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Ordovician–Silurian accretion tectonics of the Lachlan Fold Belt, southeastern Australia

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The Lachlan Fold Belt of southeastern Australia contains a remnant ocean basin with Cambrian igneous basement of intra-arc and backarc boninitic to tholeiitic volcanics and island-arc calc-alkaline volcanics overlain by ?Upper Cambrian to dominantly Ordovician siliciclastic turbidite successions derived from Gondwana and deposited in a huge submarine turbidite fan(s). Much of the remnant ocean basin is preserved in accretionary subduction complexes that are characterised by abundant coherent successions with relatively sparse mélanges. The lack of chaotic rocks reflects the accretion of thick (2–5 km) siliciclastic turbidite successions and low rates of underthrusting. Three previously recognised accretionary subduction complexes are located in western Victoria (Stawell and Bendigo Zones), eastern Victoria (Tabberabbera Zone) and along the eastern coastline of southeast Australia (Narooma subduction complex). In addition, a short-lived west-dipping subduction zone is proposed to account for the areally restricted Howqua River Zone along the eastern margin of the Melbourne Zone in eastern Victoria. The Howqua River Zone contains gently dipping mélanges and subduction-related blueschist fragments. The subduction complex in the Tabberabbera Zone is considered to extend throughout the remnant ocean basin succession of the Wagga–Omeo Zone of the central Lachlan Fold Belt. Apart from the Howqua River Zone, these subduction complexes are an end-member in the spectrum of accretionary complexes that contrast with more chaotic assemblages as preserved in southwest Japan.

KEY WORDS: accretion tectonics, Lachlan Fold Belt, siliciclastics, southeastern Australia, subduction complex.

INTRODUCTION

The Lachlan Fold Belt of southeastern Australia has been a topic of considerable debate in terms of its tectonic setting and development (Powell 1984; Coney *et al.* 1990). A convergent-margin setting has been favoured, as is indicated by the drawn-out history of calc-alkaline igneous activity and contractional deformation (Fergusson & Coney 1992a; Collins 1998; Scheibner & Basden 1998). It has been argued that much of the Lachlan Fold Belt formed three subduction complexes, one each in the western subprovince (Stawell and Bendigo Zones), central subprovince (Tabberabbera Zone) and eastern subprovince (Mallacoota Zone) (Gray 1997; Gray & Foster 1997, 1998; Soesoo *et al.* 1997; Gray *et al.* 1998, 2002; Foster & Gray 2000; Spaggiari *et al.* 2002a). The inferred subduction complex settings of the western and central subprovinces have been challenged on the basis of the lack of diagnostic subduction complex lithologies, and most strongly on structural differences from other subduction complexes such as the Shimanto Belt (VandenBerg 1999; Taylor & Cayley 2000). The debate over the inferred subduction complexes of the Lachlan Fold Belt continued from a prior controversy over the nature of the basement of the Lachlan Fold Belt (Chappell *et al.* 1988). It was argued that the Lachlan Fold Belt contained a basement of Precambrian continental units ('basement terranes') and that these were consistent with the compositional and mineralogical variation of granites. Matching of zircon age spectra between granites and Ordovician clastic rocks has now cast considerable doubt on the suggestion that these granites were derived from Precambrian basement (Gray 1995; Collins 1998). Nevertheless, the hypothesis has been revisited that parts of the Lachlan Fold Belt have a continental-type basement. Cayley *et al.* (2002) argued on the basis of structural style and inferences from magnetic patterns across Bass Strait that central Victoria is underlain by a northern extension of the Precambrian crust of Tasmania [the 'Selwyn Block', this is equivalent to the marginal plateau of Packham (1973 p. 372) and is also a synonym of the Victorian microcontinent of Scheibner (1987) and Scheibner & Basden (1998)]. This paper considers the issue of the inferred subduction complexes in the Lachlan Fold Belt from the perspective of an accretionary orogen, as is particularly well illustrated by the geology of Japan (Isozaki 1996, 1997a, b; Kimura 1997). The stratigraphic assemblage and structural features of the subduction complexes are reviewed and their characteristics related to the process of underthrusting of the thick siliciclastic turbidite succession that dominates much of the belt. Modifications to the tectonic scenario portrayed by Foster and Gray (2000) are suggested, including an additional short-lived, west-dipping subduction zone at the eastern margin of the Melbourne Zone in eastern Victoria and an enlarged subduction complex in the Tabberabbera Zone to include the Wagga–Omeo Zone.

GEOLOGICAL SETTING

The Lachlan Fold Belt lies east of the Delamerian Fold Belt in southeastern Australia (Figure 1). The latter consists of a Neoproterozoic passive margin succession formed on rifted cratonic Precambrian crust with several successive rift events after the initial continental breakup of Rodinia at approximately 800–700 Ma (Preiss 2000). During the Delamerian Orogeny at 520–490 Ma, convergence in the palaeo-Pacific Ocean east of the margin resulted in an island arc – passive margin collision in western Victoria (VandenBerg *et al.* 2000 pp. 374–378) and ophiolite obduction in Tasmania (Berry & Crawford 1988; Crawford & Berry 1992). These events indicate that the setting of the Lachlan Fold Belt was in the oceanic realm east of Gondwana.

The Lachlan Fold Belt has Cambrian to Carboniferous rock assemblages developed over 700 km across strike and subdivided into western, central and eastern subprovinces (Figure 1) (Gray 1997; Gray & Foster 1998; Foster *et al.* 1999). The oldest unit present consists of Cambrian mafic volcanic successions overlain by pelagic chert and rare limestone (Crawford 1988; VandenBerg *et al.* 2000 pp. 24–46). Ordovician rocks are much more widespread and include the quartz turbidite succession that characterises much of the fold belt and is typically over 2000 m thick (VandenBerg & Stewart 1992; VandenBerg *et al.* 2000 pp. 51–61). In the eastern subprovince, an Ordovician calc-alkaline to shoshonitic mafic volcanic island arc is surrounded by Ordovician quartz turbidite successions (Glen *et al.* 1998; Fergusson & Fanning 2002).

Post-Ordovician rocks abound and include local deep-marine units, shallow-marine units, and subaerial successions, including abundant silicic igneous rocks and some mafic volcanics. The Melbourne Zone in the western subprovince (Figure 1) is dominated by Silurian–Devonian deep- to shallow-marine sediments that formed in a depo-

