Annu. Rev. Earth Planet. Sci. 2000. 28:47–80

EVOLUTION AND STRUCTURE OF THE LACHLAN FOLD BELT (OROGEN) OF EASTERN AUSTRALIA

David A. Foster and David R. Gray
Department of Geology, University of Florida, PO Box 112120, Gainesville, Florida 32611, e-mail: dfoster@geology.ufl.edu. Also at Australian Geodynamics Cooperative Research Centre, Department of Earth Sciences, La Trobe University, Melbourne, Victoria, Australia
Australian Geodynamics Cooperative Research Centre, Department of Earth Sciences, Monash University, Melbourne, Victoria, Australia

Key Words tectonics, Lachlan Fold Belt, Australia, Paleozoic, continental accretion, Gondwana

■ **Abstract** The Lachlan Fold Belt (Lachlan Orogen) of eastern Australia was part of a Paleozoic convergent plate margin that stretched around the supercontinent of Gondwana from South America to Australia. Lower Paleozoic (545–365 Ma) deep-water, quartz-rich turbidites, calcalkaline volcanic rocks, and voluminous granitic plutons dominate the Lachlan Orogen. These rocks overlie a mafic lower crust of oceanic affinity. Shortening and accretion of the Lachlan occurred through stepwise deformation and metamorphism from Late Ordovician (∼450 Ma) through early Carboniferous times, with dominant events at about 440–430 Ma and 400–380 Ma. The development and accretion of the Lachlan Orogen and other related belts within the Tasmanides added about 2.5 Mkm^2 to the surface area of Gondwana. The sedimentary, magmatic, and deformational processes converted an oceanic turbidite fan system into continental crust of normal thickness. The addition of this recycled continental detritus and juvenile material to Australia represents an under-recognized continental crustal growth mechanism that has been important thoughout earth history.

INTRODUCTION

The Lachlan Fold Belt (Lachlan Orogen) occupies the central part of the north-south trending, Neoproterozoic to Mesozoic Tasmanides (Scheibner 1974) along the eastern margin of Australia (Figure 1, see color insert). The Lachlan Orogen (Figures 1 and 2) is part of a Paleozoic orogenic system that extended some 20,000 km along the margin of Gondwana from the northern Andes through the Pacific margin of Antarctica to eastern Australia (Figure 3). The belt is composed of deformed deep-marine sedimentary rocks (quartz-rich turbidites), cherts, and mafic volcanic rocks of Cambrian to Devonian (520 Ma–350 Ma) age, and younger continental cover sequences (Cas 1983, Gray & Foster 1997). The Lach-

0084–6597/00/0515–0047$14.00

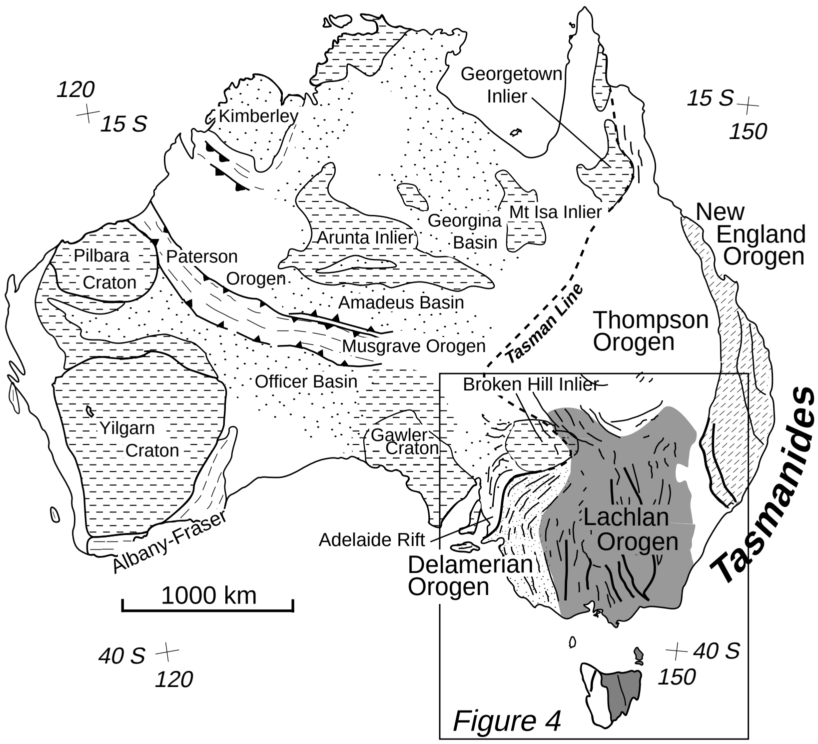

Figure 2 Map of major geological elements of Australia showing the Lachlan Orogen and other Phanerozoic orogenic belts of the Tasmanides.

lan has been described as an accretionary continental margin orogen that provides an unmodified example of Paleozoic Circum-Pacific tectonics (Coney 1992), or as a retreating subduction zone orogen (Royden 1993); it did not suffer a terminal continent–continent collision. The large volume of turbidites that make up the submarine sediment dispersal system was of similar scale to the Bengal Fan and eroded from the Cambrian (~500 Ma) Delamerian/Ross Orogen in Australia and Antarctica (Fergusson & Coney 1992b). The fan was developed mainly on oceanic crust and also within an island arc (Fergusson & Coney 1992a, Foster et al 1999, Glen et al 1998). The Lachlan crustal section is thought to comprise an upper crustal framework of thin-skinned thrust belts that flatten with depth and link into a mid-crustal detachment. The lower crust beneath the detachment is imbricated oceanic crust containing possible fragments of continental crust (Gray et al 1991, Leven et al 1992, Glen 1992, Gray & Foster 1998, Korsch et al 1999). The orogen developed through stepwise continental accretion of the oceanic sequences accompanied by marked Late Ordovician-Devonian structural thickening (~300%) and shortening (~75%) to form crust ~35–40 km thick. This

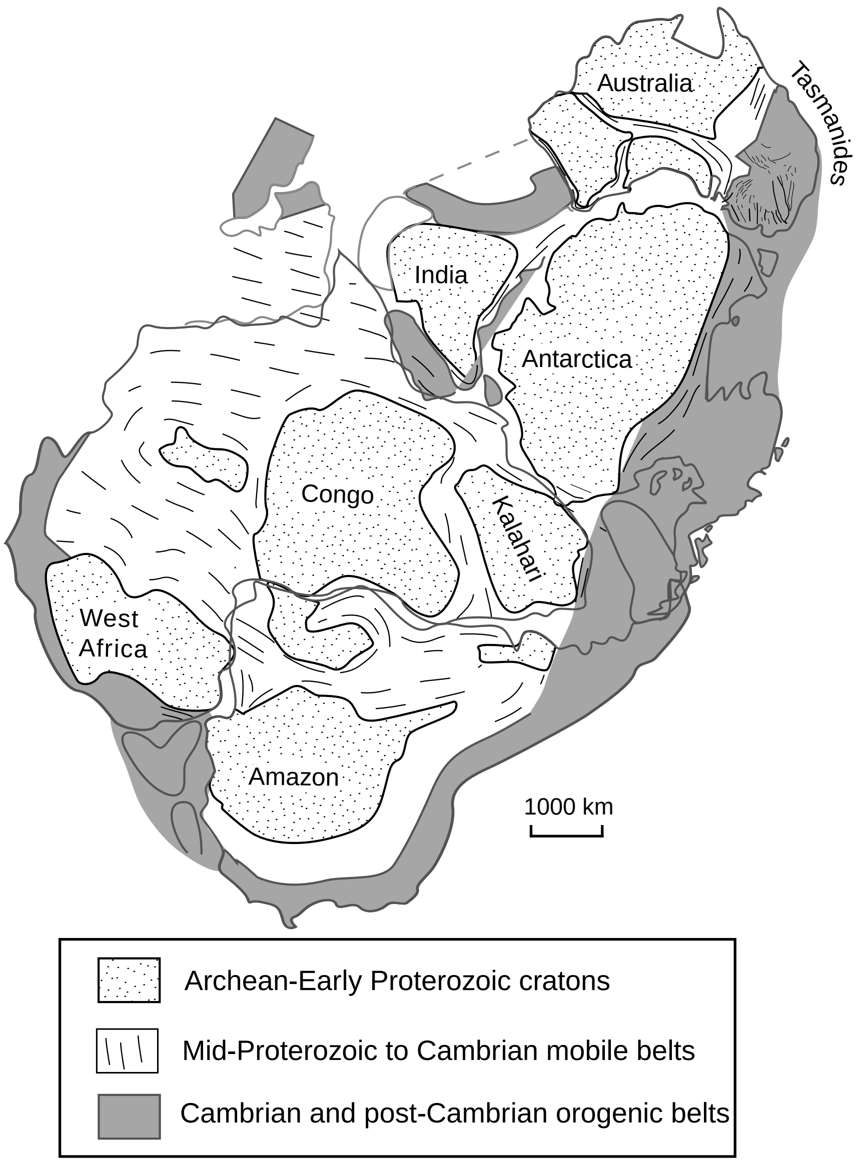

Figure 3 Map of Gondwana showing the position of the Tasmanides within a Paleozoic orogenic belt stretching from South America through Australia (reconstruction is based on Li & Powell 1993).

