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Mid to late Paleozoic shortening pulses in the Lachlan Orogen, southeastern Australia: a review

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In the late Silurian, the Lachlan Orogen of southeastern Australia had a varied paleogeography with deep-marine, shallow-marine, subaerial environments and widespread igneous activity reflecting an extensional backarc setting. This changed to a compressional-extensional regime in the Devonian associated with episodic compressional events, including the Bindian, Tabberabberan and Kanimblan orogenies. The Early Devonian Bindian Orogeny was associated with SSE transport of the Wagga-Omeo Zone that was synchronous with thick sedimentation in the Cobar and Darling basins in central and western New South Wales. Shortening has been controlled by the margins of the Wagga-Omeo Zone with partitioning along strike-slip faults, such as along the Gilmore Fault, and inversion of pre-existing extensional basins including the Limestone Creek Graben and the Canbelego-Mineral Hill Volcanic Belt. Shortening was more widespread in the late Early Devonian to Middle Devonian Tabberabberan Orogeny, with major deformation in the Melbourne Zone, Cobar Basin and eastern Lachlan Orogen. In the eastern Melbourne Zone, structural trends have been controlled by the pre-existing structural grain in the adjacent Tabberabbera Zone. Elsewhere Tabberabberan deformation involved inversion of pre-existing rifts resulting in a variation in structural trends. In the Early Carboniferous, the Lachlan Orogen was in a compressional backarc setting west of the New England continental margin arc with Kanimblan deformation most evident in Upper Devonian units in the eastern Lachlan Orogen. Kanimblan structures include major thrusts and associated fault-propagation folds indicated by footwall synclines with a steeply dipping to overturned limb adjacent to the fault. Ongoing deformation and sedimentation have been documented in the Mt Howitt Province of eastern Victoria. Overall, structural trends reflect a combination of controls provided by reactivation of pre-existing contractional and extensional structures in dominantly E-W shortening operating intermittently from the earliest Devonian to Early Carboniferous.

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Running Title: Mid to late Paleozoic shortening of the Lachlan Orogen

Abstract

In the late Silurian, the Lachlan Orogen of southeastern Australia had a varied paleogeography with deep marine, shallow marine, subaerial environments and widespread igneous activity reflecting an extensional backarc setting. This changed to a compressional–extensional regime in the Devonian associated with episodic compressional events, including the Bindian, Tabberabberan and Kanimblan orogenies. The Early Devonian Bindian Orogeny was associated with SSE transport of the Wagga–Omeo Zone that was synchronous with thick sedimentation in the Cobar and Darling basins in central and western New South Wales. Shortening has been controlled by the margins of the Wagga–Omeo Zone with partitioning along strike-slip faults, such as along the Gilmore Fault, and inversion of pre-existing extensional basins including the Limestone Creek Graben and the Canbelego–Mineral Hill Volcanic Belt. Shortening was more widespread in the late Early Devonian to Middle Devonian Tabberabberan Orogeny, with major deformation in the Melbourne Zone, Cobar Basin and in the eastern Lachlan Orogen. In the eastern Melbourne Zone, structural trends have been controlled by the pre-existing structural grain in the adjacent Tabberabbera Zone. Elsewhere Tabberabberan deformation involved inversion of pre-existing rifts resulting in a variation in structural trends. In the Early Carboniferous, the Lachlan Orogen was in a compressional backarc setting west of the New England continental margin arc with Kanimblan deformation most evident in Upper Devonian units in the eastern Lachlan Orogen. Kanimblan structures include major thrusts and associated fault-propagation folds indicated by footwall synclines with a steeply dipping to overturned limb adjacent to the fault. Ongoing deformation and sedimentation have been documented in the Mt Howitt Province of eastern Victoria. Overall, structural trends reflect a combination of controls provided by reactivation of pre-existing contractional and extensional structures in dominantly E–W shortening operating intermittently from the earliest Devonian to Early Carboniferous.

KEY WORDS: Carboniferous, Devonian, Lachlan Orogen, orogeny, southeastern Australia, shortening, subduction

Introduction

The Lachlan Orogen is well known for its complex history with several orogenic episodes as shown by widespread deformational events and related unconformities (Glen, 2005; Gray & Foster, 2004; Gray, Foster, & Bucher, 1997). The interplay of extensional tectonic development and episodes of shortening is characteristic of the late Silurian to Carboniferous history of the Lachlan Orogen (Collins, 2002a, 2002b; Fergusson, 2010; Scheibner & Basden, 1998; Scheibner & Veevers, 2000; VandenBerg, 2003; VandenBerg et al., 2000). Major intra-Devonian unconformities have been recognised at localities, including Bindi and Tabberabbera in eastern Victoria (Figure 1), where the rocks show strong shortening in upper Silurian and Lower Devonian units, respectively. Widespread folding and thrusting has affected Upper Devonian successions throughout the Lachlan Orogen (Gray & Foster, 2004; Powell, 1984a; VandenBerg et al., 2000).

A Southwest Pacific context, with subduction rollback and formation of marginal basin(s), provides an analogue for the Lachlan Orogen in the Cambrian and Ordovician (Collins, 2002a, 2002b). In the late Silurian to Carboniferous, the Lachlan Orogen was in a backarc setting, associated with an eastward-facing subduction zone, with extensional basins and widespread shallow to deep marine and subaerial deposition (Fergusson, 2010; Glen, 2005, 2013; Gray & Foster, 2004; Powell, 1984a; VandenBerg, 2003). Emphasis has been placed on “tectonic switching” in the extensional backarc setting with convergent deformation related to episodic subduction of topographic features on the outboard subducting plate (Collins, 2002a, 2002b; Kemp et al., 2009). Alternatively, it has been argued that intervals of extensional and compressional tectonics reflect the vagaries of plate motion with the interaction of rollback of the underthrust plate and upper plate advance/retreat (Fergusson, 2010; VandenBerg, 2003).

This paper reviews the latest Silurian to Carboniferous compressional deformation record of the Lachlan Orogen. The pattern of compressional deformation across the orogen is variable with intense deformation in some regions, whereas elsewhere sedimentation continues uninterrupted with no evidence of any shortening. This account complements an earlier synthesis on the late Silurian to Middle Devonian tectonics of the Lachlan Orogen that concentrated on extensional basin development, relationships to contractional deformation and the plate motion drivers of deformation in an arc–backarc setting (Fergusson, 2010). Deformation patterns have been widely considered in the past, particularly in the 1990’s when they were portrayed on orogen-scale sketch maps (Collins & Vernon, 1992; Fergusson & Coney, 1992; Glen, 1992; Gray, Foster, & Bucher, 1997). Abundant information has become available, including mapping (e.g. Bogong 1:100 000 geological map, Morand et al., 2005; Buffalo 1:100 000 geological map, VandenBerg et al., 2004; Dargo 1:100 000 geological map, Willman et al., 2005; Goulburn 1:250 000 geological map, Thomas & Pogson, 2012; Braidwood 1:100 000 geological map, Fitzherbert et al., 2011), deep-seismic reflection data (e.g. Cayley et al., 2011; Glen et al., 2002), paleontological reassessments of stratigraphic ages (e.g. Downes et al., 2016; Young, 2006, 2007), and abundant geochronology (Downes et al., 2016; Foster, Gray, & Bucher, 1999; numerous recent Geoscience Australia Records, e.g. Bodorkos et al., 2015). It is considered timely for a reassessment of our understanding of the role of shortening in the latest Silurian to Carboniferous of the Lachlan Orogen. Only the main aspects are covered in this review given the very large literature and data base that now exists for the Lachlan Orogen. Note that the fold interlimb angle classification used herein is after van der Pluijm and Marshak (1997): isoclinal = 0–10°, tight = 10–60°, open = 60–120°, gentle = 120–180°.

Geological setting and background

The Lachlan Orogen includes Cambrian to Carboniferous rocks in central and eastern New South Wales (NSW) west of the Sydney Basin and extending southwards into Victoria and northeastern Tasmania (Figures 1, 2). The western boundary of the Lachlan Orogen in western Victoria is generally taken along the Moyston Fault (Cayley et al., 2011), although the Grampians Supergroup west of the Moyston Fault has characteristics of the Lachlan Orogen including probable Silurian to Early Devonian sedimentation and deformation. In central NSW, the western boundary of the Lachlan Orogen is poorly defined as no obvious boundary exists between the Cobar Basin in the Lachlan Orogen and the Darling Basin farther west. Thus, the Darling Basin is not part of the Lachlan Orogen, although they have overlapping geological histories. The Darling Basin and the Melbourne Trough in central Victoria both had a foreland basin setting to uplifted, deformed units to the east in the late Silurian to Devonian (Powell, 1984a; Powell, Baillie, & VandenBerg, 2003).

Numerous structural zones are recognised across the Lachlan Orogen (Figure 1) and many of these contain widespread Ordovician turbidites and granitic rocks. The Melbourne Zone is atypical as it is thought to contain a basement of Precambrian rocks continuous with that in western Tasmania based on magnetic anomalies that are traceable from northwestern Tasmania across Bass Strait to the Victorian coastline (Cayley, 2011; Cayley, Taylor, VandenBerg, & Moore, 2002; Moore, Betts, & Hall, 2013). Cambrian igneous rocks form basement to the Lachlan Orogen on either side of the Melbourne Zone and these assemblages have an oceanic backarc and island arc association (Crawford et al., 2003; Glen, 2013). In the Stawell Zone of western Victoria, turbidites mostly lack fossils and are considered upper Cambrian (VandenBerg et al., 2000). Ordovician quartz-rich turbidites are widespread throughout much of the orogen including the southwestern part of the Melbourne Zone. In the eastern Lachlan Orogen, the Macquarie Arc consists of Lower Ordovician to lower Silurian volcanic, volcaniclastic and plutonic rocks with associated limestone that are considered to have formed in an island and fringing deep-marine paleogeography (Percival & Glen, 2007). This interpretation has been challenged and a rifted backarc setting proposed instead (Quinn, Percival, Glen, & Xiao, 2014).

The widespread Ordovician turbidites are strongly shortened with upright to moderately inclined, tight to isoclinal folds, wide areas of multiple deformations, and in some areas where stratigraphic markers abound, such as the upper Middle to Upper Ordovician Bendoc Group, zones with closely spaced thrust faults (Fergusson & VandenBerg, 1990; Glen, 1992; Glen & VandenBerg, 1987). Low-pressure to intermediate-pressure metamorphism has affected parts of the Ordovician turbidites (Offler, Miller, Gray, Foster, & Bale, 1998a; Offler, McKnight, & Morand, 1998b; Prendergast, Offler, & Zwingmann, 2012). Widespread deformation affected the Lachlan Orogen in the Late Ordovician to mid Silurian Benambran Orogeny (Glen, Meffre, & Scott, 2007), and has been considered dominant in the Stawell, Bendigo, Tabberabbera, Wagga–Omeo, Girilambone, and Narooma zones (Figure 1). Tectonic interpretation of this event is widely contested with some authors arguing for multiple subduction zones and accretion of the Cambrian–Ordovician rocks in up to three subduction complexes (Fergusson, 2003, 2014; Foster & Gray, 2000; Gray & Foster, 1997). Inferred subduction complexes in the Bendigo and Tabberabbera zones are consistent with the presence of rare high-pressure metamorphic rocks in the hanging walls of the Governor and Mt William faults on the boundaries of the Melbourne Zone (Spaggiari, Gray, & Foster, 2002a; Spaggiari, Gray, Foster, & Fanning, 2002b). More recently, Ordovician turbidites in Victoria and southern NSW are considered linked in an orocline that wraps around the northern Melbourne Zone with another hinge in eastern

Victoria joining the Tabberabbera to the Canberra and Narooma zones (Cayley, 2012; Moresi, Betts, Miller, & Cayley, 2014; Musgrave, 2015).

In the mid Silurian to Middle Devonian, the Benambran Orogeny was followed by an extensional regime with widespread basinal marine and fluvial deposition, volcanism, and related intrusions, east of the Melbourne Zone and the Cobar Basin (Cas, 1983; Glen, 2005, 2013; Powell, 1984a). The eastern part of the orogen has been considered part of a single major basin (Figure 2), the Newell Basin (Fergusson, 2010; Kemežys, 1978) in a backarc setting, although existence of a related magmatic arc is controversial (Chappell, White, Williams, Wyborn, & Wyborn, 2000). In the Late Devonian, widespread fluvial sedimentation, with more limited igneous activity, and shallow-marine deposition, developed across the eastern Lachlan Orogen (Glen, 2005; Powell, 1984a). Late Devonian paleogeography was dominated by widespread meandering river systems, with some marine incursions in the east near the base of the succession, and with some conglomeratic wedges reflecting mountainous local sources within and near the orogen (Cas, O'Halloran, Long, & VandenBerg, 2003; Meakin & Morgan, 1999; Pogson & Watkins, 1998).

The eastern part of the Tasmanides in the New England Orogen had a Lower to lower Upper Devonian island arc–backarc assemblage, and it has been suggested that this assemblage collided with the Gondwana margin in the early Late Devonian, represented by the developing Lachlan Orogen (Offler & Murray, 2011). West-dipping subduction was associated with the well-documented Upper Devonian to Carboniferous active continental margin assemblage of the New England Orogen (Murray, Fergusson, Flood, Whitaker, & Korsch, 1987). The Upper Devonian to Carboniferous arc is exposed in the Auburn and Connors subprovinces in Queensland (Donchak, Purdy, Withnall, Blake, & Jell, 2013) and Carboniferous plutons in the northeastern Lachlan Orogen are considered the rearward part of the eroded magmatic arc (Shaw & Flood, 1993).

The Tasmanides have developed at a high angle to the intraplate Alice Springs Transverse Zone, which was affected by the latest Ordovician to mainly Devonian–Carboniferous Alice Springs Orogeny (Raimando, Hand, & Collins, 2014). This zone has had over 80 km of N–S shortening in an intracontinental setting (Hand & Sandiford, 1999). The Alice Springs Orogeny is an intracontinental orogenic belt developed in response to far-field subduction zones, which existed in the Devonian to Carboniferous to the north and northeast of Australia (Domeier & Torsvik, 2014). In the northwestern Lachlan Orogen, N–S shortening potentially associated with this event is represented by thrusting of Thomson Orogen rocks southwards over Darling Basin sedimentary rocks along the Olepoloko Fault (Glen et al., 2013). Megakinking in the eastern Lachlan Orogen has also been related to N–S shortening associated with this event (Powell, 1984b; Powell, Cole, & Cudahy, 1985).

Latest Silurian to Carboniferous shortening

Pre-existing structures formed in the Benambran Orogeny and extensional structures formed in basin development have potentially controlled structures in the later pulses of shortening. Across the orogen, constraints on the timing of deformation have been provided by detailed mapping, paleontological collections and widespread geochronology, including Ar/Ar ages and U–Pb zircon ages on plutonic and volcanic rocks. The most robust constraint on the timing of deformation is the development of unconformities with overlying successions truncating underlying rocks and structures. The timing of cleavage development may be indicated by Ar/Ar ages, but the most unambiguous criterion is the presence of cleaved clasts in conglomerates either overlying or close to underlying cleaved units.

In some areas, such as in parts of the Forbes region and the Buchan Rift, Lower Devonian units are folded and faulted but the timing of this deformation is only loosely constrained because of the absence of unconformably overlying Upper Devonian successions. For the Hill End Trough in the northeastern Lachlan Orogen, debate has continued since the 1970's about the timing of the main regional shortening event. A latest Devonian–Early Carboniferous age was argued by Powell, Edgecombe, Henry, and Jones (1977) and Powell and Edgecombe (1978) who showed that Upper Devonian rocks either side of the Hill End Trough were affected by tight folding and in several areas are paraconformable to disconformable on underlying Lower Devonian units. In contrast, Packham (1999) supported Middle Devonian regional deformation of the Hill End Trough. Farther south in the Goulburn 1:250 000 geological map area, a Tabberabberan age has been proposed for regional deformation that predated deposition of Upper Devonian units (Thomas & Pogson, 2012).

Bindian deformation

The Bindian Orogeny is named after Bindi in northeastern Victoria (Figure 3) where upper Silurian rocks are intensely deformed and overlain by Lower Devonian units above an angular unconformity (VandenBerg et al., 2000). The synchronous Bowning Orogeny was named after the small town of Bowning 12 km northwest of Yass in southern–central NSW (Figure 1), and the most recent mapping showed that the unconformity between the underlying upper Pridoli to the lowest Lochkovian Elmside Formation and the overlying Sharpeningstone Conglomerate, which has an inferred age of late Lochkovian to early Pragian, is associated with uplift and gentle folding (Thomas & Pogson, 2012, p. 27). It has also been suggested that the Bowning unconformity near Yass can be attributed to an extensional event associated with basin subsidence (Glen, 2005). Although the terms "Bowning" and "Bindian" have been used in the literature as synonyms (Gray, Foster, & Bucher, 1997), they have also been used to cover distinct events in the Darling Basin (Khalifa & Ward, 2009). Following VandenBerg et al. (2000), it is suggested that the term "Bindian Orogeny" be used rather than the "Bowning Orogeny". The Bindian Orogeny caused intense deformation in parts of northeastern Victoria and less intense deformation elsewhere, including parts of the Canberra Zone and the Tumut Trough (see below).

Darling and Cobar basins

Within much of the Darling Basin sedimentation was continuous throughout the latest Silurian to Early Devonian (Bembrick, 1997; Cooney & Mantaring, 2007; Khalifa & Ward, 2009; Neef, 2012) with only meagre evidence for compressional deformation associated with the Bindian Orogeny (Figure 4). Although few controls on age exist, fossils and U–Pb zircon ages from igneous rocks in the Mt Daubeny Formation in the Koonenberry Belt (Figure 2) indicate that the succession is late Silurian at its base with deposition presumably continuous into the Early Devonian (Greenfield, Gilmore, & Mills, 2010; Neef, 2012; Neef et al., 1989). The thick succession in the Mt Daubeny Formation is located along a concave to the west curved part of the Koonenberry Fault and is consistent with extensional development of either a dextral pull-apart basin (Greenfield et al., 2010; Neef & Bottrill, 1996) or a sag basin (Neef, 2012). The Mt Daubeny Formation is relatively strongly deformed although lacks cleavage (Neef, 2012). Deformation post-dated intrusion of sills and dykes with U–Pb zircon ages of 418–414 Ma (Greenfield et al., 2010; Mills, 2002). The timing of deformation has been considered constrained to the late Lochkovian–Pragian (Figure 4) on the basis that deformation was syn-depositional with the upper part of the succession (Neef, 2012). The deformation has been related to either dextral transpression (Greenfield et al., 2010) or partly attributed to sinistral movement along the Koonenberry Fault (Neef, 2012). This localised Early Devonian deformation has timing equivalent to the later part of the Bindian Orogeny (see Discussion); although it is possible that some or most of the contractional deformation was later in the Middle Devonian (Tabberabberan Orogeny).

East of the Darling Basin, the adjoining Cobar Basin formed in an extensional setting above an east-dipping ramp at depth that has been imaged on a deep seismic line (Drummond, Goleby, Wake-Dyster, Glen, & Palmer, 1992). The Cobar Basin was considered to have formed by extension in a NE–SW direction with syn-rift deposition including widespread deep-marine turbidites in the latest Silurian to late Lochkovian followed by a post-rift phrase with shaly deep-marine turbidite deposition in the Pragian (Glen, 1990, 1991, 2005; Glen, Dallmeyer, & Black, 1992). Reassessment of timing of events in the Cobar Basin, based on revisions of paleontological ages and new radiometric ages, has rifting and deposition of the lower Cobar Supergroup in the Pridoli to earliest Lochkovian (Downes et al., 2016) and includes both the rift and post-rift phases of Glen (1991). This was followed by shallow marine to fluvial deposition of the Winduck Group in the western part of the Cobar Basin in the Lochkovian to earliest Pragian, followed by deposition of the fluvial Mulga Downs Group in the Emsian to no younger than Eifelian (Downes et al., 2016). These revisions substantially modify our understanding of the tectonic history of the Lachlan Orogen in central NSW (Figure 4) and significantly change past correlations with the Darling Basin (Bembrick, 1997; Khalifa & Ward, 2009).

Melbourne Zone and western Victoria

In the Melbourne Zone (Figure 5), deposition was also continuous from the Silurian into the Early Devonian with no evidence of any deformation (VandenBerg et al., 2000). In western Victoria in the Stawell gold mine, late-stage thrust faulting reflecting NW–SE compression is thought to have occurred at 420–414 Ma constrained by a U–Pb zircon age of 413 ± 3 Ma on a late-stage quartz-feldspar porphyry dyke (Miller, Wilson, & Dugdale, 2006). This deformation is therefore of Bindian age. Farther west in the Grampians–Stavely Zone the probable Silurian Grampians Group overlies basement of the Delamerian Orogen but has a facies assemblage similar to that of the Winduck succession of the lower Darling Basin succession. The age and the timing of deformation of the Grampians Group are poorly constrained; both predate the unconformably overlying Rocklands Volcanics that have a U–Pb zircon age of 410 ± 3 Ma (Simpson & Woodfull, 1994; VandenBerg et al., 2000). The Grampians Group may possibly have been deformed in the Silurian to Early Devonian associated with either the Benambran Orogeny or the Bindian Orogeny (Cayley & Taylor, 1997). Thus evidence exists for Bindian deformation in western Victoria whereas previously it had been considered that no Bindian deformation occurred in western Victoria (Willman, VandenBerg, & Morand, 2002).

Eastern Victoria

The clearest effects of the Bindian Orogeny are recognised in northeastern Victoria in the Limestone Creek Graben, which consists of strongly folded and foliated upper Silurian metavolcanic and metasedimentary rocks (Enano Group) that have northeast trends (Table 1; Figure 3). They are truncated at a high-angle, angular unconformity by west-dipping sedimentary and volcanic rocks of the Lower Devonian Snowy River Volcanics and the overlying Buchan Group in the Bindi Syncline (Willman et al., 1999b). The Enano Group is affected by folding and faulting and contains several foliations consistent with intense shortening of the unit (Allen, 1992). In contrast, the Wombat Creek

Graben (Figure 6), west of the Limestone Creek Graben, has a NNW strike implying Bindian ENE–WSW shortening but with significantly less intensity than in the Limestone Creek Graben (Table 1).