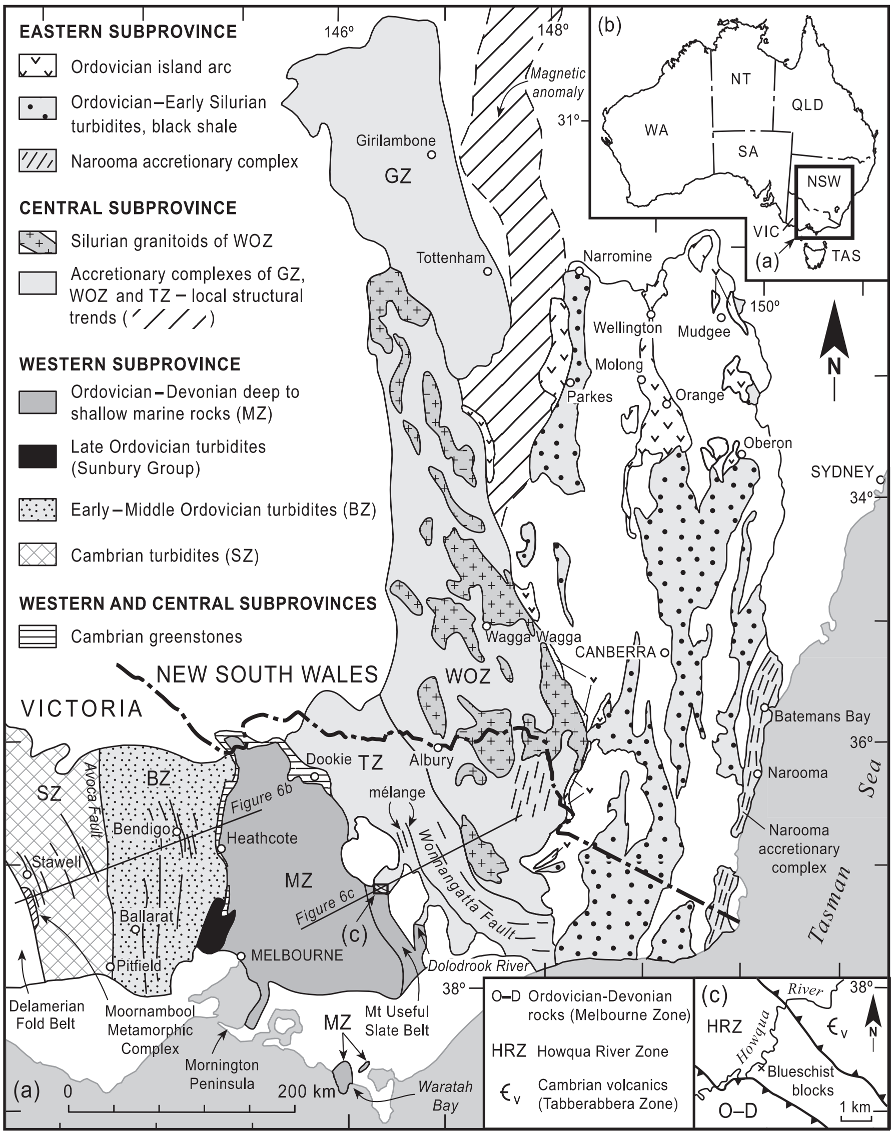

Figure 1 (a) Inferred subduction complexes of the Lachlan Fold Belt (after incorporating suggestions of Foster & Gray 2000). Note that the Tabberabbera subduction complex is expanded to include the Wagga–Omeo and Girilambone Zones of the central Lachlan Fold Belt and the Howqua River Zone is separated from this as a distinct subduction complex. BZ, Bendigo Zone; GZ, Girilambone Zone; MZ, Melbourne Zone; SZ, Stawell Zone; TZ, Tabberabbera Zone; WOZ, Wagga–Omeo Zone. Heavy lines are faults, blank areas are post-Silurian cover rocks within and outside the Lachlan Fold Belt. (b) Location of (a) in Australia. (c) Detail of the upper Howqua River area. Note that the Mt Useful Slate Belt (VandenBerg *et al.* 1995) is equivalent to the Mt Wellington Fault Zone (Gray & Foster 1998).

sitional trough. This divides the fold belt into two main parts and these have had inferred dextral strike-slip displacement (up to 500–700 km) in the Silurian to Early Devonian interval (VandenBerg *et al.* 2000 pp. 360–367; Willman *et al.* 2002). One of the most puzzling features of the Lachlan Fold Belt is the areal extent of deformation, which has been attributed to convergence along a subduction zone east of the belt (Collins 2002a, b). Foster and Gray (2000) accounted for much of the deformation pattern by postulating the development of two intra-fold belt subduction zones.

OCEAN-PLATE STRATIGRAPHY

Analysis of accretionary zones in orogenic belts involves the establishment of ocean-plate stratigraphy usually requiring detailed age determinations by microfossils (Taira *et al.* 1988; Matsuda & Isozaki 1991; Isozaki 1996, 1997a, b; Kimura 1997). The history of the ocean plate is determined by ages of mafic volcanic basement, pelagic to hemipelagic sedimentation and shallow-marine limestone deposition on seamounts. The main time constraint on accretion of the ocean-plate succession is provided by the depositional age of trench turbidite successions. Where low-grade metamorphism (e.g. prehnite–pumpellyite to pumpellyite–actinolite metamorphic facies) of accreted units is constrained by radiometric ages of new white mica growth formed during structural thickening of the prism, it post-dates accretion by as much as 10–20 million years (Isozaki 1996, 1997b).

In the Lachlan Fold Belt, this analysis has to be modified as deposition of the Ordovician turbidite succession was not controlled by a trench but was widespread across a marginal sea (Wagga marginal sea), island arc (Molong island arc) and forearc region (Monaro forearc basin) (Figure 2). Lower to Middle Ordovician turbidites extend across the entire width of the fold belt in Victoria (Figure 3) and formed much of a single huge fan analogous to the modern Bengal Fan (Fergusson & Coney 1992b). The palaeogeography is uncertain because hemipelagic sedimentation was dominant in the eastern Melbourne Zone and occurs west of, and upslope from, abundant sandy turbidite deposition in the Tabberabbera Zone. An explanation for this anomaly is dextral strike-slip movement of hundreds of kilometres along a postulated fault (the Baragwanath Transform) between the western and central subprovinces (VandenBerg *et al.* 2000 pp. 360–367; Willman *et al.* 2002). An alternative explanation is that the palaeogeographical anomaly has resulted from intense east–west shortening across this region.

Cambrian–Ordovician oceanic assemblages of the Lachlan Fold Belt are considered a remnant ocean basin (Ingersoll *et al.* 1995; Fergusson & Fanning 2002). There are two parts to the definition of a remnant ocean basin. First, it is a shrinking ocean basin such as occurs during the subduction of marginal seas (e.g. South China Sea, Philippine Sea Plate) and even more substantial ocean

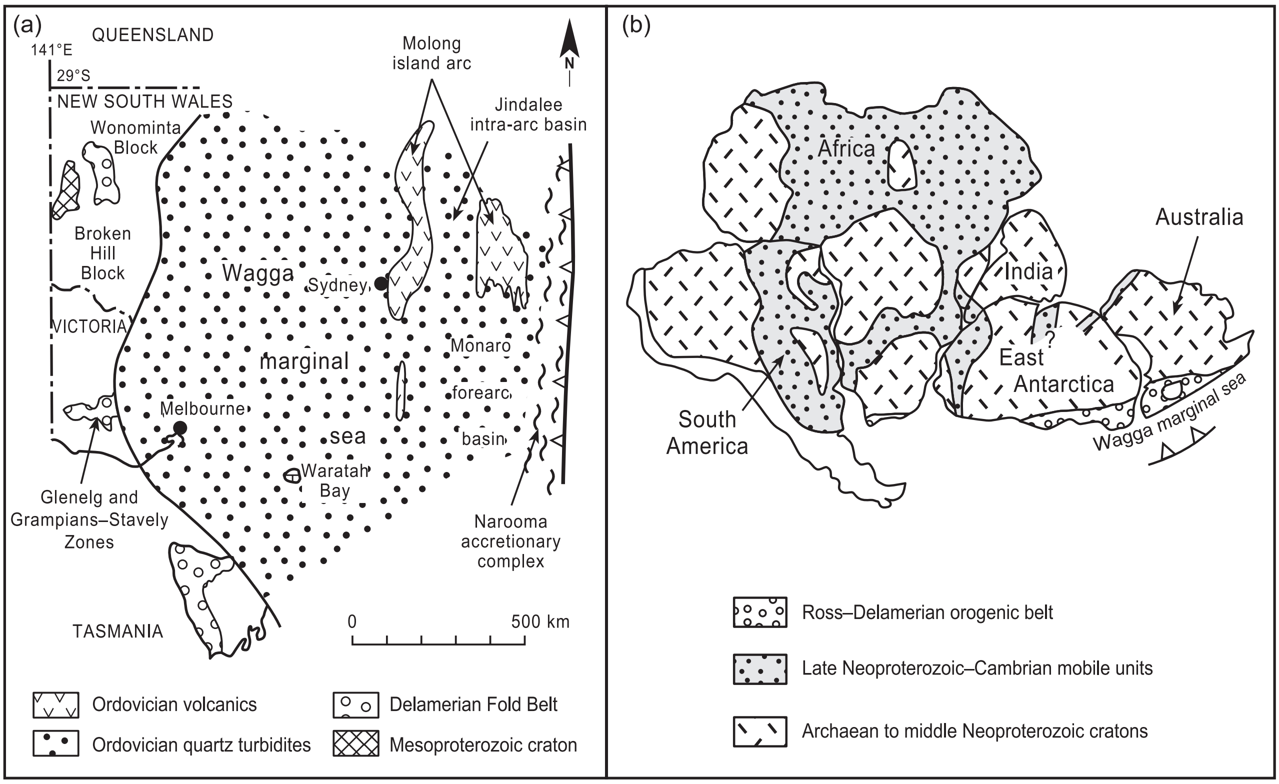

Figure 2 (a) Ordovician palaeogeographical elements of the Lachlan Fold Belt with the effects of intense east–west shortening removed (after Fergusson & Coney 1992b figure 2a). Lower Ordovician marlstone occurs at Waratah Bay. Jindalee intra-arc basin suggested by Lyons and Percival (2002). (b) Setting of the Wagga marginal sea at the eastern margin of Gondwana with Pan-African and Ross–Delamerian orogenic belts shown (modified from Fitzsimons 2000).

basins (e.g. northeast Indian Ocean). Second, sediments in the contracting ocean basin are derived from a suture zone. For example, the Triassic turbidites of the Songpan Garzi terrane in China were considered derived from the continental collision zone between the North China and South China blocks (Nie *et al.* 1994; Zhou & Graham 1996). However, U–Pb zircon whole-grain ages indicate that these sediments were sourced from the North China and South China blocks rather than from the metamorphic rocks in the Dabie Shan and Shandong regions formed during the continental collision (Bruguier *et al.* 1997). Given that the Songpan–Ganze turbidite basin is a major example of a remnant ocean basin, as discussed by Ingersoll *et al.* (1995), it would seem reasonable to extend the definition of a remnant ocean basin to any contracted ocean-floored turbidite succession of siliciclastic character.