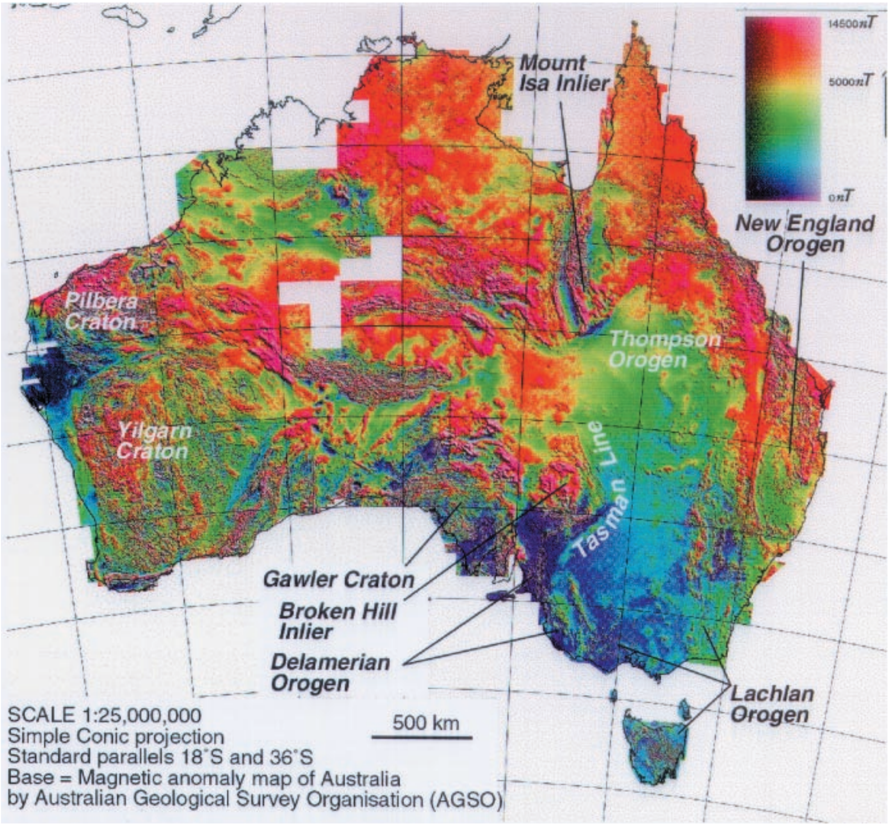

Figure 1 Magnetic anomaly map of Australia showing the difference between the Archean and Proterozoic cratons of Australia and the Phanerozoic orogenic belts. The Tasman Line marks the eastern limit of exposed Precambrian rocks. The Lachlan Orogen has a relatively quiet magnetic character, except for belts of mafic volcanic rocks resulting from the dominant Ordovician turbidite sequence. Magnetic base map is adapted from AGSO, by permission.

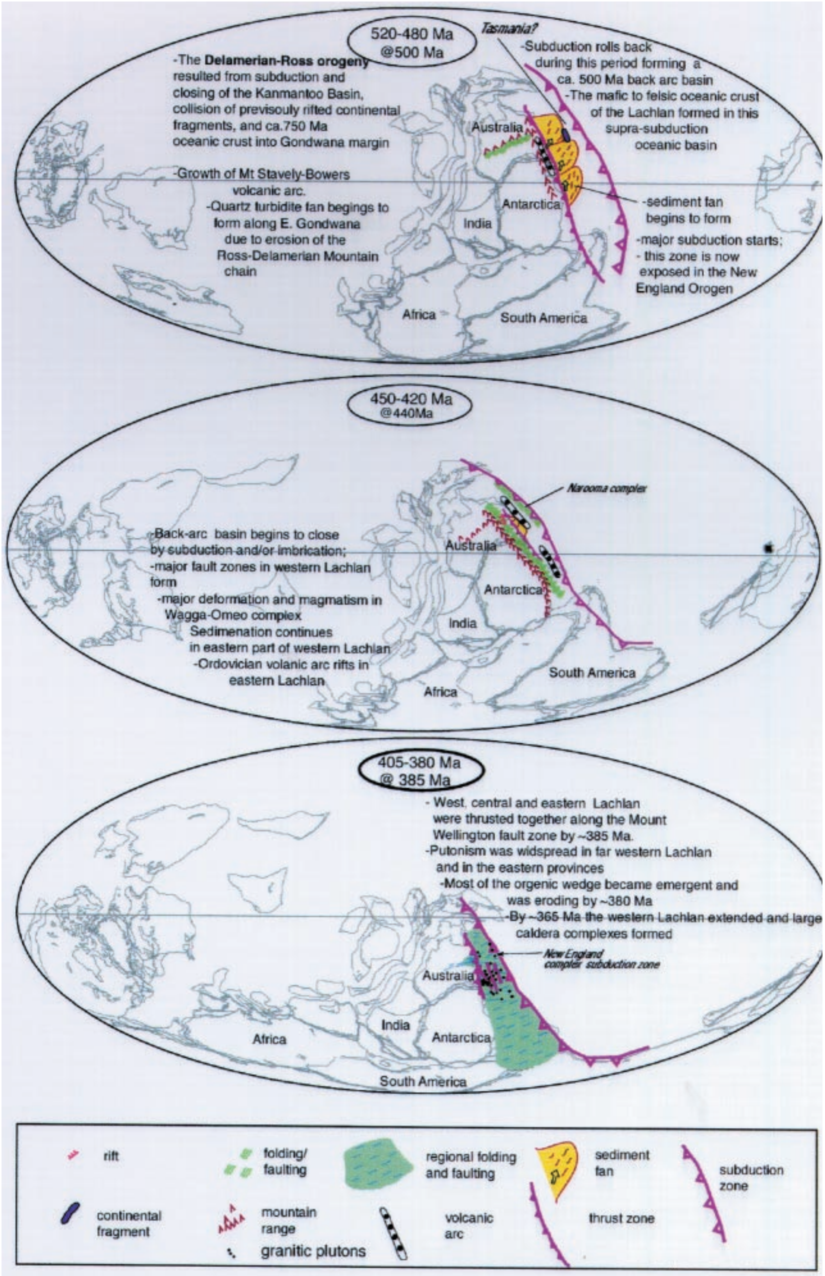

Figure 12 Plate tectonic model for the progressive development of the Lachlan Orogen from 520--380 Ma (Foster et al 1999). The plate positions and continental outlines were calculated and drawn using data in the Paleogeographic Information System/MacTM version June 7, 1997, by MI Ross & CR Scotese (PALEOMAP Project, Arlington Texas).

process included widespread magmatism and ultimately added approximately 2.5 Mkm^2 to the surface area size of Australia.

In some ways, the Lachlan Orogen differs from classical orogenic belts such as the Alps, Appalachians, and North American Cordillera, which were constructed partly of continental shelf sequences developed along margins of moderately thick (~30–40 km) continents (Coney et al 1990, Gray & Foster 1998). However, it shares similarities with other accretionary orogens such as those in central Asia, the Pan African belts of northeast Africa and Arabia (e.g. Sengor & Natal'in 1996), and the Proterozoic Yavapai Orogen south of the Wyoming craton (e.g. Hoffman 1988). The belt has similar lithotectonic assemblages, general structural style, and average level of exposure along the entire >1,000 km exposed length and across the ~700 km width of the belt (Gray 1997).

For this and other reasons, the tectonic setting and evolution of the Lachlan Orogen have been contentious (see Gray 1997, Gray & Foster 1997). Significant advances in understanding the Lachlan Orogen have been made in the last five to ten years, including improvement in understanding of: timing and patterns of deformation (Foster et al 1998, 1999); origin of the granitic plutons (Collins 1998); nature of the Ordovician arc in the east (Glen et al 1998); nature of the lower crust (Spaggiari et al 1999, Korsch et al 1999); and significance of the fault zones (Gray & Foster 1998). This paper summarizes the broad structures and nature of the Lachlan Orogen and presents an interpretation of the major tectonic events and settings.

THE TASMANIDES

In eastern Australia three north-south trending deformed belts make up the composite Tasmanides (Delamerian, Lachlan/Thomson, and New England Orogens, Figure 4). These orogens are distinguished by their lithofacies, tectonic settings, timing of orogenesis, and eventual consolidation to the Australian craton. Boundaries between them are generally not exposed and are covered by younger sequences. The more internal part, including the Neoproterozoic-Cambrian Delamerian and the western part of the Lachlan Orogen, shows pronounced curvature and structural conformity with the promontories and recesses in the old cratonic margin (Tasman Line) (Figures 1 and 2). The Lachlan and Thomson parts of the orogen have arcuate trends that coincide with the recesses of the old cratonic margin. Outboard of this, the central and eastern belts of the Lachlan and the Carboniferous-Triassic New England Orogen have more continuous trends that truncate the inner belt trends and thus show no relationship to the old cratonic margin. The older western parts of the Tasmanides (Delamerian and westernmost Lachlan) were continuous with orogenic belts of similar age in north Victoria Land, Antarctica, where they make up the Ross Orogen (Foster & Gleadow 1992, Flöttmann et al 1993, Flöttmann & Oliver 1994). The Wilson Terrain of Antarctica is equivalent to the Delamerian, whereas the Robertson Bay Terrain shows similarities to the westernmost Lachlan. The younger parts of the Tasmanides, includ-