In eastern Victoria, several major, northwest-trending strike-slip faults are developed within and adjacent to the Omeo Metamorphic Complex (Kiewa, Cassilis, and Ensay shear zones, Kancoona and Barmouth faults, Tallangatta Creek Fault Zone; Figure 3). Dextral strike-slip movements along these linked, mainly northwest-striking faults has been related to contractional deformation in the Limestone Creek and Wombat Creek graben in the Bindian Orogeny (Willman et al., 2002). These faults are associated with mylonite zones with shear sense criteria indicating dextral strike-slip shear and post-dating metamorphism in the Omeo Metamorphic Complex, which was related to the Benambran Orogeny (Morand & Gray, 1991; Morand et al., 2005; Willman et al., 1999b, 2002, 2005). Metamorphism in the Benambran Orogeny reached upper amphibolite facies with widespread development of migmatites (Morand, 1990), whereas the fault zones show greenschist facies assemblages with Ar/Ar ages of 413–403 Ma consistent with metamorphic cooling in and postdating the Bindian Orogeny (Figure 5) (Foster et al., 1999; Morand & Gray, 1991). Widely developed steep northeast to E–W-trending crenulation cleavages overprint Benambran foliation in the Omeo Metamorphic Complex and eastern Tabberabbera Zone, and are considered to have formed from N–S shortening associated with the Bindian Orogeny (Morand et al., 2005; Willman et al., 2005). Bindian refolding of Benambran folds in the region northwest of the Indi Fault has also been proposed (Willman et al., 2002).

Movement along the linked Bindian strike-slip fault system in the Omeo Metamorphic Complex has been inferred to have operated in conjunction with sinistral strike-slip along the Gilmore Fault in NSW (Morand & Gray, 1991; Willman et al., 2002). This has enabled SSE transport of a crustal block and formed the diverse structural trends in the upper Silurian graben. Regional magnetic surveys in western NSW show that these structures do not continue to the northwest (Hallet, Vassallo, Glen, & Webster, 2005), instead, they appear to merge into the eastern margin of the buried Hay–Booligal Zone under the Murray Basin (Figures 1, 2).

Southeast NSW

The tectonic development of the Tumut Trough has been controversial ever since the proposal that it was associated with a middle Silurian ophiolite suite emplaced along its eastern margin (Ashley, Brown, Franklin, Ray, & Scheibner, 1979). U–Pb zircon ages for the North Mooney Complex, the plutonic unit within the Coolac Ophiolite Suite, as well as samples of plagiogranite, leucogabbro and the Young Batholith, all fall within experimental error of each other in the range 431–427 Ma (Belousova et al., 2015; Bodorkos et al., 2013). This supports the earlier mid Silurian age of ophiolite emplacement. A ca 400 Ma age for the ophiolite suite was proposed based on U–Pb zircon ages from the rims of zircons from plagiogranites and a leucogabbro associated with ophiolitic units (Graham, Franklin, Marshall, Leitch, & Fanning, 1996), but are considered to reflect a younger event well after ophiolite emplacement (Belousova et al., 2015). Note that Fergusson (2010) supported the ca 400 Ma age for the ophiolite suite despite the shallow-marine deposition in the region at that time.

The Tumut region has a strong NNW-structural grain subparallel to the Gilmore Fault to the west and the Coolac Ophiolite Suite to the east. Within the region, Stuart-Smith, Hill, Rickard, and Etheridge (1992) showed that deformation in the Benambran Orogeny, involving formation of downward-facing folds, affects Ordovician and lower Silurian units. They also argued that an episode of Early Devonian ENE–WSW compression produced common tight to open folds and faults in all pre-upper

Lower Devonian units and post-dated the Gocup Granite with a U–Pb zircon age of 411 ± 5 Ma (Table 1; Stuart-Smith et al., 1992). Shortening associated with this deformation is relatively mild (Table 1) and is no doubt reflective of the massive, thick-bedded nature of the upper Silurian volcaniclastic succession in the Tumut region (Dadd, 1998). Deformation of the Silurian succession in the Tumut Trough has been considered Bindian, although the age constraints indicate a marginally younger timing than normal for the Bindian Orogeny (Figure 5).

South of Yass and southeast of the Tumut Trough, in the Brindabella and Tantangara region (Figure 2), Bindian deformation was recognised based on the Lower Devonian Mountain Creek Volcanics and equivalents that overlie, with an angular unconformity, the upper Silurian Cooleman Plains Group (Owen & Wyborn, 1979). From cross sections in Owen and Wyborn (1979), it is clear that the deformation involved tilting and upright gentle to locally tight folding, which may also explain the unconformity near Bowning (Thomas & Pogson, 2012). Foliation associated with more intense deformation locally affected the upper Silurian Paddys River Volcanics, some granites and the Ordovician turbidites, and reflects locally more intense Bindian deformation, which dies out eastwards to the south of Canberra (Owen & Wyborn, 1979).

In the Canberra Zone around Bungonia (Figure 2), folds and thrust faults affect the Middle to Upper Ordovician units and unconformably overly mid to upper Silurian Bungonia Group with considerable shortening (Table 1). The deformation has been constrained to the Early Devonian from the age of massive plutons of the Marulan Batholith, one of which has a U–Pb zircon age of 417 ± 5 Ma, although this age is considered too old as it conflicts with younger paleontological ages from units intruded by the plutons (Thomas & Pogson, 2012). Bindian deformation has also been recognised farther to the SSW along strike from the Bungonia region in the Araluen region (Figure 2). Here, upper Silurian units are affected by folding prior to intrusion of granites considered late Early Devonian, consistent with Bindian deformation (Powell, 1983; Wyborn & Owen, 1986). Distinguishing Bindian deformation from Benambran and younger deformations in the Canberra and Narooma zones is problematic in many areas.

Central NSW

Northwest of Forbes (Figures 2, 7), northwest-trending folds (mainly synclines) are developed along the Gilmore Fault Zone in the upper Silurian to lowest Devonian Kopyje Group of the Canbelego–Mineral Hill Volcanic Belt (Downes et al., 2016; MacRae & Pogson, 1985; Pogson 1991a, 1991b). To the southeast, these northwest-trending structures are truncated by an angular unconformity at the base of the overlying Lower Devonian Yarra Yarra Creek Group in the north-trending Murda Syncline (Downes et al., 2016; Sherwin, 1996). Thus, these northwest-trending folds formed in the Lower Devonian prior to deposition of the upper Lochkovian to Emsian Yarra Yarra Creek Group and can be considered part of the late Bindian Orogeny (see Discussion).

Tabberabberan Orogeny

The Tabberabberan Orogeny has traditionally been considered Middle Devonian shortening in the Lachlan Orogen with widespread effects accompanied by a major change from shallow- and deep-marine deposition to largely non-marine deposition (Cas, 1983; Gray et al., 1997; Scheibner & Basden, 1998, p. 188). It is argued herein that timing of the Tabberabberan Orogeny should be lengthened from the late Early to Middle Devonian, as deformation also occurred at ca 400 Ma (formation of the Currowong Syncline; Lyons, Raymond, & Duggan, 2000). In many areas constraints are too poor to distinguish this earlier deformation and the Tabberabberan Orogeny.

Victoria

The orogeny was named after Tabberabbera in eastern Victoria (Figures 1, 3) where in the Mitchell Syncline, Lower Devonian rocks are truncated by gently dipping Upper Devonian rocks above a high-angle angular unconformity (VandenBerg et al., 2000). The Mitchell Syncline is an isoclinal to tight structure with a steep, west-dipping axial plane (Table 2), and trends NNE, but swings to the SSE at its southern extremity (Fergusson & Gray, 1989). Two different explanations have been given for the tight folding that formed the Mitchell Syncline. Willman et al. (2005) argued that this syncline was localised by reactivation of the pre-existing Kalk Kalk Fault to form the Wentworth Fault on the eastern limb of the Wentworth Syncline. The Wentworth Fault is recognised from the absence of the conglomeratic Wild Horse Formation and development of strongly sheared rocks along the contact of the Devonian rocks with the underlying Ordovician turbidites (Willman et al., 2005). Alternatively, the Mitchell Syncline may have formed from shortening of a pre-existing half-graben succession, as shown by eastward thinning of the conglomeratic Wild Horse Formation (Fergusson & Gray, 1989). The adjacent underlying Ordovician succession, locally below the sub-Devonian unconformity has been refolded by the Tabberabberan deformation. East of the Wentworth Syncline, isoclinal to tight F_1 folds are folded from upright to recumbent as the unconformity is approached, whereas west of the syncline the Ordovician rocks have a zone with vertically plunging, refolded F_1 folds (Fergusson & Gray, 1989).

The Melbourne Zone is characterised by widespread development of Tabberabberan, mainly northerly to northwesterly upright, open to tight trending folds (Table 2). The Silurian–Devonian succession in the eastern Melbourne Zone consists of deep-marine turbidite successions that are folded about north to northwest-trending folds with increasing deformation eastwards, including multiple folding and foliation development, towards the Governor Fault (Gray, 1995; Murphy & Gray, 1992; VandenBerg, Willman, Hendrickx, Bush, & Sands, 1995; VandenBerg et al., 2006). In the western part of the zone, fold axial traces have sinuous patterns with trends swinging from NE to WNW indicative of refolding of northerly trending folds by late ENE folds (Figure 3). Timing of the Tabberabberan Orogeny in central and eastern Victoria has been questioned by Taylor (2006), who has argued that it occurred earlier than previously considered at ca 400 Ma. This timing is based on stratigraphic age constraints and U–Pb zircon ages of some cross-cutting plutons (Figure 5) including the Wilsons Promontory Granite (395 ± 4 Ma; Elburg, 1996) and the Bulla Granite (392 ± 5 Ma; Bierlein, Arne, Keay, & McNaughton, 2001). A maximum upper constraint in the eastern Melbourne Zone is provided by stratigraphically lowest fish faunas in the unconformably overlying Mt Howitt Province (Figure 5), which are considered mid to late Givetian (Cas et al., 2003).

The Buchan Rift has a syn-rift succession consisting of the upper Lochkovian to Pragian Snowy River Volcanics followed by post-rift shallow marine carbonate sedimentation of the Emsian Buchan Group (Glen, 2005; VandenBerg et al., 2000). In contrast to the Mitchell Syncline 70 km to the west, and the Boulder Flat Graben 65 km east (Table 2), the Buchan Rift has only weak to moderate deformation. Large parts of the Snowy River Volcanics have low to subhorizontal dips (Orth, VandenBerg, King, Nott, & Tickell, 1993; Orth, VandenBerg, Nott, & Simons, 1995), as is also true of other Lower Devonian volcanic units in northeastern Victoria north of Benambra (Figure 3) (VandenBerg, Hendrickx, Willman, Magart, & Simons, 1998a). Steeply dipping faults, such as the Emu Egg Fault, formed during rifting and have been reactivated in inversion (Gray & Gregory, 2003; Orth et al., 1995). The overlying Buchan Group shows 20–30% fold shortening along with reactivation of faults associated with rifting (Gray & Gregory, 2003). Some of the faults are northeast-trending and oblique to the main synclinorial axial trace and considered by Gray and Gregory (2003) to have been controlled by the structural grain in the underlying Ordovician succession.

Evidence of Tabberabberan deformation in the Stawell and Bendigo zones is restricted to a thrust fault in the Stawell gold mine post-dating contact metamorphism produced by the Early Devonian Stawell Granite and indicative of NE–SW compression (Miller et al., 2006; Phillips et al., 2012), and reactivation of the Mt William Fault along the eastern margin of the Bendigo Zone (VandenBerg et al., 2000).

Darling and Cobar basins

Field mapping of the lower part of the Darling Basin succession in the MacCullochs Range (Figure 2) has revealed local complicated dome and basin refold patterns with dominant ENE-trending folds, but with gentle interlimb angles, and are thought to have been produced by the Tabberabberan Orogeny (Neef, 2005, 2012). Structures attributed to the Tabberabberan Orogeny in the Koonenberry Belt (Table 2) include very gentle NNW-trending folds in the southwestern part and the gentle Menamurtee Anticline adjacent to the Koonenberry Fault (Neef, 2004, 2012; Neef & Larsen, 2003). Regional unconformity C in the Darling Basin (Figure 4) matches the younger part of the Tabberabberan Orogeny (Alder et al., 1998; Bembrick, 1997; Khalifa & Ward, 2009), although age control on its timing is poor.

The structure and tectonic history of the Cobar region (Table 2) has been presented in detail by Glen (1985, 1990) with modifications suggested by Downes et al. (2016). Extensional development of the Cobar Basin as a ramp basin (Drummond et al., 1992) was followed by a complex history of inversion involving ENE–WSW compression resulting in strong deformation along the eastern side of the basin. Multiple deformations have occurred with late NE–SW-trending folds overprinting early northwest-trending structures (Glen, 1985, 1990). The timing was determined from geochronology with regional shortening recognised at 400–395 Ma based on Ar/Ar, K/Ar and Rb/Sr ages on low-grade metamorphism (Glen et al., 1992). Revised paleontological ages and new radiometric ages have been interpreted by Downes et al. (2016) to show a late Tabberabberan timing for deformation in the Cobar Basin. This new work resolves one of the paradoxes of the deformation of the Cobar Basin. Deformation was interpreted at 400–395 Ma (Glen et al., 1992) yet no identifiable clastic wedge, associated with this shortening and uplift, was found in the Winduck and overlying Mulga Downs groups 40 km southwest of Cobar. The age of the Mulga Downs Group has been reassessed as Emsian to no younger than Eifelian (Downes et al., 2016), rather than upper Lower to Upper Devonian (Figure 4). Note that apart from local angular discordances across the Winduck–Mulga Downs groups' contact, these units are mostly conformable (Glen, 1982). The new paleontological age for the Mulga Downs Group does not completely rule out the possibility of deformation at 400–395 Ma in the Cobar Basin. The upper limit of deposition of the Mulga Downs Group is poorly constrained and it could have ceased in the Emsian allowing earlier deformation than that inferred by Downes et al. (2016).

In the Griffith region 275 km south of Cobar, the Cocoparra Group was considered Upper Devonian (Colquhoun, Meakin, & Cameron, 2005), but its age has also been reassessed as Emsian–Eifelian, similar to the Mulga Downs Group (Downes et al., 2016). As for the Cobar region, the major deformation has been included in the Tabberabberan Orogeny (Downes et al., 2016), although no upper limit to the timing of deformation has been established. Folds in the Griffith region have several fold trends (Table 3) and reactivation of early thrust faults has resulted in the development of footwall synclines (Colquhoun et al., 2005).

Central NSW

In the Forbes region (Figures 7, 8), the timing of formation of the Currowong Syncline is well constrained (Lyons et al., 2000; Packham, 2003). The Currowong Syncline is north-plunging, asymmetrical, with a near-vertical eastern limb and a gentle east-dipping western limb (Figure 9a) and formed by E–W shortening. The youngest unit in the syncline is the Carawandool Volcanics with a U–Pb zircon age of 404 ± 2 Ma (Lyons et al., 2000). Massive granitic intrusions with U–Pb zircon ages of 400 Ma and 395 Ma cut across the syncline (Figures 5, 8), giving an interval of ca 4 Ma for the deformation (Lyons et al., 2000). The succession and syncline are truncated by an angular unconformity at the base of the Upper Devonian Hervey Group in the NNE-trending Tullamore Syncline (Lyons, Raymond & Duggan, 2000). Formation of the Currowong Syncline is an example of the “Cobar deformation” (Scheibner & Basden, 1998, p. 188).

The geology of the Lachlan Orogen east and south of Parkes is important as it contains numerous unconformities and also has the intersection of two significant zones of deformation: the Coolac–Narromine Fault Zone and the Parkes Fault Zone (Figure 7; Lyons et al., 2000). Cycles of uplift are shown by unconformities in the Ordovician, mid Silurian, base of the upper Silurian–Lower Devonian Derriwong Group and base of the Upper Devonian Hervey Group (Figure 10) (Lyons et al., 2000; Simpson, Cas, & Arundell, 2005). The Parkes Thrust occurs at the boundary of cleaved rocks to the east and uncleaved to poorly cleaved rocks to the west (Meffre, Scott, Glen, & Squire, 2007). It occurs along the axial trace of a syncline, indicated by the map pattern and orientation of bedding within the mid Silurian Forbes Group (Figures 9b, 10). East of the Forbes Group in a region of generally poor exposure are mapped equivalents of the Cotton Formation, various volcanic units and farther east, the Kirribilli Formation. The structure of the Parkes Fault Zone has been portrayed as numerous, steeply west-dipping fault slivers of these various units (Meffre et al., 2007; Raymond et al., 2000a). The Kirribilli Formation is multiply deformed with downward facing folds and three cleavages and has been thrust eastwards over the Parkes Syncline during reactivation in the Kanimblan Orogeny (Meffre et al., 2007; Raymond et al., 2000a). It is likely that some Tabberabberan deformation has affected the Parkes Fault Zone synchronously with formation of the Currowong Syncline (Lyons et al., 2000).

East and southeastern of the Cobar Basin, Tabberabberan deformation may also have affected widespread upper Silurian to Devonian successions that have open to gentle, upright, folds with northwest, north and northeast trends (Figure 7; Table 2). The Murda Syncline is an open, upright structure with a pinched synclinal hinge in the west, but to the east has a wide, flat, central limb, with a steeper section dipping 40–60° to the west along the eastern side of the structure (Sherwin, 1996). Northwest of the Murda Syncline, the Yarra Yarra Creek Syncline, containing the Yarra Yarra Creek Group, is northwest-trending with a steeply dipping southwestern limb (MacRae & Pogson, 1985; Pogson 1991a, 1991b). Farther east, this fold trend curves to E–W perpendicular to the Murda Syncline (Figure 7). This is indicative of “banana-bending” style refolding (Hood & Durney, 2002). Paradoxically, no refolding is apparent in the map patterns of the underlying Kopyje and Derriwong groups (see Discussion). No upper limit to the deformation in the Murda and Yarra Yarra Creek synclines has been established, so it is possible that these structures were either partly or wholly formed by Kanimblan deformation.

Northeastern Lachlan Orogen

The roles of the Tabberabberan versus the Kanimblan orogenies have been debated for the northeastern Lachlan Orogen. The problem has been to resolve the extent of Tabberabberan deformation, particularly in the northern Hill End Trough succession with Packham (1999, 2003) arguing for a Tabberabberan timing of inversion. Widespread Tabberabberan deformation is argued for the Goulburn region (Figure 11), where tight folding and cleavage development predated deposition of the Upper Devonian Lambie Group in the Cookbundoon Syncline (Thomas & Pogson, 2012; Thomas et al., 2013a, 2013b). Disoriented cleaved clasts occur in the Cowpers Creek Conglomerate along the western side of the Cookbundoon Syncline and indicate erosion of uplifted cleaved rocks to the west and southwest in the Middle Devonian (Powell & Fergusson, 1979). A high-angle angular unconformity has been mapped between the Upper Devonian and underlying units (Powell & Fergusson, 1979; Thomas & Pogson, 2012); the youngest unit involved in the pre-Late Devonian folding is the lower Emsian Lake Bathurst Limestone Member (Table 2) (Thomas & Pogson, 2012). Thus the deformation is constrained to the late Early Devonian to Late Devonian. Units such as the Tarago Conglomerate, at the base of the Mulwaree Group in the Braidwood region (Felton & Huleatt, 1977; Fitzherbert et al., 2011), and the Bullamalita Conglomerate (413–412 Ma), at the base of the Bindook Complex in the Goulburn region, indicate Early Devonian uplift that preceded the main phase of folding (Thomas & Pogson, 2012).

Abundant fault zones and shear zones have been mapped in Ordovician–Silurian rocks east of Yass and Cowra (Thomas & Pogson, 2012). Shear zones in the Wyangala Batholith, 25 km southeast of Cowra, have Ar/Ar plateau ages of 380–360 Ma that were considered broadly overlapping with the Tabberabberan Orogeny (Forster, Lister & Lennox, 2014; Lennox, Forster, & Williams, 2014). A range of Ar/Ar ages on hydrothermal activity and metamorphism has been determined for greenschist metamorphic facies rocks in the Hill End Trough north of the Bathurst (360–340 Ma; Foster et al., 1999; Lu, Seccombe, Foster, & Andrew, 1996). These were interpreted as reflecting Middle Devonian deformation and metamorphic cooling by Packham (1999), but considered indicative of several events, dominantly Kanimblan deformation and metamorphism, by Durney and Hood (2003).

Northeast of Bathurst, a Middle Devonian thrust system with Ordovician Sofala Volcanics and Adaminaby Group in the hanging wall have been interpreted as thrust to the southwest over Silurian and Devonian units of the Hill End Trough succession (Glen & Watkins, 1999). A north-trending thrust, dipping gently to the west, with Sofala Volcanics in the hanging wall and upper Silurian Chesleigh Formation in the footwall, was documented by Rowley (in Glen & Watkins, 1999). This thrust fault was folded by E–W-trending folds, which had also been documented in the Sofala Volcanics along the unconformity at the base of the Upper Devonian succession (Powell, Gilfillan, & Henry, 1978) and farther east in rocks now mapped as part of the Adaminaby Group (Fergusson, 1979; Watkins et al., 1997). Middle Devonian thrusting was also reported by Glen and Watkins (1999) from the mapping of Scott et al. (1999) north of Orange along the western margin of the Hill End Trough.

In the northeastern Lachlan Orogen, along the western side of the Hill End Trough, Upper Devonian units in the north have a low-angle unconformity with the underlying upper Lower Devonian rocks, such as the Garra Formation (Powell & Edgecombe, 1978), which is mostly found west of the Upper

Devonian units. In contrast, east of the Upper Devonian rocks, the basal Upper Devonian unconformity is developed upon mainly Ordovician Macquarie Arc rocks, consistent with pre-Late Devonian deformation (Glen & Watkins, 1999). East of the Hill End Trough, as found west of it, the size of the angular discordance across the Upper Devonian basal unconformity increases southwards, consistent with increasing Middle Devonian deformation southwards (Powell & Edgecombe, 1978; Powell & Fergusson, 1979).

Southeastern NSW

In southeastern NSW, a conjugate set of strike-slip faults have developed related to E–W shortening in the Middle Devonian (Lewis, Glen, Pratt, & Clarke, 1994). It is possible that some of these structures developed earlier in association with emplacement of plutons of the Early Devonian Bega Batholith (Fergusson, 2010). Reactivation of strike-slip faults, such as sinistral strike-slip offset along the Kancoona Fault resulting in displacement of the Early Devonian Yackandandah Granite, may also have occurred in the Tabberabberan Orogeny (Sandiford, Martin, & Lohe, 1988; VandenBerg et al., 2000).

