician rocks in the cores of regional folds and in upthrust blocks reflecting younger deformational events. Widespread Silurian and Devonian deposition is inferred across the eastern Lachlan Fold Belt from numerous outliers away from the main belts of outcrop. Abundant plutonic rocks of Silurian to Middle Devonian age (Figure 2) have intruded the Ordovician rocks and it is probable that they were temporally associated with thick overlying volcanic successions that have since been removed by erosion (Richards & Collins 2004). In many areas, Silurian and Devonian deposition was continuous across the Silurian–Devonian boundary and therefore in this account the Newell Basin also includes overlying Early to Middle Devonian successions of the eastern Lachlan Fold Belt.

Large variations existed in environment and stratigraphic thickness across the Newell Basin. Areas of basement are indicated by local conglomeratic wedges containing basement-derived clasts (e.g. conglomerate at base of the Copper Creek Shale, Ngunawal Basin, Abell 1991, p. 47; basaltic clasts in the Toolamanang Formation, Capertee High, Meakin & Morgan 1999, p. 70; basement-derived conglomerate/breccia in the Avonmore Subgroup of the Buchan Basin, Willman *et al.* 1999, p. 137–140) but it is difficult to identify the distribution of these highs through time. A basement high, Budawang Land, inferred by Kemežys (1978) in the southeastern Newell Basin (Figure 2) contains widespread deformed Ordovician turbidites intruded by elongate Devonian plutonic rocks of the Bega and Moruya Batholiths and it is likely that in the Early Devonian, volcanic successions of the Newell Basin covered much of it (Richards & Collins 2004, figure 5). Development of the Newell Basin is illustrated by reference to several constituent basins mainly in the New South Wales portion of the Lachlan Fold Belt where they are most widely developed.

Tumut Trough, Canberra–Yass and Ngunawal Basins

The succession of the Newell Basin is well displayed by the Tumut Trough, Canberra–Yass and Ngunawal Basins in the central part of the Lachlan Fold Belt (Figure 2). Late Ordovician to Early Silurian units occur in the basal parts of the Tumut Trough and Canberra–Yass Basins and are deep marine quartz and lithic turbidites of the Bumolee Creek Formation around Tumut, the Mundoonen Sandstone near Yass and the Murrumbateman Formation, Black Mountain Sandstone and State Circle Shale at and north of Canberra (Figure 3; Crook *et al.* 1973; Basden 1990; Abell 1991; Colquhoun *et al.* 2003). Late Benambran deformation separates Late Ordovician to Early Silurian units from overlying Late Silurian units of the Canberra–Yass Basin and this break is also developed in the Tumut region (Stuart-Smith *et al.* 1992). In the lower Tumut Trough succession, deep marine environments prevailed along with mafic volcanism and sparse silicic volcanics (Frampton Volcanics) that have a U–Pb zircon age of 428 ± 6 Ma (Stuart-Smith *et al.* 1992). By the Late Silurian widespread silicic volcanics and volcanoclastics of the Blowering Formation were accumulating in the Tumut Trough probably in a shallow marine environment (Figure 3a; Basden 1990; Dadd 1998). Basin evolution in the Tumut Trough was driven by extension in small pull-apart basins along

the Mooney Mooney Fault System with formation of local metamorphic core complexes (Stuart-Smith 1990; Stuart-Smith *et al.* 1992). Extension is consistent with the backarc geochemistry of associated mafic volcanic units (Dadd 1998; Collins 2002b). The change from deep marine environments in the early Wenlock to shallow marine conditions in the Late Silurian indicates that sedimentation more than kept pace with extension.

In the Canberra–Yass Basin, massive S-type ignimbrites of the Hawkins Volcanics locally contain late Wenlock shallow marine sedimentary rocks (e.g. Bango Limestone Member, Sherwin & Strusz 2002) and are overlain by Wenlock to late Ludlow shallow marine sedimentary rocks (Figure 3b, c; Cramsie *et al.* 1973; Owen & Wyborn 1979; Abell 1991; Colquhoun *et al.* 2003; Pogson 2009). This second main marine interval is overlain by the Laidlaw Volcanics which is the highest unit in the succession at Canberra (Figure 3c) but to the northwest at Yass these volcanics are overlain by shallow marine sedimentary rocks of the early Ludlow Silverdale Formation, and in turn by deeper marine late Ludlow to early Lochkovian shales of the upper Hattons Corner Group (Figure 3b; Rickards & Wright 1999). The persistent intercalation of shallow marine sedimentary rocks and silicic ignimbrite indicates that the succession was always near sea level consistent with continual subsidence throughout deposition. Only in the Late Silurian at Yass did subsidence outstrip sedimentation as shown by the deepening environment through time. East of Canberra, the Ngunawal Basin has basal shallow marine sedimentary rocks overlain by a thick succession of deep marine sedimentary and volcanic rocks of inferred Late Silurian age (Figure 3c; Bain *et al.* 1987; Abell 1991). Rapid deepening and prolonged deep marine conditions imply considerable extension consistent with deeper marine conditions in the Late Silurian succession at Yass.

In the Yass and Tumut regions, the Silurian successions are unconformably overlain by Early Devonian volcanics representing renewed silicic igneous activity and presumably associated with extension (Glen 1992, 2005). At Tumut, this extension followed a phase of contractional deformation responsible for an angular unconformity (Basden 1990; Stuart-Smith *et al.* 1992). The Early Devonian succession includes the thick Mountain Creek Volcanics that are overlain by the late Pragian to Emsian Murrumbidgee Group of mainly shallow marine limestone representing a long interval of slow subsidence (Figure 3b; Owen & Wyborn 1979; Colquhoun *et al.* 2003). Six U–Pb ages of 410–400 Ma given by Graham *et al.* (1996) for plagiogranites and a leucogabbro associated with the Coolac Ophiolite Suite, and other ophiolitic fragments in the Tumut–Cootamundra region, indicate that emplacement of these rocks significantly overlapped with limestone deposition of the Murrumbidgee Group. Some of these ages have been challenged by Lyons & Percival (2002) on the basis of a zircon U–Pb age of 428 ± 2 Ma on the Young Granodiorite that has intruded ophiolitic rocks.

Hill End Trough and adjoining highs

In the northeastern Newell Basin, the paleogeography consisted of the deep marine Hill End Trough and adjoining areas of thinner, shallow marine to subaerial deposition along the Capertee and Molong Highs including the Wollondilly Basin in the south (Figure 2; Packham 1968; Cas 1977, 1983). The Hill End Trough comprises a thick succession of deep-marine mudstone and thin sandstone interlayered with prominent intervals of volcanoclastic sandstone deposited by mass flows and derived from neighbouring volcanic centres. No basement is exposed in the Hill End Trough but Ordovician basement occurs on the highs. Local shallow marine deposition occurred along the Molong and the Capertee Highs in the Llandovery (Pogson & Watkins 1998; Meakin & Morgan 1999). Wenlock deposition consisted of silicic volcanics and volcanoclastics along parts of the Molong High but is lacking elsewhere (Figure 4). In the Late Silurian shallow marine sedimentation and silicic volcanism were widespread

along the Capertee High (Dungeree Volcanics and equivalents, Figure 4a). On the western margin of the Capertee High, the basal part of the Late Silurian shallow marine succession is overlain by a thick wedge of deep marine slope clastics at the margin of the Hill End Trough (Figure 4a; Meakin & Morgan 1999). Along the eastern side of the Molong High near Orange, shallow marine deposition and minor volcanism is shown by the Late Silurian Anson Formation and is overlain by the Mullions Range Volcanics that are a locally thick pile of silicic volcanics and volcanoclastics deposited in quiet deepwater environments indicating deposition in the western part of the Hill End Trough near the shelf edge (Pogson & Watkins 1998, p. 138). Deep-water conditions continued in overlying units including deposition of mudstone and turbidites of the Early Devonian Cunningham Formation (Figure 4b). The Hill End Trough succession contains few age specific fossils but the base of the succession is considered as no older than late Ludlow (Packham *et al.* 2001). These relationships are consistent with extensional development of the Hill End Trough in the Late Silurian during deposition of the Anson Formation and Dungeree Volcanics. On the Orange 1:100 000 geological map high-angle reverse faults are shown between units of the Hill End Trough and the Molong High (Meakin *et al.* 1997). These are portrayed in Figure 4b as normal faults that formed during rifting of the Hill End Trough and were subsequently reactivated in younger regional deformation as suggested in the interpretation of deep seismic profile 97AGS–EL2 (Glen *et al.* 2002). The thick Early Devonian successions in the Hill End Trough and the widespread deposition of the Cunningham Formation north of Orange are indicative of Early Devonian extension.