The source of the Ordovician sandstones in the Lachlan Fold Belt is problematic. Sedimentary provenance and ages of detrital micas (*ca* 500 Ma) indicate a source in the Delamerian–Ross orogenic belt that formed from plate convergence at the ancient Gondwanan margin (Turner *et al.* 1996; Fergusson & Tye 1999). Detrital zircons from Ordovician sandstones have very similar age distributions with prominent Grenville (1300–900 Ma) and Pacific-Gondwana (700–480 Ma) signatures (Ireland *et al.* 1998; Williams 2001; Fergusson & Fanning 2002). This combined signature is recorded in orogenic belts within West Gondwana such as in the Pan-African belts and might conceivably extend under the ice in East Antarctica and provided a source along with the Delamerian–Ross mountains (Figure 2b) (Fitzsimons 2000; Veevers 2000).

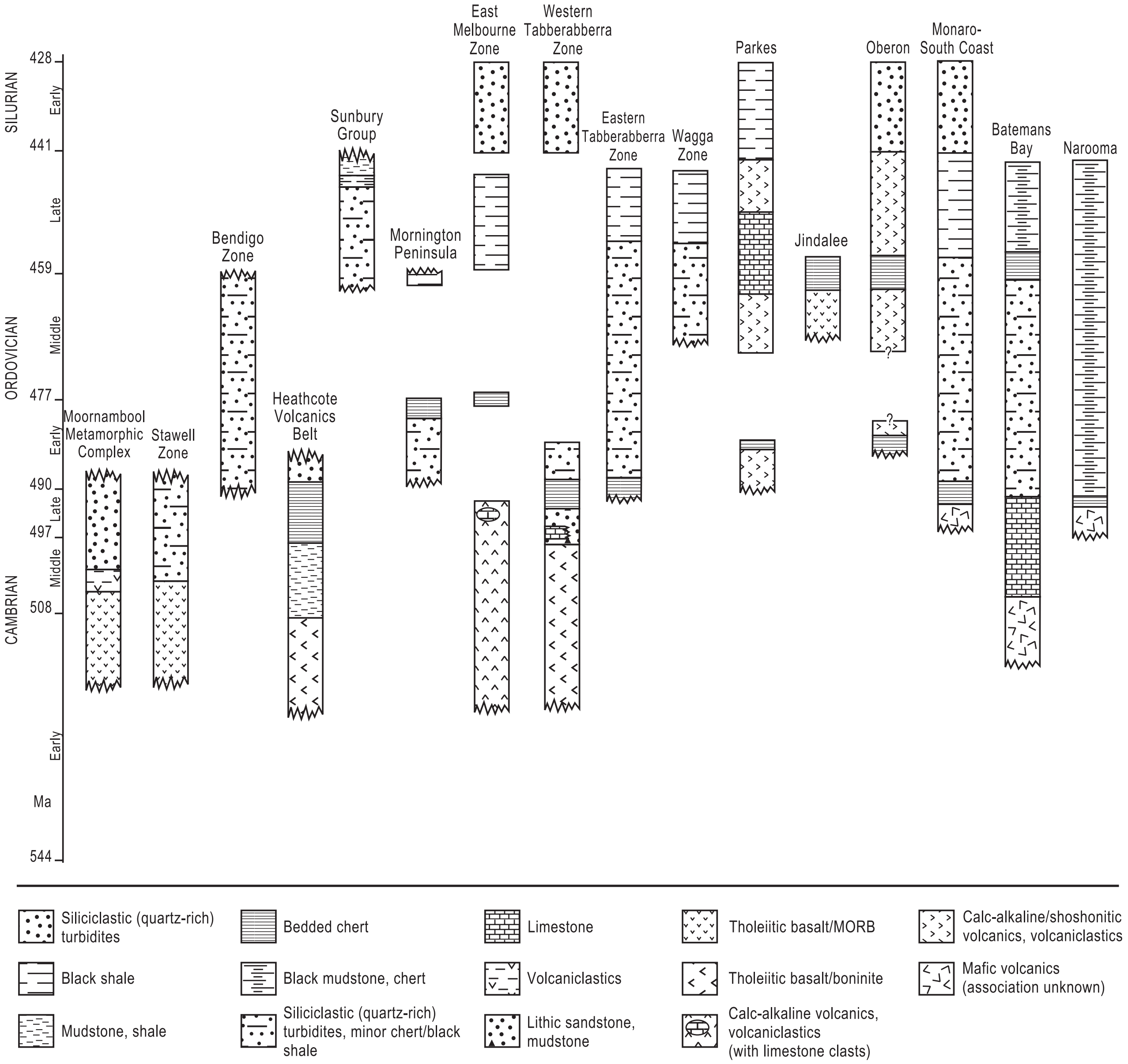

Figure 3 Stratigraphic columns from areas in the Lachlan Fold Belt where Cambrian–Ordovician rocks are exposed and have some age constraints (graptolites, conodonts, shelly faunas).

Western subprovince

The volcanic basement of the western subprovince consists of tholeiitic basalts in the western Stawell Zone, including amphibolites of the Moornambool Metamorphic Complex metamorphosed at pressures up to 800 MPa (depth of ~24 km: Watchorn & Wilson 1989; Phillips *et al.* 2002). Mafic volcanics have also been found along the Avoca Fault from the subsurface (drillcore and from mine dumps) near Pitfield (Morand *et al.* 1995). The geochemistry of the volcanics from near Pitfield and in the western Stawell Zone is consistent with a backarc basin setting (Ramsay *et al.* 1998; Cayley & Taylor 2001 pp. 56–58). The volcanic basement is most widely exposed along the Heathcote Volcanics Belt and consists of tholeiitic lava, boninite, mafic volcaniclastics and related intrusions (Crawford *et al.* 1984; VandenBerg *et al.* 2000 p. 30). Age constraints on the volcanic basement in the Stawell and Bendigo Zones come from the Heathcote Volcanics Belt where Middle Cambrian fossils occur in overlying shale and mudstone. These are, in turn, overlain by chert and succeeded by Lancefieldian siliciclastic turbidites at the base of the thick Lower to Middle Ordovician succession that is well established from abundant graptolite localities (Figure 3) (Cas & VandenBerg 1988). Further west in the Stawell and western Bendigo Zones, the siliciclastic turbidites lack fossils and are considered Late Cambrian to earliest Ordovician. The southern end of the Heathcote Volcanics Belt is lost along adjoining fault zones that terminate in Upper Ordovician quartz-rich turbidites and black shale of the Sunbury Group. The sedimentary rocks and their fossil content indicate pelagic and mass-flow sedimentation consistent with a deep-marine setting for the Stawell and Bendigo Zones in the Cambrian to Ordovician (Cas & VandenBerg 1988; VandenBerg *et al.* 2000 p. 46). Across the Stawell and Bendigo Zones, there is an overall decrease in age of the major turbidite packages (Figure 3), and this indicates eastward progradation of the turbidite wedge but is also consistent with the overall eastwards accretionary growth of the western subprovince (Gray & Foster 1997).

Basement of the Melbourne Zone is exposed in the Mt Useful Slate Belt of VandenBerg *et al.* (1995) and consists of calc-alkaline intermediate to silicic volcanics and volcaniclastics of inferred Cambrian age (Crawford *et al.* 1984; VandenBerg *et al.* 2000 pp. 37–38). The volcanics and related rocks formed in a shallow-marine setting in part as indicated by the presence of hyaloclastites, limestone clasts and rare fossil debris (Cayley *et al.* 2002). These rocks are fault-bound and no primary stratigraphic relationships with younger rocks are preserved. Rare Lower Ordovician black shale, chert and phosphorite occur in the eastern Melbourne Zone but in general Lower to Middle Ordovician rocks are missing. Upper Ordovician Mt Easton Shale occurs in fault contact with the Cambrian volcanics. Much of the Mt Useful Slate Belt consists of Silurian mud-rich and sand-rich turbidite successions, although fossils are scarce (VandenBerg *et al.* 1995).

In the southwestern Melbourne Zone on Mornington Peninsula, a Lower Ordovician quartz turbidite succession contains in its upper part a condensed succession of chert and black shale (Figure 3). VandenBerg *et al.* (2000 pp. 357–360) and Cayley *et al.* (2002) suggested that these rocks overlie a thin continental basement that is supposedly a northern extension of Tasmanian Precambrian crust (see Discussion).

In summary, the basement of the western subprovince consists of three igneous associations: (i) an association of tholeiitic basalts and boninite volcanics in the Heathcote Volcanics Belt; (ii) an association of tholeiitic basalts with backarc affinity in the Stawell Zone; and (iii) a calc-alkaline intermediate to silicic volcanic association developed in the eastern part of the Melbourne Zone.