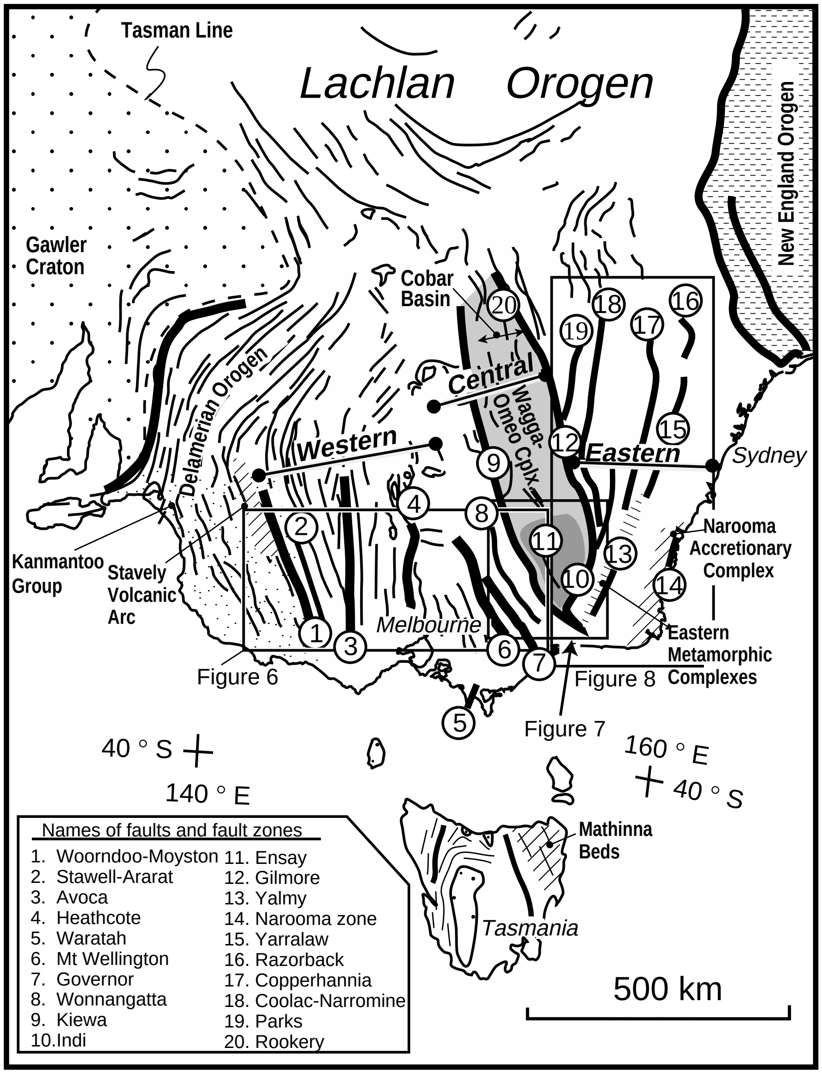

Figure 4 Structural trend map of the Lachlan Orogen and Tasmanides combining aeromagnetic trend lines and outcrop traces from regional maps and satellite images (after Foster et al 1999). The western, central, and eastern subprovinces are identified, along with major faults (1–20).

ing the New England Orogen, were fragmented by the opening of the Tasman Sea during the Cretaceous and early Tertiary (Veevers et al 1991). Rifted and separated parts of the Tasmanides, as well as younger outboard terrains, are now located in New Zealand, New Caledonia, and Lord Howe Rise (Gibson & Ireland 1996, Adams & Kelley 1998, Aitchison et al 1998).

DELAMERIAN OROGEN

The Delamerian Orogen is an arcuate, craton-verging thrust belt (Figure 4) with foreland-style folds and detachment-style thrusts to the west, and a high T/low P metamorphic hinterland to the east (Marshak & Flöttmann 1996). The high-grade part is characterized by polyphase deformation, amphibolite grade metamorphism, and intrusion of syn- and post-tectonic granites (Sandiford et al 1992). During the Middle Cambrian (~500 Ma), allochthonous sheets consisting of NW-verging duplexes of Cambrian Kanmantoo Group were emplaced over the less deformed and Neoproterozoic Adelaidean metamorphosed shelf sequence of the external zone (Jenkins & Sandiford 1992, Flöttmann et al 1994) (Figure 4). Relatively rapid unroofing is suggested by juxtaposition of these high-grade rocks and their syn-tectonic granites (520–490 Ma) with undeformed, high-level silicic granites and volcanics intruded at ~485 Ma (Sandiford et al 1992; Turner et al 1992, 1993, 1994). Exhumation of the Delamerian Orogen and the formerly continuous Ross Orogen of Antarctica provided a source for the extensive Cambro-Ordovician turbidite sequences of the Lachlan Orogen to the east (Turner et al 1996, Foster et al 1998).

LACHLAN OROGEN

Stratigraphy and Structural Framework

The Lachlan Orogen consists of three separate and distinct subprovinces (Figure 4), each with differences in rock type, metamorphic grade, structural history, and geological evolution (Figure 5). The western and central subprovinces are dominated by a turbidite succession consisting of quartz-rich sandstones and black shales. The eastern subprovince consists of mafic volcanic, volcaniclastic, and carbonate rocks, as well as quartz-rich turbidites and extensive black shale in the easternmost part (VandenBerg & Stewart 1992). The nature of the basement to the turbidite succession is less certain. In the western subprovince, Cambrian (~500 Ma) mafic volcanic rocks of oceanic affinities underlie the quartz-rich turbidite succession, whereas in the eastern subprovince the oldest rocks observed are Ordovician arc volcanic rocks and a Late Cambrian/Early Ordovician (~500–480 Ma) chert/turbidite/mafic volcanic sequence.

Although differences exist among the three subprovinces, little evidence suggests that they are far traveled with respect to each other. The subprovinces probably all formed along the same Gondwanan margin at different distances from the continental margin and different positions within the sediment fan, with the

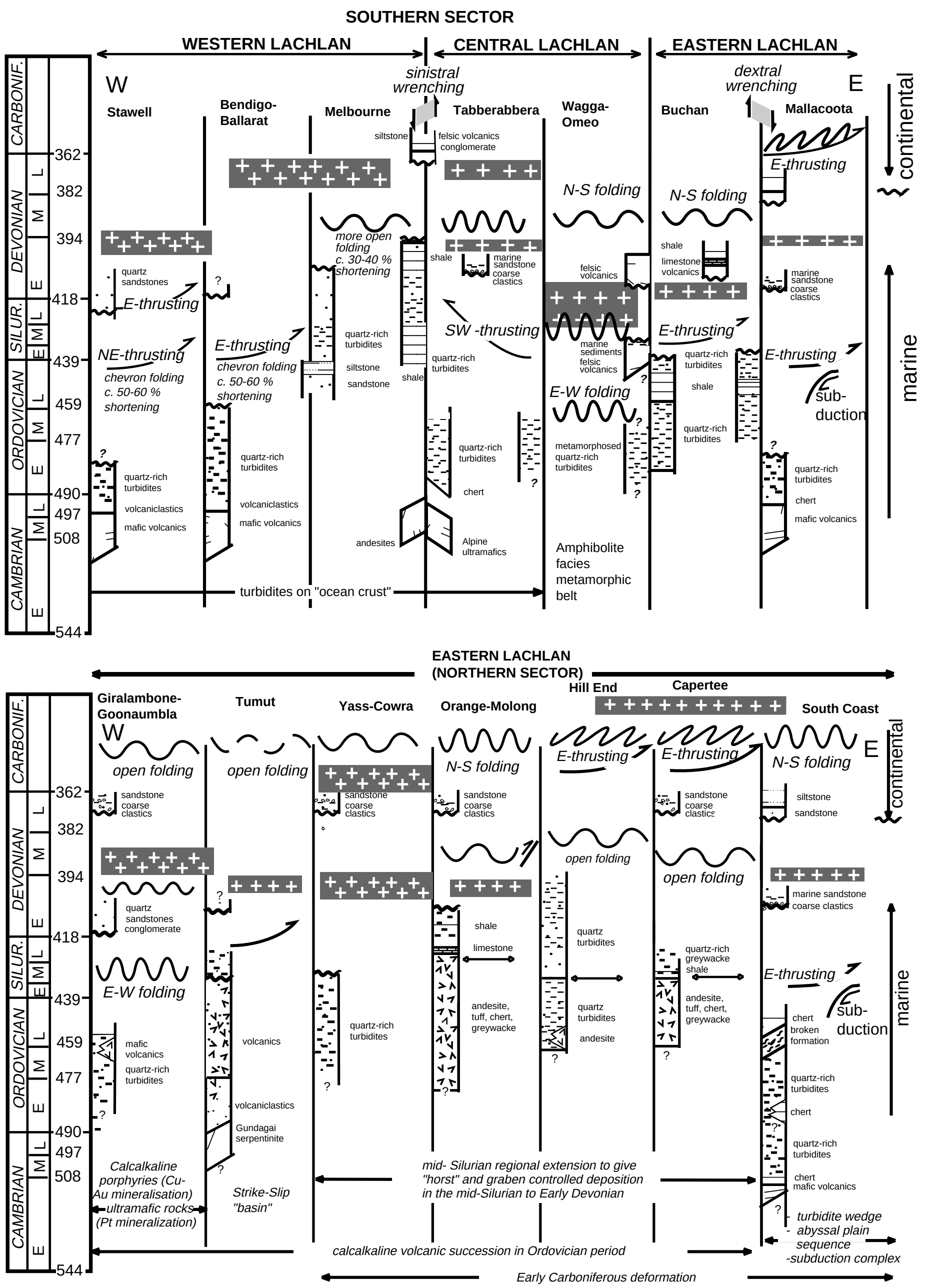

Figure 5 Time–space plot showing the relationships between sedimentation, deformation, and plutonism (*white crosses*) for the southern and northern Lachlan Orogen.

development within or away from the volcanic arc (Coney 1992). Moreover, the consistency of stratigraphy and structures around the southern end of the central metamorphic complex (Figure 4) suggests that the central and eastern subprovinces were linked from early in the Paleozoic (Wilson et al 1999). Strike-slip translations have been proposed between some of the subprovinces, on their bounding faults juxtaposing parts of the Paleozoic margin that developed along strike from each other (VandenBerg & Stewart 1992, Glen et al 1994). Importantly, though, determinations of preserved wrench components of displacement along faults are always less than 50 km (Gray & Foster 1998).

Structurally, the Lachlan consists mainly of a simple sequence of upright chevron folds and steep faults. (Folds range from open to tight.) Within this sequence, a number of fault-bounded structural zones show differences in structural trends, the timing and nature of deformation, and tectonic vergence (Figures 6, 7, and 8). These zones show no simple accretionary trends, and the Orogen is not dominated by thrust-belts verging toward the craton. The western subprovince consists of an east-vergent thrust system with alternating zones of northwest- and north-trending structures (Gray & Willman 1991a,b; Wilson et al 1992; Foster et al 1996). The central subprovince is dominated by northwest-trending structures and consists of a southwest-vergent thrust-belt linked to a fault-bounded metamorphic complex (Morand & Gray 1991). The eastern subprovince is dominated by a north-south structural grain and east-directed thrusting associated with inverted extensional basins in the west, along with an east-vergent thrust system in the east that links into an accretionary complex. The central subprovince separates the regions of different lithostratigraphy that were subsequently juxtaposed along the regional fault systems, both within and bounding the central belt (Fergusson et al 1986, Morand & Gray 1991, VandenBerg & Stewart 1992, Glen 1992).