Cowra Trough

The basal unit in the northern part of the Cowra Trough is the Kabadah Formation which is a volcanoclastic unit that contains Early Silurian graptolites and corals and is thought to have been deposited in a shallow marine environment (Figure 4c; Percival & Glen 2007). Provenance of the Kabadah Formation is complex with abundant mafic-intermediate volcanic detritus derived from the Macquarie Arc, as well as: ultramafic detritus and chromite, considered sourced from the Fifield ultramafic complexes to the west; garnet and silicic volcanic clasts heralding volcanism that formed the overlying Canowindra Volcanics; and granite and metasedimentary clasts derived from an uplifted metamorphic terrain (Barron *et al.* 2007). The formation is considered to have formed following uplift during the Benambran Orogeny associated with closure of the Wagga Marginal Sea (Barron *et al.* 2007).

The Wenlock development of the Cowra Trough was marked by S-type subaerial to shallow marine volcanics of the Canowindra Volcanics that are a northern continuation of the Hawkins Volcanics of the Canberra–Yass Basin (Figure 4c). The Late Silurian of the Cowra Trough and the western part of the Molong High is characterised by shaly units deposited in quiet deep water and redeposited limestone (Burrowang Limestone) derived from the shallow marine Ludlow Narragal Limestone of the Molong High (Figure 4c; Meakin & Morgan 1999). This deepening in the Late Silurian reflects the major extensional event that formed the Hill End Trough. Shallow marine conditions returned in the late Pridoli (Wansey Formation) associated with intermediate to mafic volcanism of the Cuga Burga Volcanics followed by formation of the limestone carbonate shelf (Garra Formation) throughout the late Lochkovian to Emsian (Figure 4c).

Girilambone, Wagga–Omeo and Tabberabbera Zones

In the west, the Newell Basin adjoins and in some areas continues into the Girilambone, Wagga–Omeo and Tabberabbera Zones in which Ordovician rocks were affected by the Late Ordovician to Early Silurian Benambran Orogeny (Fergusson *et al.* 2005; Glen *et al.* 2007). Abundant granitic plutons intruded the Wagga–Omeo Zone in the Early Silurian and are associated with silicic volcanics including the Ugalong Dacite as shown on the Forbes and Cargelligo 1:250 000 geological maps (Lyons *et al.* 2000; Colquhoun *et al.* 2005). In the Girilambone Zone, widespread latest Silurian to Early Devonian sedimentary and volcanic rocks were deposited probably continuous with the Devonian successions in the Cobar Basin, Tumut Trough and Canberra–Yass Basin (Figure 2; Sherwin 1996). The succession is illustrated by reference to a cross section across the southern Murda Syncline and another across the Currowong Syncline (Figure 5a, b; Sherwin 1996; Lyons *et al.* 2000). The Kopyje and Derriwong Groups contain silicic volcanics that overlie basal basement-derived conglomerate and interfinger with shallow marine clastics. These units were folded prior to deposition of the shallow marine to fluvial Yarra Yarra Creek Group (Figure 5a). In the Currowong Syncline deep water turbidite successions of the Yiddah and Pullabooka Formations overlie basement derived conglomerate and are succeeded by a thick pile of dominantly silicic volcanics (Figure 5b; Lyons *et al.* 2000). Folding occurred prior to intrusion of the Dalrida Granite (Lyons *et al.* 2000). Major extension is indicated by formation of the thick succession in the Jemalong Trough with milder extension interrupted by a short episode of inversion in the Murda Syncline (Figure 5a).

In eastern Victoria, localised Silurian–Devonian basinal successions are developed in and adjacent to the Wagga–Omeo Zone but are presumably relicts of much more widespread deposition (Figure 2). The inferred Early Silurian Seldom Seen Conglomerate and Towanga Sandstone reflect uplift and erosion of Ordovician rocks during the Benambran Orogeny and were themselves subsequently involved in Benambran deformation (Figure 5c). Rifting followed indicated by deposition of the Late Silurian Enano Group with a thick lower unit of silicic volcanics followed by deep marine sedimentary and volcanic rocks with age control provided by transported limestone clasts in the Limestone Creek Graben (Willman *et al.* 1999; VandenBerg *et al.* 2000). In the Wombat Creek Graben (Figure 2) silicic volcanics are overlain by a marine to subaerial sedimentary succession but its age is no better constrained from limestone clasts than Silurian (VandenBerg 2003). Contractional and strike-slip deformation affected the Limestone Creek and Wombat Creek Grabens in the Early Devonian (VandenBerg *et al.* 2000; Willman *et al.* 2002). Following the Bindian Orogeny, complicated and widespread Early Devonian silicic volcanism, incorporating basement-derived clastic successions, formed the Snowy River Volcanics in a rift setting (Orth *et al.* 1995; VandenBerg *et al.* 2000; VandenBerg 2003). Early Devonian silicic volcanism in cauldron structures also occurred west of the Buchan Basin in outliers such as those to the north of the Wombat Creek Graben (VandenBerg *et al.* 2000; VandenBerg 2003). The Mount Tambo Group (Figure 2) with basement-derived conglomerate and silicic volcanics may also be of Early Devonian age (Willman *et al.* 1999; VandenBerg 2003). Deposition of the Snowy River Volcanics in the Buchan Basin/Rift and the Avonmore Subgroup in the Bindi Syncline was followed by development of a limestone-mudstone platform in the Emsian (Figure 5c; Willman *et al.* 1999; VandenBerg *et al.* 2000). Early Devonian silicic volcanism and marine sedimentation formed the Errinundra Group contained in the Boulder Creek Syncline further east and the succession was almost certainly more widely developed than indicated by present-day exposures (VandenBerg *et al.* 2000; VandenBerg 2003). Extensional episodes are inferred for the Late Silurian and Early Devonian (VandenBerg *et al.* 2000; Willman *et al.* 2002; VandenBerg 2003).

The late Early Devonian Wentworth Group occurs in the Mitchell Syncline, a narrow structure in the southwestern Tabberabbera Zone that cuts across the northwest–southeast

regional structural trends in the underlying Ordovician turbidites. The Wentworth Group has been studied on the Dargo 1:100,000 Geological Sheet by Willman *et al.* (2005) who inferred a marginal to shallow marine environment in a wide coastal plain setting with a single source to the north. They noted that the conglomeratic Wild Horse Formation thinned southwards and disappears entirely near Tabberabbera. Thick conglomerate of the Wild Horse Formation occurs on the western limb of the Mitchell Syncline, west of Tabberabbera (Fergusson & Gray 1989, figure 3; VandenBerg *et al.* 2000, p. 133). The implication is that the unit in the southern Mitchell Syncline thins eastward across the structure and is consistent with localised western derivation for this basement-derived conglomerate. The Wentworth Group was affected by strong contractional deformation in the Middle Devonian (Fergusson & Gray 1989; Willman *et al.* 2005).