Central subprovince

The central subprovince is dominated by the Ordovician quartz-rich turbidite succession with a lower unit of dominantly turbidites and an upper unit of black shale, overlain by a Lower Silurian turbidite succession in the Tabberabbera and Wagga–Omeo Zones (Figure 3) (Fergusson 1998; VandenBerg *et al.* 2000 pp. 51–61). Igneous basement to the turbidite succession has been found along the western boundary of the Tabberabbera Zone at several localities including Dookie, Howqua River and the Dolodrook River (VandenBerg *et al.* 2000 p. 32). The igneous rocks are boninitic and tholeiitic volcanics, include some ultramafic rocks and are similar to the tholeiitic basalt and boninite association of the western subprovince (Crawford *et al.* 1984). In the Howqua River, the igneous basement is overlain by Upper Cambrian clastics, chert and Lancefieldian turbidites, whereas at the Dolodrook River, ultramafic rocks are associated with Upper Cambrian limestone and lithic sandstone (Fergusson 1998; VandenBerg *et al.* 2000 pp. 43–44). The limestone is shallow marine but is interpreted as olistoliths in mass-flow deposits in a deep-marine setting (VandenBerg *et al.* 2000 p. 46). Lower Ordovician chert occurs below the Ordovician turbidites along the Wonnangatta Fault west of Tabberabbera (Fergusson 1998). Chert of Early to Middle Ordovician ages occurs interbedded with the turbidite succession (e.g. southeast of Tabberabbera: Stewart & Fergusson 1988).

Much of the Ordovician turbidite succession in the central subprovince lacks age-specific fossils and is therefore poorly dated. The Girilambone Zone contains the Girilambone Group that consists of a western unit and a unit in the east and south (Iwata *et al.* 1995). The western unit contains turbidites, chert and minor mafic volcanics with very low-grade regional metamorphism. The eastern and southern unit has higher metamorphic grade with several foliations. In the higher grade Girilambone Group, slivers of mafic schists occur and have been interpreted as ophiolitic fragments that represent oceanic basement to the turbidite succession (Scheibner & Basden 1998 p. 133), but more work is required to establish this. Similar low-grade and higher grade units also occur in the Wagga–Omeo Zone. Most of the scarce fossils in the central subprovince indicate uppermost Middle to Late Ordovician ages (Iwata *et al.* 1995; Percival 2000) with Early Ordovician graptolites found in black shale within the turbidite succession in northeastern Victoria (Kilpatrick & Fleming 1980).

In the Howqua River, west of the Cambrian slice of tholeiitic and boninitic volcanics but still east of the

Melbourne Zone is a 2–3 km-wide belt (Figure 1) that is herein called the Howqua River Zone. The western contact of the Howqua River Zone is the Howqua Fault with slate and phyllite of the Melbourne Zone further west; the eastern contact is the Yaw Fault with Cambrian volcanics of the Tabberabbera Zone to the east (Spaggiari *et al.* 2002a). The Howqua River Zone consists of highly disrupted Ordovician turbidites and blocks of Cambrian mafic volcanics, including blueschist fragments metamorphosed at temperatures of <450°C and at pressures of 700–900 MPa (Spaggiari *et al.* 2002a, b). Age constraints are based on local black shale containing Darriwilian–Gisbornian graptolites (Harris & Thomas 1938), reconnaissance SHRIMP ages of 450 ± 23 Ma on titanite in blueschist and Ar–Ar ages of 446 ± 2 Ma on slate that indicate Late Ordovician metamorphism (Spaggiari *et al.* 2002a).

Eastern subprovince

The eastern subprovince includes the Molong volcanic province, the Monaro forearc basin and the subduction complex at Narooma and Batemans Bay on the New South Wales south coast. In the Molong volcanic province, the oldest part of the succession consists of Lower Ordovician (lower Bendigonian) chert, mudstone and mafic–intermediate volcanics, intrusions and volcaniclastics found in the Parkes, Wellington and Oberon regions (Figure 3) (Sherwin 1996; Percival *et al.* 1999; Butera *et al.* 2001; Murray & Stewart 2001). No rocks containing late Bendigonian to early Darriwilian fossils are known from the Molong volcanic province suggesting either a long hiatus and/or erosion. Upper Ordovician volcanics, volcaniclastics, hemipelagic sediments and limestone are abundant and represent a major phase of island-arc growth (Fergusson & Colquhoun 1996; Glen *et al.* 1998). In the Mudgee region, the Upper Ordovician volcanics and related rocks overlie chert of late Darriwilian – early Gisbornian age and underlying quartz turbidites that contain no fossils but are presumably of Middle Ordovician age (Fergusson & Colquhoun 1996; Murray & Stewart 2001). A similar stratigraphy is recognised to the east of Oberon (Murray & Stewart 2001 figure 4, Oberon East column). These relationships demonstrate that the arc expanded across the Ordovician turbidite succession.

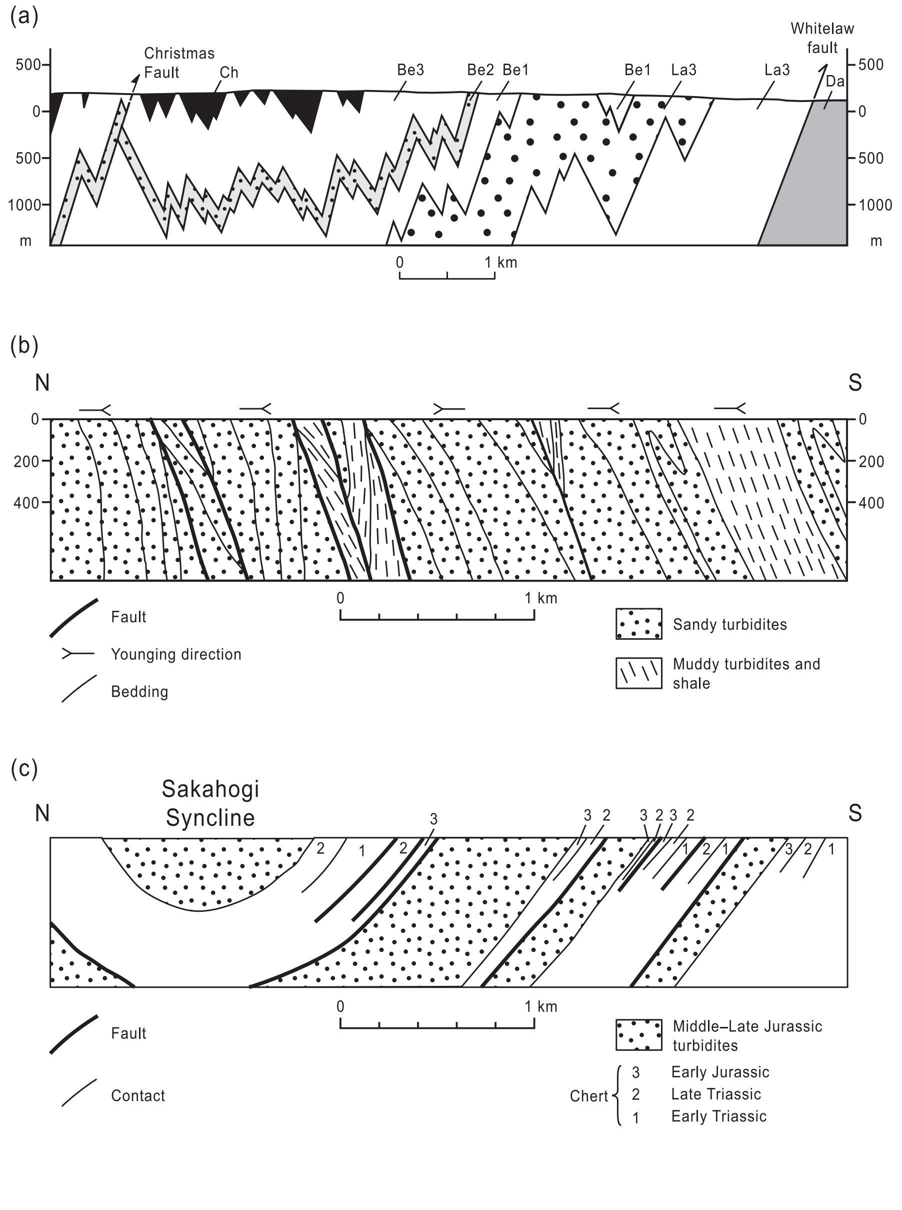

Figure 4 (a) West–east cross-section of folded quartz turbidites of the Bendigo Zone (redrawn from Willman 1992). Location is immediately north of Bendigo (Figure 1). Quartz turbidite succession is in stratigraphic order as determined from abundant (several hundred) graptolite localities. Subsurface structure also constrained by abundant underground workings. Key: east of Whitelaw Fault, latest Middle Ordovician (Da, Darriwilian); west of Whitelaw Fault, Early Ordovician (La3, Lancefieldian subzone 3; Be1–3, Bendigonian subzones 1–3; Ch, Chewtonian). Christmas Fault is an accommodation structure on the limb of an anticline (fault dies out at depth) whereas the Whitelaw Fault is a major thrust that dips steeply west and presumably has been rotated from an initial gentle dip during crustal shortening. (b) Cross-section of Eocene Shimanto Belt rocks from Cape Muroto, Shikoku (modified from Taira *et al.* 1988 figure 23, cross-section CD). (c) Cross-section of part of the Mino–Tanba Belt, Inuyama area, southwest Japan (modified from Matsuda & Isozaki 1991 figures 2, 3). In all cross-sections vertical scale = horizontal scale.