The Western Subprovince

The western subprovince (Figure 6) is a folded turbidite sequence cut by a series of strike-parallel, west-dipping, reverse faults that link into a mid-crustal detachment fault to form an east-vergent thrust system (Gray 1988; Cox et al 1991; Gray & Willman 1991a,b; Gray et al 1991; Foster et al 1996). These major faults are steeply dipping zones, up to 2 km wide, of strongly deformed rocks with intense development of obliquely trending crenulation cleavages that are generally, but variably, associated with steeply plunging meso- and micro-folds. The faults expose Cambrian (~500 Ma) metavolcanics (tholeiitic basalts, boninites, andesites, and rare ultramafics), cherts, and volcaniclastics in their immediate hanging walls. Although the Cambrian rocks are all fault-bounded, they form basement to the younger clastic succession, and have mid-ocean ridge basalt (MORB) or back-arc basin (BAB) affinities (Crawford & Keays 1978, Crawford et al 1984). Relict blueschist facies assemblages occur in mafic rocks of the Heathcote and the Stawell-Ararat fault zones (Spaggiari et al 1999, Wilson et al 1992). These metavolcanic rocks are heterogeneously deformed with undeformed blocks containing relict igneous textures surrounded by shear zones consisting of

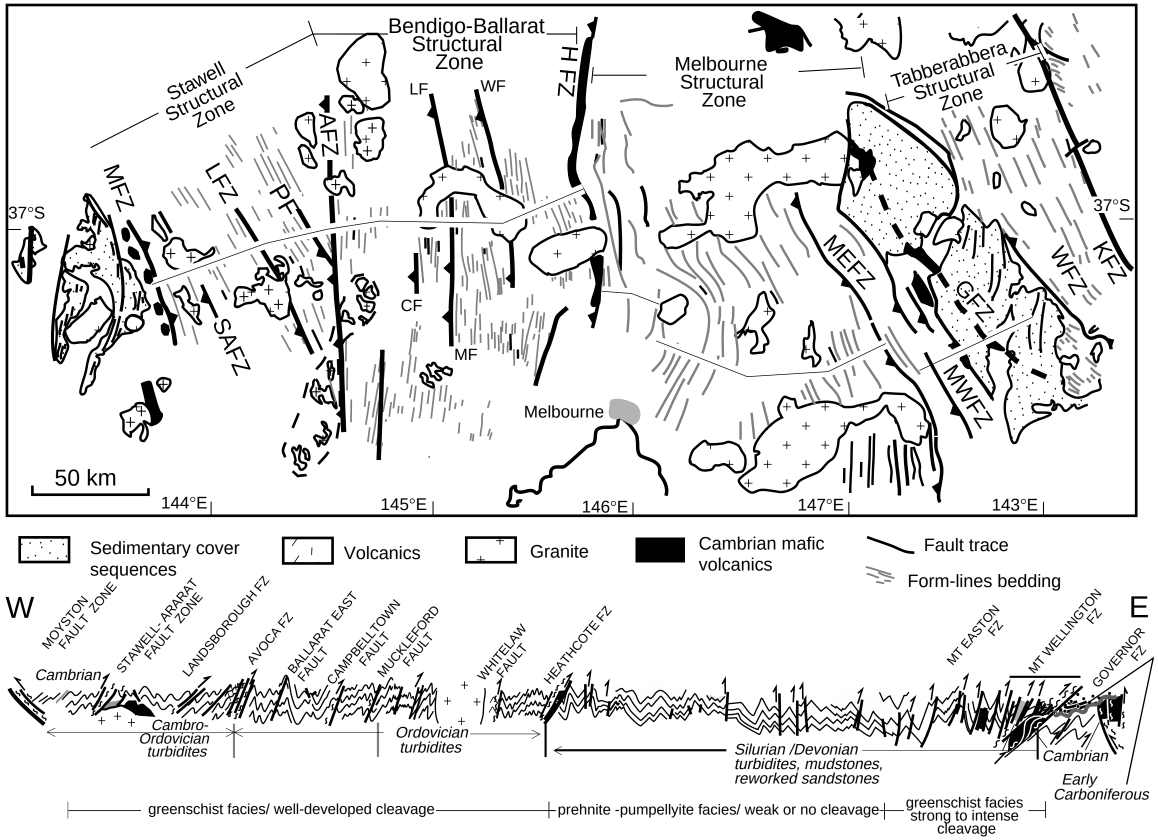

Figure 6 Structural trend map and profile of the western Lachlan orogen incorporating the Stawell, Bendigo-Ballarat, and Melbourne structural zones (Gray & Foster 1998, Foster et al 1999). Faults are shown as bold lines and include MFZ, Moyston fault zone; SAFZ, Stawell-Ararat fault zone; LFZ, Landsborough fault zone; PF, Percydale fault; AFZ, Avoca fault zone; BEF, Ballarat East fault; CF, Campbelltown fault; LF, Leichardt fault: MF, Muckleford fault; WF, Whitelaw fault; HFZ, Heathcote fault zone; MEFZ, Mount Easton fault zone; MWFZ, Mount Wellington fault zone; GFZ, Governor fault zone; and WFZ, Wonnangatta fault zone.

talc and serpentinite. The metavolcanic belts represent peeled-off segments of the upper oceanic crust and are spaced at 110–150 km intervals in the western Lachlan Orogen (Gray & Foster 1998).

Stratigraphy above the metavolcanic rocks is dominated by Cambrian-Ordovician (~500–470 Ma) quartz-rich turbidites in the west and a sequence of Ordovician to Devonian (~480–390 Ma) strata in the east. Stratigraphic control is based on a relatively complete graptolite zonation (VandenBerg 1988). The younger strata in the east include black shale, mudstone, and reworked sandstone (Moore et al 1998).

The turbidites now consist of chevron-folded sandstone and mudstone layers, which reflect up to 65% shortening above the mid-crustal detachment (Gray & Willman 1991b). Regional scale anticlinoria and synclinoria, with a slaty cleavage that ranges from weakly fanning to axial surface in style, are cut by steeply east and west dipping reverse faults and by quartz veins (Gray et al 1991). The main fabric development, related to mica growth in both slate and psammite, occurred late in the chevron fold development after fold lock-up and attainment of maximum tectonic thickening (Gray & Willman 1991b, Yang & Gray 1994). Overall, tectonic shortening ranges from 30–50% (owing largely to folding) in the eastern segment, and from 60–70% in the other zones because of folding, cleavage development, and faulting (Figure 6).

Hanging wall stratigraphy of major faults indicates that detachments occur at the base of the Ordovician turbidite sequence (Lancefieldian, ~490 Ma) and within the Cambrian mafic volcanics of the western Lachlan (Gray & Willman 1991a,b). Deep seismic profiling and microseismicity studies suggest that the detachment is at ~15–17 km depth (Gray et al 1991, Gibson et al 1981) and shallows to the east where it is exposed as the Mt. Wellington fault zone.

The western boundary of this subprovince is the Moyston fault zone (Foster & Gleadow 1992, Cayley & Taylor 1999). This fault is a 20-km wide zone that dips steeply eastward and places amphibolite facies rocks of the Lachlan on low-grade rocks of the Delamerian. The Moyston fault appears to have developed as a back thrust or a retro-wedge to the growing east-vergent system (Foster et al 1999, Cayley & Taylor 1999).

Metamorphism of the turbidites is mainly epizonal to anchizonal in the west between the Stawell and Heathcote faults, with b_o lattice spacing of phengites indicative of intermediate pressure regional metamorphism in a low geothermal gradient environment (Offler et al 1998a); metamorphism is anchizonal to diagenetic east of the Heathcote fault. Exceptions to the low greenschist to subgreenschist grade include schistose to hornfelsed contact zones of Devonian (~400 Ma) plutons (Offler et al 1998a) and the amphibolite facies rocks unroofed in the hanging wall of the Moyston fault (Cayley & Taylor 1999).

The Central Subprovince

The Central subprovince (Figure 7) is dominated by the fault-bounded Wagga-Omeo metamorphic complex of greenschist to upper amphibolite facies rocks

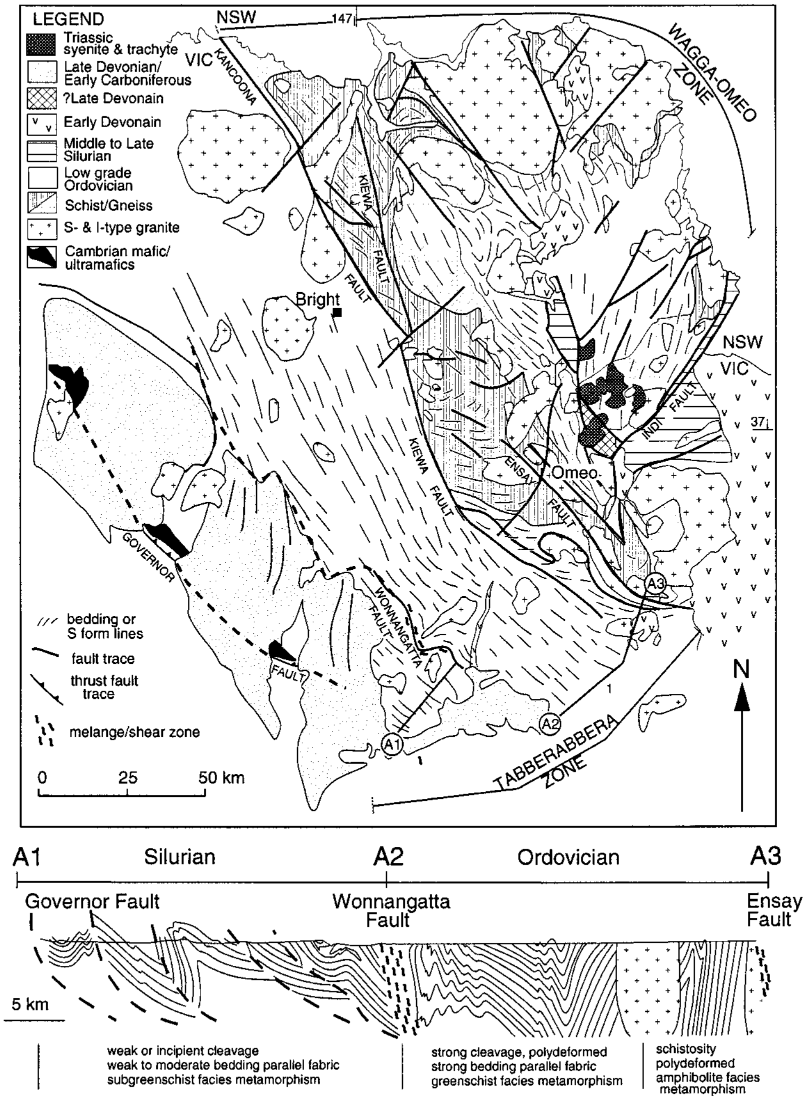

Figure 7 Structural trend map and profile of the central Lachlan orogen incorporating the Wagga-Omeo and Tabberabbera zones (Fergusson 1987; Morand & Gray 1991; Gray & Foster 1998). The frontal fault of the Tabberabbera zone is the Governor fault zone. Abbreviations are as follows: GFZ, Governor fault zone; WFZ, Wonnangatta fault zone; and EF, Ensay fault.