EARLY DEVONIAN EXTENSIONAL BASIN IN WESTERN NEW SOUTH WALES – DARLING BASIN

In western New South Wales, the Cobar Basin formed as part of the larger Darling Basin with scattered centres of mainly silicic volcanism in the southeast and widespread thick sedimentation in the latest Silurian to Early Devonian followed by sand-dominated shallow marine and fluvial sedimentation in the Middle to Late Devonian (Glen *et al.* 1996; Alder *et al.* 1998; Scheibner 1998; Cooney & Mantaring 2007). Numerous depocentres were developed in the Darling Basin including a fault-bounded succession in the Bancannia Trough between the Broken Hill and Wonominta Blocks (Cooney & Mantaring 2007). The Cobar Basin developed with rapid subsidence and deposition of a thick succession of deep marine turbidites indicating major extension (Glen 1990). Continuing deposition in the Middle to Late Devonian has been related to a foreland basin setting to the Lachlan Fold Belt to the east inferred from provenance and paleocurrent directions (Powell 1984). Given the width of the basin and the very thick successions developed in some depocentres overlying a continental basement, such as 8000 m in the Bancannia Trough and over 10,000 m in the Lake Popelle Trough in the central part of the basin, it is feasible that extension has been involved in basin subsidence, although punctuated by several contractional deformation events (Willcox *et al.* 2003; Neef 2005; Cooney & Mantaring 2007). Major inversion occurred in the eastern part of the basin in the late Early Devonian at ca 400 Ma (Glen 1990; Glen *et al.* 1992).

FORELAND BASIN IN CENTRAL VICTORIA – THE MELBOURNE TROUGH

In contrast to many of the Silurian–Devonian basins in the eastern Lachlan Fold Belt, the Melbourne Trough has evolved as a foreland basin developed upon a relict of the much more widespread Ordovician marine basin. Ordovician sedimentary rocks in the Melbourne Zone include turbidites and pelagic sedimentary rocks in the southwest, pelagic sedimentary rocks in the northeast and shallow marine limestone in the southeast (VandenBerg *et al.* 2000). In contrast to zones to the west and east, the Melbourne Trough was not affected by contractional deformation of the Benambran Orogeny and deep marine sedimentation continued from the Ordovician to Silurian in the northeast and southwest. The Melbourne Trough contains no evidence of igneous activity in the Silurian to Early Devonian and was not affected by either extensional or contractional deformation in this interval (VandenBerg 2003).

Basin development and tectonic setting of the Melbourne Trough in the light of paleocurrent and provenance data has been discussed by Powell *et al.* (2003). Paleocurrents

from sandstone interbedded with the mudstone-dominant Silurian to Lower Devonian succession indicate derivation ranging west to south prior to deposition of the Pragian Wilson Creek Shale. The main source in the Silurian to Early Devonian is considered to have been the Delamerian Fold Belt with additional input from the uplifted Stawell and Bendigo Zones. Alternatively, detrital zircon ages were interpreted to indicate a sediment source in the distant East and West Gondwana collision zone by Squire *et al.* (2006). However, ages of detrital zircons in sedimentary rocks of the eastern Delamerian Fold Belt and Bendigo–Stawell Zones have much the same age patterns as those of Melbourne Trough sedimentary rocks (Squire *et al.* 2006) indicating that reworking may have occurred either in addition to or instead of transport from a distant source. Gradual shallowing of the succession occurred in the Late Silurian to Early Devonian in the western Melbourne Trough reflecting infilling of this part of the basin (VandenBerg *et al.* 2000). In the Emsian, the eastern Melbourne Trough shows evidence of an eastern source along with incoming of a volcanic component.

LACHLAN FOLD BELT IN NORTHEASTERN TASMANIA

In northeastern Tasmania, the Lachlan Fold belt is dominated by the turbiditic Mathinna Supergroup of Early Ordovician to Early Devonian age and intruded by the Early to Late Devonian Blue Tier Batholith with associated extrusive equivalents (Powell *et al.* 1993; Black *et al.* 2005). Most authors support continuous deep marine sedimentation from the Early Ordovician through the Silurian to Early Devonian and have considered that the Mathinna Basin formed with a similar geometry to the Melbourne Trough (Powell *et al.* 1993, 2003). Alternatively, Reed (2001) argued that the older part of the succession was affected by recumbent folding formed during the Benambran Orogeny and that northeastern Tasmania was more likely a continuation of the Lachlan Fold Belt east of the Melbourne Trough, a concept not supported by Black *et al.* (2005). Black *et al.* (2005) regarded the Blue Tier Batholith as likely to have formed in an active backarc region associated with a convergent margin.

SILURIAN TO MIDDLE DEVONIAN CONTRACTIONAL HISTORY

Widespread contractional deformation is a hallmark of the Lachlan Fold Belt (Collins & Vernon 1992; Fergusson & Coney 1992; Glen 1992; Gray *et al.* 1997; Gray & Foster 2004). Maps of the deformation patterns have been shown in these papers but a major difficulty with this approach is that in many areas, timing of deformation is poorly constrained and numerous deformations are widely and variably developed. Timing of deformation has been inferred from the structural succession in stratigraphic units of different ages, an approach that is problematic where Ordovician quartz turbidite successions are the sole unit exposed over large areas. For example, Ordovician rocks on the south coast of New South Wales have prominent, early north-trending near-isoclinal folds that have been attributed to end-Silurian deformation inland but along the coast are regarded as related to Late Ordovician to earliest Silurian subduction (Powell 1984; Offler *et al.* 1998). $^{39}\text{Ar}/^{40}\text{Ar}$ ages from slates, quartz veins and granitic mylonites also have been used to infer deformation ages (Foster *et al.* 1999) but their interpretation has been controversial especially at sub-epizonal metamorphic grades (Fergusson & Phillips 2001). In the central and eastern Lachlan Fold Belt, $^{39}\text{Ar}/^{40}\text{Ar}$ ages show complex patterns indicating reactivation in several deformational episodes along and near strike-slip shear zones (Foster *et al.* 1999).

In the Late Ordovician to Early Silurian, contractional deformation was associated with the Benambran Orogeny that produced continental crustal thicknesses from the oceanic Wagga Marginal Sea in western Victoria (Stawell and Bendigo Zones) and the central Lachlan Fold Belt including the Tabberabbera, Wagga–Omeo and Girilambone Zones (Foster *et al.* 1999; VandenBerg *et al.* 2000; Fergusson *et al.* 2005). Additional effects are widespread in the eastern Lachlan Fold Belt including parts of the Macquarie Arc and Ordovician–Early Silurian turbidite successions (Glen 1992; Glen *et al.* 2007). Two distinct phases of the orogeny are recognised in some areas; (1) a Late Ordovician to earliest Silurian phase, and (2) an Early Silurian phase, which was referred to as the Quidongan Orogeny by Crook *et al.* (1973) but is now regarded as part of the Benambran Orogeny (VandenBerg 1999; Collins & Hobbs 2001; Glen *et al.* 2007). As noted above, distinctions of this type are not possible in many areas owing to the lack of post-Ordovician units and the ambiguity inherent in the interpretation of sub-epizonal metamorphic ages determined by the $^{39}\text{Ar}/^{40}\text{Ar}$ method (Fergusson & Phillips 2001). U–Pb zircon ages indicate emplacement of many granitic intrusions in the central and eastern Lachlan Fold Belt in the Early to Late Silurian (Keay *et al.* 1999; Lyons *et al.* 2000; Collins & Hobbs 2001; Colquhoun *et al.* 2005; Kemp *et al.* 2006). This is consistent with widespread silicic volcanism in this interval and overlaps with the younger part of the Benambran Orogeny. Metamorphism in the Cooma Complex at 433 ± 3 Ma (Williams 2001) is also related to the second phase of the Benambran Orogeny (Collins & Hobbs 2001).