Northeastern Tasmania

The Eastern Tasmanian Terrane is part of the Lachlan Orogen as it consists of an Ordovician to Devonian quartzose turbidite succession (Mathinna Supergroup) intruded by plutons of the Early to Late Devonian Blue Tier Batholith (Black, McClenaghan, Korsch, Everard, & Foudoulis, 2005; Seymour et al., 2014). It has been considered comparable to the Melbourne Zone (Powell, Baillie, Conaghan, & Turner, 1993), but Seymour et al. (2014) have highlighted difficulties in making correlations with Victorian zones. In comparison, the Western Tasmanian Terrane has a connection with the Melbourne Zone as is shown by magnetic anomalies mapped across Bass Strait (Cayley et al., 2002). The Mathinna Supergroup is divided into the Ordovician Tippogoree Group, characterised by turbidites with stripy cleavage in sandstones and a zone of recumbent isoclinal folds, and the upper Silurian to Lower Devonian Panama Group with east-vergent, steeply inclined, upright folds (Calver, Baillie, Banks, & Seymour, 2014; Reed, 2001; Seymour et al., 2014). The contact has been considered an unconformity by Reed (2001), but is now recognised as a fault (Calver et al., 2014). The timing of deformation has been debated with a consensus emerging that the western Tippogoree Group was affected by Benambran deformation, followed by Middle Devonian thrusting to the west (Reed, 2001; Seymour et al., 2014). In contrast, the Panama Group was affected by the Tabberabberan Orogeny, which also produced foliation in older plutons of the Blue Tier Batholith, giving a tight 390–388 Ma age on the timing of deformation (Black et al., 2005). Megakinking is thought to have resulted in rotation of the main structural trends and was correlated with Carboniferous megakinking in southeastern NSW (Goscombe, Finlay, McClenaghan, & Everard, 1994), although the changes in structural trends have also been related to forceful emplacement of plutons (Seymour et al., 2014).

Kanimblan Orogeny

In this section emphasis is placed on the deformation as recorded in the Upper Devonian successions across NSW and far eastern Victoria along with the Upper Devonian to Lower Carboniferous rocks of the Mt Howitt Province in central–eastern Victoria (Figures 1, 3, 12). In pre-Upper Devonian rocks the extent of the Kanimblan Orogeny is generally difficult to establish and in some areas of the Lachlan Orogen, such as the Yass region and northeastern Lachlan Orogen north of Bathurst, disputed (Durney & Hood, 2003; Glen & Watkins, 1999; Hood & Durney, 2002; Packham, 1999, 2003; Powell et al., 1977). Structures in Upper Devonian rocks are mainly synclines typically with northerly trends, although some structures are developed at a high-angle to north (Figure 13). Major thrust faults occur mainly along the western sides of some synclines with the most spectacular example being the Springdale Fault shown by a deep seismic line south of Forbes (Figures 9c, 13; Glen et al., 2002). Values of shortening determined for cross sections are given in Table 3 and plotted in Figure 13. These shortening values are consistent with previous claims that the northeastern Lachlan Orogen was most strongly affected by the Kanimblan Orogeny (Gray & Foster, 2004; Gray et al., 1997; Powell, 1984a), although it is clear that the values of shortening vary within regions as well as across the orogen.

Central Victoria–Mt Howitt Province

The Mt Howitt Province of central Victoria consists of a northwest-trending set of three major basins with generally internal, gentle northwest folds (Cas et al., 2003; VandenBerg et al., 2000). Overall shortening is low (9–15%) with regional low-angle dips apart from adjacent to bounding faults. Several unconformities occur in the Mansfield Basin and reflect reverse faulting and compressional folding interrupting Late Devonian deposition with development of the partly fault-bound Jamieson Syncline (O’Halloran & Cas, 1995; VandenBerg et al., 1995, 2006). The Barkly Thrust, along the southwestern side of the Macalister Syncline, has the largest displacement of all the bounding faults in the Mt Howitt Province, with Cambrian rocks in the hanging wall offset as much as 2 km over the Devonian succession, with a footwall syncline adjacent to the fault (VandenBerg et al., 2000).

The Mt Howitt Province has been interpreted as a graben affected by a component of sinistral shear related to the development of “syn-sedimentary”, NNE-trending anticlines between the basinal structures (Powell, 1984a). In contrast, Cas et al. (2003) related the history of the Mt Howitt Province to episodes of extension and compression accompanying sedimentation that may have involved some oblique movement. They interpreted the Mt Howitt Province as a successor basin formed in an intermontane setting, rather than an inverted rift with a shear component.

Eastern Victoria–southeastern NSW

In eastern Victoria west and southwest of the Genoa River area, the Combyingbar Formation forms three apparently en échelon synclines each with a north to NNE trend (Figures 12, 13). In contrast, in adjacent southeastern NSW no such en échelon patterns are apparent and the Upper Devonian succession probably formed part of a widespread sheet now preserved in numerous erosional remnants (Figure 12). The three synclinal remnants in eastern Victoria, and the Combyingbar Formation in the Genoa River area (Figure 12), are generally gently dipping successions with upturned to locally overturned dips adjacent to steep bounding faults, such as the Combienbar Fault adjacent to the Combienbar Syncline (Simpson, Fergusson, & Oranskaia, 1997). In southeastern NSW, Rixon, Bucknell and Rickard (1983) documented north-trending structures in the Upper Devonian sedimentary successions north and south of Eden and found many monoclinal and box folds (“mega kink folds”) related to E–W compression (Table 3). They suggested that these structures probably were controlled by reverse slip on underlying basement faults and that the deformation reflected a relatively thin sedimentary succession overlying basement.

The Budawang Synclinorium (Figure 13), in contrast to other Upper Devonian units in the southeastern Lachlan Orogen, shows shortening of ~20–40% achieved by upright, open-tight folds (Table 3) (Cooper, 1992; Powell, 1983). A somewhat different interpretation of the Budawang

Synclinorium was given by Glen and Lewis (1990), who depicted prominent boundary thrusts and common box-fold geometries, in addition to common upright folds along the surface parts of their cross sections. The synclinorium contains a relatively thick sedimentary succession reaching 3000 m northwest of Batemans Bay (Powell, 1983) and this may have accommodated greater shortening by internal folding compared to other Upper Devonian units where thinner successions overlie granite and multiply deformed Ordovician metasedimentary successions.

Northeastern Lachlan Orogen

The highest values of shortening in the Upper Devonian units of the Lachlan Orogen occur in its northeastern part (Figure 13). They are more intensely deformed than those in southeastern NSW and Victoria (Meakin & Morgan, 1999; Powell & Edgecombe, 1978; Pogson & Watkins, 1998; Powell et al., 1977). Tight, upright folds in the Upper Devonian units are well developed along the western side of the Hill End Trough on the Molong High, with shortening decreasing southwards (Figure 13; Table 3). Along the eastern side of the Hill End Trough, the Upper Devonian units display areas with tight folding, with a western, steeply dipping to overturned limb along synclines such as the Mt Dulabree Syncline and the Cookbundoon Syncline (Powell & Fergusson, 1979; Powell et al., 1977). Elsewhere, open to gentle, upright folds are developed and include a zone of abundant faults in the southeastern part of the Mt Frome Syncline southeast of Mudgee (Figure 13; Glen & Watkins, 1999). Overturning of western limbs of some Kanimblan synclines is associated with west-dipping thrust faults as in the Mt Dulabree and Cookbundoon synclines (Fergusson & VandenBerg, 1990; Thomas & Pogson, 2012). East of Goulburn, the Yarralaw Fault, a Tabberabberan thrust, was reactivated in the Kanimblan resulting in overturned Silurian rocks being thrust over Upper Devonian gently west-dipping rocks (Thomas & Pogson, 2012).

Central West NSW

Kanimblan shortening has resulted in the development of open folds and formation of west-dipping thrusts, including reactivation of earlier fault zones such as the eastern part of the Parkes Fault Zone (Table 3; Figures 7–10). An example of this structural style is the Parkes Syncline (Figures 9b, 10), which has a partially fault-bounded, steeply east-dipping, western limb that is faulted against the Ordovician–(?)Silurian Kirribilli Formation. The eastern limb is steeply west-dipping in the north, but dips moderately to gently west in the south (see figure 5 in Powell, Fergusson, & Williams, 1980). The structure of the southern Parkes Syncline is akin to that of a fault-propagation fold (Suppe, 1985), and consistent with reactivation of a thrust fault in the eastern part of the Parkes Fault Zone. To the east, the Bumberry Syncline also has a structure indicative of a fault-propagation fold with a long, gently, east-dipping, western limb and a short, steeply dipping to overturned, northeastern limb (Raymond et al., 2000a). A thrust fault is located on the northeastern side of the Bumberry Syncline and dips to the northeast (Figure 7); it has minimal offset with Middle Devonian volcanics thrust over the Upper Devonian succession in the Bumberry Syncline (Raymond et al., 2000a).

Farther east is the Mandagery Syncline (Figure 7), which is associated with a long belt of folded Upper Devonian rocks, with local tight folds and well-developed axial planar cleavage (Lyons et al., 2000). The Mandagery Syncline has two parts, a northwest-trending northwestern segment that is oblique to the NNE-trending structures farther south and has been interpreted in different ways. One interpretation is that the northwest-trending segment is an early structure that is refolded by the NNE-trending folds as shown on the Molong 1:100 000 geological map (Krynen, Morgan, Scott, Raymond, & Warren, 1997). Alternatively, it has been argued that the northwest-trending syncline is a late structure that has refolded the NNE-trending folds and has been correlated with the sequence of multiple deformation in the Taemas Bridge area, 20 km southwest of Yass (Durney & Hood, 2003; Hood & Durney, 2002).

Significant Kanimblan thrust faults have been identified by seismic reflection profiles including the Marsden Thrust along the western side of the gentle Tullamore Syncline and the Springdale Fault along the western side of an unexposed, ~10°W-dipping succession that has been interpreted as Upper Devonian Hervey Group (Glen et al., 2002). The significance of the well-rounded, gentle antiform in the hanging wall of the Springdale Fault is uncertain (Figure 9c); it is geometrically similar to a ramp anticline but the listric shape of the underlying fault is inconsistent with it being a ramp anticline. Instead the fold may be either a weak fault-propagation fold or an inverted roll-over anticline. In seismic line 99AGS-L1, the Marsden Thrust was recognised as a composite structure with thrust faults and steeply dipping faults interpreted as a strike-slip flower structure (Glen et al., 2002). This seismic line crosses the unexposed Marsden Thrust in a northwest-trending segment, in contrast to the mainly NNE trend of this structure. Thus, the strike-slip component may reflect some sinistral strike-slip movement along this northwest-trending part of the fault caused during E–W compression.

An angular unconformity within the Upper Devonian succession has been proposed along the northeastern limb of the Tullamore Syncline (Figure 7). This is based on a reassessment of the age of the Wallingalair Group from late Early Devonian to probable Late Devonian, although this reassessment is from a fossil fish fauna collected from only one site (Young, 2006). An unconformity was previously mapped between overlying Upper Devonian Hervey Group and underlying Wallingalair Group, which elsewhere is considered late Early Devonian (Sherwin, 1996). The significance and extent of this unconformity can only be evaluated by reassessment of the paleontological ages of the Wallingalair Group; the reassessed age is problematic given that farther south the Wallingalair Group is mapped along strike with the Trundle Group, which has a late Early Devonian age in the Currowong Syncline (see above).

The least deformed Upper Devonian rocks in the central west are in the Weddin Mountains, 60 km south of Forbes (Figures 12, 13), where strata dip ~10° southwest and are very gently folded about a northwest-trending, upright syncline (Raymond & Wallace, 2000). This contrasts with the open-tight folds developed in Upper Devonian rocks elsewhere in the region.

Darling Basin and Koonenberry Belt

The Darling Basin extends from the Cobar region west to the Broken Hill Block and is dominated by weakly to locally moderately deformed rocks. Seismic profiles in the basin show very gentle anticlines and synclines, with major troughs and basement highs. Over much of the basin dips are generally <5° (see seismic profiles in Khalifa, 2009; Khalifa & Ward, 2009; note that these profiles are vertically exaggerated). Thus, most of the Kanimblan deformation in the Darling Basin (Table 3) reflects low shortening with very gentle, upright folds and steeply dipping faults (Khalifa & Ward, 2009). Deformation appears locally enhanced along major faults including the Koonenberry Fault (Greenfield et al., 2010; Neef, 2012). Steeper dips also occur along the boundary faults of the Bancannia Trough, although it is possible that part of this deformation reflects downwarping associated with extensional development and weak inversion during the Kanimblan Orogeny (see cross sections in figure 3 in Neef, Bottrill & Ritchie, 1995). Basin development and deformation in the

Darling Basin has been related by Neef (2005, 2012) to reactivations of a conjugate system of strike-slip faulting along the Koonenberry Fault and the unexposed Darling River Lineament.

Discussion

Orogenies – timing and duration

The orogenic history of the Lachlan Orogen has been episodic with pulses including the Benambran, Bindian, Tabberabberan and Kanimblan (Gray et al., 1997). Given the short duration of these pulses, a longer interval of orogeny embracing all of them called the "Lachlan Orogeny" has been suggested (Cas, 1983; Collins, 2002a). In contrast, Glen (2005) adopted a cyclical approach and identified a Lachlan supercycle that was subdivided into Benambran, Tabberabberan and Kanimblan cycles. These cycles are synonymous with the three major paleogeographic realms identified for the Lachlan Orogen with a Cambrian–early Silurian oceanic realm, followed by a mid Silurian–mid Devonian mixed realm with deep marine troughs, shallow marine shelves, fluvial deposition, and widespread igneous activity, and followed by a Late Devonian dominantly fluvial realm (Cas, 1983; Powell, 1984a; Scheibner & Basden, 1998). The role of extension has been emphasised especially in the first two realms/cycles with widespread rift basins and primitive mafic igneous activity indicative of thin lithosphere (Collins, 2002a; Glen, 2005). The simple idea of a long-lived "Lachlan Orogeny" as an all-embracing term is difficult to apply in the context of these changing paleogeographic realms and their differing tectonic settings. However, as discussed below, it is clear that deformation and sedimentation must have overlapped during the Devonian in the Bindian and Tabberabberan, and Carboniferous Kanimblan orogenic episodes. Timing and duration of each of these orogenic pulses is a subject of continuing debate as more information is acquired.

The Bindian Orogeny is the least widely recognised of these three orogenic pulses and is most significantly developed in northeastern Victoria and adjacent parts of NSW (Figure 14). In the Limestone Creek Graben, the age of the succession is probably Ludlovian with possible Pridolian (VandenBerg et al., 2000), and in the Yass region, upper Silurian units are conformable with an overlying lowermost Devonian unit below the unconformity (Thomas & Pogson, 2012). Most upper Silurian units in northeastern Victoria and southeastern NSW are only broadly constrained in age and a general lower limit for the Bindian Orogeny is ca 420 Ma (Figure 5). An upper limit to the deformation age is also imprecise as typically the units immediately above the unconformity lack fossils, but a U–Pb zircon age from the Snowy River Volcanics of 411 ± 3 Ma (Morand & Fanning, 2009) provides a reasonable constraint. Note that in the Yass–Goulburn region, numerous U–Pb zircon ages have been determined on volcanic units, but these ages are typically too old in comparison with well-established paleontological ages and are thought to reflect zircon inheritance (Thomas & Pogson, 2012). Limestone successions above the Lower Devonian volcanic successions have late Pragian to early Emsian ages (Thomas & Pogson, 2012; VandenBerg et al., 2000) giving a definitive upper limit of ca 410 Ma. Cooling ages from fault rocks associated with the Bindian Orogeny in the southern Wagga–Omeo Zone between 413 and 403 Ma (Foster et al., 1999) are consistent with cooling postdating uplift. In the Tumut Trough, the 411 ± 5 Ma age for the Gocup Granite provides a maximum age for Bindian deformation (Stuart-Smith et al., 1992) and indicates possible variation in timing of the orogeny. Overall, timing is generally limited to a 10 Ma interval at 420–410 Ma, but includes deformation along the Gilmore Fault in central NSW that predates deposition of the Yarra Yarra Creek Group (ca 410 Ma) and marginally later in the Tumut Trough (Figure 5).

Timing of the Tabberabberan Orogeny has been regarded as Middle Devonian, although consideration of the “Cobar deformation” requires a reassessment. The difficulty of determining the duration of regional deformation events is well illustrated by the Melbourne Zone (Figure 5). Throughout much of this zone the succession is Silurian to Lower Devonian and the youngest unit affected by the deformation, the Cathedral Group, lacks fossils and the most reliably dated widespread unit is the Wilson Creek Shale that straddles the Pragian–Emsian boundary (VandenBerg, 2003). It was argued that the deformation occurred at ca 400 Ma on the basis of the lowest constraint provided by the minimum age of folded rocks and upper constraints provided by cross-cutting plutons (Taylor, 2006). The problem with this argument is that these plutons occur in the far west and south of the zone (Figures 1, 3) and it is implied, but not stated in Taylor (2006), that the deformation must have been synchronous throughout the zone. This assumption is not considered justified given that in many zones of active deformation, for example in fold-thrust belts, over time deformation migrates into adjacent basins consistent with the bulldozer model of thrusting and wedge development (Davis, Suppe, & Dahlen, 1983; Konstantinovskaia & Malavieille, 2005). For much of the eastern part of the Melbourne Zone the duration of the deformation is no more accurately constrained than 400–385 Ma.

Timing of the Tabberabberan Orogeny has to be reconciled with the “Cobar deformation” named for a pulse of shortening in NSW at ca 400 Ma (Scheibner & Basden, 1998) and established for the Currowong Syncline (Figure 5). However, for much of the Melbourne Zone, and also the Wentworth Syncline at Tabberabbera, the Tabberabberan Orogeny encompasses the timing of the Cobar deformation as well as the widely accepted Middle Devonian duration. The most reliable constraint on timing, as pointed out by Packham (2003), is from the Currowong Syncline, where the deformation was at ca 400 Ma within the late Early Devonian (Figures 5, 8). Thus, the Tabberabberan Orogeny is considered to encompass a longer interval (405–380 Ma) than generally discussed (Figure 5). In the Goulburn region, and elsewhere in the eastern Lachlan Orogen, the timing of initiation of the Tabberabberan Orogeny is only broadly constrained as post ca 405 Ma and pre-Late Devonian (Figure 5). Conglomeratic wedges developed prior to this in the Goulburn region indicate even earlier deformation/uplift (Thomas & Pogson, 2012). Ar/Ar ages for the Wyangala Batholith of 380–360 Ma (Foster et al., 2014; Lennox et al., 2014) are younger than the Tabberabberan Orogeny and are synchronous with sedimentation of the Upper Devonian succession. It is unclear if these either represent cooling ages developed after, but associated with the Tabberabberan Orogeny, as argued by Packham (1999) for Ar/Ar ages in the northern Hill End Trough, or if deformation and uplift occurred during Late Devonian sedimentation as in the Mt Howitt Province in east–central Victoria. Conglomeratic wedges thinning to the north occur in the upper Lower to Middle Devonian Mulga Downs and Cocoparra groups and indicate sources to the south with detritus derived from uplifted and deformed regions (Figure 15), including a northern continuation of the Melbourne Zone (Colquhoun et al., 2005; Downes et al., 2016; Glen, Powell, & Khaiami, 1987; Powell, 1984a). A conglomeratic unit at the base of the Upper Devonian succession containing abundant cleaved clasts occurs in the western limb of the Cookbundoon Syncline north of Goulburn (Powell & Fergusson, 1979) and indicates derivation from a neighbouring Tabberabberan uplift to the west.

Timing and duration of the Kanimblan Orogeny is poorly constrained given the lesser abundance of paleontological age control in Upper Devonian units and much less developed igneous activity in the Late Devonian. In the Mt Howitt Province (Figures 3, 13), unconformities in the Mansfield Basin indicate contractional deformation in the Late Devonian synchronous with sedimentation (O’Halloran & Cas, 1995; VandenBerg et al., 2000). The succession in the Mt Howitt Province continues into the

Lower Carboniferous based on fossil fish faunas (Cas et al., 2003) indicating a Carboniferous age (post ca 350 Ma) for the weak terminal folding. In the Darling Basin, generally weak deformation postdated deposition of the Ravendale Formation and stronger deformation has affected Upper Devonian units to the east in the Lachlan Orogen, which are all considered no younger than Late Devonian (Bembrick, 1997; Meakin & Morgan, 1999; Pogson & Watkins, 1998). Conglomeratic wedges are developed in the higher parts of the Upper Devonian succession along the western and eastern margins of the Hill End Trough. Paleocurrents in these units indicate derivation from an uplifted Hill End Trough (Meakin & Morgan, 1999; Pogson & Watkins, 1998; Powell, 1984a). Thus the Hill End Trough formed an upthrust block in the latest Devonian (Powell, 1984a, figure 222) and indicates initiation of Kanimblan deformation in this region (Figure 16). Clast types are mainly lithic to quartz sandstones consistent with derivation from the Hill End Trough, but no cleaved clasts have been reported (Meakin & Morgan, 1999; Pogson & Watkins, 1998). The most reliable upper constraint for the termination of the Kanimblan Orogeny is provided by Carboniferous plutons that cut across Upper Devonian rocks and younger structures in the northeastern Lachlan Orogen. Most of these plutons have U–Pb zircon ages of 326–314 Ma, with two older ages at 358 ± 5 Ma and 341 ±3 Ma for relatively small plutons (Bodorkos et al., 2010; Meakin & Morgan, 1999). This indicates a duration of 360–330 Ma, although, as noted above for deformation in the Melbourne Zone, pinning down the timing of deformation should not rely on an assumption of synchronous regional deformation.

The most controversial aspect of timing in the Lachlan Orogen relates to the extent of Tabberabberan versus Kanimblan deformation in the Hill End Trough and southwards into the Yass–Goulburn region. Local conformity between Upper and Lower Devonian units in the northeastern Lachlan Orogen has been demonstrated by Powell and Edgecombe (1978), but there are still many places where Upper Devonian rocks unconformably overlie older successions, non-conformably overlie granites, and locally faults are truncated at the unconformity (Glen & Watkins, 1999; Packham, 2003). Nevertheless, the general conformity of structural trends, style and cleavage development found in rocks either side of the unconformity at the base of the Upper Devonian, indicate that most regional folds in the northern Hill End Trough probably have a significant Kanimblan component. How these Kanimblan structures relate to Tabberabberan structures developed in the Goulburn region to the south is not known. Southwest of Yass the Emsian–Eifelian Hatchery Creek succession is conformable on the underlying Lower Devonian limestone indicating deformation is post-Eifelian. Multiple deformation affected the Lower Devonian succession 20 km southwest of Yass in the Taemas–Cavan area and was considered Kanimblan given that structural trends are similar to those in Upper Devonian rocks 65 km to the NNW (Hood & Durney, 2002; Durney & Hood, 2003). In contrast, the timing of regional deformation for the Yass succession has been considered to be partly or wholly Tabberabberan (Packham, 2003; Thomas & Pogson, 2012).