(Morand 1990). The subprovince consists of complexly deformed Ordovician metasedimentary rocks dominated by Early to Middle Silurian (~440–425 Ma) deformation, and is intruded by Silurian to Devonian (~430–400 Ma) granites (Morand & Gray 1991, Glen 1992, Fergusson & Coney 1992b, Wilson et al 1999). Much of the complex, which represents the main locus of Paleozoic intermediate to high-grade, low-pressure metamorphism in the Lachlan Orogen, is bounded by major amphibolite-upper greenschist facies and mylonitic strike-slip faults, especially on the western and eastern margins (Kancoona, Kiewa, Ensay, Cassilis faults on the west and the Gilmore fault in the east; Gray & Foster 1998). For example, the Kiewa fault zone is a 1.5-km wide, steeply west-dipping mylonite zone, with S-C fabrics indicating an early dextral strike-slip movement, overprinted by post-Middle Devonian faults with sinistral strike-slip movement (Morand & Gray 1991). Part of the southeastern margin is bounded by a major thrust fault (Indi Fault) (Morand & Gray 1991).

External to the subprovince on the southeast side is a low metamorphic grade, north-northwest trending belt of chevron-folded and faulted Ordovician turbidites in the east and Silurian turbidites in the southwest (Tabberabbera Zone) (Fergusson 1987, 1998). A 2-km wide melange zone (Wonnangatta Fault) separates thick-skinned structures, dominated by folds with tighter wavelengths (~10 km), larger amplitudes (~10 km), and polydeformation, from a thin-skinned zone with only one set of fold structures cut by north-dipping reverse faults (Fergusson 1987, Gray & Foster 1998). Both the Ordovician and Silurian strata are characterized by very strong bedding-parallel fabrics that are tectonic in nature because they form axial surfaces to early buckled quartz veins. At the boundary fault (Governor fault) between the central and western subprovinces, tectonic vergence changes from west to east facing, respectively. Ultramafic to mafic melange zones including blueschist facies blocks are exposed at this interface within a series of steep anastomosing faults (VandenBerg et al 1995, Spaggiari et al 1999, Gray & Foster 1998).

The Wagga-Omeo complex metasediments are associated with large volumes of Early Silurian and Devonian (~430–400 Ma) granite. Peak metamorphic temperatures and pressures in the southern part of the complex were ~700°C and ~3.5 kbar (Morand 1990), producing anatectic migmatites and diatexites (Wilson et al 1999). Erosional unroofing of the metamorphic complex in the Middle-Late Silurian, documented in the Wombat and Cowombat rifts, requires shallow overburden and rapid unroofing (Morand 1990, Foster et al 1999). Wrenching on the northwest-trending marginal shear zones combined with thrusting along the leading edge led to emplacement of the Wagga-Omeo complex as a southeast-moving crustal wedge in the Late Silurian to Early Devonian (~420–400 Ma) (Morand & Gray 1991).

The Eastern Subprovince

The Eastern subprovince (Figure 8) is characterized by a series of anticlinorial and synclinorial zones bounded by both east- and west-dipping reverse faults. Folding is more open (interlimb angles of 70°–120° with shortenings of 24–33%

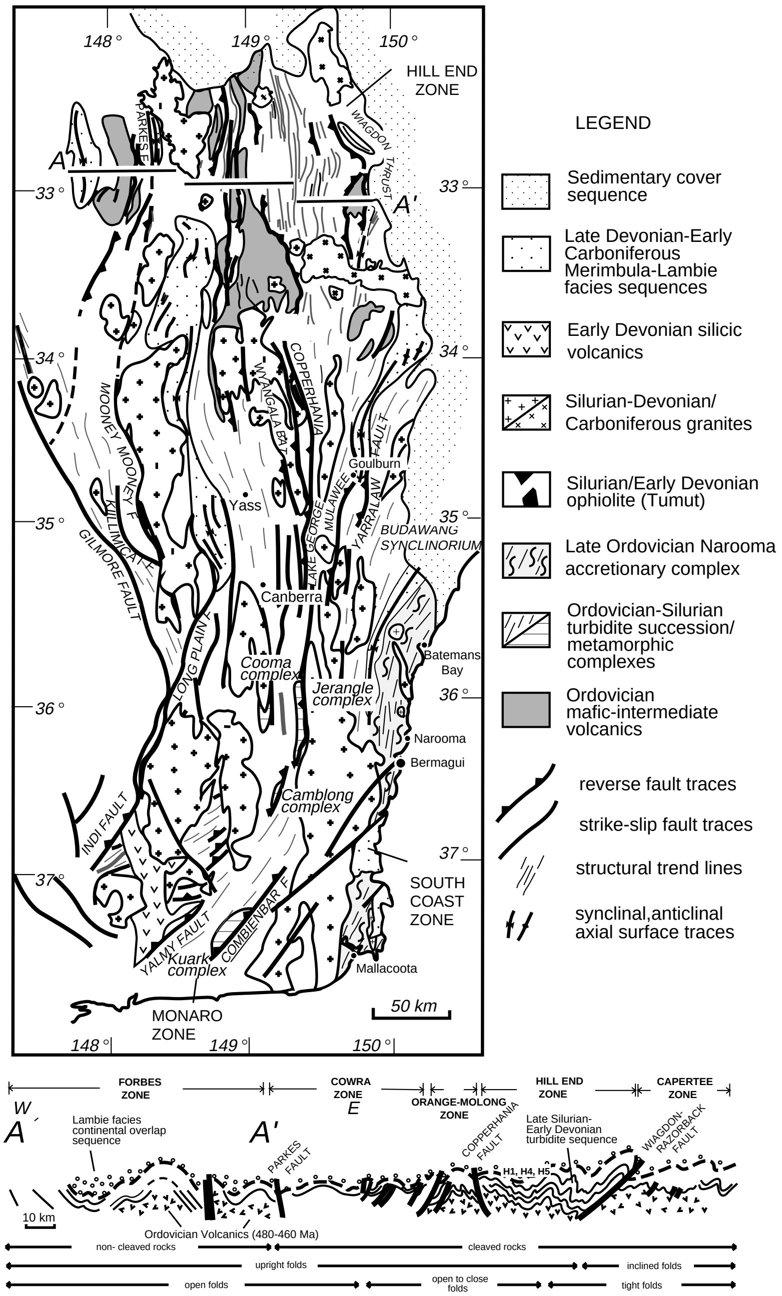

Figure 8 Structural trend map and profile of the eastern Lachlan orogen (Gray 1997). Geological zones, major faults, and bedding form lines are shown. Anticlinoria are dominated by Ordovician metavolcanic rocks and shallow water deposits, whereas synclinoria are dominated by turbidites (Powell 1984).

(Fergusson & Coney 1992a), with an overall east vergence and an eastward increase in degree of cleavage development. The regional folds become tight and inclined toward the Capertee anticlinorial zone. Inversion of a series of former Mid-Silurian to Late Devonian extensional basins represented by alternating troughs (rift basins with turbidites) and highs (carbonates and Ordovician volcanic rocks) has controlled the present distribution of synclinorial and anticlinorial zones respectively (Powell 1984, Glen et al 1998).

A major feature of the eastern Lachlan is the calcalkaline volcanic arc basement (Glen et al 1998). The volcanic rocks outcrop as four belts of calcalkaline to shoshonitic basalts and andesites that erupted from a series of intra-oceanic centers on an abyssal plain covered by the turbidite deposits (Fergusson & Coney 1992b, VandenBerg & Stewart 1992, Glen et al 1998). After eruption, the relatively thick strong arc crust dominated the deformational history of the eastern Lachlan Orogen, so that when subjected to transtension in the middle Paleozoic, it rifted into a series of linked basins. Some of these rifted basins evolved into small spreading centers (e.g. Tumut: Stuart-Smith 1991; Dadd 1998) The Ordovician arc basement probably also exists beneath the Wagga-Omeo complex, where it may have contributed to the fertile source of the Silurian to Devonian granitoids.

The eastern part of the subprovince is characterized by the chevron-folded turbidites and brittle thrusts of the Bungonia-Delegate thrust belt (Yalmy, Yarralaw, Razorback, and Copperhannia faults) (Fergusson & VandenBerg 1990). In the southern part, structural repetition or interleaving of the Ordovician and Silurian turbidite package is responsible for an inferred listric-fault system (Glen & VandenBerg 1987). To the north, the faults dip steeply ($>60°$) and clearly cut the chevron-folded sequences (Fergusson & VandenBerg 1990). This thrust belt is now juxtaposed against the coastal facies belt of Powell (1984) and includes a broken formation (melange) of a Late Ordovician/Early Silurian ($\sim$460–440 Ma) accretionary complex within a Late Cambrian/Early Ordovician ($\sim$500–480 Ma) chert/basalt/turbidite sequence (Miller & Gray 1996, Offler et al 1998b). Several isolated north-south, elongated, low pressure/high temperature metamorphic complexes (Cooma, Jerangle, Cambalong and Kuark complexes) occur within the Bungonia-Delegate thrust belt. They are associated with foliated granitoids and have very narrow north-south trending metamorphic zones defined by biotite, knotted schist (cordierite), sillimanite zone rocks, migmatites, and anatectic granite (Glen 1992). The narrow metamorphic zones are east-directed shear zones characterized by multiple cleavages, mesoscopic sheath folds, transposition layering, shear bands and S-C fabrics, and quartz c-axis fabrics. Thrusting produced gneissic banding, mylonitic layering, and secondary foliations in the granites, and complex, polyphase folding in the wallrocks (Paterson et al 1990). These metamorphic complexes were emplaced to the present level of exposure on the Devonian thrusts (Glen 1992, Foster et al 1999) and provide a window into the crustal source regions of the higher-level granitoid plutons.