In the Late Silurian little evidence exists of contractional deformation in the Lachlan Fold Belt (Figures 3–5). Dispersed contractional deformation occurred in the Early Devonian with intense shortening of the Wombat Creek and Limestone Creek Graben in northeastern Victoria (Bindian Orogeny) and parts of the Ngunawal Basin east of Canberra with moderate deformation in the Tumut Trough (Bowning Orogeny, Figure 7; Powell 1984; Stuart-Smith *et al.* 1992; VandenBerg *et al.* 2000). Deformation of this age was also strongly developed in the coastal zone along the southeastern part of the Lachlan Fold Belt (“Budawang Land” in Figure 2; Fergusson & VandenBerg 1990; Glen 1992). Contractional deformation was synchronous with intrusion of some plutons of the Early Devonian Bega Batholith as shown by the development of ductile contractional structures and shear zones in eastern Victoria (Burg & Wilson 1988). However, most Bega Batholith plutons are regarded as having been emplaced in an extensional setting (Richards & Collins 2004). An episode of Early Devonian deformation in the Emsian at ca 400 Ma was most intense in the Cobar Basin but with effects recognised eastwards into the Jemalong Trough (Glen 1992; Lyons *et al.* 2000).

The Middle Devonian Tabberabberan Orogeny is the culmination of the Early to Middle Devonian interval of dispersed contractional deformation and was associated with the cessation of all deep-water deposition in the Lachlan Fold Belt (Cas 1983; Powell 1984; VandenBerg *et al.* 2000). Deformation was most intense across the Melbourne Trough with high strain and multiple deformations along its eastern margin (VandenBerg *et al.* 1995; Gray 1997; VandenBerg *et al.* 2000). East of the Melbourne Zone, intense deformation was localised in the Wentworth Group of the Mitchell Syncline with weak overprinting deformation affecting the multiply-deformed Ordovician turbidites of the Tabberabbera and Wagga–Omeo Zones (VandenBerg *et al.* 2000; Willman *et al.* 2002). Further east, Tabberabberan deformation is evident in the Buchan Basin where contractional structures accompanied by reactivation of early normal faults have been documented in parts of the basin (Orth *et al.* 1995; Gray & Gregory 2003).

In the Lachlan Fold Belt of eastern New South Wales, a major problem has been to untangle the effects of Early to Middle Devonian deformation from Early Carboniferous deformation. Regional deformation of the Hill End Trough is considered to be Carboniferous by Powell (1984) and Middle Devonian by Packham (1999). At least localised Middle

Devonian deformation has affected parts of the Hill End Trough and neighbouring regions (Glen & Watkins 1999). The paraconformable nature of the Early and Late Devonian units in many areas of the northeastern Lachlan Fold Belt, and the widespread development of slaty cleavage and tight folds in Upper Devonian rocks, indicate significant Early Carboniferous deformation (Powell *et al.* 1977; Powell & Edgecombe 1978).

The interplay of contractional and extensional deformation across the Lachlan Fold Belt and through time is a complex issue. It is clear that contractional and extensional deformations have alternated through time and in some intervals quite rapid changes from contraction to extension, and vice versa, have been proposed. Thus for the Benambran Orogeny, Glen (2005) suggested that an extensional episode occurred between the early and late contractional phases. In the latest Silurian to Early Devonian the situation is more complicated as contractional deformation in parts of the eastern Lachlan Fold Belt appears to be synchronous with extension occurring associated with initiation of the Cobar and Darling Basins (Glen 1992, 2005).

SILURIAN TO MIDDLE DEVONIAN STRIKE-SLIP FAULTS

In addition to widespread contractional deformation in the Silurian to Middle Devonian interval, strike-slip faulting is also a feature of the Lachlan Fold Belt especially in eastern Victoria and southeastern New South Wales (Figure 7). A network of faults with strike-slip movement occurs neighbouring the Tabberabbera Zone and in the southern Wagga–Omeo Zone and includes the Kancoona, Kiewa, Barmouth and Ensay Faults, the Tallangatta Creek Fault Zone and the Cassilis Shear Zone in addition to other structures (Figure 7; Willman *et al.* 1999, 2002, 2005). Dextral strike-slip movement along these structures seems to have mainly occurred in the Early Devonian during the Bindian–Bowling Orogeny (Willman *et al.* 2002). Southward movement of several fragments within the Wagga–Omeo Zone, which is bounded to the north by the Gilmore Fault with sinistral strike-slip movement, resulted in thrusting along the Indi Fault and contractional deformation of the Limestone Creek Graben (VandenBerg *et al.* 2000; Willman *et al.* 2002). Shear sense criteria including shear zone fabrics such as S- and C-planes and the shapes of sheared plutons provide the best evidence for the dextral shear sense (Morand & Gray 1991; Willman *et al.* 1999, 2005). The fault network is thought to reflect an anastomosing pattern of shearing throughout the region. This has been attributed to significant southward lateral transport of the eastern Lachlan Fold Belt (the Benambra Terrane) along the inferred Baragwanath Transform (Figure 7; VandenBerg *et al.* 2000; Willman *et al.* 2002) and this is considered in more detail below.

The Gilmore Fault has been considered a significant strike-slip fault in the central Lachlan Fold Belt with sinistral movement responsible for closing the Tumut Trough during the Bowling Orogeny (Stuart-Smith 1991). No offset markers have been identified along the Gilmore Fault so that displacement is unquantified but is probably modest (<50 km). Southeasterly movement of the Wagga–Omeo Zone may also account for extensional opening of depocentres in the Darling Basin in the latest Silurian–Early Devonian (Figures 7, 8).

Faults with strike-slip displacements are also mapped in southeastern New South Wales and eastern Victoria in the Budawang Land where plutons of the Bega and Berridale Batholiths are laterally displaced (Figure 7; Lewis *et al.* 1994). Examples include 24 km of dextral displacement shown by offset of the Kameruka Granodiorite along the northeast-trending Burragate Fault and 10 km of sinistral strike-slip offset of part of the Berridale Batholith along the northwest-trending Berridale Fault (Lewis *et al.* 1994). These faults are considered Middle Devonian in age although it is possible that they have formed over a protracted period of pluton emplacement. Much of the Bega Batholith formed in an

extensional regime (Richards & Collins 2004) and strike-slip displacements may have developed as transfer faults between different elongate zones of extension and pluton emplacement. Alternatively, shorter contractional regimes associated with east–west compression may have produced a conjugate pattern of strike-slip faults with northeast-trending dextral faults and southwest-trending sinistral faults (Figure 7).

DISCUSSION

Global setting

Australia in the Silurian and Devonian was part of East Gondwana which faced the Panthalassan Ocean (Figure 8), the Paleozoic and early Mesozoic precursor to the Pacific Ocean. The Tasmanides are part of the Terra Australis Orogen, the Neoproterozoic to early Mesozoic orogenic belt that developed along the Panthalassan active margin of Gondwana (Cawood 2005). It is probable that during much of the history of the orogen an active convergent margin existed along its 18,000 km length. When the continuation of the convergent margin along the Panthalassan margins of Euramerica and Siberia are added to the Gondwanan Panthalassan margin (Figure 8), their total length is comparable to that of the present-day subduction zones around the “Pacific ring of fire” (ca 45,000 km).

Early to Middle Paleozoic setting of the Tasmanides

The Late Silurian to Middle Devonian setting of the Lachlan Fold Belt is most widely attributed to a largely continental style backarc (Scheibner & Veevers 2000; Collins 2002a, b; Glen 2005; Collins & Richards 2008; Kemp *et al.* 2009). This tectonic setting is placed in context by reference to the preceding Ordovician and contemporary Silurian–Devonian tectonics of the Tasmanides.