Structural styles

Structural styles in the Lachlan Orogen are widely variable and dependent on the ductility of the rock units being affected, their prior deformation history and the amount of strain associated with each deformation event. Widespread folding with associated axial planar foliation development is recognised in many areas along with common multiple deformation. Thrust and strike-slip faulting is also widespread with the application of principles of thin-skinned tectonics and the development of fold-thrust belts to parts of the Lachlan Orogen (Glen, 1992). The approach in this account has been to determine the extent and style of structures based mainly on the ages of rocks where timing constraints for deformations can be reasonably determined.

Basin inversion and structural inheritance

The significance of structural control and inheritance provided by early rift structures in subsequent contractional deformation is widely recognised (McClay, 1995). Well documented examples of inverted rift basins in orogenic belts include the Cretaceous Salta Rift in the Eastern Cordillera of the Andes in northwestern Argentina (Monaldi, Salfity, & Kley, 2008) and inverted rift basins in the Atlas Mountains of Morocco (Beauchamp, 2004). In the latter example, superposed folding is associated with inversion across a prominent transfer fault, caused by shortening of a rifted basin formed prior to opening of the North Atlantic Ocean. In the central and eastern Lachlan Orogen, cycles of rifting and post-rift phase thermal subsidence are evident in Silurian to Devonian volcanic and sedimentary successions (Figure 5) (Glen, 2005). Identification of rift-related structures in the Lachlan Orogen has been more difficult given the structural complexity and many regions of incomplete exposure, but nevertheless early normal faults subsequently reactivated in contraction have been recognised including faults in the Buchan Rift (Gray & Gregory, 2003).

In northeastern Victoria, the Wombat Creek and Limestone Creek graben are considered inverted rifts (Willman et al., 2002). Strong deformation has overprinted the Limestone Creek Graben and pre-existing extensional structures are not identified. In contrast, contractional deformation of the Wombat Creek graben is much weaker. The Wombat Creek Graben is bounded to the east and north by a curving fault that has formed a down-dropped block, typical of a piston-cylinder mechanism for formation of caldera structures. Additionally, the succession is mostly southwest-dipping with only weak cleavage development indicative of weak inversion. Inversion has possibly overprinted earlier bed rotation by formation of a rollover anticline along a listric fault active during NE–SW extension and subsequently reactivated as the reverse Newlands Fault (Figure 6). In the Buchan region, early normal faults associated with the formation of the Buchan Rift have been reactivated in the later contractional deformation (Gray & Gregory, 2003; Orth et al., 1993, 1995).

The structural pattern in the Forbes region is also suggestive of structural control provided by early rift structures. The Canbelego–Mineral Hill belt of upper Silurian to lowest Devonian volcanic and sedimentary rocks is mainly preserved in synclines that are northwest-trending and developed east of the Rookery Fault at Cobar, but adjacent to the Gilmore Fault Zone (Figures 2, 7). The association of sedimentary and volcanic rocks is consistent with rifting (Glen, Clare, & Spencer, 1996). Subsequent inversion in the Lower Devonian resulted in northwest-trending, tight to open, upright folds (Table 1), but the succession is affected by low-strain at the outcrop scale with only weak cleavage development (Downes et al., 2016). The mid to upper Lower Devonian Yarra Yarra Creek Group unconformably overlies these inferred inverted rifts but the deformation in the younger unit has not affected the underlying structures, at least at the map-scale (Figure 7). Farther south, in the Currowong Syncline, the thick Carawandool Volcanics are also consistent with formation of a north-trending rift (the Jemalong Trough of Lyons et al., 2000) that was inverted in the Tabberabberan Orogeny at ca 400 Ma.

Rifting has not been recognised in the Silurian–Devonian Melbourne Trough, which has formed in a foreland setting to the eastern Lachlan Orogen (Powell et al., 2003). A strong pre-existing structural control is evident for deformation in the eastern Melbourne Zone. Structural trends in the adjoining Tabberabbera Zone are dominantly northwesterly in the northern part of the zone and change from northwest to generally E–W in the southern part of the zone (Figure 3) (Willman et al., 2002). The Governor Fault and the dominant structural grain of the Tabberabbera Zone seem to have controlled structural trends that formed in the younger deformation in the eastern Melbourne Zone to the west (Figure 3). Note that the structural trends in the Melbourne Zone are more N–S in the southeastern part of the zone adjacent to the southern Tabberabbera Zone where the structural grain is more generally E–W. This pattern seems to have been repeated for the Carboniferous deformation as is evident for structural trends along the western margin of the Mt Howitt Province (Figures 3, 13). In contrast, the Mitchell Syncline to the north of Tabberabbera is NNE-trending and strongly oblique to the Benambran structural grain in the Tabberabbera Zone and the Tabberabberan structural grain in the eastern Melbourne Zone (Figure 3). It has also been suggested that the northeastern trends in the part of the inverted Buchan Rift were structurally controlled by the underlying Yalmy–McLaughlin Fault (Gray & Gregory, 2003).

Contraction and strike-slip faults

All three orogenies discussed in this review reflect at least localised shortening, but the Bindian event is also associated with significant strike-slip faulting associated with SSE movement of the Wagga–Omeo Zone (Fergusson, 2010; Morand & Gray, 1991; Willman et al., 2002). Formation of depocentres in the Darling Basin accompanied SSE movement of the Wagga–Omeo Zone that accounts for intense deformation of the Limestone Creek Graben (Figure 14). Additionally, contractional deformation in the Canbelego–Mineral Hill Volcanic Belt, Tumut Trough and the Brindabella–Tantangara region all seems related to movement of this block with shortening reflecting deformation partitioning associated with transpressional deformation along the Gilmore Fault. It is well established that deformation partitioning along strike-slip faults can result in contractional deformation approximately perpendicular to the fault (Teyssier, Tikoff, & Markley, 1995). Possible deformation of the Mt Daubeny Formation in the Bindian Orogeny may also reflect this mechanism with dextral transpression resulting in inversion (Greenfield et al., 2010). It has also been suggested that sinistral movement along the Olepoloko Fault allowed opening of depocentres in the Darling Basin (Glen et al., 1996). It is less clear why E–W shortening on the NSW South Coast in the Bindian Orogeny occurred synchronously with sedimentation in the deep-marine, extensional Hill End Trough and Wollondilly–Ngunawal Basin (Figure 14). Overall, the pattern of deformation associated with the Bindian Orogeny is enigmatic; escape tectonics with SSE movement of a major block within the central and western Lachlan Orogen is difficult to understand in a broader extensional-compressional backarc setting (see below). The association of extensional and contractional zones is a feature of the Indian–Asian collision zone with tectonic escape (strike-slip faults), major zones of contractional deformation and zones of extension, including Lake Baikal (Yin, 2010). It is also possible that the SSE movement of the Wagga–Omeo Zone in the Bindian Orogeny reflects extrusion caused by the interaction of E–W shortening and the eastward projection of the Broken Hill Block, as has been inferred from analogue modelling of the Benambran Orogeny by Burton (2010).

In the Tabberabberan Orogeny the structural trends vary but overall are aligned approximately N–S (Figure 15) consistent with E–W shortening. In the Melbourne Zone the structural trends are considered controlled by the pre-existing structural grain in the adjoining Tabberabbera Zone and are less evident in the western part of the Melbourne Zone, where structures are more north-trending, apart from in zones of multiple deformation (Table 2). Cross sections and mid-crustal magnetic anomalies are consistent with a décollement developed at depths of 10–15 km below the eastern part of the Melbourne Zone (McLean, Morand, & Cayley, 2010; VandenBerg et al., 2006). Thin-skinned deformation is also evident in the Cobar Basin with seismic lines interpreted as indicating décollement at depths of 3–6 km (Glen, Drummond, Goleby, Palmer, & Wake-Dyster, 1994). In southeast NSW and eastern Victoria, a conjugate set of strike-slip faults reflected E–W shortening with some faults, such as the Kancoona Fault, reactivated from earlier events (Fergusson, 2010; Glen, 1992, 2005).

Conglomeratic-lithic sandstone units occur high in the stratigraphy of the Cocoparra and Mulga Downs groups with paleocurrents indicating derivation from the south and east (Figure 15) and indicate sources within the Lachlan Orogen including Ordovician to Devonian rocks. These sources were most likely uplifted in the earlier part of the Tabberabberan Orogeny and considered by Powell (1984a, figure 212) as reflecting a major source in southeastern NSW and adjacent Victoria. The Mailman Gap Member in the upper Cocoparra Group, now considered Lower to Middle Devonian (Downes et al., 2016), contains a small percentage of cleaved clasts in addition to dominant quartzite and vein quartz clasts indicative of a source from uplifted deformed Ordovician–Silurian rocks (Colquhoun et al., 2005). This source was most likely a northern continuation of the Tabberabbera Zone (Figure 15). The easterly source documented by Powell, Khaiami, and Scheibner (1987), in addition to the southern source, reflects Tabberabberan uplifts to the east such as in the Currowong Syncline and possibly the Parkes Fault Zone.

East–W shortening has also applied to the Kanimblan Orogeny with the deformation dying out to the southwest and west (Gray et al., 1997; Powell, 1984a). The Darling Basin has only been mildly deformed, apart from along the Koonenberry Fault, where localised deformation is more intense and along the margins of the Bancannia Trough (Neef, 2012). As has been pointed out by numerous researchers, the role of thrusting is significant with many footwall synclines developed adjacent to Kanimblan thrusts (Colquhoun et al., 2005; Glen, 1992, 2005) indicating development of these folds as fault-propagation structures ahead of advancing thrust tips. Thrusting over such a wide zone must reflect the development of out-of-sequence thrusts as suggested by Glen (2005) and has been well demonstrated in the intracontinental Yanshan belt of the North China Craton (Li, Zhang, Cope, & Lin, 2016). Most thrusts are west-dipping following the pattern in the Tabberabberan Orogeny with a dominant east vergence. This pattern is distinctive compared to many fold-thrust belts in convergent margin settings that verge away from, rather than towards, the site of the convergent margin. As in fold-thrust belts, sedimentation was synchronous with deformation as shown by unconformities developed in the Mt Howitt Province, Ar/Ar ages indicating cooling during the Late Devonian (Forster et al., 2014; Lennox et al., 2014) and uplift evident during deposition of the higher parts of the Upper Devonian succession either side of the Hill End Trough (Figure 16) (Meakin & Morgan, 1999; Pogson & Watkins, 1998).

Multiple deformation and folding of unconformable successions

Multiple deformation is widely documented in the Lachlan Orogen (e.g. Glen, 1990; Hood & Durney, 2002; Powell, 1983; Powell et al., 1985). Multiple deformations have been related to a single orogenic event as for example in the Melbourne Zone, where dome-and basin interference folds patterns and late overprinting cleavage occur in the northern part of the zone (Gray & Mortimer, 1996; Morand, Hughes, & Jones, 1997). For the South Coast of NSW, Powell (1983) recognised deformation associated with each of the orogenic episodes including the Benambran Orogeny. The last of these deformations is mega-kinking with earlier structures being reoriented as a result of N–S shortening supposedly in the Carboniferous (Powell et al., 1985). This is a controversial topic given that late swings in structures have been widely recognised across the orogen and vary in style from the kink folds documented on the NSW South Coast to more rounded, overprinting late folds referred to as ‘banana” bending (Type 2 interference fold patterns of Ramsay, 1967) by Hood and Durney (2002). These late folds are evident in the Melbourne Zone where they are considered part of the Tabberabberan deformation (Morand et al., 1997). A complicated structural succession, with four deformations that formed in contractional to contractional/strike-slip regimes was documented in a very detailed study of the Taemas Bridge area, 25 km southwest of Yass (Hood & Durney, 2002). The affected rocks consist of the Lower Devonian Murrumbidgee Group and these rocks are sensitive strain indicators that have responded to complex patterns of stress changes.

Folding of unconformable successions has been documented at various places throughout the Lachlan Orogen (e.g. Tabberabbera; Fergusson & Gray, 1989), and these sites are critical for allocating structures to particular orogenic events, as for example in the Forbes region (Figure 7). At Tabberabbera, a particular style of folding of the unconformity has occurred with refolding of the underlying folds immediately below the unconformity that is not recognised away from the unconformity. A similar pattern with early folds in Ordovician turbidites refolded to a recumbent orientation adjacent to the folded unconformity at the base of the Devonian Merrimbula Group was also documented adjacent to the southern Budawang Synclinorium (C. McA. Powell, G. J. McDermott, & M. J. Readford, unpublished data). In contrast, in the Forbes region, map-scale folds, such as the Currowong Syncline, and underlying obliquely trending Canbelego–Mineral Hill Volcanic Belt, appear not to have been affected by folding of unconformably overlying successions.

In another style of folding of unconformable successions, early folds are reactivated, rather than refolded, during deformation and control the style and orientation of cover folds, with examples from the Cantabrian Zone of northern Spain (Alonso, 1989). One example of this style is where a cover synform is found above a basement synform. This occurs at Goulburn, where the Upper Devonian succession occupies several fold hinges that have overall synformal geometry (the Cookbundoon Syncline) and unconformably overlies an overall synformal structure in the underlying basement Ordovician to Devonian succession (Figure 12). This relationship would seem to reflect reactivation of the basement synform by a tangential longitudinal strain mechanism during the deformation that affected both cover and basement (Alonso, 1989, figure 16).

These differences in fold styles associated with folding the overlying unconformable succession may be largely a reflection of scale. Smaller wavelength folds in the Ordovician turbidites, as at Tabberabbera and the southern Budawang Synclinorium have been refolded. Whereas larger wavelength structures, as at Goulburn, have been reactivated rather than refolded.

Oroclines and orogeny

Identification of a major orocline linking Cambrian, Ordovician and Lower Silurian units of the Bendigo, Tabberabbera and Canberra zones, has been related to the dextral strike-slip system of linked faults and shear zones in northeastern Victoria (Cayley, 2012; Moresi et al., 2014; Musgrave, 2015). This analysis is a major reinterpretation of structures in the Lachlan Orogen with major implications, but a full explanation has yet to be given in the literature. These oroclines were considered unlikely by Glen (2013) given their linking of the Bendigo and Tabberabbera zones. They were discussed by Packham and Hubble (2016) and considered incompatible with the tectonic setting for the Silurian–Devonian history of the Lachlan Orogen, amongst other issues.

There are, however, two issues that are resolved by recognition of a double orocline. Firstly, mapped structural trends in combination with magnetic trends do suggest some sort of cryptic linking of units between the Bendigo and Tabberabbera zones around the northern Melbourne Zone and at least crudely support the link of the southeastern Tabberabbera Zone to the Canberra Zone, although the critical hinge region is covered by the Buchan Rift (Cayley, 2012). It should be noted that the structural pattern north of the Melbourne Zone is complex as the Stawell Zone seems to terminate along the Bootheragandra Fault (Figure 1). Secondly, patterns of boninite and tholeiitic metabasalts in the Cambrian greenstone belts bordering the Melbourne Zone are mirrored. In parts of the Heathcote Greenstone Belt, boninites are east of backarc basin tholeiitic basalts, whereas east of the Melbourne Zone in the Howqua River belt the boninites are southwest of the tholeiitic metabasalts (Crawford, 1988; Spaggiari, Gray, & Foster, 2004). This pattern can be accounted for by linking the Bendigo and Tabberabbera zones in the proposed orocline of Cayley (2012). A similar pattern is evident from the South Coast of NSW, where boninites of inferred Cambrian age have been dredged from the continental slope (Packham & Hubble, 2016), whereas backarc basalts have been found in coastal exposures at Melville Point (Stokes, Fergusson, & Offler, 2015). Thus, the Cambrian boninitic volcanic rocks seem to form a marker horizon that can be traced around the inferred oroclines. The geometry of the oroclines is incompletely known as significant parts of them are not exposed such as to the north of the Melbourne Zone, in parts of eastern Victoria and southwards into Bass Strait.

South-southeast movement of the Wagga–Omeo Zone with associated strike-slip faulting and contractional deformation along the Gilmore Fault Zone, and in the Limestone Creek Graben, is consistent with formation of the double orocline in the southern Lachlan Orogen, as a result of collision of the VandieLand continental fragment with the active Gondwana margin (Moresi et al., 2014). Rollback north of the collision zone certainly is also consistent with basin formation in the Darling Basin and Lachlan Orogen, but how this relates to contractional deformation along the NSW South Coast in the Bindian Orogeny is uncertain. The Cayley (2012) model certainly provides a potentially viable explanation of the contentious three subduction zone model as well as the position and possible movement of the Wagga–Omeo Zone. A complete explanation of the geometry of the double oroclines and their development through the Silurian and Devonian has yet to be published so their full significance and implications are considered a topic of future work.

Plate tectonic setting

The plate tectonic setting for the Lachlan Orogen in the Silurian to Carboniferous is divided into an earlier late Silurian to early Late Devonian phase and a younger phase associated with tectonic development of the New England Orogen. In the late Late Devonian to Early Carboniferous, the tectonic setting of the Lachlan Orogen was a backarc behind the New England arc–backarc system that continued to develop as an east-facing continental margin arc (Glen, 2013; Offler & Murray, 2011). In contrast, the tectonic setting for the late Silurian to early Late Devonian history of the Lachlan Orogen is less straightforward. The difficulty is that although a general arc-backarc setting is widely interpreted for the Lachlan Orogen in this interval (Collins, 2002a, 2002b; Fergusson, 2010; Glen, 2005, 2013; Scheibner & Veevers, 2000; VandenBerg, 2003), the actual site of the magmatic arc is rarely nominated. It has been argued that most of the S-type and I-type granites of Silurian–Devonian age in the Lachlan Orogen, apart from the small Marulan Batholith around Bungonia, have a magmatic affinity inconsistent with a convergent margin setting (Chappell et al., 2000).

In the late Silurian to Middle Devonian, a magmatic arc associated with a west-dipping subduction zone may have been associated with igneous rocks in the eastern Lachlan Orogen, such as the Bega Batholith and volcanic rocks that are abundant in the northeastern Lachlan Orogen. The Quialigo

Volcanics south of Goulburn, and other volcanic units in the northeastern Lachlan Orogen, have an arc to backarc magmatic affinity (Thomas & Simpson in Thomas & Pogson, 2012, p. 1170, figure 185). The Capertee and Molong highs that bound the Hill End Trough, are associated with abundant mafic to silicic volcanism, and can be interpreted as an intra-arc rifted basin, analogous to the Havre Trough north of the Taupo volcanic zone (Cas & Jones, 1979). In the late Silurian to Middle Devonian, an alternative tectonic interpretation is that the Lachlan Orogen was an extensional–contractional backarc and that the magmatic arc lay farther east. One possible reason for the lack of a magmatic arc is that it could have been lost during rapid tectonic erosion along an east-dipping subduction zone. Rapid tectonic erosion is happening today in the forearc of the Central American subduction zone and is also a common process in many other active subduction zones (Meschede, Zweigel, & Keifer, 1999; Stern, 2011).

The interplay of extensional and contractional deformation in a backarc to arc setting for the Lachlan Orogen was reviewed by Fergusson (2010) in some detail. It was concluded that the back and forth changes from extension to contraction reflected a delicate balance between overriding plate advance and retreat with respect to the trench. Additionally, geometrical control of plate widths and distances to plate edges are considered to control extensional as opposed to contractional deformation (Schellart, 2008; Schellart, Stegman, Farrington, Freeman, & Moresi, 2010). It is not considered that topographic features on the underthrusting plate play any more than a local role in controlling magmatic gaps and uplift within the forearc, but do not cause major deformation in the backarc as claimed by Collins (2002b).

Conclusions

The orogenic history of the Lachlan Orogen in the latest Silurian to Early Carboniferous contains three major episodes of orogenic shortening. The first episode was the Bindian Orogeny (including the Bowning Orogeny) and had a 10 million year duration at 420–410 Ma with some later deformation in the Tumut Trough. Deformation in the Bindian Orogeny was associated with transport of the Wagga–Omeo Zone to the SSE with accompanying contractional deformation related to block margins and shortening in the eastern part of the orogen. This deformation was synchronous with thick deposition in the Darling Basin, Hill End Trough and Wollondilly–Ngunawal Basin. The tectonic pattern of the Bindian Orogeny is unclear and it may have been associated with formation of a double orocline (Cayley, 2012). In contrast, the late Early to Middle Devonian Tabberabberan Orogeny was controlled by E–W shortening with structural trends reflecting pre-existing structures such as rifted basins and earlier formed contractional structural trends in basement, as is well illustrated by the structure of the eastern Melbourne Zone and the adjacent Mitchell Syncline in the Tabberabbera Zone. The Kanimblan Orogeny reflects the same general E–W shortening reinvigorated in the Late Devonian to Early Carboniferous. Orogeny has occurred over longer intervals than generally considered for the Tabberabberan and Kanimblan events as indicated by conglomeratic wedges and Ar/Ar ages.

The tectonic setting of these orogenic events reflects a general arc–backarc setting although the location of the arc remains unresolved, apart from in the late Late Devonian when it was clearly the magmatic arc associated with the New England Orogen. The primary control is considered to be plate motions at a convergent margin with episodes of rollback especially in the late Silurian and mid-Lower Devonian controlling extensional basin formation interspersed with overriding plate advance in the earliest Devonian and late Early Devonian to Early Carboniferous.