Apart from the metamorphic complexes, the dominant metamorphic assemblage is white mica-chlorite in pelites in the eastern subprovince (Smith 1969, Offler & Prendergast 1985, Farrell & Offler 1989). Metamorphic conditions are characteristic of the greenschist facies, with P/T conditions of 330–450°C and 1–7 kbar (Farrell & Offler 1989). In the extreme southeast part of the belt (Narooma zone), very highly strained cherts and pelites were deformed at temperatures of ~260°C and pressures of ~3 kbar (Offler et al 1998b).

Rift basin inversion in the north results largely from east-directed thrusting along earlier-formed extensional faults and their associated detachment (Glen 1992, Glen et al 1992). This deformation occurred at ~400 Ma in the west in the Cobar Basin (Glen et al 1992) and at ~380 Ma and 360 Ma in the east in the Hill End Basin (Glen & Watkins 1999, Packham 1999, Foster et al 1999). The age of thrusting within the eastern part (Bungonia-Delegate thrust-belt) is thought to range from Early Silurian to Middle Devonian based on age constraints of granitic plutons (Fergusson & VandenBerg 1990).

The deformed Ordovician through Early Devonian sequence of the eastern Lachlan is overlain by Late Devonian-Early Carboniferous (~370–360 Ma) molasse (Lambie facies), which was folded into a series of open meridional folds in the Early Carboniferous (~360–340 Ma) (Figure 8). Intensity of this Early Carboniferous deformation, as recorded by fold tightness in Lambie facies rocks, increases dramatically eastward toward the New England Orogen (Powell 1984).

Magmatism

Granitoid plutons cover up to 36% of the exposed Lachlan Orogen, with maximum development in the central and eastern subprovinces (Figure 9). The broad compositional characteristics of these rocks, based on the I-type and S-type classification, are summarized by Chappell et al (1988). In the western Lachlan, granites are moderately shallow level, are mainly post-deformational plutons, and have narrow (1–2 km wide) contact aureoles or very shallow level subvolcanic plutons associated with caldera-collapse rhyolites and ash flows. Shallow level plutons are also common in the eastern subprovince. Deeper plutons associated with regional low-P/high-T metamorphism are less common and are associated with migmatites and K feldspar-cordierite-andalusite-sillimanite gneisses of the Wagga-Omeo, Cooma, Cambalong, and Kuark complexes.

Granite intrusion occurred mainly during several time intervals. Between 430 and 415 Ma, the syntectonic plutons in the high-grade metamorphic complexes of the central and eastern subprovinces were emplaced (Williams et al 1983, Williams 1992, Keay et al 1998, Wilson et al 1999). In the eastern Lachlan, the voluminous plutons of the Bega batholith (Williams et al 1983) and the other large elongate batholiths extending north to the Wyangula batholith also intruded during this time. By 405–390 Ma, plutonism in the eastern subprovince migrated eastward, closer to the Pacific coast; a large number of high-level plutons intruded into the western subprovince, as did the mainly post-tectonic plutons of the central

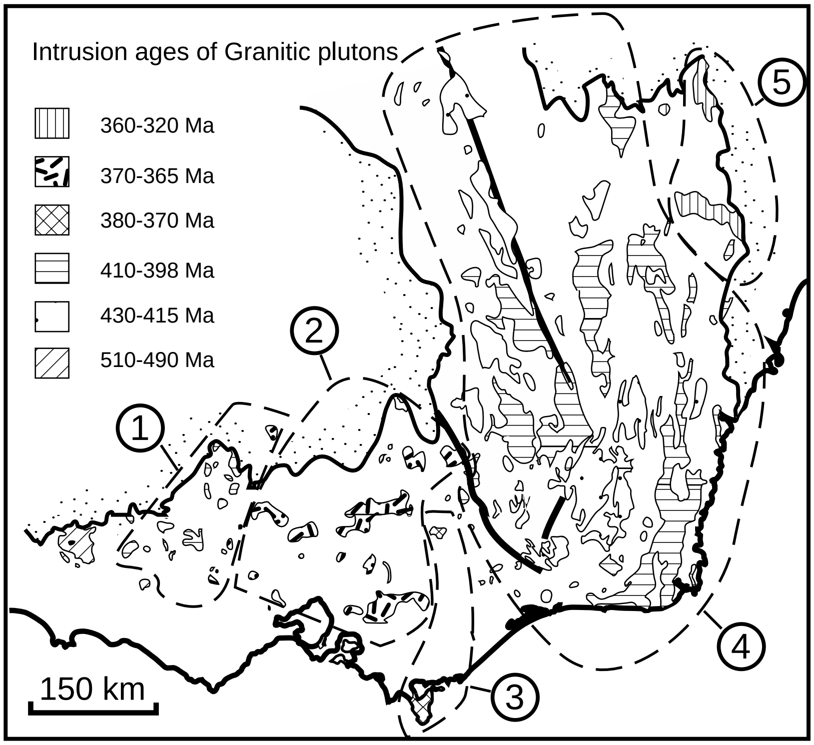

Figure 9 Map of intrusion ages of granitic plutons of the Lachlan orogen. Numbers show the five main areas of magmatic activity (Gray & Foster 1997).

province (Powell 1983, Bucher 1998). The 370–360 Ma plutons are typical of the central Victorian magmatic province where the granitic plutons are closely associated with caldera complexes (Richards & Singleton 1981, Bucher 1998).

The outcrop patterns of the plutons suggest five major granite provinces, which presumably reflect the mode and timing of emplacement relative to tectonism, and the state of stress at the particular level of emplacement (Gray 1997, Gray & Foster 1997). Elongate north-northwest trending granites define the Wagga-Omeo complex. North-south trending granites of the eastern subprovince are elongated parallel to the regional structural grain. Many of these granites are syn-tectonic with major mylonites developed along their eastern margins. In the western Lachlan, post-tectonic granites of the central Victorian magmatic province are east-west trending, have elongated form, and were probably emplaced by stoping.

The Paleozoic igneous rocks range from basalt/gabbro to alkali feldspar granite. Some are strongly peraluminous, including cordierite-bearing granite (S-type), whereas others are metaluminous hornblende-biotite granitoids (I-type) (Chappell et al 1988, Collins 1998). Previous models held that the compositional variations depended on the crustal source terrains (thought to be Proterozoic) and that the typical linear variation trends were related to variable amounts of restite unmixing (e.g. Chappell et al 1988, McCulloch & Chappell 1982). Based on larger Nd, Sr, and Pb isotopic data sets, as well as geochemical data, it now appears that the different granite types are related mainly to various degrees of mixing between subduction-generated, mantle-derived mafic magmas and partial melts of two crustal components: *1*) the mafic oceanic/island arc basement and *2*) the Ordovician turbidite sequence (CM Gray 1990; Collins 1996, 1998; Keay et al 1997; Gray et al 1998). Inherited zircon in both the I- and S-type plutons contain the same age populations as the Ordovician turbidites, and the two pluton types have similar isotopic trends (Collins 1998). This magma generation and mixing process is apparent in the high-grade metamorphic belts (e.g. Cooma and Omeo) where complete gradations from metasediments to metatexite to diatexite to granite, associated with mafic igneous rocks, are exposed (e.g. Collins 1998, Wilson et al 1999). The distinctive I-S line (White & Chappell 1983) of the eastern Lachlan Orogen could be the eastern limit of the thick turbidite wedge (Collins 1998) or a thrust boundary that brings up deeper crustal levels on the west side (Hendrix 1999).

Rifts, Foreland Basins, and Cover Sequences

The Lachlan Orogen was extended at different times throughout the Paleozoic (e.g. Cas 1983, Coney et al 1990, Foster et al 1999). Extensional periods were marked by localized development of rift basins and half grabens accompanied by extensive granitic magmatism and silicic volcanism (Gray 1997, Figure 18). During the Late Silurian and Devonian, rifts may have been linked in a broad basin-and-range style, distributed extensional or transtensional system (Cas 1983). This developed in response to subduction rollback, collapse of the Late Ordovician/Early Silurian thickened crust, or highly oblique convergence between Australia and the Pacific. Rift basins within the Lachlan Orogen are now preserved as elongate zones of clastic sedimentary cover sequences, and silicic volcanic rocks, locally with intrusions of A-type granitoids. The rift basins represent structural/topographic remnants of inverted extensional basins that were generally bounded by north-south trending extensional faults. The chemical compositions of basaltic rocks in the Lachlan are also indicative of an extensional back arc setting for the mid-Paleozoic (Collins 1999).

Half-graben sequences are typified by the Cobar Basin, which is an overlap/cover basin to the central Lachlan (Glen et al 1994), and the succession of troughs and highs in the northern part of the eastern Lachlan (Glen 1992). Other regions have been interpreted as strike-slip basins, such as the Tumut Basin (Stuart-Smith 1991) and the Mansfield and Combienbar Basins (Powell 1984). Ages of sedimentary and volcanic rocks within the rifts provide an approximate timing for extension.

The northwest part of the eastern Lachlan Orogen underwent regional extension after the Early Silurian (~440–430 Ma) deformation in the Wagga-Omeo complex. Short-lived (<30 Ma) rift basins (Cowombat and Wombat rifts, Figure 7) developed within the uplifted metamorphic complex and were subsequently deformed in the Late Silurian (~420 Ma). Several rift basins developed east of the metamorphic belt during the Late Silurian to Early Devonian (~420–400 Ma) (e.g. Cobar, Cowra and Hill End Basins, Figures 4 and 8).