Ordovician rocks of the Lachlan Fold Belt include the Macquarie Arc and the widespread quartz turbidite succession that inundated most of the Cambrian oceanic basement (VandenBerg & Stewart 1992; Percival & Glen 2007). The tectonic setting has been a matter of varying interpretations including multiple subduction zones (Gray *et al.* 1997; Foster & Gray 2000; Fergusson 2003, 2009; Meffre *et al.* 2007). Formation of the Ordovician Macquarie Arc has been related by most authors to a west-dipping subduction zone along the eastern side of the exposed Lachlan Fold Belt (Powell 1984; Squire & Miller 2003); although some models have switching of subduction polarity across the Macquarie Arc during accretion (Fergusson 2003, 2009; Glen *et al.* 2007). A major episode of crustal thickening and magma generation affected the central Lachlan Fold Belt in the Late Ordovician to Early Silurian Benambran Orogeny (Figure 1; Powell 1984; Collins & Hobbs 2001). Some authors have argued for substantial strike-slip translations associated with convergence during and after the Benambran Orogeny (VandenBerg *et al.* 2000; Willman *et al.* 2002; Glen 2005).

The Benambran Orogeny involved substantial contractional deformation in the Wagga Marginal Sea west of the Macquarie Arc in the Girilambone, Wagga–Omeo, Tabberabbera, Bendigo and Stawell Zones. Deformation in the Tabberabbera Zone and the Stawell and Bendigo Zones has been related to the development of double divergent subduction zones on either side of the Melbourne Zone (Gray & Foster 1997, 2004; Foster & Gray 2000). Supporting evidence for the subduction complex in the Tabberabbera Zone has been provided by Willman *et al.* (1999) and VandenBerg *et al.* (2004) who documented *mélange* zones and

evidence for tectonic disruption of unlithified sediments. Formation of the Girilambone and Wagga–Omeo Zones as a subduction complex west of the Macquarie Arc, followed by collision in the Early Silurian with the Stawell and Bendigo Zones further west, was proposed by Fergusson (2003, 2009). Alternatively, it has been argued that backarc deformation in the Wagga Marginal Sea was controlled by the presence of thick and rigid continental crust under the Melbourne Trough (VandenBerg *et al.* 2000; Cayley *et al.* 2002). These authors also argued for major dextral translation of the Lachlan Fold Belt northeast and east of the Melbourne Trough beginning in the Benambran Orogeny and culminating in the Bindian–Bowling Orogeny (see below).

The transition from the Ordovician oceanic setting with one or more subduction zones to a Late Silurian continental backarc setting lasted over 20 million years. Contractional deformation associated with the Benambran Orogeny in the former Wagga Marginal Sea west of the Macquarie Arc and the Stawell–Bendigo Zones (Figure 9), had largely ceased by the end of the Early Silurian. During the Late Silurian and into the Devonian, the shallow portion of a single subducted slab or multiple slabs would have still been sinking into the upper mantle and may have caused upper mantle instability. This may have been a factor in development of widespread igneous activity as was originally proposed for the western Lachlan Fold Belt by Soesoo *et al.* (1997). Mafic volcanism has been associated with upper mantle thermal instability due to the presence of a shallow sinking subducted slab under northeast Asia (Zhao 2009). In contrast to northeast Asia, the Late Silurian to Middle Devonian Lachlan Fold Belt, apart from the Melbourne Trough, developed on recently formed and fertile continental crustal susceptible to largescale melting if thermal input was available (Collins & Hobbs 2001). Another consequence of one or more shallow sinking slabs in the upper mantle is widespread subsidence associated with dynamic topography as occurs in the present-day Indonesian region (Lithgow-Bertelloni & Gurnis 1997).

The Melbourne Trough and the Mathinna Basin in the Silurian to Early Devonian both reflect deposition in long-lived basins with most sediment being derived from Gondwana; uplift of the Bendigo–Stawell Zones is the most likely source for the major sedimentary pulses in the western Melbourne Trough (Powell *et al.* 2003; VandenBerg 2003). These basins show no evidence of processes related to the backarc setting of the Lachlan Fold Belt apart from in the Middle Devonian when contractional deformation affected the Melbourne Trough (VandenBerg *et al.* 2000). In northeastern Tasmania, the late Early to Middle Devonian development of the Blue Tier Batholith with associated volcanics and accompanying Middle Devonian contractional deformation at ca 390–389 Ma reflected igneous activity and convergence in a backarc setting (Black *et al.* 2005).

Ordovician rocks have limited exposure in central Queensland and are more widespread in the western part of the Hodgkinson–Broken River Orogen of north Queensland. In central Queensland the Anakie Inlier includes the Fork Lagoons beds, a unit of highly deformed low-grade metasedimentary rocks with mafic volcanics and Upper Ordovician limestone (Withnall *et al.* 1995). The tectonic setting of the Fork Lagoons beds is not clear although a Late Ordovician backarc setting was favoured by Withnall *et al.* (1995). The western part of the Hodgkinson–Broken River Orogen includes Late Ordovician island arc rocks consistent with an offshore convergent margin setting reminiscent of the Macquarie Arc (Henderson 1987; Withnall & Lang 1993).

The Hodgkinson–Broken River Orogen has widespread Silurian–Devonian deep marine turbidite, chert and mafic volcanic successions that are intensely deformed with abundant mélangé reflecting tectonic disruption at early to late stages during deformation (Arnold & Faulkner 1980; Peters 1993; Withnall & Lang 1993). A less deformed basinal succession of equivalent age is preserved in the Graveyard Creek Subprovince further west (Withnall & Lang 1993). Silurian plutonic rocks occur further west again in the Georgetown

Inlier and Greenvale Subprovince (Withnall *et al.* 1997). These three assemblages have been interpreted by Henderson (1980, 1987) as an east-facing convergent margin system with a magmatic arc, forearc basin and subduction complex. An alternative proposal is that they formed in a backarc setting (Arnold & Faulkner 1980) although this explanation is less compatible with widespread stratal disruption in the eastern part of the orogen.

In the latest Silurian to Devonian, the New England Fold Belt had an island arc setting (Calliope Island Arc) which may have extended southwards to include the Tamworth Group west of the Peel Fault (Figure 1). The Calliope Island Arc is considered to have faced westwards and collided with the East Gondwana margin at ca 380 Ma in the Late Devonian (Murray & Blake 2005; Murray 2007). This is consistent with the model of Aitchison & Flood (1995) whereby the Tamworth Group formed as a west-facing island arc that was accreted to the Gondwana margin in the Late Devonian. An alternative interpretation for the Tamworth Group has it as an east-facing island arc with the same polarity as the convergent margin in the Carboniferous of the New England Fold Belt (Leitch 1975; Offler & Gamble 2002). The Calliope Island Arc formed an offshore island arc but its relationship to the Lachlan Fold Belt is unknown. It may have been similar to either the New Hebrides Arc of the western Pacific or it may have matched something akin to the Honshu Arc offshore from mainland East Asia. Thus, whether the subduction zone associated with this island arc was independent of the Lachlan Fold Belt or not remains unestablished.

Tectonics of the Late Silurian–Middle Devonian Lachlan Fold Belt and controls of overriding plate deformation

The Lachlan Fold Belt north and east of the Melbourne Trough in New South Wales and eastern Victoria in the Late Silurian to Middle Devonian is considered to have been associated with a subduction zone to the east (Scheibner 1998; Collins 2002a, b; Glen 2005). Major igneous activity, thick sedimentation, rapid deepening in some basins indicative of extensional tectonics, and widespread contractional deformation are all features most easily explained by an association with an active east-facing subduction zone. Widespread tectonic and magmatic activity is indicative of association with a plate boundary and alternation of contractional-extensional events of the eastern Lachlan Fold Belt is typical of subduction-related settings, for example southeast Asia (Morley 2001, 2002, 2009) and the southern Andes (Fildani & Hessler 2005).