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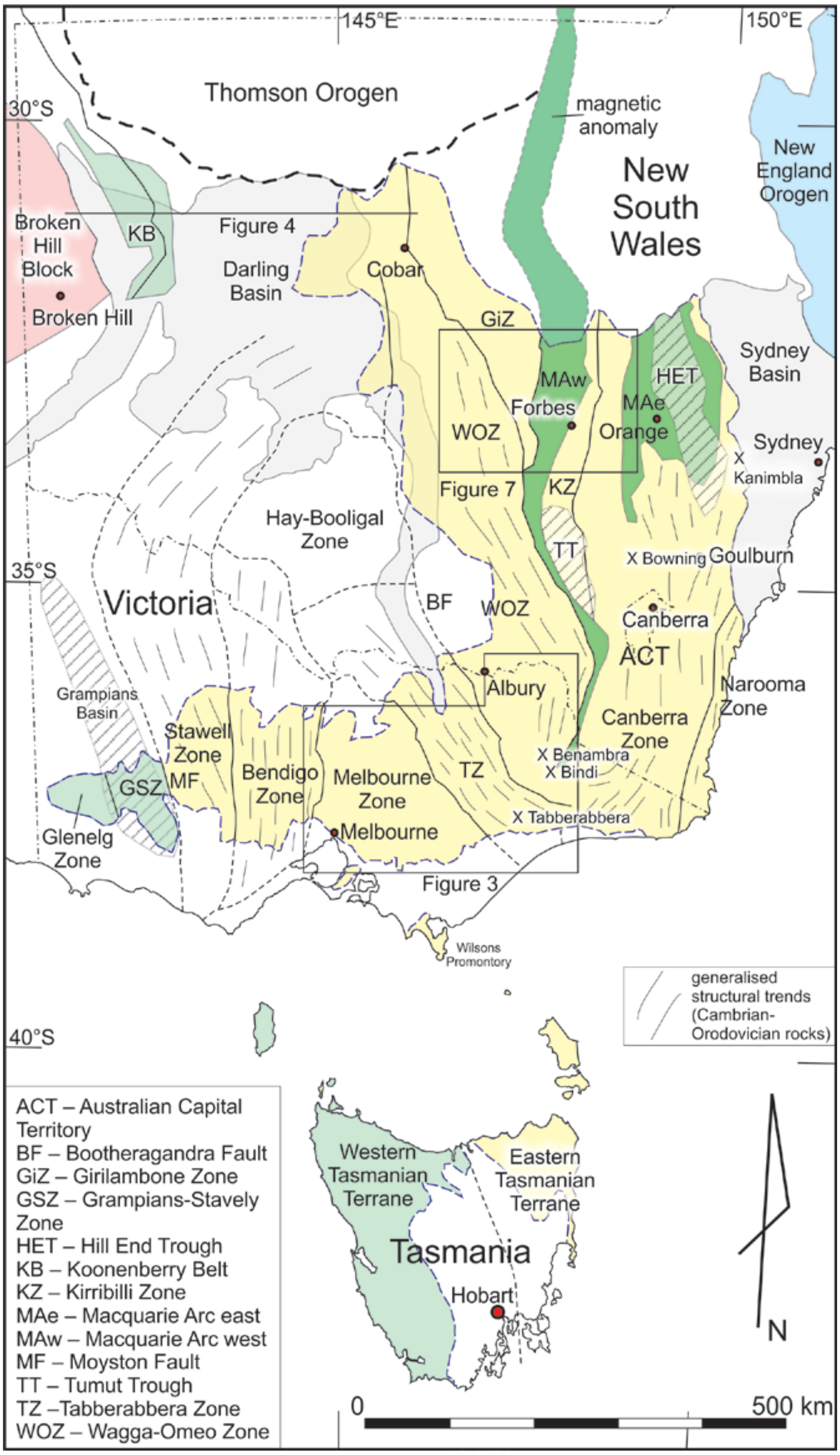

Figure 1. Map of southeastern Australia showing the main zones of the Lachlan Orogen (pale yellow), with the Macquarie Arc (dark green), and the Delamerian Orogen (pale green). Generalised structural trends are shown for Cambrian–Ordovician rocks and are based on orientations of exposed structures and magnetic data. They illustrate the proposed double orocline in Victoria and southern NSW (Cayley, 2012; Musgrave, 2015). Crosses show locations of critical localities in the Lachlan Orogen for which the main orogenies are named after.

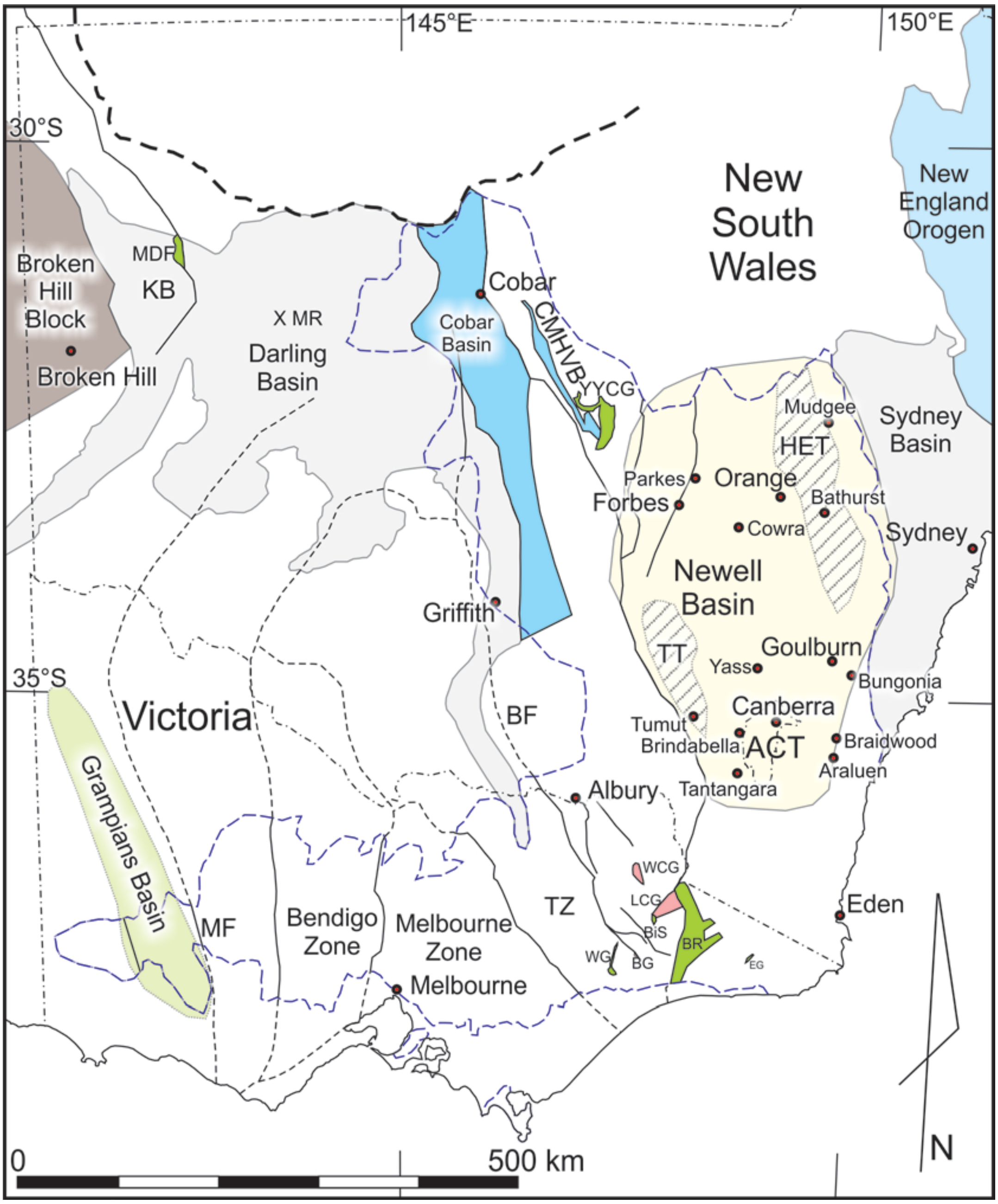

Figure 2. Map showing the main late Silurian to Middle Devonian sedimentary basins and significant structures in the Lachlan Orogen. Note that the extent of these basins reflects main areas of known deposition and most would have extended well beyond the boundaries given here. Abbreviations: ACT, Australian Capital Territory; BG, Barmouth Group; BF, Bootheragandra Fault; BiS, Bindi Syncline; BR, Buchan Rift; CMHVB, Canbelego–Mineral Hill Volcanic Belt; EG, Errinundra Group; HET, Hill End Trough; LCG, Limestone Creek Graben; MDF, Mt Daubeny Formation; MR, MacCullochs Range; WCG, Wombat Creek Graben; TT, Tumut Trough; WG, Wentworth Group; YYCG, Yarra Yarra Creek Group.

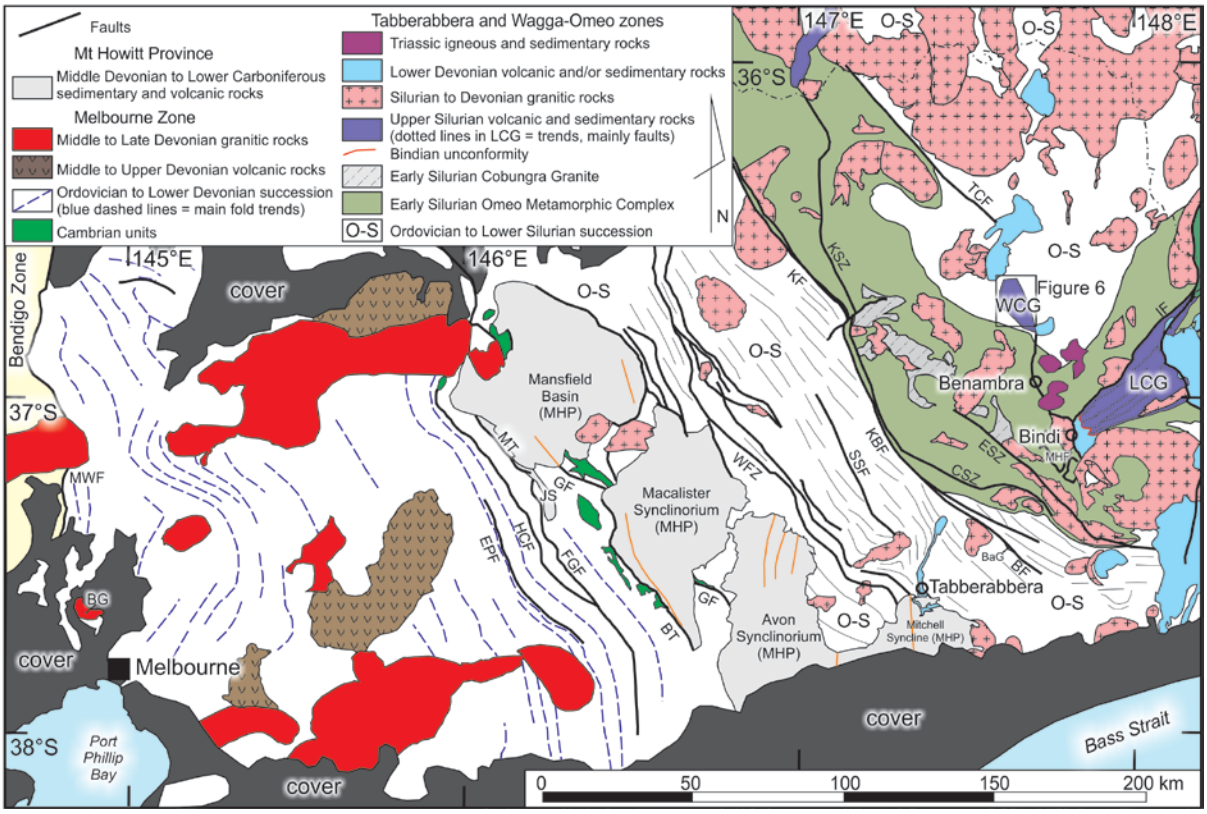

Figure 3. Map of the Lachlan Orogen in part of central and eastern Victoria showing the principal structures in the Melbourne Zone, Tabberabbera Zone (main trends of folds/cleavage shown as faint lines), and Wagga–Omeo Zone. See Figure 1 for location. Abbreviations: BF, Barmouth Fault; BaG, Barmouth Group; BG, Bulla Granite; BT, Barkly Thrust; CSZ, Cassilis Shear Zone; ESZ, Ensay Shear Zone; EPF, Enoch Point Fault; FGF, Fiddlers Green Fault; GF, Governor Fault; HCF, Howes Creek Fault; IF, Indi Fault; JS, Jamieson Syncline; KF, Kancoona Fault; KBF, Kiewa-Barmouth Fault; KSZ, Kiewa Shear Zone; LCG, Limestone Creek Graben; MHF, Mount Hopeless Fault; MHP, Mt Howitt Province; MT, Mansfield Thrust; MWF, Mount William Fault; SSF, Sawmill Spur Fault; TCF, Tallangatta Creek Fault; WCG, Wombat Creek Graben; WFZ, Wonnangatta Fault Zone.

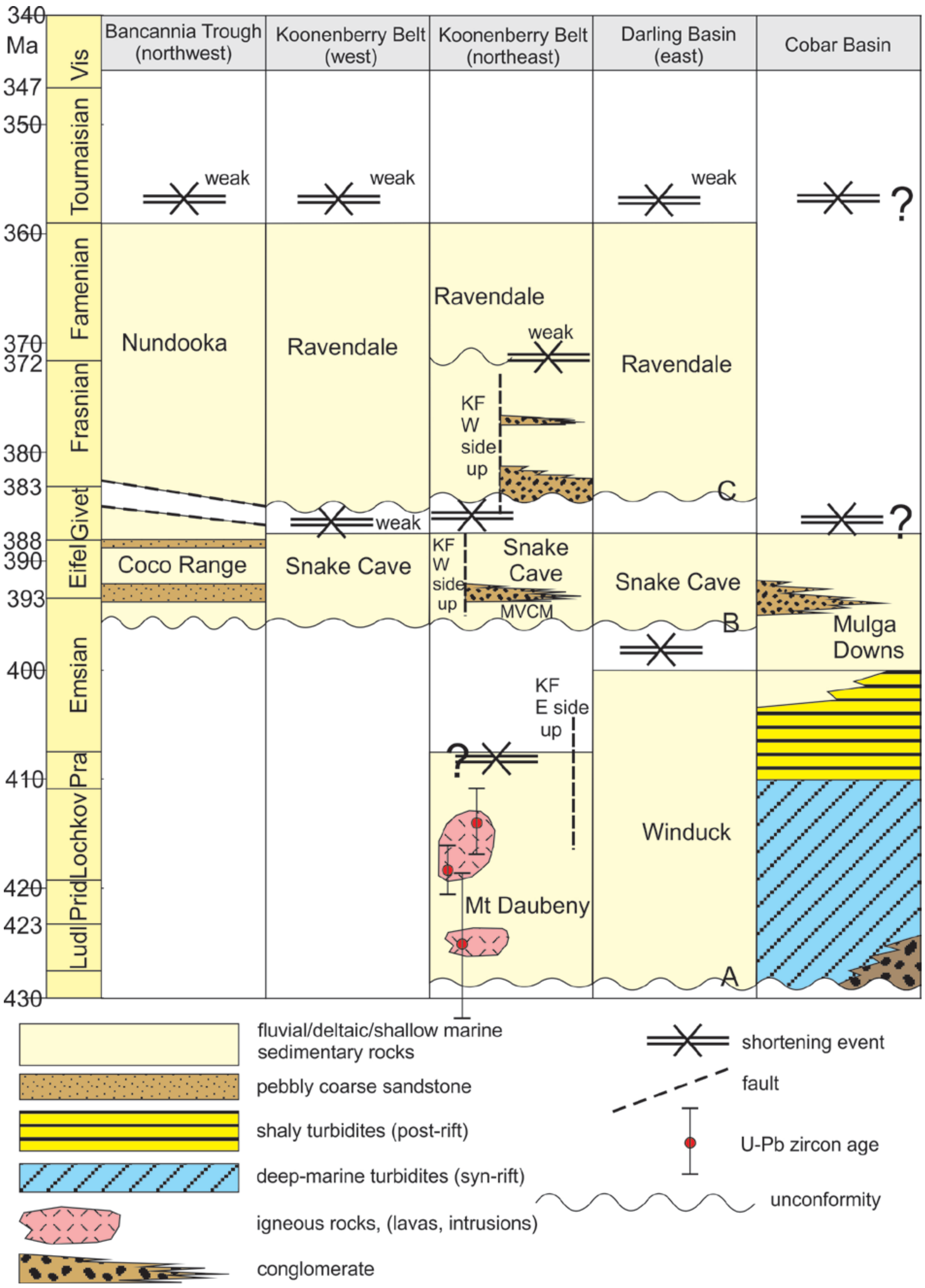

Figure 4. Time–space diagram across the Darling Basin from the Bancannia Trough eastwards to the Cobar Basin compiled from numerous sources (Alder et al., 1998; Bembrick, 1997; Downes et al., 2016; Greenfield et al., 2010; Khalifa & Ward, 2009; Neef, 2012). U–Pb zircon ages for igneous rocks in the Mt Daubeny Formation are 425 ± 7 Ma for the lower volcanic unit, and 418 ± 2 Ma and 414 ± 3

Ma for upper intrusive igneous rocks (Greenfield et al., 2010). Unconformities A, B, and C are widely recognised in the Darling Basin (Bembrick, 1997; Khalifa & Ward, 2009). Note that the lack of Upper Devonian units in the Cobar Basin reflects the revision of the age of the Mulga Downs Group by Downes et al. (2016). See Figure 1 for location of this transect. Abbreviation: KF, Koonenberry Fault.

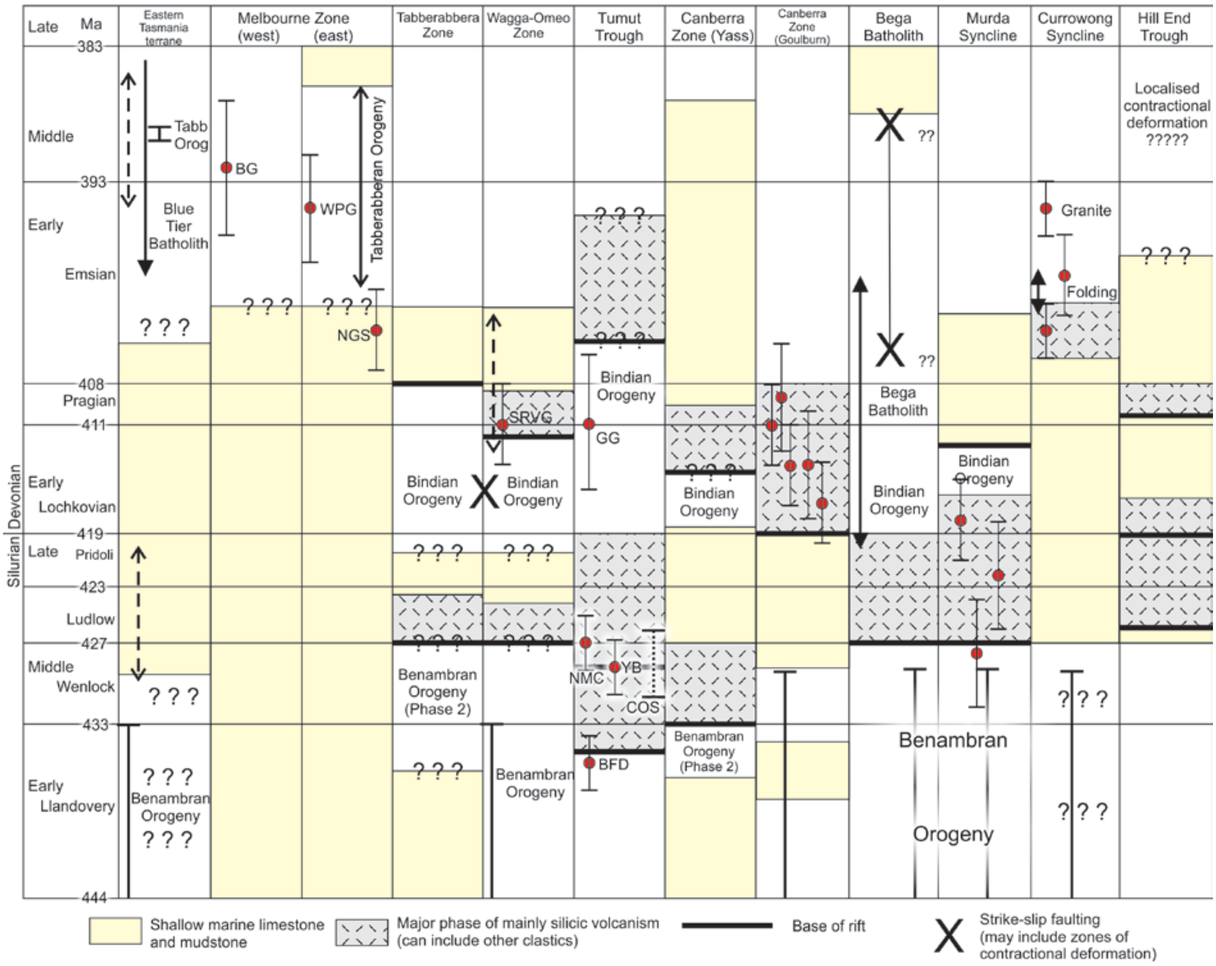

Figure 5. Time–space diagram showing timing of deformation in the Bindian and Tabberabberan orogenies for numerous zones and areas in the Silurian to Middle Devonian. Sources of radiometric data (unless specified ages are U–Pb zircon ages): (1) Eastern Tasmanian Terrane, Ar/Ar ages (430–420 Ma and 395–385 Ma) from Bierlein, Foster, Gray, and Davidson (2005) and ages of the Blue Tier Batholith (400–374 Ma) and Tabberabberan Orogeny (390–389 Ma) from Black et al. (2005); (2) Melbourne Zone, an age for a tuff in the Nortons Gully Sandstone (NGS) near the top of the succession 404 ± 3 Ma (Morand & Fanning, 2006), 392 ± 5 Ma for the Bulla Granite (BG) from Bierlein et al. (2001) and 395 ± 4 Ma for the Wilsons Promontory Granite (WPG) (Elburg, 1996); (3) Wagga–Omeo and Buchan zones, Ar/Ar ages of 413–403 Ma (Foster et al., 1999), an age of 411 ± 3 Ma for the basal Snowy River Volcanic Group (SRVG) (Morand & Fanning, 2009);, (4) Tumut Trough, 436 ± 2 Ma for the Blacks Flat Diorite (BFD) and 427 ± 2 Ma for the North Mooney Complex (NMC) (Bodorkos et al., 2013), Coolac Ophiolite Suite (COS) with ages in the range 431–427 Ma (Belousouva et al., 2015; Bodorkos et al., 2013), 429 ± 2 Ma for the Young Batholith (YB) (Lyons et al., 2000), 411 ± 5 Ma for the Gocup Granite (GG) (Stuart-Smith et al., 1992); (5) Canberra Zone, paleontological ages for the Yass succession are preferred over U–Pb zircon ages which are typically too old (Thomas & Pogson, 2012), U–Pb zircons ages for igneous rocks east and south of Goulburn include 417 ± 3 for a pluton in the Marulan Batholith, 414 ± 4 Ma for the Gundary Volcanics, 414 ± 3Ma, 411 ± 3 Ma, and 409 ± 4 Ma for units in the Quialigo Volcanics, and 414 ± 3 Ma for the Barallier Ignimbrite (Black,

2005, 2006; Thomas & Pogson, 2012; Wilde, 2002); (6) Murda Syncline in the southern Girilambone Zone, Mineral Hill Volcanics 428 ± 4, 422 ± 4, and 418 ± 3 Ma (Downes et al., 2016); and (7) Currowong Syncline, 404 ± 2 Ma for the Carawandool Volcanics and ages of 395 ± 2 Ma and 400 ± 3 Ma for plutonic rocks (Lyons et al., 2000).