Other regions show Early and/or Late Devonian bimodal volcanism associated with extension; this includes the Woods Point mafic-felsic dyke swarm in the eastern part of the western sub-province: 375 Ma (Arne et al 1998) and Early and Late Devonian silicic volcanism [Rocklands Rhyolite, near the Delamerian-Lachlan boundary: ~410 Ma (CM Fanning, unpublished data)]; Central Victorian caldera complexes: ~360–370 Ma (Bucher 1998; Richards & Singleton 1981); Snowy River volcanics: Early Devonian (Talent 1965).

Other large preserved sequences of clastic cover appear to be related in part to the late stages of regional compression and crustal thickening. These basins, like the Late Devonian to Carboniferous Mansfield basin (O'Halloran & Cas 1995), overlap the major fault zones and were probably initiated as foreland basins, although they may have become extensional later in their history.

Crustal Structure

Crustal thickness in the Lachlan Orogen ranges from 40 to 52 km under the eastern highlands of Australia, and from 35–36 km in the western subprovince, to 26 km in the eastern Lachlan (Finlayson et al 1980, Gibson et al 1981). The southeastern part of the eastern subprovince is characterized by an upper crust with P-wave velocities between 5.6–6.3 km/sec, a lower crust with velocities between 6.7–7.4 km/sec, and a low velocity zone at a depth of about 15–20 km (Finlayson et al 1980). In the western subprovince, the upper crustal velocities range between 5.3–5.9 km/sec with a change to ≥6.3 km/sec at a depth of 17 km (Gibson et al 1981).

Limited deep seismic reflection profiles (Pinchin 1980, Leven et al 1992, Gray et al 1991, Korsch et al 1999) provide evidence for the nature and geometry of the lower crust. Petrologic evidence from xenoliths in young volcanic rocks (Griffin & O'Reilly 1987, Clemens 1988) suggests a lower crust dominated by subhorizontal alternating mafic and felsic layers, but structural interpretations of seismic profiles suggest the existence of a structurally complex lower crust cut by shear zones. The Tibbinbilla-Braidwood seismic traverses, which have short traverse lengths (<10 km) and were shot above granites, show intracrustal reflections (particularly at 10–12 km, and a pronounced low-velocity zone at 22–28 km) with a depth to the reflection Moho of 41 km (Pinchin 1980). The Tumut seismic traverse shows that steep faults exposed at the surface (Killimicat and Mooney Mooney faults) correspond to east-dipping, listric-shaped, nonreflective zones (Leven et al 1992). These are truncated by a series of strong, continuous, gently west-dipping reflectors interpreted to represent a detachment at ~20 km depth. The Cobar seismic traverses show a Moho depth of 30–33 km and a mid-crustal detachment that varies in depth from 25 to 12–16 km (Glen et al 1994).

The Heathcote seismic data (Gray et al 1991) in the western subprovince shows a reflection Moho at approximately 36 km. The steeply dipping Heathcote fault-zone appears as a moderately dipping reflector that flattens with depth to ~15 km (Figure 10). The lower crust appears structurally complex and has been interpreted as a westward-dipping duplex or crustal stacking-wedge developed on a ramp that originates at the crust–mantle boundary (Gray et al 1991). The Grampians seismic reflection traverse shows a duplexed lower crust at the boundary between the Delamerian and Lachlan. In the upper crust, the Moyston fault is marked by a steep, east-dipping, highly reflective zone (Korsch et al 1999).

Timing of Deformation and Regional Events

The timing of orogenic events in the Lachlan Orogen is broadly defined by the ages of strata over regional unconformities and by stitching plutons (Gray & Foster 1997). More recently, Ar-Ar data from metamorphic white mica in the low-grade meta-sedimentary rocks give precise estimates on the timing of cleavage formation and regional deformation events (Foster et al 1999). Ar-Ar results for rocks in the high-grade metamorphic complexes give the timing of exhumation, so wherever possible, deformation in these areas is controlled by U-Pb zircon data.

The Ar-Ar geochronologic and thermochronologic data, interpreted along with other geological data, allow us to define when specific regions within the Lachlan Orogen first underwent significant deformation, metamorphism, faulting, and reactivation (Foster et al 1999). Deformation in the Lachlan Orogen was initiated between ~455 and 430 Ma in three areas: the western subprovince where it migrated eastward, the central subprovince where it migrated to the southwest, and the eastern subprovince in the Narooma accretionary complex. The western subprovince is characterized by major deformation in the Stawell and Bendigo-Ballarat zones between ~455 and 440 Ma, and fault reactivation at ~430–410 Ma (Foster et al 1996, 1998, 1999). The eastern bounding faults of the western Lachlan, in the Mount Wellington fault zone, were active between 410 and 385 Ma (Figure 11) (Foster et al 1998, 1999) and were reactivated during Carboniferous (~360–340 Ma) time (VandenBerg et al 1995).

The central subprovince underwent major deformation in the high-grade metamorphic complex between 440 and 430 Ma (Wilson et al 1999, Foster et al 1999) and was exhumed between ~410 and 400 Ma, as shown by mica dates from the shear zones bounding the complex (Foster et al 1999). To the west, in low-grade metasediments, deformation began at ~440–430 Ma and migrated southwestward to ~410–416 Ma. Later deformation took place in the Tabberabbera structural zone when it collided with the western subprovince at ~400–380 Ma, and again at ~360–340 Ma (VandenBerg et al 1995, Foster et al 1998).

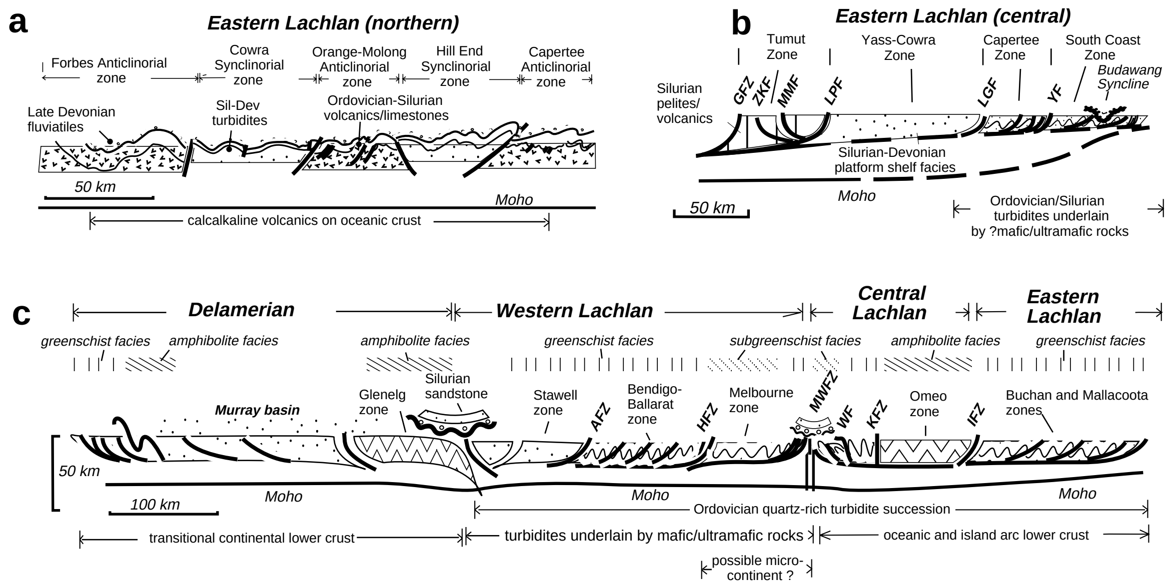

Figure 10 Schematic west-east crustal structural profiles showing the main geological and metamorphic aspects of the Lachlan Orogen (Gray 1997, Gray et al 1998). Locations of profiles: (a) Eastern Lachlan at 33° S latitude; (b) Eastern Lachlan at 36° S latitude; (c) entire Lachlan at 37° S latitude. Abbreviations: GFZ, Gilmore fault zone; KFZ, Killimicat fault zone; MMF, Mooney Mooney fault; LPF, Long Plain fault; LGF, Lake George fault; YF, Yarralaw fault; AFZ, Avoca fault zone; HFZ, Heathcote fault zone; MWFZ, Mt Wellington fault zone, WF; Wonnangatta fault; KFZ, Kiewa fault zone; IFZ, Indi fault zone.

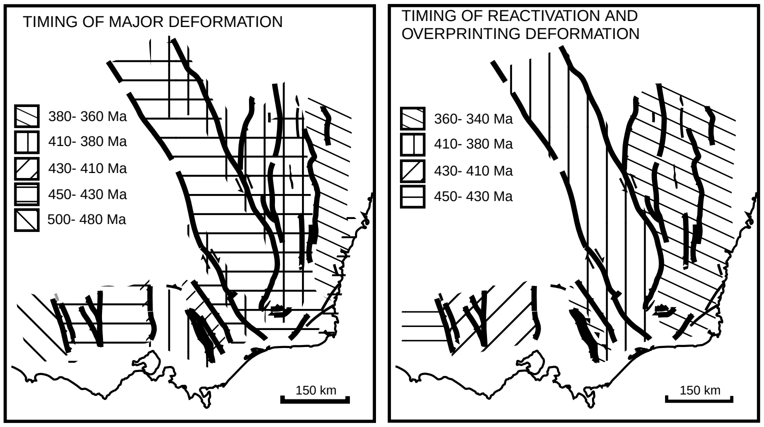

Figure 11 Maps of the Lachlan Orogen showing timing of deformation events and fault reactivation, based on ^{40}Ar-^{39}Ar geochronology and other geological constraints (Foster et al 1999).