Different conclusions have been drawn about the controlling factors of overriding plate deformation in modern subduction zones depending on which plate motion data and reference frames have been used. Some authors have concluded that upper plate motion is the main control (Jarrard 1986; Heuret & Lallemand 2005; Heuret *et al.* 2007). Thus pull-back of the overriding plate away from the trench causes upper plate extension as is evident from westward absolute plate motion of the Philippine Sea Plate and seafloor spreading behind the Mariana Arc (Schellart *et al.* 2007, figure 1). An alternative conclusion is that upper plate deformation is controlled by retreat of the hinge of the subducting slab, i.e. rollback. This, together with distance from lateral plate edges and length of subducting slabs, has been considered the main control on the formation of extensional backarc basins along the eastern margin of Asia (Schellart *et al.* 2007, 2008; Schellart 2008a, b). Trench retreat is pronounced near lateral slab edges as illustrated by backarc spreading behind the New Hebrides Arc and in the northern Tongan system (Schellart *et al.* 2002). The distance of over 3000 km between the Lachlan Fold Belt along the East Gondwana margin and its nearest lateral plate edge (Figure 8) is comparable to that for the central Andes and is consistent with limited rollback for the Lachlan sector of the East Gondwana active margin. For the Lachlan Fold Belt, the

situation must have involved a delicate balance between limited rollback causing backarc extension, but no seafloor spreading, and advance of the overriding plate producing contractional deformation (VandenBerg 2003, p. 155). East Gondwana may have advanced eastwards towards Panthalassa providing a potential source of episodes of contractional deformation in the Lachlan Fold Belt.

In the Late Silurian, extension caused development of deep-water basins such as the Hill End Trough, Ngunawal Basin, the Wombat Creek and Limestone Creek Graben, and deepening in other basins such as at Yass and the Cowra Trough (Figures 2, 6, 9). The interval of extension in the Late Silurian may have been as long as 5–10 million years, comparable with shorter periods of backarc spreading in western oceanic Pacific backarc basins (Sdrolias & Müller 2006). Late Silurian development is dominated by extension, due to advance of the overriding plate being exceeded by rollback of the subducting plate.

In the earliest Devonian, extension changed to contraction manifested by the Bindian–Bowling Orogeny with effects in various parts of the Lachlan Fold Belt (Figure 7). Areas including the Hill End Trough, Melbourne Trough and Darling Basin, which had just been initiated, were not affected. Development of the Darling Basin has been attributed to northeast–southwest extension in the Late Silurian to Early Devonian (Glen *et al.* 1996; Cooney & Mantaring 2007). This was synchronous with contractional deformation in the eastern Lachlan Fold Belt and how these episodes are related remains unresolved. One possibility is that southeast escape of the Wagga–Omeo Zone has produced extension and initiation of depocentres in the Darling Basin (see below, Figure 9). In the Early Devonian, contractional deformation in some areas was followed by extensional tectonics as shown by various Early Devonian successions such as in the Tumut Trough and Buchan Basin and also parts of the Bega Batholith. By the latest Early Devonian, contractional deformation was again widespread and culminated in the Middle Devonian Tabberabberan Orogeny. Thus overall, the Early to Middle Devonian represents an interval whereby advance of the overriding plate was sufficient to cause contractional deformation in several phases interspersed with intervening extension still reflecting rollback of the subducting plate.

Comparisons with active plate tectonic settings

Glen (1992, 2005) has highlighted the role of extension in the formation of basins within the Lachlan Fold Belt east and northeast of the Melbourne Trough. He suggested that a common succession within these basins has syn-rift related silicic volcanism followed by a post-rift phase with deposition of sedimentary successions of shale and limestone (Figures 3–6) with the development of steer’s head geometries (White & McKenzie 1988). Steer’s head geometries result from the younger thermal subsidence phase of sedimentation overlapping and extending well beyond the limits of the earlier rift phase. This is because stretching in lithospheric mantle, and subsequent cooling, contraction and thermal subsidence, occurs over a broader extent compared to narrower zones of stretching in the more rigid overlying crust (White & McKenzie 1988).

Backarc basins of the Southwest Pacific have been compared with the Silurian to Devonian Lachlan backarc by Collins (2002b). The problem with this analogy is that the Southwest Pacific contains abundant oceanic crust formed mainly by backarc spreading whereas this was at most extremely limited in the Lachlan Fold Belt in the Silurian to Devonian interval. The Cenozoic Basin and Range Province in the southwestern United States has also been cited as comparable to the Silurian–Devonian Lachlan Fold Belt (Powell 1984, p. 324), but this region lacks widespread marine deposition and has not been affected by widespread contractional deformation.

Comparison of the Late Silurian to Middle Devonian Lachlan Fold Belt with the Cenozoic Andes has been useful for placing the role of contractional deformation within the context of advance of the overriding plate (Oncken *et al.* 2006; Schellart 2008a). However, the Andes are not a suitable analogue for the Lachlan Fold Belt as they are dominated by non-marine basins throughout the Cenozoic in contrast to the abundant marine sedimentation of the Lachlan Fold Belt in the Silurian to Middle Devonian. As well, a combination of circumstances in the Andes, including a low erosion regime, has allowed development of the Central Andean Plateau (Oncken *et al.* 2006), a feature which has no equivalent in the Silurian to Middle Devonian Lachlan Fold Belt.

East Asia and the adjoining western Pacific and Indian Oceans are a modern system that potentially provides insight into some of the enigmatic processes in the Lachlan backarc (Figure 10). It is not a suitable modern analogue but comparison in regard to some processes is useful. In the Cenozoic, East Asia was affected by indentation tectonics with lateral escape of fragments to the east resulting in opening of extensional basins, major strike-slip displacements and contractional deformation (Tapponnier *et al.* 1982; Burchfiel 2004). Rollback on the Western Pacific and Indian Ocean subduction zones provided impetus for extensional tectonics within East Asia and is the cause of a complex arrangement of basins in Southeast Asia (Northrup *et al.* 1995; Morley 2001, 2002, 2009; Morley *et al.* 2001; Schellart & Lister 2005). The complicated history of inversion and strike-slip events within these basins is attributed to contraction arising from Himalayan–Tibetan convergence (Morley 2002, 2009). East Asia overall is a backarc region characterised by high heat flow and is therefore susceptible to extensional deformation related to rollback and compressional/strike-slip deformation caused by advance of fragments from the Himalayan collision zone (Hall & Morley 2004; Schellart & Lister 2005). Extensional features such as the Lake Baikal Rift, over 3000 km west of the associated subduction zone, and anomalous igneous activity are related to thermal instability generated by a shallow slab in the upper mantle (Figure 10; Zhao *et al.* 2006; Zhao 2009). East Asia has widespread Cenozoic mafic igneous activity but lacks the abundant silicic magmatism of the Late Silurian to Middle Devonian Lachlan Fold Belt. Nevertheless, the association of intermittent extensional basin formation and inversion events are features common to the Lachlan Fold Belt and East Asia. These are likely to reflect the same plate controls with rollback and upper plate advance providing the impetus for the overall tectonic patterns.