In the western Molong volcanic province, the Jindalee Group, which lies between the Ordovician island-arc rocks of the Parkes and Molong Zones, contains MORB volcanics and chert of late Darriwilian – early Gisbornian age (Lyons & Percival 2002). East of Parkes quartz turbidites (Kirribilli Formation) are associated with the late Darriwilian – early Gisbornian Mugincoble Chert (Raymond & Wallace 2000). Relationships between the turbidite–chert units and the bordering Ordovician volcanics are poorly known, although the lithological units and known ages are similar to comparable units of the Mudgee and Oberon regions.

Lower to Middle Ordovician turbidites have been mapped in eastern Victoria and along the New South Wales south coast (VandenBerg & Stewart 1992). The Upper Ordovician Bendoc Group and the Lower Silurian Yalmy Group also occur in inland parts of the eastern subprovince and parts of the central subprovince and indicate deep-marine starved sedimentation followed by renewed turbidite deposition (VandenBerg *et al.* 2000 pp. 58–60, 83–88).

At Batemans Bay and Narooma, relationships with basaltic basement are exposed although in both areas rocks are highly deformed with widespread mélange (Miller & Gray 1996, 1997). South of Batemans Bay at Melville Point the base of the Lower Ordovician turbidite succession overlies uppermost Cambrian – lowermost Ordovician bedded chert and black mudstone that in turn overlies altered mafic volcanics (Figure 3) (Powell 1983; Bischoff & Prendergast 1987; Fergusson & Frikken 2002). Further east at Burrewarra Point, Middle to Upper Cambrian limestone occurs associated with mafic volcanic breccias among the quartz turbidites in an interpreted accreted seamount fragment (Bischoff & Prendergast 1987). Also in the Batemans Bay region is a unit of bedded chert, black mudstone with thin white siltstone and lithic sandstone beds, chert contains conodonts of Darriwilian–Gisbornian age and black mudstone has yielded Eastonian and Bolindian graptolites (Jenkins *et al.* 1982; Fergusson & Frikken 2002). At Narooma, basaltic pillow lava (probable basement) is associated with a succession of chert and black mudstone with conodonts indicating possible deposition continuous from the Cambrian–Ordovician boundary through the Ordovician (Figure 3) (Stewart & Glen 1991).

Basement to the Ordovician island arc and quartz turbidite successions throughout most of the eastern subprovince is not exposed and it is not known how far the boninitic volcanics and tholeiitic basalts of the Tabberabbera Zone extend eastwards. Collins (1998) argued that granitoids throughout the eastern Lachlan Fold Belt formed by three-source component mixing with one of the sources being Cambrian greenstone preserved at depth.

STRUCTURE

Coherent units

The structure of the Stawell and Bendigo Zones is dominated by coherent, strongly folded turbidite successions and illustrates the typical style of deformation in Ordovician rocks of the Lachlan Fold Belt. Faults within these zones contain more intense deformation with transposition foliations, multiple fold phases and late crenulation cleavages (Gray & Willman 1991; Gray & Foster 1998; VandenBerg *et al.* 2000 pp. 218–256). The coherent nature of the succession is particularly well illustrated by very detailed mapping of the Bendigo goldfields where abundant graptolite sites show the presence of a tightly folded, coherent stratigraphic succession (Figure 4) (Willman 1992). Structures are northwest-trending in the Stawell Zone and north-trending in the Bendigo Zone (Figure 1). Shortening is high, usually in excess of 60%, and apart from the western part of the Stawell Zone, structures are east vergent throughout. Faults are responsible for repetition of the succession with major faults along the western boundary of the Stawell Zone and the eastern boundary of the Bendigo Zone (faults bounding the Heathcote Volcanics Belt). Apart from the western part of the Stawell Zone where higher metamorphic grades occur, metamorphism across both zones is consistently lower greenschist to zeolite facies with illite crystallinity indicating a slight decrease in metamorphic conditions from west to east (Offler *et al.* 1998). Metamorphic conditions in the Moornambool Metamorphic Complex indicate lower thermal gradients than those of metamorphic complexes in the central and eastern subprovinces (VandenBerg *et al.* 2000 pp. 64–65; Phillips *et al.* 2002) and might lend some support to the subduction complex interpretation.

Structures in the Ordovician rocks of the central and eastern subprovinces range from upright tightly folded and faulted low-grade units to more completely recrystallised rocks with poorly developed lithological layering and multiple generations of foliations/cleavages (Gray & Foster 1998; VandenBerg *et al.* 2000 pp. 279–323). At higher metamorphic grades, as in the Tottenham region of the Girilambone Zone (Figure 1), biotite zone rocks have well-developed subhorizontal foliation post-dated by upright folds and lie west of Ordovician island-arc rocks with younger, open, upright, north-trending folds that also affect overlying Silurian–Devonian units (Sherwin 1996). Metamorphism higher than biotite grade is widespread in the Wagga–Omeo Zone with scattered occurrences southeast and south of Canberra and continuing southwards into eastern Victoria (Carson & Rickard 1998; Scheibner & Basden 1998 p. 422; VandenBerg *et al.* 2000 pp. 65–69). Metamorphism in the Wagga–Omeo Zone ranges from low greenschist to upper amphibolite facies grades with sillimanite and andalusite, and constrained by ages of plutons and unconformities to the Early Silurian (VandenBerg *et al.* 2000 pp. 279–323; Collins & Hobbs 2001).

Mélange

Mélange zones are widespread in the Lachlan Fold Belt, although they are relatively minor in extent. In the western subprovince, the Moornambool Metamorphic Complex at the western margin of the Stawell Zone was identified as a metamorphosed tectonic mélange by Cayley and Taylor (2001), but Phillips *et al.* (2002) did not support this. Parts of the Heathcote Volcanics Belt are a tectonic mélange with diverse fragments of Cambrian volcanics, intrusions and local blueschist facies mafic volcanics (Spaggiari *et al.* 2002a, b). In the Tabberabbera Zone, Fergusson (1987) mapped tectonic mélange along the