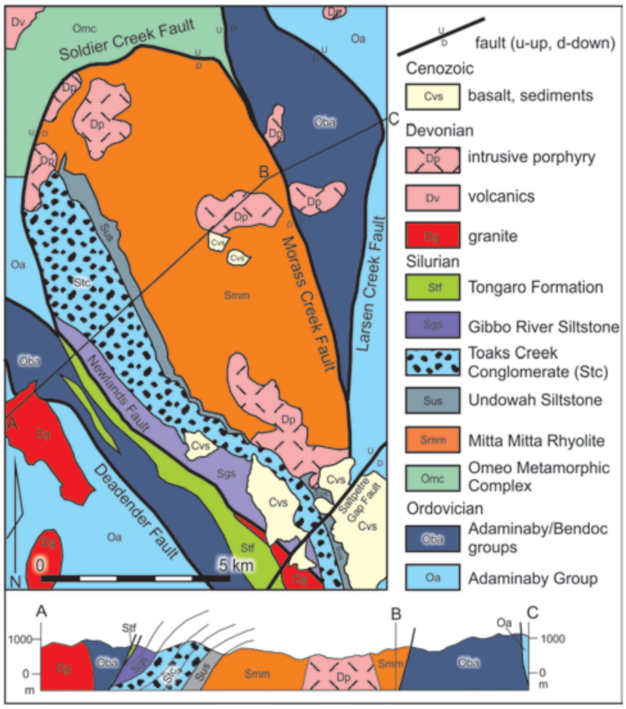

Figure 6. A simplified interpretation map and cross section (HS~VS) of the northern part of the Wombat Creek Graben in northeastern Victoria. Modified from parts of the Benambra and Dart 1:50 000 geological maps (VandenBerg et al., 1998a, 1998b, cross section JKL). See Figure 3 for location.

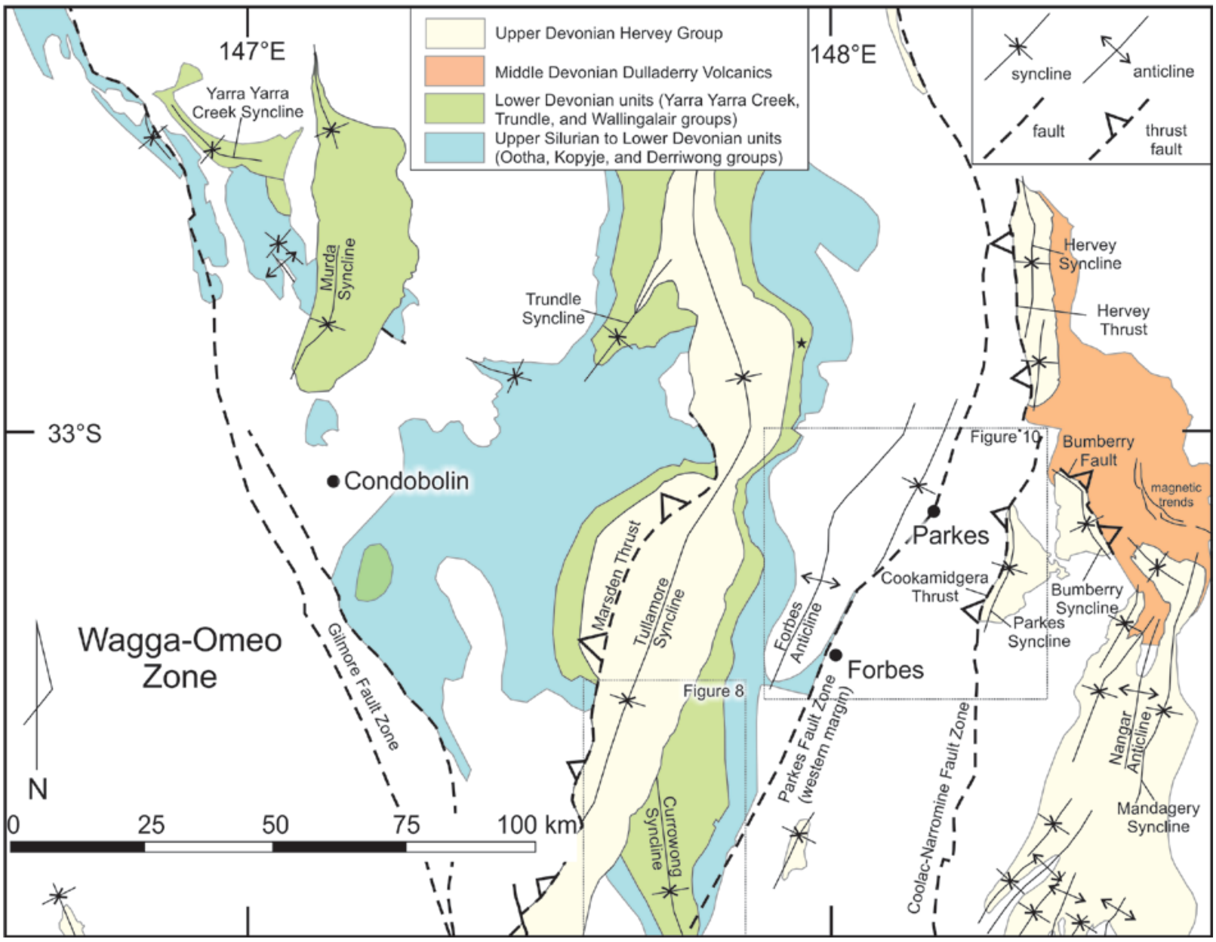

Figure 7. An interpretative geological map of the Forbes region showing the upper Silurian to Devonian units west of the Coolac–Narromine Fault Zone and Middle to Upper Devonian units east of this fault zone and structures. Large parts of the region are covered by Quaternary sediments but aeromagnetic data indicate likely subsurface extent of units. Ordovician, early to middle Silurian granitic rocks and Devonian volcanic rocks east of the Coolac–Narromine Fault Zone are all undifferentiated and blank on the map. Only anticlines and synclines are shown for reasonably well-constrained structures indicated by the distribution of exposed stratigraphic units and orientation data of bedding. Star, fossil locality of Young (2006) where the Wallingalair Group is considered Upper Devonian and indicating an unconformity within the Upper Devonian succession (Table 3). Map compiled from digital maps including aeromagnetic and radiometric data (Geoscience Australia and Geological Survey of New South Wales). See Figure 1 for location.

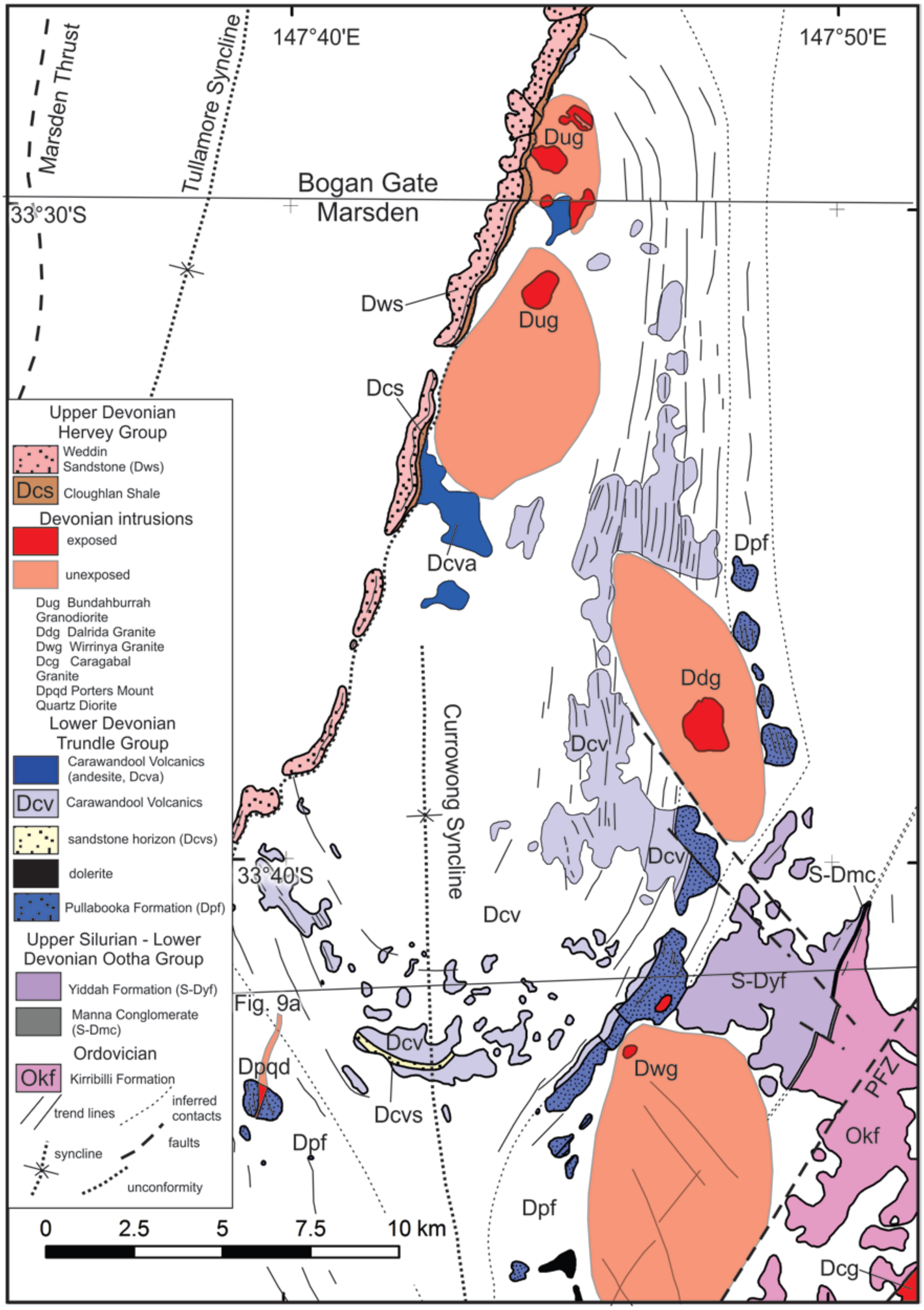

Figure 8. Map of the main outcrops of units defining the Currowong Syncline, compiled and reinterpreted from the Bogan Gate and Marsden 1:100 000 geological digital maps (Raymond & Wallace, 2000; Sherwin et al., 2000). See Figure 7 for location and Figure 9a for cross section.

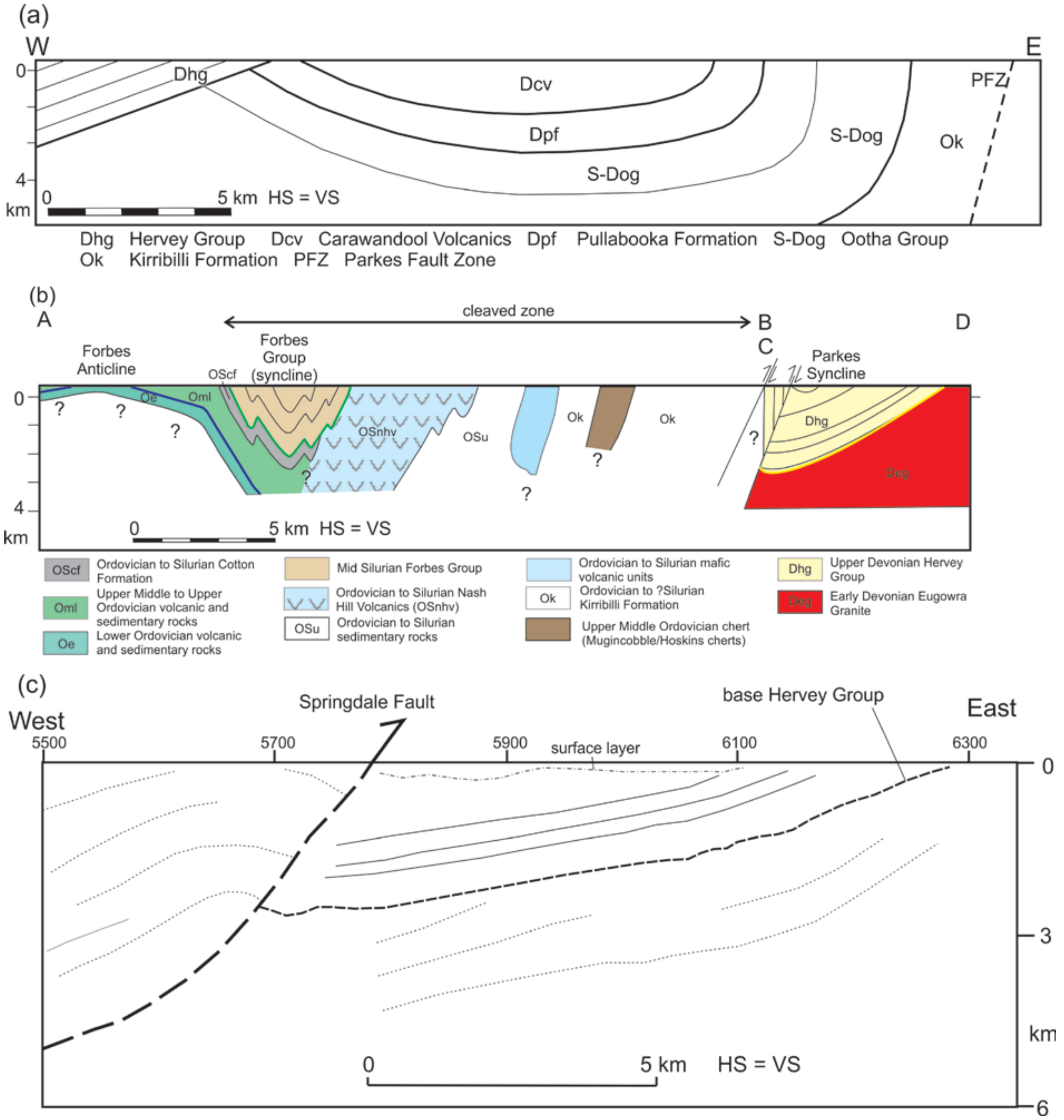

Figure 9. Cross sections based on surface geology with subsurface control provided by deep seismic lines where available. Horizontal scale = vertical scale for all cross sections. (a) Currowong Syncline (see Figures 8, 13 for location) redrawn and reinterpreted from the Marsden 1:100 000 geological map (Raymond & Wallace, 2000) and deep seismic line 99AGS-L1 (Glen et al., 2002). (b) Forbes Anticline and Parkes Fault Zone (see Figure 10 for location). (c) The Springdale Fault redrawn based on reflectors shown on seismic line 99AGS-L3, see (Glen et al., 2002). Dotted lines below the Hervey Group and west of the Springdale Fault show interpreted bedding in undifferentiated Silurian–Devonian sedimentary rocks. See Figure 13 for location.

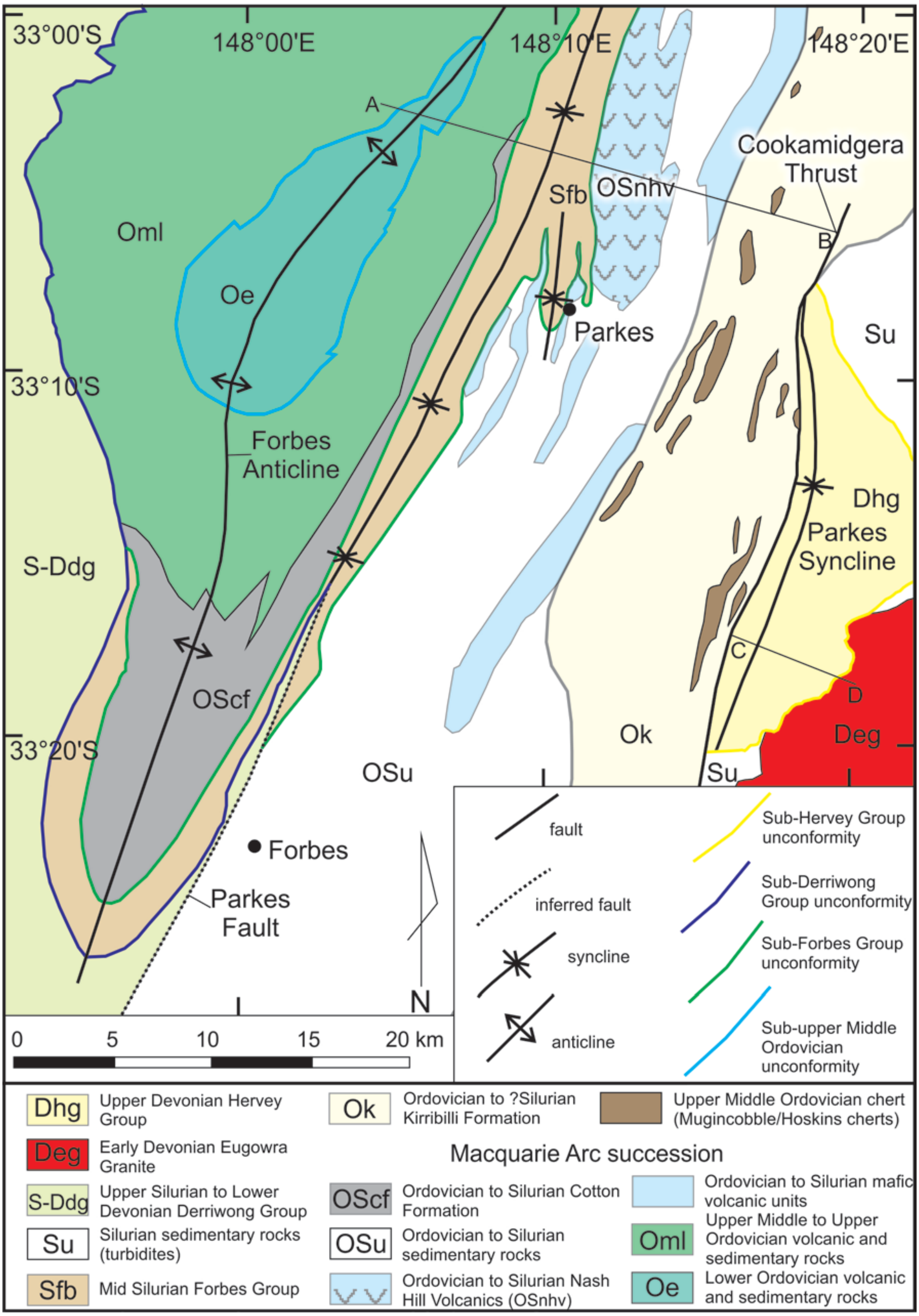

Figure 10. Geological interpretation map of the Forbes Anticline, Parkes Fault Zone, and Coolac–Narromine Fault Zone with Quaternary cover removed and constrained by aeromagnetic and radiometric data. Map compiled from data in the Parkes and Bogan Gate 1:100 000 geological maps (Sherwin et al., 2000), the Parkes Special 1:100 000 geological map (Krynen et al., 1990), Simpson et al. (2005), Meffre et al. (2007) and the author (unpublished data). See Figure 7 for location.

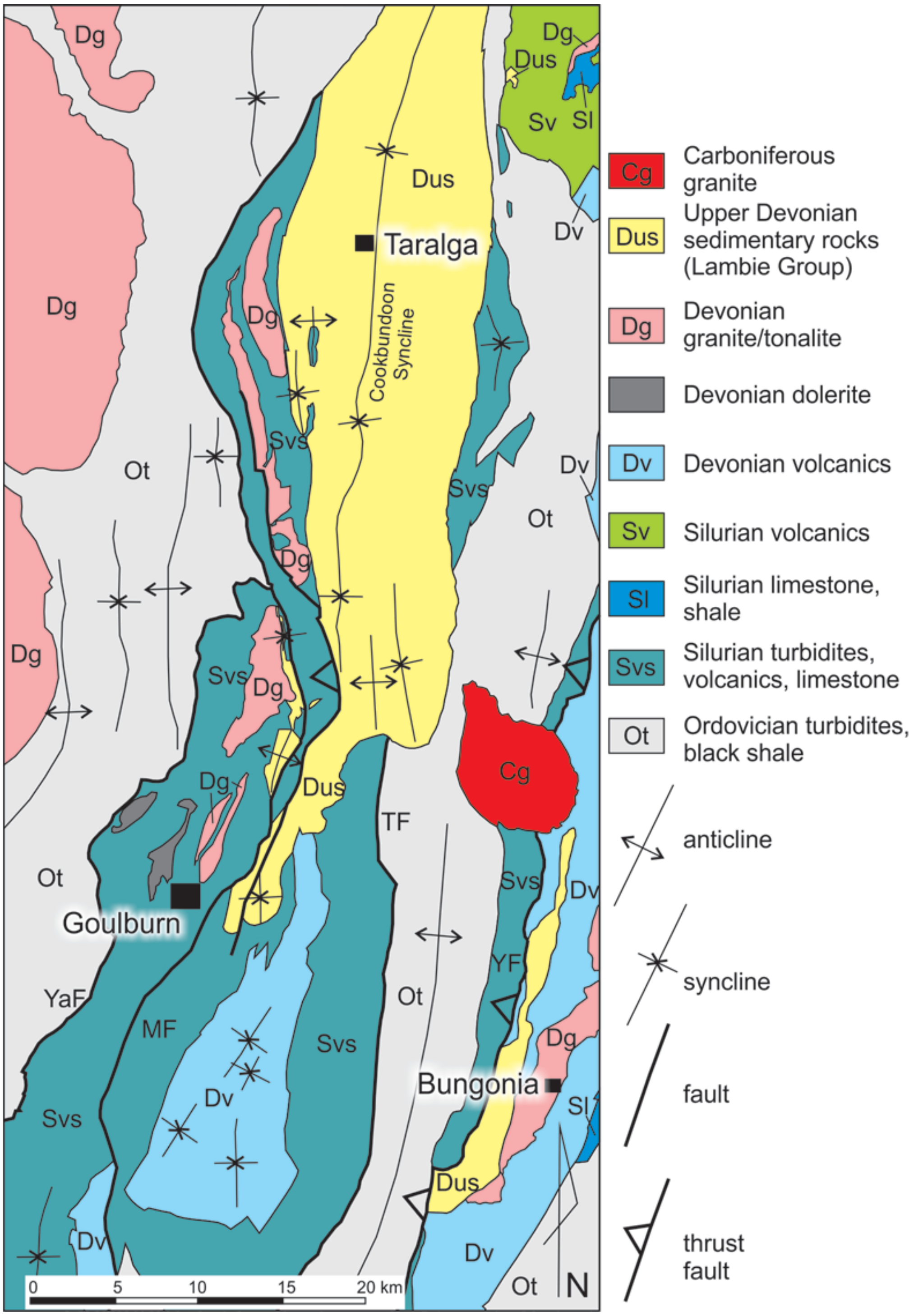

Figure 11. Map of the southern Cookbundoon Syncline and the underlying Tabberabberan structures in the Ordovician–Devonian succession. Permian and younger units are not shown. Only the most significant faults and folds are shown. Note how the main synclinal axial trace of the Cookbundoon Syncline in the Lambie Group is close to the middle of the underlying synclinorial Silurian and Devonian units. Modified and reinterpreted from Thomas et al. (2013a, 2013b). Abbreviations: MF, Mulwaree Fault; TF, Towrang Fault; YaF, Yarra Fault; YF, Yarralaw Fault. See Figure 13 for location.