Tectonic switching

Collins (2002a, b) has emphasized the extensional character of the Lachlan backarc reflecting the influence of rollback. He used the term “tectonic switching” for the alternating episodes of extension and contraction that characterises the Silurian to Middle Devonian of the Lachlan Fold Belt. To account for the alternating episodes of extensional and contractional deformation, he suggested that subduction of buoyant oceanic plateaux resulted in backarc contractional deformation. The effects of the subduction of topographic features on overriding plates are well documented for convergent margins. For example, subduction of major submarine ridges has resulted in uplift, erosion and the development of unconformities on Espiritu Santo in the New Hebrides Arc (Meffre & Crawford 2001). In the New Hebrides Arc, subduction of topographic ridges is associated with an intra-arc basin up to 2500 m deep and an elevated arc-backarc transition (Meffre & Crawford 2001). Subduction of various topographic features has caused complicated fault block segmentation and localised uplift in the forearc of coastal Costa Rica (Fisher *et al.* 1998). In a backarc setting, subduction of the Nazca Ridge has produced uplift of over 500 m over a broad region in the Amazonian

foreland basin northeast of the Peruvian Andes (Espurt *et al.* 2007). Subduction of topographic features on the subducting plate has produced segmentation and large-scale structural features, such as the flat-slab regions and associated uplifts in the Andes (Jordan *et al.* 1983; Gutscher *et al.* 2000) and it is conceivable that subduction of submarine ridges and other topographic features may have produced some of the complex variations in paleogeography in the Lachlan backarc and nearby regions. For example, the development of the Hill End Trough in the northeastern Lachlan Fold Belt and development of depocentres in the Darling Basin (Figure 7b) might reflect distortions of backarc topography by long-term subduction of a topographic feature on the underriding plate.

The widest zone of deformation and thickest crust in the Andean system occurs in the central Andes (Lamb *et al.* 1997; Oncken *et al.* 2006). This is considered to be controlled by trenchward movement of the overriding plate and distance from the lateral plate edge, and is not related to subduction of topographic features on the subducting plate (Schellart 2008a). Regional contractional deformation in the Lachlan backarc is therefore better related to overall plate motion with upper plate trenchward advance of East Gondwana towards Panthalassa.

The role of igneous activity in the development of new crust in eastern Australia during cycles of extension and compression has been emphasised by Collins & Richards (2008) and Kemp *et al.* (2009). These papers have been mainly concerned with the control of rollback in developing outboard magmatic arcs and inboard S-type magmatism and have attributed short contractional deformation episodes to subduction of topographic features on the underriding plate following Collins (2002a, b). Whereas, it is considered here that advance of the overriding plate is the most plausible explanation for contractional deformation at least for the Early to Middle Devonian of the Lachlan Fold Belt.

Role of laterally displaced fragments

It has been argued that all of the Lachlan Fold Belt east of the Melbourne Zone has moved southeast along the hypothetical Baragwanath Transform resulting in the development of an eastern margin to the Melbourne Trough in the late Early Devonian (VandenBerg *et al.* 2000; Willman *et al.* 2002). An earlier model suggested that the Wagga–Omeo Zone had been moved southeast but with only limited displacement of 50 km or so (Morand & Gray 1991) whereas the larger fragment was envisaged as having moved at least 600 km. The main reasons for advocating the hypothetical Baragwanath Transform are: (1) lack of thick Ordovician turbidite successions in the eastern Melbourne Trough and the abundance of these successions further east in the adjoining Tabberabbera Zone and other zones in the apparently down-current location (VandenBerg & Stewart 1992), and (2) the marked contrast between the Silurian–Devonian history of the Melbourne Trough and the Lachlan Fold Belt to the northeast and east (the Benambra Terrane; VandenBerg *et al.* 2000; Willman *et al.* 2002).

The hypothesis of 600 km strike-slip translation is considered one of several options for tectonic development of the Lachlan Fold Belt but is not favoured here. The Baragwanath Transform is difficult to recognise in basement trends, constrained by magnetic and gravity lineaments, in western New South Wales (Figure 7; Hallet *et al.* 2005). The Stawell Zone curves from a northwest to a northeast trend and continues to the north of the Hay–Booligal Zone and shows no offset along the northwest continuation of the Baragwanath Transform that has been inferred to underlie the eastern faulted margin to the Melbourne Zone (Figure 7). Thus, the only feasible location for any northern continuation of the hypothetical fault requires at least 40° curvature to the east so that the fault continues along the eastern margin of the Hay–Booligal Zone (Figure 7). This angle is increased when the succession in the

Melbourne Zone is undeformed given that it narrows to the north (Figures 7, 9). Thus the geometry of the Baragwanath Transform has to be changed from that shown by Willman *et al.* (2002, figure 6) resulting in a fault with substantial curvature and implying considerable anticlockwise rotation of the Benambra Terrane rather than simple strike-slip displacement. The Benambra Terrane is truncated southwards by the present-day Victorian coastline so that its southward extent is unknown and thus the amount of lateral displacement required to remove it from the Melbourne Trough is a minimum estimate (VandenBerg *et al.* 2000; Willman *et al.* 2002; Powell *et al.* 2003). Additionally, the suggestion that a Benambran subduction zone existed in the Tabberabbera Zone allows for offset between this and the Melbourne Zone to have developed in the Late Ordovician to Early Silurian. This subduction zone may have involved considerable dextral oblique convergence, not just normal convergence, thereby providing one explanation for the mismatch in Ordovician paleogeography pointed out by VandenBerg & Stewart (1992).

Southeast transport of several fragments making up the Wagga–Omeo Zone in eastern Victoria and southern New South Wales is indicated by the strike-slip fault system active in the Bindian–Bowling Orogeny as outlined earlier (Figure 7) and outlined by VandenBerg *et al.* (2000) and Willman *et al.* (2002). In terms of an East Asian analogue, this is equivalent to tectonic escape; although in the case of the earliest Devonian Lachlan Fold Belt this is driven by convergence in the overriding plate during advance of East Gondwana, rather than by escape from a continental collision zone as in East Asia. Large-scale dextral strike-slip displacement along the eastern margin of the Melbourne Trough has been suggested to explain the lack of an eastern source to the Melbourne Trough prior to the late Early Devonian (VandenBerg *et al.* 2000; Willman *et al.* 2002; Powell *et al.* 2003). An alternative interpretation is that the eastern margin of the Melbourne Trough, represented by the Tabberabbera and Wagga–Omeo Zones, was relatively subdued in the Silurian to Early Devonian and it was only during the late Early Devonian that deformation and uplift in the western parts of these zones reached a point where an eastern source was generated for the Melbourne Trough. The lack of an eastern source is not an unusual feature elsewhere in the Lachlan Fold Belt, for example, in the eastern Darling Basin an eastern source is first indicated in the early Middle Devonian (Powell 1984, p. 320) somewhat later than that in the eastern Melbourne Trough.

An alternative model incorporating major strike-slip displacement is that fragments of the Lachlan Fold Belt have been transported considerable distances from the south–southeast and that this accounts for the development of Ordovician quartz turbidites on both sides of the Macquarie Arc (Glen 2005; Glen *et al.* 2007). Although this model can account for the anomalous Ordovician quartz turbidite deposition on either side of the Macquarie Arc it is not considered feasible as convincing strike-slip faults with the required offsets and kinematic histories have not been documented.

CONCLUSIONS

In the Early Silurian, the Benambran Orogeny had widespread effects in the Lachlan Fold Belt with the development of thickened crust associated with one or more subduction zones. In the Wenlock, widespread silicic igneous activity began in the final phase of the Benambran Orogeny. This activity became more widespread in the evolving backarc setting associated with continuing development of a convergent margin to the east, although no definitive magmatic arc associated with this subduction has been recognised within the Lachlan Fold Belt. In the Late Silurian, rollback along the subduction zone caused extensional basin development including formation of the Hill End Trough, Ngunawal Basin, Limestone Creek

and Wombat Creek Graben, and deepening in the Cowra Trough and Yass region. Limited rollback during the Late Silurian continued into the Early to Middle Devonian as shown by renewed extensional basin development with formation of the Buchan Basin, Jemalong Trough, Cobar Basin and Darling Basin and continuing development of the Hill End and Cowra Troughs. Interspersed contractional events in the Early to Middle Devonian are interpreted to have resulted from advance of the overriding East Gondwana plate towards Panthalassa.