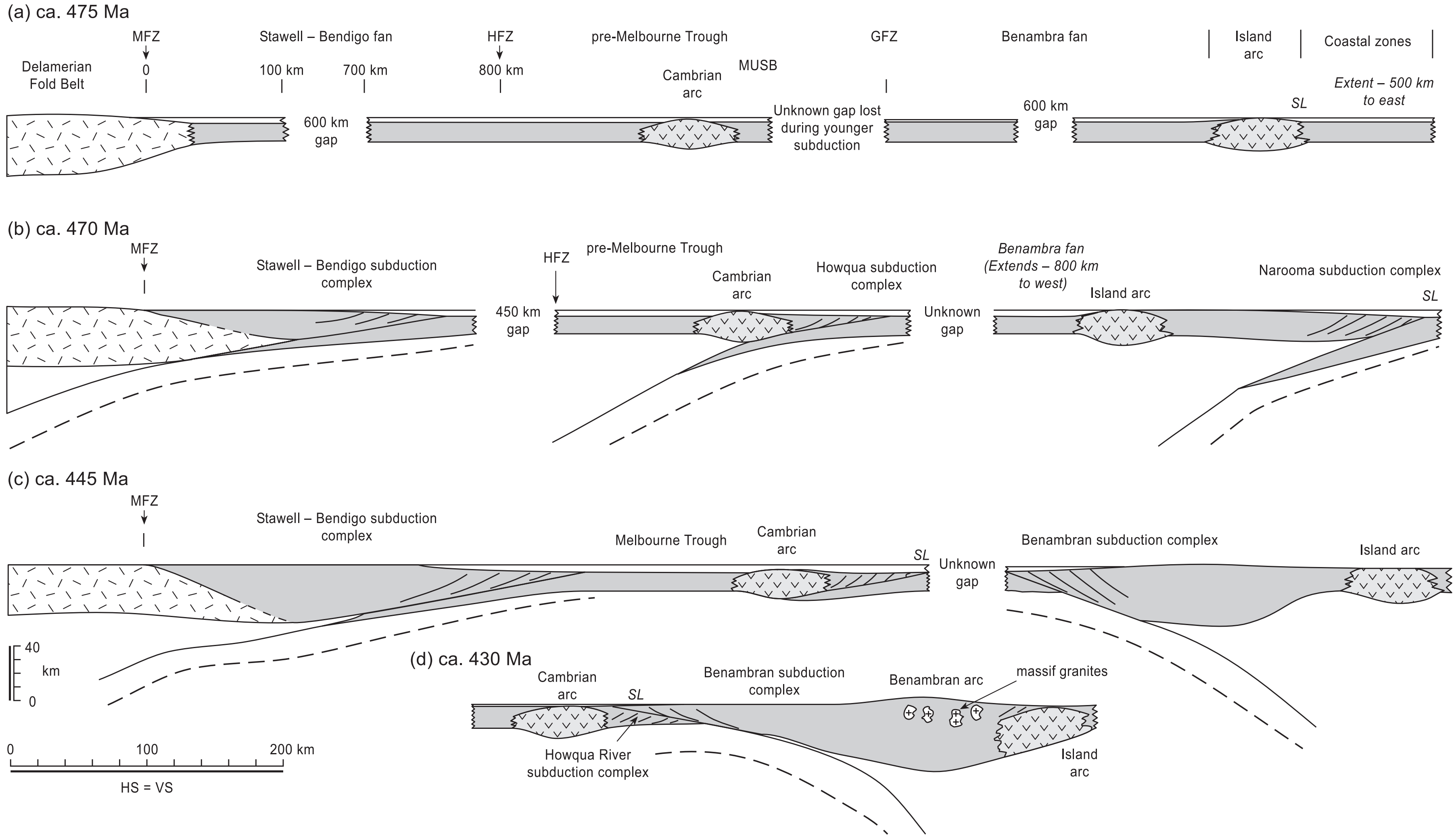

Figure 5 Schematic cross-sections of the evolution of intra-fold belt subduction zones in the Late Ordovician to Early Silurian interval of southeastern Australia. Cross-sections are drawn to scale with approximate crustal thicknesses constrained by modern analogues (Taira *et al*. 1998), known stratigraphic thicknesses and shortening estimates. (a) Early Middle Ordovician. (b) Late Middle Ordovician. (c) Latest Ordovician. (d) Early Silurian. In all cross-sections vertical scale = horizontal scale. GFZ, Governor Fault Zone; HFZ, Heathcote Fault Zone; MFZ, Moyston Fault Zone; MUSB, Mt Useful Slate Belt; SL, sea-level.

Wonnangatta Fault and several more belts have been recognised in the northwestern part of the zone (Watson & Gray 2001). The Howqua River Zone is characterised by an upright folded, but initially gently dipping, intense foliation/layering with zones of tectonic mélange (Spaggiari *et al.* 2002a, b). Mélanges from the Tabberabbera Zone were attributed to at least partial stratal disruption of sedimentary units when in an unlithified state, a feature that indicates relatively high fluid pressures and deformation relatively early in the tectonic history. Similar features have also been recognised in tectonic mélanges along the New South Wales south coast at Batemans Bay and Narooma (Miller & Gray 1996, 1997; Fergusson & Frikken 2002). Additionally, tectonic mélanges are associated with fault zones in rocks that contain abundant mudstone, as in the Goulburn region and the New South Wales south coast (Fergusson & VandenBerg 1990; Miller & Gray 1996, 1997).

TECTONIC HISTORY

In this section, a scheme is presented for the tectonic history of the Cambrian to Early Silurian history of the Lachlan Fold Belt and incorporates a west-dipping subduction zone associated with the Howqua River Zone in addition to the two subduction zones recognised in the double divergent subduction zone model for the western and central subprovinces (Gray & Foster 1997, 1998; Gray 1997; Soesoo *et al.* 1997; Gray *et al.* 1998, 2002; Foster & Gray 2000; Spaggiari *et al.* 2002a). Collins and Vernon (1992) inferred that an east-dipping subduction zone west of the Wagga–Omeo Zone generated an arc in the central Lachlan Fold Belt during the Benambran Orogeny. They subsequently modified this hypothesis to explain development of the Wagga–Omeo Zone by delamination. This process can be considered as a type of upper mantle subduction that produced contractional deformation and magmatism in the overlying crust (Collins 1994; Collins & Vernon 1994). Scheibner and Basden (1998 pp. 130–132) considered that an east-dipping subduction zone west of the Ordovician Molong island arc generated a possible subduction complex in the Wagga marginal sea.

Cambrian

The boninite–tholeiitic basalt association formed in an intraoceanic arc setting (Crawford *et al.* 1984; Crawford & Keays 1987). The type example of this is the Izu–Bonin–Marianas island arc that formed a zone averaging 300 km wide (locally up to 450 km wide) and several thousand kilometres long in the Eocene (Bloomer *et al.* 1995). The crustal generation rate was probably equivalent to a slowly spreading mid-ocean ridge and was formed by a poorly understood process (Bloomer *et al.* 1995). The crust of the Izu–Bonin–Marianas island arc has a thickness of 8.5–20 km and contains abundant tonalite as exposed in the Izu collision zone of central Japan (Taira *et al.* 1998). The backarc tholeiitic basalts of the Stawell Zone (see above) presumably formed by backarc spreading west of the intraoceanic arc.

The tectonic setting of the Cambrian calc–alkaline igneous association of the eastern Melbourne Zone is less straightforward. Cayley *et al.* (2002) noted compositional similarities of the Cambrian volcanics of the eastern Melbourne Zone to the post-collisional Mt Read Volcanics of Tasmania (Crawford *et al.* 1992) and the Mt Stavely Volcanics of western Victoria, and inferred a similar continental setting. Tectonic reconstruction for central Victoria is speculative. One scenario is that it involved events similar to those in western Victoria and Tasmania with obduction of the oceanic boninite – tholeiitic basalt association over the Gondwanan passive margin followed by post-collisional volcanism, as represented by the Mt Read Volcanics in Tasmania (Berry & Crawford 1988; Crawford & Berry 1992; Crawford *et al.* 1992) and the Mt Stavely Volcanics in western Victoria (VandenBerg *et al.* 2000 pp. 374–379). Another scenario is that these Upper Cambrian rocks are part of the oceanic assemblage (Figure 3) and formed as a Cambrian island arc that developed after the initial phase of rapid island-arc crust formation, consistent with the marine setting of the association.

Once the effects of younger deformation are removed, the Cambrian oceanic and island-arc basement must have extended as much as 1000–2000 km outboard of the Gondwanan margin (Figure 2) (Fergusson & Coney 1992a, b). By the Middle Cambrian, the Gondwanan margin was no longer a passive margin but was undergoing a complicated set of events involving plate convergence that affected eastern Gondwana from Queensland through the Ross Orogen of Antarctica (Stump 1995; Withnall *et al.* 1996; Preiss 2000; VandenBerg *et al.* 2000 pp. 374–379). The arrangement of Cambrian subduction zones in the palaeo-Pacific Ocean related to this active margin is poorly understood and it is conceivable that major strike-slip displacements have led to across-strike duplication of the Cambrian oceanic basement. In Figure 5a, no attempt is made to portray the location of intra-oceanic subduction zones that might have existed in this oceanic realm. By the Late Cambrian to earliest Ordovician, the thick quartz turbidite succession had prograded across the oceanic basement of the Stawell Zone. The lack of bedded chert between the volcanics and overlying turbidites in the western Stawell Zone implies that backarc spreading only briefly pre-dated turbidite deposition (Watchorn & Wilson 1989).

Ordovician – Early Silurian

By the Early Ordovician, the quartz turbidite wedge had prograded across the underlying ocean sediments to the New South Wales south coast (Figure 3). The Izu–Bonin–Marianas island arc, the modern analogue for much of the basement to the turbidite succession, has a complex bathymetry with many submarine ridges and rifted segments (Taylor 1992). By analogy, the Ordovician turbidite pile would have had to mantle complicated basement topography with the turbidite succession onlapping and thinning onto submarine highs. This could account for the lack of Ordovician quartz turbidites in the eastern Melbourne Zone where the pre-existing island arc formed a submarine ridge.

Development of Middle to Late Cambrian hemipelagic to pelagic successions overlying igneous basement implies that subduction had largely ceased in the oceanic realm apart from that associated with the Cambrian island arc in the eastern Melbourne Zone. Subduction at the eastern margin of the fold belt in the Early Ordovician is required to account for island-arc volcanism of the Molong volcanic province, although this seems to have been relatively short-lived (Figure 3). Deposition of much of the Ordovician quartz turbidite succession was concurrent with an interval of tectonic quiescence. Subduction renewed, presumably along the west-dipping subduction zone, in the Darriwilian, as shown by the growth of the island arc and the development of the subduction complex on the New South Wales south coast (Powell 1984; Miller & Gray 1996, 1997).