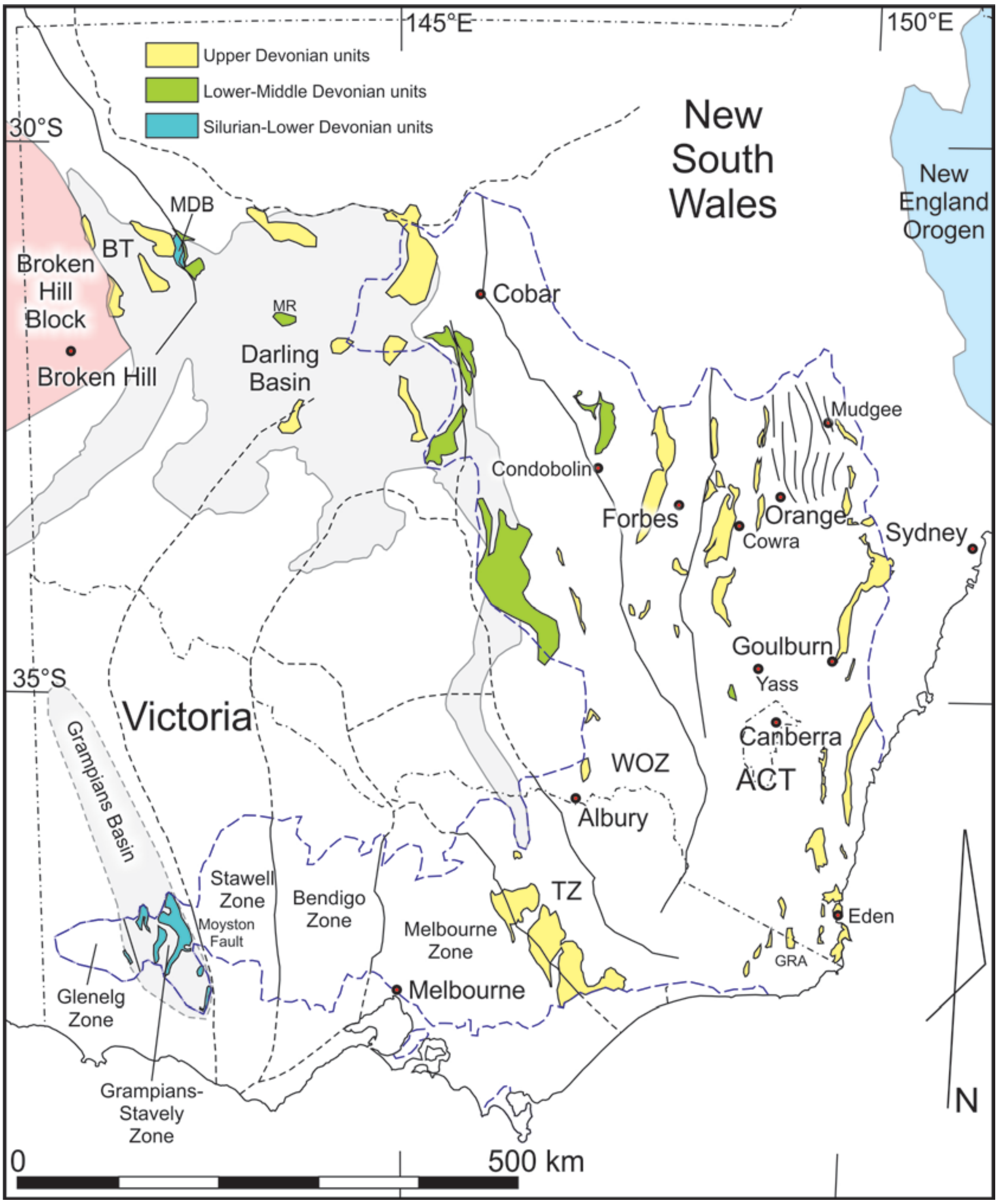

Figure 12. Map of the Lachlan Orogen showing the main areas of upper Lower to Upper Devonian fluvial and shallow marine strata in the Lachlan Orogen, upper Silurian to Devonian dominantly fluvial strata in the Darling Basin, and fluvial to shallow marine strata of the Grampians Group in western Victoria. Note that only the Upper Devonian units in the eastern Melbourne Zone are considered to extend into the Lower Carboniferous (see text). Structural trends are shown in the northeastern Lachlan Orogen; note the age of these trends is disputed (see text). Abbreviations: ACT, Australian Capital Territory; BT, Bancannia Trough; GRA, Genoa River area; MDB, Mt Daubeny Basin; MR, MacCullochs Range; TZ, Tabberabbera Zone; WOZ, Wagga–Omeo Zone.

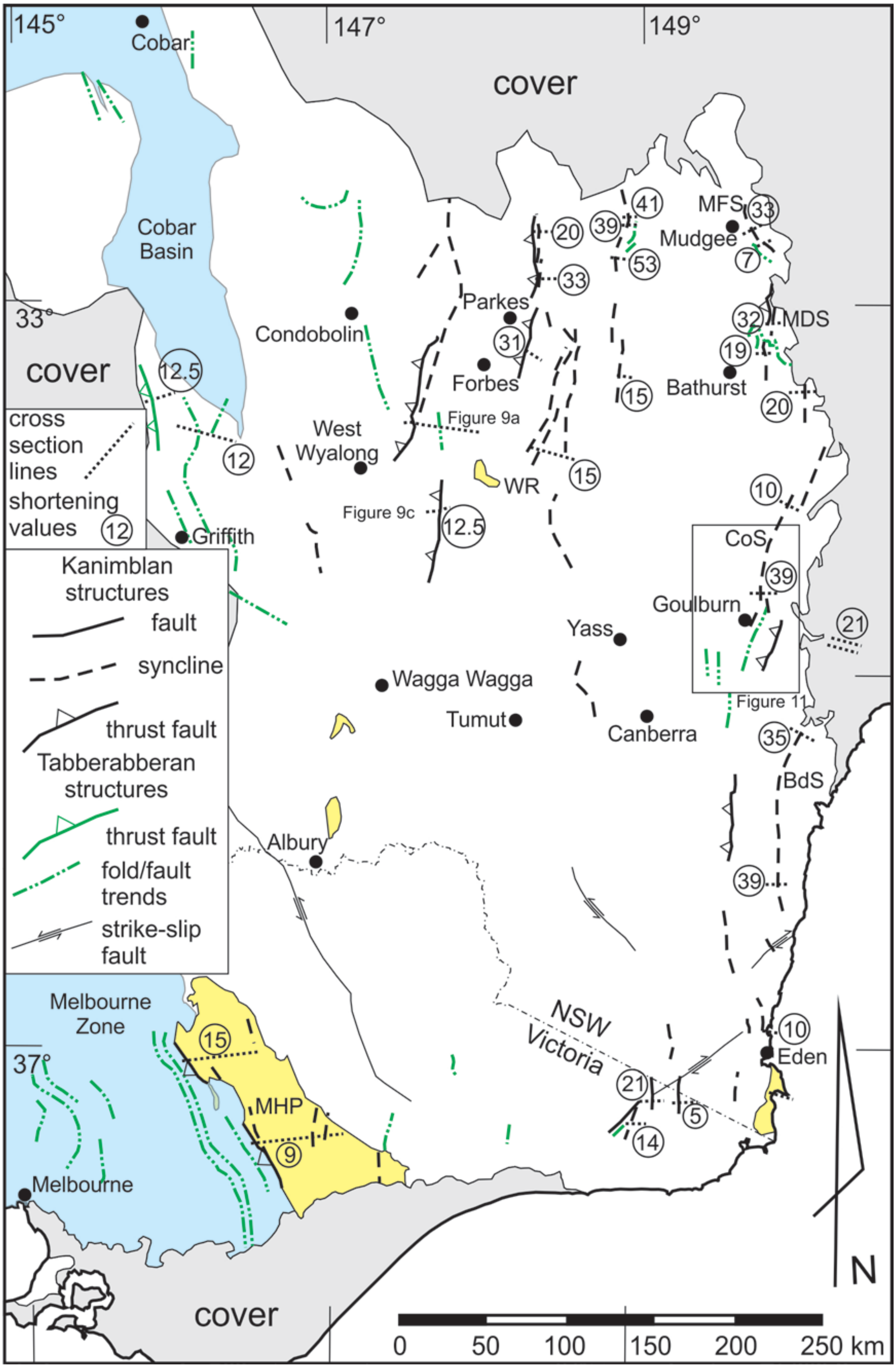

Figure 13. Tabberabberan and Kanimblan structures in the Lachlan Orogen of eastern NSW and adjacent Victoria. Numbers (circled) indicate values of shortening calculated from cross sections (Tables 2, 3) and approximate locations shown on figure. Abbreviations: BdS, Budawang Synclinorium; CoS, Cookbundoon Syncline; MDS, Mt Dulabree Syncline; MFS, Mt Frome Syncline; MHP, Mt Howitt Province; WR, Weddin Range.

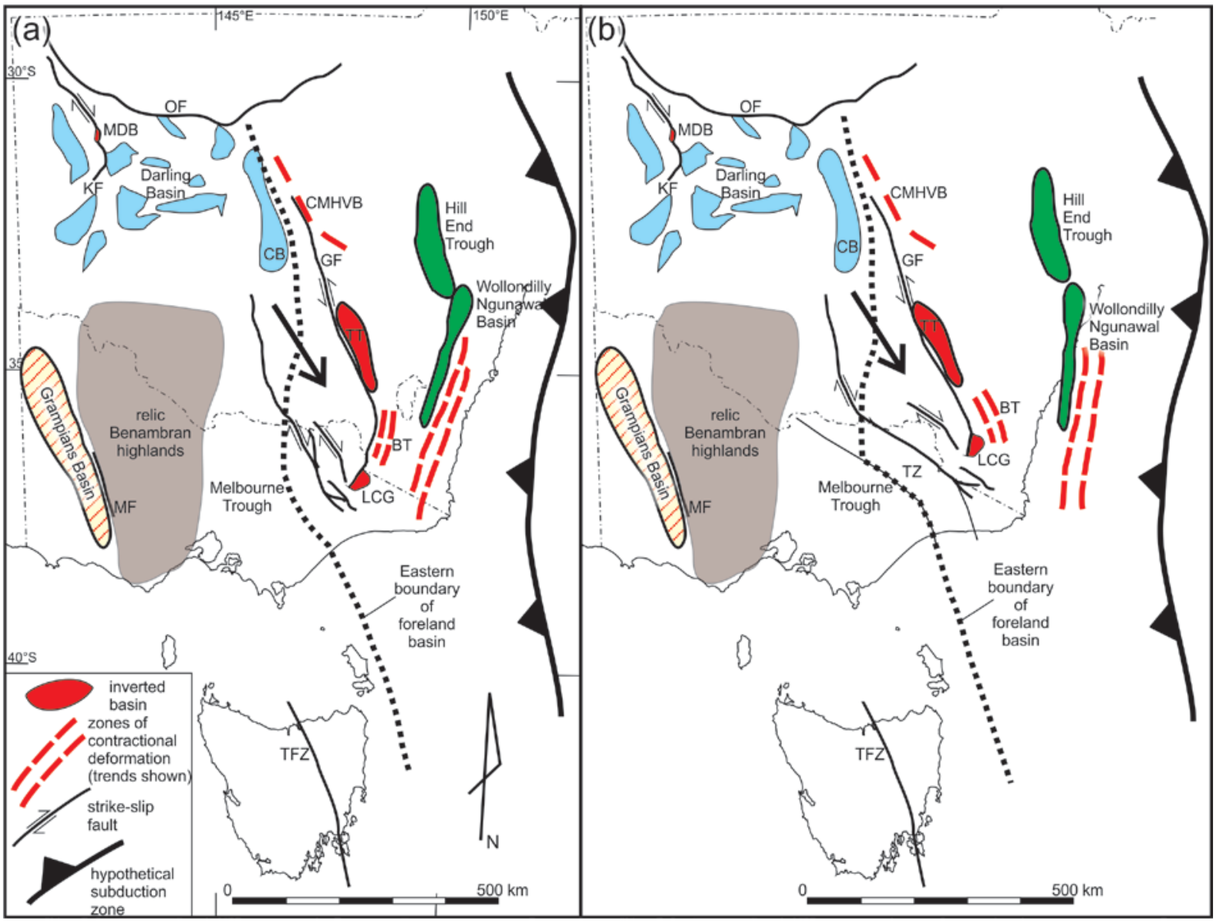

Figure 14. (a) Interpretation map of the Bindian Orogeny showing the main strike-slip faults and zones of contractional deformation related to a hypothetical west-dipping subduction zone along the eastern margin. Arrow indicates SSE transport of the Wagga–Omeo Zone. (b) Palinspastic reconstruction with positions of Bindian structures and deformation zones after removal of E–W Kanimblan shortening (see Figure 15b) and Tabberabberan shortening using shortening estimates for the Melbourne Zone after Gray et al. (2006) and the Cobar Basin after Glen (1985) (Table 1). See also Fergusson (2010, figure 9). Abbreviations: BT, Brindabella Tantangara;, CB, Cobar Basin; CMHVB, Canbelego-Mineral Hill Volcanic Belt; GF, Gilmore Fault; KF, Koonenberry Fault; LCG, Limestone Creek Graben; MDB, Mt Daubeny basin; MF, Moyston Fault; OF, Olepoloko Fault; TFZ, Tamar Fracture Zone; TT, Tumut Trough; TZ, Tabberabbera Zone.

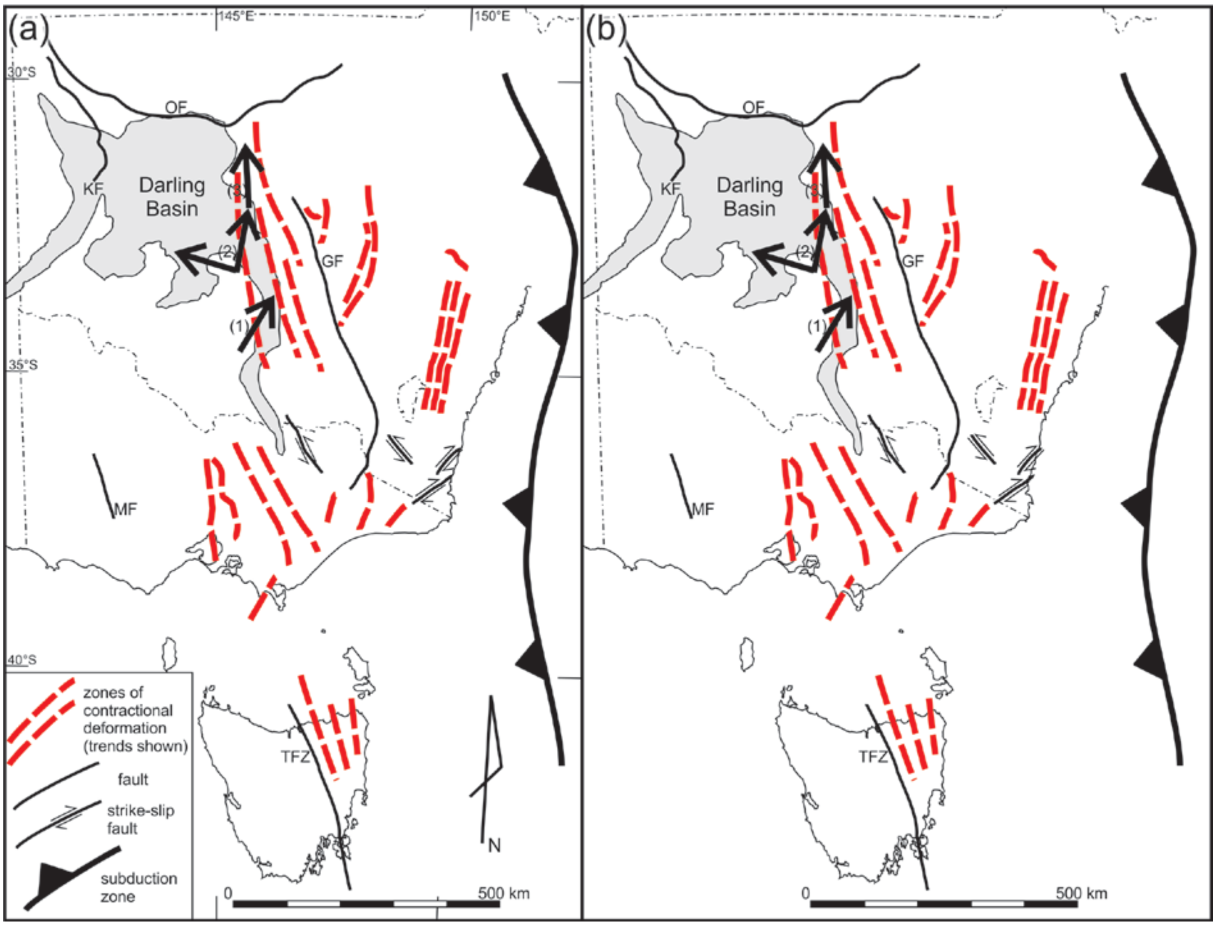

Figure 15. (a) Interpretation map of the Tabberabberan Orogeny showing the main strike-slip faults and zones of contractional deformation related to a hypothetical west-dipping subduction zone along the eastern margin. Arrows indicate paleocurrent directions in conglomeratic-sandstone units high in the Lower to Middle Devonian succession: (1) Mailman Gap Member (Rankin Formation), Cocoparra Group (Colquhoun et al., 2005, 034°), (2) Keginni Conglomerate Member (Bundycoola Formation), Mulga Downs Group (Powell et al., 1987, 287° to 011°), (3) Bundycoola Formation, Mulga Downs Group (Glen et al., 1987, 357°). (b) Palinspastic reconstruction with positions of Tabberabberan structures and deformation zones after removal of E–W Kanimblan shortening using representative shortening values of 12.5% for eastern Victoria and southern NSW (applied over 360 km), 27.5% for the Goulburn-Canberra region (applied over 220 km), 27.5% for the northeastern Lachlan Orogen (applied over 200 km), and 12.5% for central NSW–West Wyalong (applied over 160 km). This reconstruction assumes Kanimblan shortening is evenly developed across pre-Upper Devonian units. Abbreviations: GF, Gilmore Fault; KF, Koonenberry Fault; MF, Moyston Fault; OF, Olepoloko Fault; TFZ, Tamar Fracture Zone.

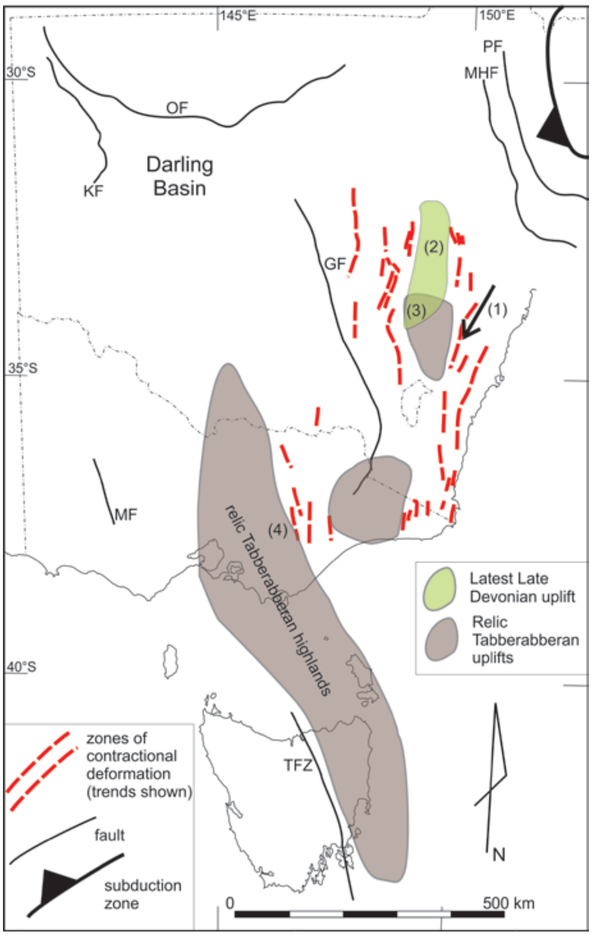

Figure 16. Interpretation map of the Kanimblan Orogeny showing faults for reference and zones of contractional deformation related to a west-dipping subduction zone developed in the New England Orogen. Numbers: (1) arrow shows paleocurrent direction in lithic sandstone interval in the middle part of the Lambie Group in the southern Cookbundoon Syncline (Powell, 1984a, figures 220, 222, current direction 210°). (2) Latest Late Devonian uplift of the Hill End Trough (Meakin & Morgan, 1999; Pogson & Watkins, 1998; Powell, 1984a). (3) Ar/Ar cooling ages of 380–360 Ma for the Wyangala Batholith indicating uplift during Late Devonian (Forster et al., 2014; Lennox et al., 2014). (4) Unconformities developed in the Mansfield Basin in the northern Mt Howitt Province indicate uplift of the deformed Melbourne Zone and deformation synchronous with sedimentation during the Late Devonian (Cas et al., 2003; O’Halloran & Cas, 1995). Abbreviations: GF, Gilmore Fault; KF, Koonenberry Fault; MF, Moyston Fault; OF, Olepoloko Fault; TFZ, Tamar Fracture Zone.