Plate motions are considered the primary driver of deformation and tectonic changes in the Lachlan Fold Belt east and northeast of the Melbourne Trough. The Late Silurian to Middle Devonian context of the Lachlan Fold Belt is a continental backarc setting, related to a long subduction zone distant from any lateral plate edge, and with a delicate balance between overriding plate advance and rollback of the subducting plate that drove the complicated alternation of extensional and contractional episodes. Additionally, events accompanying the Benambran Orogeny produced upper mantle instability and dynamic topographic effects that impacted on subsequent backarc development.

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FIGURE CAPTIONS

Figure 1 Map of eastern Australia showing the main orogenic belts and features relevant to the Silurian–Devonian active Gondwanan margin of Panthalassa. Abbreviations: BT = Bancannia Trough, BHB = Broken Hill Block, CRS = Cape River Subprovince, CTP = Charters Towers Province, GB = Grampians Basin, GCS = Graveyard Creek Subprovince, GS = Greenvale Subprovince, GWOTZ = Girilambone–Wagga–Omeo–Tabberabbera Zones, GZ = Glenelg Zone, MB = Mathinna Basin, MeT = Menindee Trough, MT = Melbourne Trough, SBZ = Stawell-Bedigo Zones, WB = Wonominta Block.

Figure 2 Extensional basins of the Newell Basin in the eastern Lachlan Fold Belt. See Figure 1 for location. Numbers and lines refer to locations of schematic stratigraphic cross sections in Figures 3 to 5. MTG = Mount Tambo Group.

Figure 3 Cross sections of the Yass-Canberra Basin, Ngunawal Basin and Tumut Trough showing the undeformed stratigraphic relationships, facies and approximate thicknesses. (a) A west–northwest–east–northeast cross section across the Tumut Trough 10 km north of Tumut; compiled from data and interpretations in Basden (1990) and Stuart-Smith *et al.* (1992). (b) A

west–east cross section across the Canberra–Yass Basin at Yass; compiled from data and interpretations in Cramsie *et al.* (1973) and updated from the map of Colquhoun *et al.* (2003) and age determinations by Sherwin & Strusz (2002) and Pogson (2009). (c) A west–east cross section across the Canberra–Yass Basin and Ngunawal Basin 20 km south of Canberra; compiled from data and interpretations in Owen & Wyborn (1979) and Abell (1991). U–Pb age of the Hawkins Volcanics is from a sample collected ca 15 km west–northwest of Canberra (Kemp *et al.* 2006).

Figure 4 Cross sections of the Hill End Trough and marginal features including the Capertee High, Molong High and Cowra Trough showing undeformed stratigraphic relationships, facies and approximate thicknesses. (a) A southwest–northeast cross section across the Hill End Trough and Capertee High through Cudgegong; compiled from data and interpretations in Meakin & Morgan (1999) with revisions of ages from Pogson (2009). (b) A southwest–northeast cross section across the Molong High and Hill End Trough northeast of Orange; compiled from data and interpretations in Pogson & Watkins (1998). (c) A west–east cross section across the Cowra Trough and western part of the Molong High 5 km north of Cumnock; compiled from data and interpretations in Meakin & Morgan (1999) and Pogson & Watkins (1998). Radiometric age of the Canowindra Volcanics is from Black (2005) and Pogson (2009).

Figure 5 Cross sections of the Jemalong Trough, Limestone Creek Graben and Buchan Rift showing the undeformed stratigraphic relationships, facies and approximate thicknesses. (a) A west–east cross section across the Jemalong Trough preserved near the southern end of the Murda Syncline in the western part of the Narromine 1:250,000 Geological Map; compiled from data and interpretations in Sherwin (1996). (b) A west–east cross section across the Jemalong Trough in the Currowong Syncline through Wirrinya; compiled from data and interpretations in Lyons *et al.* (2000). (c) A west–east cross section across the southwestern end of the Limestone Creek Graben near Bindi; compiled from data and interpretations in Willman *et al.* (1999) and VandenBerg *et al.* (2000).

Figure 6 Time-space diagram for various elements across the Lachlan Fold Belt for the Silurian–Middle Devonian interval. Base of rift cycles partly after Glen (2005, figure 10). Columns compiled from data in the following sources: Mathinna Basin after Powell *et al.* (1993) and Black *et al.* (2005); Melbourne Trough after VandenBerg *et al.* (2000), Powell *et al.* (2003) and VandenBerg (2003); Tabberabbera Zone and Limestone Creek Graben–Buchan Basin after VandenBerg *et al.* (2000), Willman *et al.* (1999, 2002, 2005) and VandenBerg (2003); Tumut Trough, Canberra–Yass Basin, Ngunawal Basin, Jemalong Trough, Cowra Trough and Hill End Trough see references in Figures 3–5; Bega Batholith after Powell (1984) and Richards & Collins (2004). Abbreviation: Tabb Orog = Tabberabberan Orogeny.

Figure 7 Map of the Lachlan Fold Belt in New South Wales and Victoria showing some structural zones (darker shade) with their subsurface continuations (lighter shade) and the subsurface Hay–Booligal Zone based on geophysical data (VandenBerg *et al.* 2000; Hallet *et al.* 2005). Numerous faults are shown: BaF = Barmouth Fault, BeF = Berridale Fault, BT = Baragwanath Transform, BuF = Burrigate Fault, CSZ = Cassilis Shear Zone, Ensf = Ensay Fault, GF = Gilmore Fault, IF = Indi Fault, KF = Kancoona Fault, KiF = Kiewa Fault, KoF = Koonenberry Fault, MF = McLaughlan Fault, PCF–CF = Pheasant Creek Fault–Combienbar Fault, TCFZ = Tallangatta Creek Fault Zone, WF = Wonnangatta Fault. Distribution of most intense Bindian–Bowling contractional deformation in eastern Lachlan Fold belt is shown

(modified after Fergusson & Coney 1992, figure 6). Trend lines in the Thomson Fold Belt are from gravity and magnetic data from Geoscience Australia.

Figure 8 Paleogeographic reconstruction for the Early Devonian (390 Ma) modified from the reconstruction of Scotese (2001).

Figure 9 (a) Reconstruction for the Late Silurian of the Lachlan Fold Belt (modified from Fergusson 2009, figure 3e). Abbreviations: LCG–WCG = Limestone Creek Graben–Wombat Creek Graben, WB–NB = Wollondilly Basin–Ngunawal Basin. (b) Reconstruction for the Early Devonian showing major basins of the Lachlan Fold Belt and depocentres of the Darling Basin (Cooney & Mantaring 2007, figure 13). Melbourne Trough is shown in undeformed extent in both diagrams but its northern termination is in the subsurface and is not shown. Note distortion of Lachlan Fold Belt northeast of the Melbourne Trough reflecting unfolding of the Middle Devonian shortening across the Melbourne Trough that wedges out to the north.

Figure 10 Major tectonic features of East Asia and associated subduction zones of the western Pacific Ocean interpreted from the Etopo2 database. Basins and major features after Morley (2001, 2002), Morley *et al.* (2001), Hall & Morley (2004) and Schellart & Lister (2005). Note that the Sichuan Basin is a foreland topographic depression related to uplift of the adjacent Tibetan Plateau.

Figure 1.

Figure 2.

Figure 3.

Figure 4.

Figure 5.

Figure 6.

Figure 7.

Figure 8.

Figure 9.

Figure 10.