Subduction was also initiated in the backarc region in the late Middle Ordovician (Wagga marginal sea:

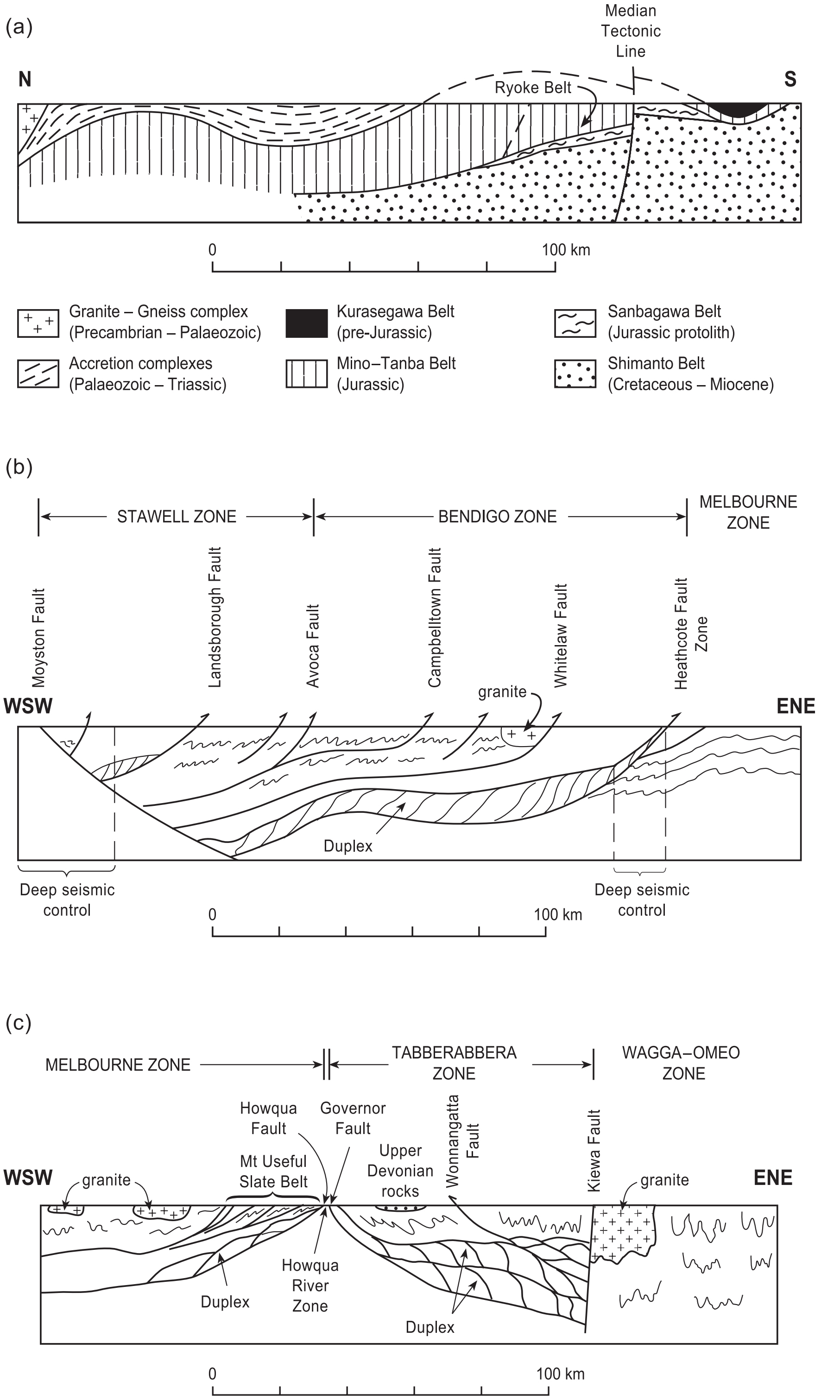

Figure 6 (a) 'Nappe-style' structure of the accretion complex of southwest Japan (modified from Isozaki 1996 figure 6). (b–c) 'Nappe-style' stacking of subduction complexes in the Lachlan Fold Belt of Victoria. Constraints on the crustal section include deep seismic lines of Gray *et al.* (1991) and Korsch *et al.* (2002). See Figure 1 for location. In all cross-sections vertical scale = horizontal scale.

Figure 5b). In the western subprovince, the late Middle Ordovician to Early Silurian palaeogeography consisted of possible shallow-marine deposition in the Grampians west of the Stawell and Bendigo Zones, deformation and uplift in the Stawell and Bendigo Zones and deep-marine sedimentation to the east in the Melbourne trough with sediment derived from the southwest (VandenBerg *et al.* 2000 pp. 380–381). Detrital mica ages of 450–440 and 500 Ma in the Melbourne Zone sediments indicate derivation from uplifted deformed rocks of the Stawell and Bendigo Zones (Foster *et al.* 1998 p. 243). This arrangement is consistent with the internal structure of the Stawell and Bendigo Zones that indicates they developed as an east-tapering wedge (Gray & Foster 1997). There is an overall progression across these zones in the stratigraphic range of turbidite-type rocks with the oldest successions in the west and the youngest in the southeast (Figures 1, 3). This progression is suggestive of accretionary growth and consistent with a subduction complex setting (Gray & Foster 1997). Ar–Ar ages indicate a Late Ordovician timing of white mica growth associated with major deformation in both zones beginning at approximately 457 Ma and continuing into the Early Silurian (Foster *et al.* 1998, 1999; VandenBerg 1999). This age could indicate that subduction began even earlier at *ca* 470 Ma (cf. Isozaki 1997b), although this seems unlikely given the continuing widespread quartz turbidite deposition into the upper Middle Ordovician (see below). Formation of the wedge is attributed to a gently inclined west-dipping subduction zone that disrupted the pre-existing thick Lower to Middle Ordovician turbidite succession.

No magmatic arc has been identified to be associated with the west-dipping subduction zone that formed the Stawell and Bendigo Zones. Not all subduction zones are associated with active volcanic arcs, as is shown by the Andes that lack of magmatic arcs over the flat-slab part of the subduction zone (Jordan *et al.* 1983). Low convergence rates might also have contributed to the absence of magmatic arc.

Fergusson and Fanning (2002) related subduction zones in the Wagga marginal sea and development of a wide subduction complex in the Stawell and Bendigo Zones to the termination of widespread sand deposition across the Ordovician turbidite fan in the eastern Lachlan Fold Belt. This resulted in deposition of the starved black shale unit in the Late Ordovician, although subsequently sand deposition resumed in the Early Silurian (VandenBerg *et al.* 2000 pp. 83–88).

Gray and Foster (1997) proposed the development of a subduction complex in the Tabberabbera Zone and formation of a related magmatic arc in the Wagga–Omeo Zone (Collins & Vernon 1992; Collins & Hobbs 2001). Mélange and blueschists in the Howqua River Zone are inferred to have formed in the early Late Ordovician from underplating related to this subduction zone (Spaggiari *et al.* 2002a). The incorporation of Lower Silurian turbidites in the Tabberabbera Zone and the abundance of magmatic activity in the late Early Silurian of the Wagga–Omeo Zone indicate that subduction was much later than that implied by the Howqua River Zone. A speculative reconstruction is proposed in Figure 5 whereby subduction in the Wagga marginal sea is initiated in two west-dipping subduction zones in the latest Middle Ordovician, as inferred from the widespread cessation of sand deposition on the turbidite fan in the central and eastern subprovinces. The western subduction zone is related to the Stawell and Bendigo Zones as discussed above.

The eastern subduction zone is inferred to explain the older age of subduction in the narrow Howqua River Zone (Spaggiari *et al.* 2002a). In contrast to the Stawell and Bendigo Zones, palaeogeography is poorly constrained for the Howqua River Zone but the abundance of disrupted rocks and the presence of blueschists are indicative of a subduction zone setting (Spaggiari *et al.* 2002a, b). Timing of subduction is constrained to the late Middle Ordovician to early Late Ordovician, and the absence of the Upper Ordovician black shale unit in the Howqua River Zone implies that the subduction event was short-lived. The polarity of the subduction zone is poorly constrained: a westerly dip is shown in Figure 5. Only a tiny part of this accretion complex is exposed and most is assumed buried in the subsurface (Figure 6c).

Subduction that formed the Wagga–Omeo Zone arc was initiated by the latest Ordovician and was active through the Early Silurian, resulting in accretionary growth of the Tabberabbera Zone with an eastern belt of Ordovician turbidites and chert and a western belt with Cambrian to Lower Silurian rocks, including the thick Lower Silurian turbidites of the Cobbannah Group (Fergusson 1998). The Tabberabbera Zone contains zones of chaotic rocks and slices of oceanic basement and chert (Fergusson 1998; Watson & Gray 2001) but nevertheless has much more in common with the Stawell and Bendigo Zones than subduction complexes such as the Mino–Tanba and Shimanto Belts (Figure 6a: see Discussion). The initiation of this subduction zone at approximately 440 Ma might have developed after or immediately before the cessation of subduction in the Narooma subduction complex (Figure 5). How subduction developed either side of the Molong arc is considered a contentious issue and far from completely resolved.