Table 1. Bindian Orogeny – most significant areas.

Location	**Structure**[a]	**Shortening**[b]	**Timing constraints**	**References**
Wombat Creek Graben (NE Victoria, Figures 3, 6)	NNW strike, dip moderately to steeply to SW (a homoclinal structure, Figure 6), with a tight syncline SW of the Newlands Fault, weak cleavage, surrounding Morass Creek and Soldier Creek faults appear as a partial enclosed piston cylinder fault formed during formation of the basal Mitta Mitta Rhyolite	15% (tilting), measured in cross section JL (Figure 6b), VandenBerg et al. (1998b), note that some of the tilting could reflect formation of a rollover anticline during extensional development of the graben	Deformation postdates inferred upper Silurian age of the Wombat Creek Group (Figure 5, Wagga–Omeo Zone) and predates the Cravenville Igneous Province with U–Pb zircon ages of 413 to 400 Ma (Early Devonian)	VandenBerg (2003); VandenBerg et al. (1998a)
Limestone Creek Graben (NE Victoria, Figure 3)	NE-trending folds and faults, strongly folded with abundant tight folds, strong foliation development (with 3 foliations), wide mylonite zone on the Indi Fault, which dips to the NW and has had major thrust motion	45% (folding/faulting, no allowance for strain associated with foliation development), measured in cross section Z_0-Z_3 in Allen (1992)	Deformation postdates the upper Silurian Enano Group, the deformed rocks are truncated by an angular unconformity at the base of the Lower Devonian Snowy River Volcanics, a U–Pb zircon age of 411 ± 3 Ma from an ignimbrite near the base of the Snowy Mountains Volcanics (Morand & Fanning, 2009) provides an upper age limit to the deformation (Figure 5, Wagga–Omeo Zone)	Allen (1992); VandenBerg (2003); Willman et al. (1999b)
Barmouth Group (E Victoria, Figure 3)	Units strike NNW, folded about tight upright folds, strongly to moderately cleaved, unit is fault-bounded	50% (folding, no allowance for strain associated with foliation development), measured in cross section GH in Willman et al. (1999a)	Timing constraints are based on inferences of the age of the unit and regional assessment of deformation timing	VandenBerg (2003); Willman et al. (1999a)
Tumut Trough (SW New South Wales, Figure 1)	NNW-trending folds, units, faults, upright, tight-open folds with cleavage	5% (folding, no allowance for strain associated with foliation development), measured in cross section	Deformation affects upper Silurian units and postdates the Gocup Granite (U–Pb zircon age of 411 ± 5 Ma), folds are truncated by angular unconformity at base	Basden (1990); Stuart-Smith, et al. (1992)

		AC in Stuart-Smith et al. (1992)	of upper Lower Devonian Minjary Volcanics and Gatelee Ignimbrite (Figure 5, Tumut Trough)	
Canberra Zone (SSW of Canberra in the Tantangara and Nungar–Brindabella blocks, Figure 2)	Intensity of deformation is variable with NNE-trending folds and at least local axial planar cleavage, foliation is developed in granites and volcanic rocks	Shortening effects are variable and die out to the east	Deformation affects upper Silurian granites, lower Silurian sedimentary rocks and upper Silurian Cooleman Plains Group and unconformably overlain by flat-lying to gently dipping Lower Devonian Kellys Plains Volcanics and Mountain Creek Volcanics	Owen & Wyborn (1979)
E Canberra Zone (Bungonia, Araluen and NSW South Coast, Figures 2, 11)	NNE-trending folds and faults (Figure 11), upright to moderately inclined to the west tight-open folds and common thrust faults, foliation development is highly variable with localised multiple deformation	76% (folding, faulting, only weak cleavage is developed in this section), measured in cross section UV in Fergusson & VandenBerg (1990) and includes a component of Benambran shortening	Deformation affects Ordovician to Lower Devonian units but structures are cross-cut by plutons of the Marulan Batholith with a U–Pb zircon age of 417 ± 5 Ma, farther south on Araluen Ordovician and upper Silurian units appear conformable with the major folding postdated by Early Devonian granites (Figure 5, Canberra Zone Goulburn)	Fergusson & VandenBerg (1990); Powell (1983); Thomas & Pogson (2012); Wyborn & Owen (1986)
N and NW of Condobolin (central NSW, Figure 7)	NW-trending upright, open to tight folds in a synclinal belt in upper Silurian to lowest Lower Devonian Kopyje Group (Figure 7), these rocks contain common axial planar cleavage	Kopyje Group on Bobadah in cross sections Kl and OP (Pogson, 1991a) has 47% and 37%, respectively	Cleavage development was considered early from relationships with unfoliated late dykes (Pogson, 1991a). In the Murda Syncline, upper Lochovian to Emsian Yarra Yarra Creek Group angularly unconformably overlies the Kopyje Group constraining the NW-trending folds to the pre-mid Lochkovian (Sherwin, 1996, 1997) (Figure 5 Murda Syncline)	Downes et al. (2016); MacRae & Pogson (1990); Pogson (1991a, b); Sherwin (1996, 1997)
Koonenberry Belt (Mt Daubeny	Folds have variable trends, folds in the north are SE-plunging and form a major syncline-anticline pair,	Shortening is variable, in the north 39% measured in cross section AB, in the south 19%	Age of the Mt Daubeny Formation is upper Silurian to Lower Devonian constrained by fossils and U–Pb zircon	Greenfield et al. (2010); Neef (2012); Neef et

Formation, Figure 2)	whereas in the south most dips are to the east forming a monocline with N–S-trending and E–W-trending folds, folds are mainly upright and open to gentle, some steeply dipping faults, these rocks lack cleavage	measured in cross section IJ, both in figure 3 in Neef et al. (1989)	ages on igneous rocks (andesitic volcanics near the base of the unit have an age of 425 ± 7 Ma, intrusive rocks higher in the succession have ages of 418 ± 2 Ma and 414 ± 3 Ma), the deformation is considered syn-depositional with the upper part of the unit and therefore within the Lochkovian–early Pragian (Figure 4) (Neef, 2012), although much of the deformation could be younger (Tabberabberan, predating the unconformably overlying Upper Devonian Ravendale Formation)	al. (1989)

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[a] Note that the fold interlimb angle classification used herein is after van der Pluijm & Marshak (1997): isoclinal = 0–10°, tight = 10–60°, open = 60–120°, gentle = 120–180°. [b] Shortening, calculated using formula: Shortening = $[(l_o-l_1)/l_o].100$, where l_o = original undeformed length, l_1 = deformed length. Shortening calculations have taken into account folding and offset along faults (where known), but have not taken into account strain associated with foliation development.

Table 2. Tabberabberan Orogeny – most significant areas.

Location	Structure	Shortening	Timing	References
Melbourne Zone (central Victoria, Figures 1, 3)	Folds trend NW, but common swings in fold trends occur, in the SW folds trend NNE (Figure 3), open, upright folds in west with increasing deformation towards the eastern boundary with folds and foliation dipping moderately to west with multiple deformation	Western and central parts 32%, eastern part 53%, Mt Wellington Fault Zone 64% (Gray, Willman, & Foster, 2006; Foster & Gray, 2007)	The youngest folded units are of Emsian age and plutonic rocks that cross-cut them have U–Pb zircon ages of 369–376 Ma, the oldest plutons are 395–392 Ma (Figure 5 Melbourne Zone) (Bierlein et al., 2001; see text)	Gray (1995); Gray et al. (2003);, VandenBerg (2003)
Mitchell Syncline (E Victoria, Figure 3)	NNE trend, upright tight to isoclinal syncline, eastern side of syncline is faulted in the north, and in south the central part of the syncline is faulted, only weak cleavage development, tectonic melanges occur in places reflecting faulting in the core of the syncline	Cross sections a and c (Fergusson & Gray, 1989) give 57% and 63% respectively and reflect the tight to isoclinal folding	The Wentworth Group in the Mitchell Syncline is considered probably Emsian, and is angularly unconformably overlain by flat-lying sandstones of the Upper Devonian–Lower Carboniferous Avon Supergroup of the Mt Howitt Province (Figure 5 Tabberabbera Zone)	Fergusson & Gray (1989); VandenBerg (2003); Willman et al. (2005)
Buchan Rift (E Victoria, Figure 2)	NNE trend of inverted Buchan Rift with upright, open-tight folds in sedimentary units, volcanic units generally have low dips, no cleavage is recorded in any units	Part of cross section AB in Orth et al. (1993) 13%, cross section in figure 3(b) in Gray & Gregory (2003) 15%, although the limestones show higher buckle shortening adjacent to reactivated normal faults (20–30%)	The age of the Buchan Group is Emsian, but no upper constraint exists for the deformation of the Buchan Rift	Gray & Gregory (2003); Orth et al. (1993, 1995); VandenBerg et al. (2000)
Boulder Flat Graben (E Victoria, Figure 2)	NE-trending, upright, isoclinally folded with strong cleavage, unit is bounded to NW by the Combienbar Fault and to SW by the Bungywarr Fault	Cross section G1-H in VandenBerg et al. (1990) 58%	The succession is probably lower Emsian (Erinundra Group) and is angularly unconformably overlain by the Upper Devonian Combyingbar Formation	VandenBerg (2003); VandenBerg et al. (1990, 1991)

Goulburn region (SE NSW, Figures 2, 11)	NNE-trending, tight folds with variably developed foliation, W-dipping faults (Figure 11)	Cross section YZ in Thomas et al. (2013b) 35%, inflated by Carboniferous shortening	The youngest unit involved in the deformation is the Emsian Lake Bathurst Limestone Member and farther north the Quialigo Volcanics (U–Pb zircon ages range 414–409 Ma) is angularly unconformably overlain by the Upper Devonian Lambie Group (Figure 5 Canberra Zone Goulburn)	Thomas & Pogson (2012)
Currowong Syncline (central NSW, Figures 7, 8)	The Currowong Sycline is a tight fold with an axial plane dipping 60°E, the E limb is subvertical and the W limb dips moderately to gently east (Figure 9a)	Cross section AB in Raymond & Wallace (2000) 35%, inflated by Carboniferous shortening	The youngest folded unit is the Carawandool Volcanics (U–Pb zircon age 404 ± 2 Ma), the syncline is intruded by plutons with U–Pb zircon ages of 395 Ma and 400 Ma giving a tight constraint of ca 400 Ma for the folding (Figure 5, Currowong Syncline)	Lyons et al. (2000)
Parkes Fault Zone–Forbes Anticline (central NSW, Figures 7, 10)	The Forbes Anticline is an open, south plunging fold that appears to form the complementary anticline to the Currowong Sycline, on the eastern limb the Forbes Group forms a tight, upright syncline with well-developed axial planar cleavage (in contrast cleavage is lacking in the Forbes Anticline, east of this syncline is a region of poor exposure including the multiply-deformed Kirribilli Formation farther east (Figure 9b)	Cross section in Figure 9b drawn from published maps and unpublished data (C. L. Fergusson), 44% shortening in the syncline containing the Forbes Group, Forbes Anticline in cross section AB on the Bogan Gate 1:100 000 geological map (Sherwin, Raymond & Wallace, 2000) 14%	Deformation timing is poorly constrained (see text), but considerable shortening must have occurred prior to deposition of the Upper Devonian Hervey Group and is thought to be mainly late Early to Middle Devonian (Tabberabberan)	Clarke & Sherwin (1990); Krynen, Sherwin, & Clarke (1990), Lyons et al. (2000); Meffre et al. (2007), Raymond et al. (2000); Sherwin et al. (2000)

N and NW of Condobolin (central NSW, Figure 7)	NE of the Kopyje Group is the tight-open Yarra Yarra Creek Syncline containing the Lower Devonian Yarra Yarra Creek Group, the syncline trends NW and swings to a ESE trend to the SE, it has a steeply dipping SW limb associated with faults, and a moderately to gently dipping NE limb, the Yarra Yarra Creek Group is less deformed and typically lacks cleavage, some local NE–trending folds refold the unit and are considered fault-related; to the east is the NNE-trending upright open Murda Syncline in Yarra Yarra Creek Group (Figure 7)	The Yarra Yarra Creek Syncline in cross section OP (Pogson, 1991a) 33%, and the Murda Syncline in cross section BB' (Sherwin, 1997) 9%	The Yarra Yarra Creek Group is upper Lochovian to Emsian and provides the lower constraint on the folding, but no upper constraint exists and the deformation could be either Tabberabberan or Kanimblan or a combination of both	Downes et al. (2016); Glen et al. (1996); MacRae & Pogson (1985); Pogson (1991a, b); Sherwin (1996, 1997)

Cobar Basin (in Cobar region, central NSW, Figures 1, 2)	Strongly deformed in east adjacent to Rookery Fault with tight to isoclinal folds, strong cleavage, down-dip lineation; folds and cleavage trend NE to NNW, in the north, west of bounding fault are several NNE-trending folds forming an en échelon array indicating localised sinistral shear (Glen, 1985, figure 2), folding decreases in intensity to the west where NW-trending, open, upright folds overprinted by open, upright, NE- to ENE-trending folds	Average shortening of 62% for eastern intensely deformed belt and 10–30% shortening for the western less deformed belt (Glen, 1985)	Timing has been constrained by radiometric ages including Ar/Ar, K/Ar and Rb/Sr ages provide general age of 400–395 Ma for foliation development accompanying deformation (Glen et al., 1992); re-evaluation of these ages along with U–Pb ages indicating an older age of the succession (upper Silurian to lowest Devonian) and general conformity with the overlying Mulga Downs Group, with a revised to Lower to Middle Devonian (no younger than Eifelian) age, indicates a possible late Middle Devonian age of the deformation (Figure 4 Cobar Basin) (Downes et al., 2016), an older age of deformation at 400–395 Ma cannot be ruled out, a Kanimblan overprint or even a Kanimblan age of deformation also cannot be completely ruled out	Glen (1985, 1990, 1994); field data and modelling by Smith & Marshall (1992)

Exposed eastern margin of Darling Basin (central NSW, N Riverina to Cobar district, Figures 1, 2)	NW to east-trending, gentle folds, refold structures (e.g. "ear" structure in the northern Riverina–Lake Cargelligo)	Lachlan Range syncline 12.5% (Colquhoun, Meakin, & Cameron, 2008, cross section AB), Cocoparra Syncline 12% (Cameron, Meakin, Vassallo, & Hendrickx, 2008, cross section AB) (Figure 13), Yathong Synclinorium 11% (Scheibner, 1985, cross section MM), Lachlan Downs 11% (MacRae, 1989, cross section AA), Buckambool Syncline and associated folds 20% (Glen, Felton, & Brown, 1985, cross section F4–F3), 10–30% reported by Glen (1985)	Deformation postdates the Mulga Downs and Cocopara groups which have been reassessed as upper Lower to no younger than Eifelian (Downes et al., 2016), no upper constraint, deformation is interpreted as "late" Tabberabberan by Downes et al. (2016)	Colquhoun et al. (2005); Downes et al. (2016); Glen (1985)
Koonenberry Belt (NW NSW, Figures 1, 2)	Low-angle unconformity between the Wana Karnu Group and overlying Ravendale Formation in the SW part of the Koonenberry Belt indicates localised deformation (NNW broad folds), broad NE-trending Menamurtee Anticline formed adjacent to Koonenberry Fault (eastern side)	Menamurtee Anticline cross section AD (figure 3, Neef & Larsen, 2003) 12%	Age of the Menamurtee Sandstone based on fossil fish indicates mid Emsian age for part of the unit, unconformably overlying units are considered mid to Upper Devonian (Figure 4)	Greenfield et al. (2010); Neef (2004, 2012); Neef & Larsen (2003)
NE Tasmania (Mathinna Supergroup, Figure 1)	NW- to N-trending, upright to steeply inclined, tight to open, folds with axial planar cleavage, western part is thrust to WSW over the Western Tasmania Terrane	Eastern part of cross section 30% (figure 4, Powell & Baillie, 1992)	Deformation has also produced foliation in older plutons of the Blue Tier Batholith giving an age of 390–388 Ma for the deformation (Figure 5 Eastern Tasmania terrane) (Black et al., 2005)	Calver et al. (2014); Powell & Baillie (1992); Reed (2001); Seymour et al. (2014)

Table 3. Kanimblan Orogeny – domains.

Location	Structure	Shortening	Timing	References
Hill End Trough and surrounding areas (NE Lachlan Orogen, Figures 1, 2)	Trends vary about a north direction (Figure 12), overturning of western limbs in some synclines in Upper Devonian rocks indicate local strong deformation, faults associated with folds (footwall synclines), extent of deformation in underlying units is contentious (see text)	Shortening is variable with ranges of 7–53%, examples in synclines containing Upper Devonian rocks include: Cookbundoon Synclinorium 39% (Powell & Fergusson, 1979, figure 3), 10% (Murruin Creek, Powell et al., 1977, figure 5), Mt Lambie – 20% (cross section in MacKay, 1961), Mt Horrible Syncline 19% (Powell & Edgecombe, 1978, figure 7 cross section AB), Mt Dulabree Syncline 32% (Powell et al., 1977, figure 2, cross section CD), Mt Frome Syncline 7% (cross section JK, Colquhoun et al., 1999), 33% (Powell & Edgecombe, 1978, figure 6 cross section AB), Black Rock Range 15% (Powell & Edgecombe, 1978, figure 5 cross section AB), Wellington 53% (cross section DE, Scott et al., 1999), Mt Arthur Syncline 41% and 39% (Powell et al., 1977, figure 6 cross sections CD and EF); but amount of shortening in units below the Upper Devonian unconformity is contentious (see text) (Figure 13)	Folding and faulting of Upper Devonian rocks that predates Carboniferous granites in the region (Figure 5 Hill End Trough) (358–314 Ma, Bodorkos et al., 2010; Meakin & Morgan, 1999)	MacKay (1961); Meakin & Morgan (1999); Pogson & Watkins (1998); Powell & Edgecombe (1978); Powell & Fergusson (1979); Powell et al. (1977)
South Coast NSW and NE Victoria (Figures 12, 13)	In NE Victoria the Upper Devonian rocks occur in north-trending strongly asymmetric synclines with steep to overturned dips adjacent to steeply dipping faults on both the western and eastern sides of	NE Victoria – 14% Combienbar Syncline, 21% Buldah Syncline (Simpson & Fergusson, 1997a, cross sections E–F and LM), 5% Genoa River area (Simpson & Fergusson, 1997b, cross section NO), about 10% in Eden district (Rixon et al., 1983), higher shortening further N, 39% W of Bodalla (C. Fergusson unpub.	Deformation is constrained as post Late Devonian and predates Carboniferous plutons that are	Cooper (1992); Powell (1983); Rixon et al. (1983); Simpson & Fergusson (1997a, b); Simpson et al.

	different structures. In the Eden region and west of the Budawang Synclinorium, most of the structures are weak, open-gentle folds, with steeper dips near faults, and common monoclinal folds ("mega kink folds"), farther north in the Budawang Synclinorium folds are gentle to open with locally steep limb dips at the margins of the structure	data, Bumbo Creek), 35% NNW of Batemans Bay in Budawang Syncliorium (Powell, 1983, figure 25), 21–22% in Budawang Synclinorium (Cooper, 1992, Shoalhaven River and Ettrema Creek cross sections) (Figure 13)	unconformably overlain by the Sydney Basin succession in the northern Budawang Synclinorium	(1997); Wyborn & Owen (1983, 1986)
Central–western NSW (Figures 7, 8, 10, 12, 13)	Mainly north-trending folds with common variations in trends and local refolding of folds, common bounding faults (Figure 7), but mainly gentle to open folds, Weddin Mountains show low dip with a very broad syncline, on east limb of Tullamore Syncline on Narromine 1:250 000 geological sheet	Hervey Syncline 20% and 33% (Powell, et al., 1980, figure 2AB, CD), Parkes Syncline 31% (Powell et al., 1980, figure 5CD), Grenfell 15% (Raymond et al., 2000, cross section CDE), unexposed syncline east of the Springdale Fault 12.5% (Glen et al., 2002, seismic line 99AGS-L3, 5700 to 6300 CDP) (Figure 9c, 13)	Deformation is post-Upper Devonian, no upper constraint	Glen et al. (2002); Lyons et al. (2000); Powell et al. (1980); Sherwin (1996)
Mt Howitt Province in central-eastern Victoria (Figures 3, 13)	A NW-trending belt with north–trending very gentle folds (Figure 3) with regional very low dips apart from adjacent to bounding reverse faults, major reverse faults along western side of belt	Licola–Avon synclinoria 9% (cross section in VandenBerg, 1977), Mansfield Basin 15% (O'Halloran & Cas, 1995, figure 2b) (Figure 13)	Deformation is post-Early Carboniferous, no upper constraint, unconformities indicate deformation in the Late Devonian (Figure 5 Melbourne	Cas et al. (2003); O'Halloran & Cas (1995); VandenBerg (1977); VandenBerg et al.

			Zone east)	(2000)
Darling Basin (western NSW, Figures 1, 2)	Wide variations in structural trends from N to E–W, common folds related to faults such as the faults bounding the Bancannia Trough, the Koonenberry Fault and other less well documented faults in the basin, ENE-trending broad to open upright folds in the Winduck Group in the MacCullochs Range with associated vertical faults	Seismic profiles show that large areas have very low-angle to subhorizontal layers in the subsurface, e.g. seismic lines across the Blantyre Sub-basin show 3% (Khalifa & Ward, 2009, figure 11; Willcox et al, 2003), shortening is greater in the MacCullochs Range with 9.5% and 14% in cross sections AB and CD respectively (Neef, 2005, figure 4), also locally adjacent to faults shortening is greater, Mulga Downs Group in the Cooper Mine Range adjacent to Koonenberry Fault 16% (Neef & Bottrill, 1996, figure 3 cross section CD)	Deformation is post-Upper Devonian (Figure 4), upper constraint is unconformably overlying probable Permian and younger units	Bembrick (1997); Cooney & Mantaring (2007); Khalifa & Ward (2009); Neef (2005, 2012); Neef et al. (1989); Willcox et al. (2003)