The Wagga–Omeo and Girilambone Zones occupy the central Lachlan Fold Belt and are dominated by Ordovician metasedimentary rocks and granitic plutons that were deformed during the Benambran Orogeny (Scheibner & Basden 1998 pp. 132–133). Much of these zones have relatively poor exposure and structures are poorly documented compared to the Stawell, Bendigo and Tabberabbera Zones. Initial deformation might have occurred in a subduction complex setting (Fergusson & Fanning 2002), but the situation is difficult to evaluate given the poor exposure and the effects of later deformation including Silurian strike-slip faulting and thrusting of the Wagga–Omeo and Girilambone Zones eastwards over the island-arc terrane (Morand & Gray 1991; Willman *et al.* 2002).

A distinctive feature of the Wagga–Omeo Zone is the aligned northwest-trending Early Silurian granitic plutons (Figure 1) (Gray 1997 figure 17) that have been interpreted by both Gray and Foster (1997) and Collins and Hobbs (2001) as a magmatic arc related to the subduction zone to the west. The Wagga–Omeo Zone, long considered a low-pressure type metamorphic belt, is analogous to the Ryoke Belt in Japan, which resulted from granite emplacement and metamorphism superimposed within a pre-existing Jurassic accretion complex in an arc environment (Nakajima 1994).

DISCUSSION

Nature of accretion

In contrast to well-established uplifted subduction complexes such as the Shimanto Belt of southwest Japan and the Kodiak Formation of Alaska, the turbidite-dominant zones of the Lachlan Fold Belt are structurally simpler and contain much wider and thicker accreted fault slices (Figure 4) (Sample & Moore 1987; Kimura 1997). Sediment thicknesses in the Lachlan examples are in excess of 2000 m (VandenBerg *et al.* 2000 pp. 51–61) and underlying igneous crust is inferred to have been 8.5–20 km thick on the basis of the analogous Izu–Bonin–Marianas island arc (Taira *et al.* 1998). Further, convergence rates were low, as is demonstrated for the Stawell, Bendigo and Howqua River Zones by the lack of associated arc magmatism, although blueschist metamorphic blocks are preserved (Spaggiari *et al.* 2002a, b).

Criticism of the inferred subduction complex settings of the western and central Lachlan Fold Belt has been directed at the structural style with the abundance of coherent rocks and the lack of mélange belts considered inappropriate for this setting (VandenBerg 1999; Taylor & Cayley 2000). For example, Isozaki (1997b) noted that chaotic units were dominant in the 3000 km-long Jurassic accretion complex (Mino–Tanba Belt) of east Asia. However, the prevalence of chaotic units in the Mino–Tanba Belt has been attributed to subduction of seamounts that typically causes disruption of accreted coherent units and preservation of slices of lower oceanic stratigraphy such as igneous basement and bedded chert. As noted above, chaotic units do occur in the Lachlan Fold Belt complexes, especially where the deeper levels of the stratigraphy are found but are nevertheless of overall minor extent. This anomaly is a consequence of the thicker than normal turbidite succession in the Lachlan Fold Belt (>2000 m) in contrast to turbidite units typically <1000 m thick in most convergent margin settings. The thick turbidite succession mantled the underlying sea floor so that sea-floor topography was smoothed and accretion of intact slices of turbidites has therefore dominated the wedge.

The Lachlan subduction complexes are significantly less structurally dismembered than many subduction complexes and are therefore not comparable to those of the Shimanto and Mino–Tanba Belts that contain widespread igneous basement and chert. They have more in common with coherent-strata-dominated subduction complexes such as the Coffs Harbour association and Shoalwater terrane of the New England Fold Belt, the Torlesse of New Zealand and the accretionary units of the Songpan–Garzi terrane in China (Fergusson 1982; MacKinnon 1983; Fergusson *et al.* 1990; Zhou & Graham 1996). In contrast, most of the Shimanto and Mino–Tanba Belts of southwest Japan have imbricate thrust sheets no more than 2–3 km apart (Figure 4c) (Matsuda & Isozaki 1991). This contrast is marked and indicative of the greater volumes of crustal components carried into the Lachlan zones. The lack of magmatic activity associated with two of the subduction zones in the Wagga marginal sea perhaps also indicates that lower convergence rates also contributed to the more coherent structural style. The Lachlan examples serve to illustrate an end-member of accretionary subduction zones and contrast with more intricately faulted complexes.

Another issue that should be addressed is how much of the crust of the remnant ocean basin is subducted and how much is accreted. Cloos (1993) analysed the problem of subduction of thicker than normal ocean crust and concluded that igneous crust up to 15–17 km thick is inherently subductable. In the Lachlan subduction zones, it is conceivable that part of the igneous crust, in addition to all the overlying sediment, was accreted. Accretion of mafic crust would account for the greater abundance of mafic rocks at depth that has been indicated for the lower crust of southeastern Australia (Gray *et al.* 1998). Thus, the lower part of crust up to 20–25 km thick in the Wagga marginal sea would be readily subducted if the top 5–15 km were accreted in the subduction complexes.

Selwyn Block

VandenBerg *et al.* (2000) and Cayley *et al.* (2002) have argued that the presence of continental crust beneath central Victoria (the Selwyn Block) had a controlling influence on the Ordovician tectonic development. Their model includes the idea that in the Benambran Orogeny, an oceanic portion of the Wagga marginal sea in western Victoria was subjected to major shortening as it was caught between rigid continental blocks of the Gondwana margin to the west and the Selwyn Block to the east. Contraction was driven by convergence along the west-dipping subduction zone at the eastern margin of the Lachlan Fold Belt. The basis of the hypothesis is that central Victoria is underlain by a northward extension of Tasmanian crust with Precambrian continental basement inferred from tracing magnetic anomalies across Bass Strait. As considered above, a continental basement for central Victoria in the Early Palaeozoic is one of two possibilities, and in this analysis is considered here less likely than an oceanic island-arc basement.

In the central Victorian model of Cayley *et al.* (2002), shortening in the Stawell and Bendigo Zones has been driven from afar but with the Selwyn Block acting as a local indentor. This is unlikely because of the general behaviour of ocean crust during crustal-scale deformation. Even though a thick sedimentary section overlay the igneous basement of the western Wagga marginal sea, the underlying igneous ocean crust would have controlled its ultimate strength. In addition, much of this igneous crust had formed as much as 50 million years prior to the initiation of deformation, and would therefore have had considerable time to cool and strengthen. As is well illustrated by plate-tectonic processes, ocean crust is stronger than continental crust. Typically, ocean plate boundaries are narrow in comparison to wide zones of deformation in continental crust (e.g. Himalayan–Tibetan collision zone). For example, deformation is widespread in continental mountain belts in northern Iran, Turkey and the Balkans as opposed to the more rigid behaviour of regions that have probable ocean basement, even where overlain by thick sedimentary sequences, such as in the Caspian and Black Seas (Sengör 1984; Allen *et al.* 2002).

Crustal structure

A new interpretation of the crustal structure of central Victoria is presented based on the tectonic scenario discussed above (Figure 6). Victoria is more suited for constraining crustal structure than elsewhere in the Lachlan Fold Belt given the insights from available deep seismic data and the constraints provided by surface geology (Gray *et al.* 1998; Korsch *et al.* 2002). In southwest Japan, and other accretionary complexes such as southern Alaska, accretionary units are interpreted on the basis of regional considerations and deep-seismic data to be stacked vertically to form major gently dipping sheets (Page *et al.* 1986; Isozaki 1997b). In keeping with the well-established structure of subduction complexes, the thrust pile youngs outwards and downwards away from the magmatic arc to the trench/palaeo-trench (Isozaki 1996). This principle is followed in construction of the crustal sections in Figure 6. Note that the crust as shown is dominated by the stacked accretionary units formed from accretion of the remnant ocean basin succession as best shown in the Stawell and Bendigo Zones but less well established for the central subprovince where the extent of the subduction complex in the Wagga–Omeo and Girilambone Zones remains less certain due to their less well understood structure.

CONCLUSIONS

The Lachlan Fold Belt is dominated by several stacked accretionary subduction complexes formed from frontal accretion of a thick remnant basin turbidite succession with accreted igneous basement, chert and limestone. In contrast to other accretion complexes, the lack of the lower ocean plate units is a reflection of the lack of topography on the subducting plate due to the blanketing effect of the thick turbidite succession. The arrangement of subduction zones in the Wagga marginal sea devised by Gray and Foster (1997) is revised with a new subduction zone inferred for the narrow Howqua River Zone at the western margin of the Tabberabbera Zone. Given the poor understanding of structure in the central subprovince, it is considered that the extent and number of subduction complexes will remain a subject of continuing debate.

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