The oldest recorded deformation in the eastern subprovince took place in the Narooma complex ∼455–445 Ma (Offler et al 1998b) when it was outboard of, and separated from, the rest of the present eastern subprovince. The inland parts of the eastern subprovince are dominated by 400–380 Ma contractional deformation (Glen et al 1992, Foster et al 1999), with a central and northeastern region of 380–360 Ma deformation (Packham 1999, Foster et al 1999). These younger episodes overprint the earlier fabrics such as those in the Narooma complex. The Silurian extensional event predated this contractional deformation phase. Although mild Carboniferous (∼360–340 Ma) deformation is very widespread, intense Carboniferous deformation is almost unique to the northern part of the Lachlan Orogen in the eastern subprovince (Glen 1992). Carboniferous deformation partly reflects the progressive eastward accretion of the Tasmanides and is probably related to amalgamation of the New England orogen. The Carboniferous event could also be related to the rapid movement of Australia toward the South pole, which may have also caused the Alice Springs orogeny in central Australia (e.g. Li et al 1990).

In the past, a framework of six orogenic events were proposed for the Lachlan Orogen during the Paleozoic. It now appears that some of these events are localized and strongly time-transgressive. Because of the complex and localized pattern of deformation during the Ordovician, Silurian, and Devonian, we have preferred to refer to the whole interval as the Lachlan Orogeny (Gray & Foster 1997, Gray et al 1997; see also Cas 1983). Based on the present data, it could also be argued that two major events dominate the middle Paleozoic—one at ∼440–430 Ma and one at ∼390–380 Ma (Foster et al 1999). Because significant tectonic activity in terms of strike-slip faulting and plutonism continued between these events, however, we prefer to use the broader framework. The regional ~360–340 Ma Kanimblan event seems to be widespread over a relatively short interval in time, so we retain this usage.

TECTONIC EVOLUTION

Background

The progressive west-to-east younging of upper crustal segments in the Tasmanides led to concepts of large-scale continental accretion for eastern Australia. Most tectonic models suggest arc-continent collisional interaction along the Gondwana continental margin in the Paleozoic (Oversby 1971; Solomon & Griffiths 1972; Scheibner 1974; Crook 1974, 1980; Cas et al 1980; Powell 1983). Cratonization occurred either by back-arc accretion in a marginal sea setting (Cas et al 1980; Powell 1983, 1984) or in a convergent continental margin setting, involving some form of plate interaction to the east. Disputes relate to the tectonic setting in the Ordovician and Cambrian periods (continental rift or oceanic setting?) and the nature of the basement to the voluminous quartz-rich turbidite succession (continental, oceanic, or mixed?). Observations of modern fan systems indicate that large parts of such fans accumulate on oceanic rather than continental crust (Curray 1982) because of buoyancy. The presence of Cambrian (2500 Ma) tholeiites and boninites of MORB or BAB affinities suggest an oceanic setting associated with a possible island arc(s) for the Cambrian (Crawford & Keays 1978, Crawford et al 1984). The Narooma accretionary complex (Miller & Gray 1996) within Late Cambrian and Early to Late Ordovician chert-turbidite sequences is suggestive of an oceanic setting. There is little evidence for Proterozoic continental crust under most of the Lachlan (e.g. Gray et al 1998, Collins 1998). Therefore, a continental rift setting for the Cambrian is unlikely. For the Ordovician (~480 Ma), a volcanic island arc existed in the east with the western subprovince representing a back-arc basin.

The western and eastern subprovinces probably represent different parts of a complex oceanic setting for the following reasons: 1) The easternmost part of the western subprovince was in an open, east-facing basinal setting until the late Early Devonian (~400 Ma); 2) during Silurian-Devonian times the eastern subprovince was under extension, whereas part of the western subprovince was still a continental margin sediment-prism dominated by turbidites; 3) during the Cambrian-Ordovician, the western subprovince was in an oceanic setting with turbidite deposition, while the eastern subprovince was dominated by shallow marine arc volcanism and carbonate deposition; and 4) Deformation pulses and the tectonic vergences for these two structural belts are centered about the central subprovince.

Tectonic models must also explain the extensional phases, but there is no single regional phase of extension as required by crustal thinning models (Sandiford & Powell 1986). Another aspect that must be explained is the preservation: first, of the Late Devonian (~365 Ma) volcanic cauldron complexes and exposure of the Late Devonian granites that were intruded at pressures of ≤1.7 Kb (Clemens & Wall 1981) in the western Lachlan; and second, of the high-level Ordovician Cu-Au porphyry systems in the eastern Lachlan. Their preservation indicates that only a small amount of uplift and erosion (<3 km) has occurred, particularly since ~360 Ma in these areas. Most of the erosion in the areas affected by the 440–430 Ma deformation occurred before Early Devonian time. In the west and central subprovinces, up to 10 km of exhumation occurred between 430 and 400 Ma, but much less after 400 Ma (Foster et al 1999, Offler et al 1998a, Morand & Gray 1991). This may be due a higher density, structurally thickened, mafic lower crust that prevented high elevations from developing (Coney et al 1990, O'Halloran & Rey 1999).

Tectonic History

The tectonic history of Tasmanides involved four distinct phases: Proterozoic supercontinent breakup, Paleozoic to Mesozoic continental accretion, Mesozoic-Tertiary continental breakup, and post-breakup volcanism and reactivation (Figure 12, color insert; Figures 13 and 14). The first two of these are summarized below.

Neoproterozoic Rifting The cycle of crustal extension, sedimentation, and orogeny that predated the Paleozoic evolution of the Lachlan Orogen began during the late Neoproterozoic, with initial rifting between cratonic Australia and another large continent. The best candidate for the adjacent continent at this time is Laurentia (North America), within the supercontinent of Rodinia (e.g. Hoffman 1991, Powell et al 1994, Foster & Ehlers 1998). Rifting between these continents began at ~800 Ma but did not lead to separation of the continents until about 700 Ma (Powell et al 1994). The early phases of rifting were epicontinental and are expressed as rift sequences in the Adelaide Rift and other graben west of the Tasman Line. After separation, the character of this sequence became more like a passive margin. In early Cambrian time, a renewed phase of rifting in the southeastern part of the margin formed the deepwater Kanmantoo Basin, which rapidly subsided and was filled with clastic sediments. Very shortly after deposition of the Kanmantoo sediments, the basin was inverted in the first stage of the 530–500 Ma Delamerian orogeny (Flöttmann et al 1994, Powell et al 1994) (Figure 13).

Delamerian Orogeny

The Delamerian/Ross orogeny resulted from inversion of the Neoproterozoic and early Cambrian passive margin and rift sequences, presumably driven by subduction and collision of continental fragments (Powell et al 1994, Finn et al 1998). Just west of the Lachlan Orogen, the major Delamerian element is the deformed Kanmantoo Basin, which closed due to collision of a previously rifted continental fragment (Glenelg zone ± Tasmania) and an island arc (Stavely volcanic arc)

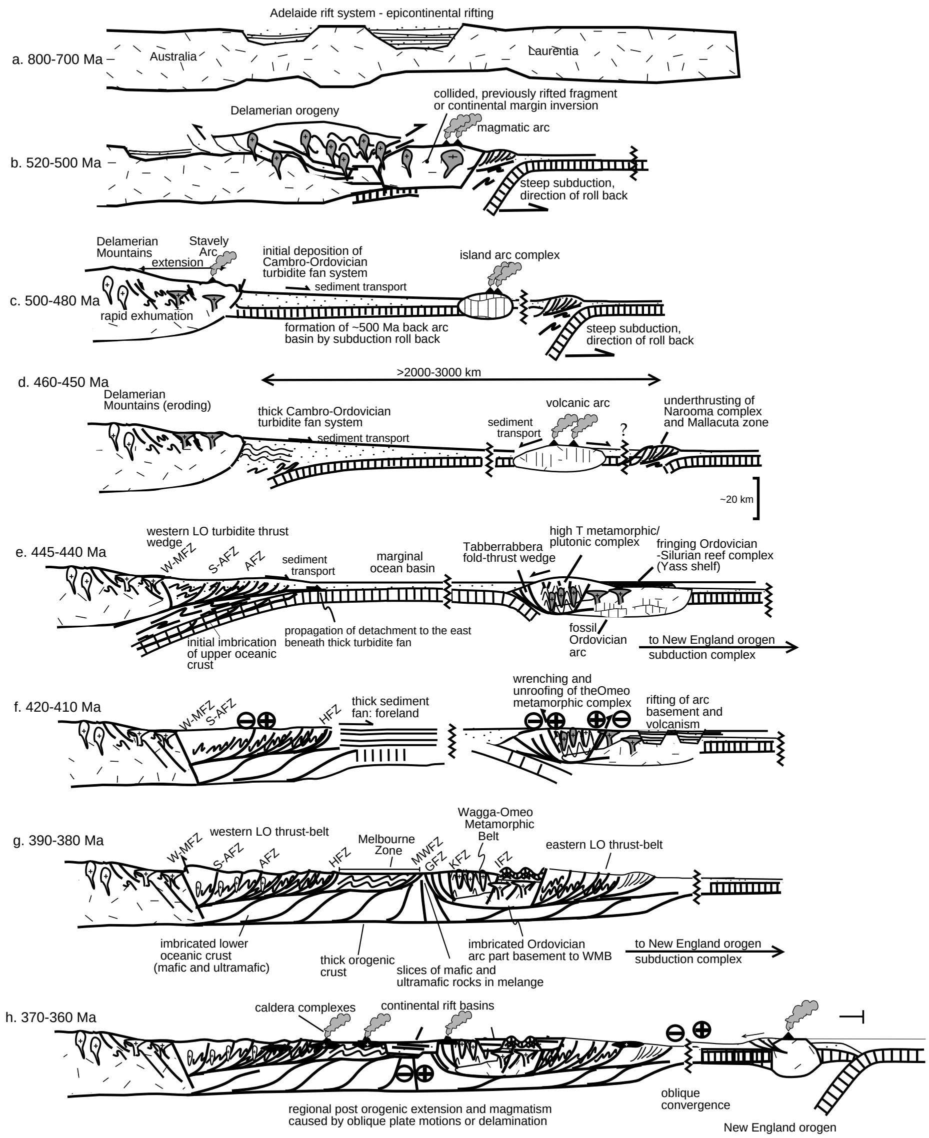

Figure 13 Progressive plate tectonic element model for eastern Australia from 800–360 Ma.

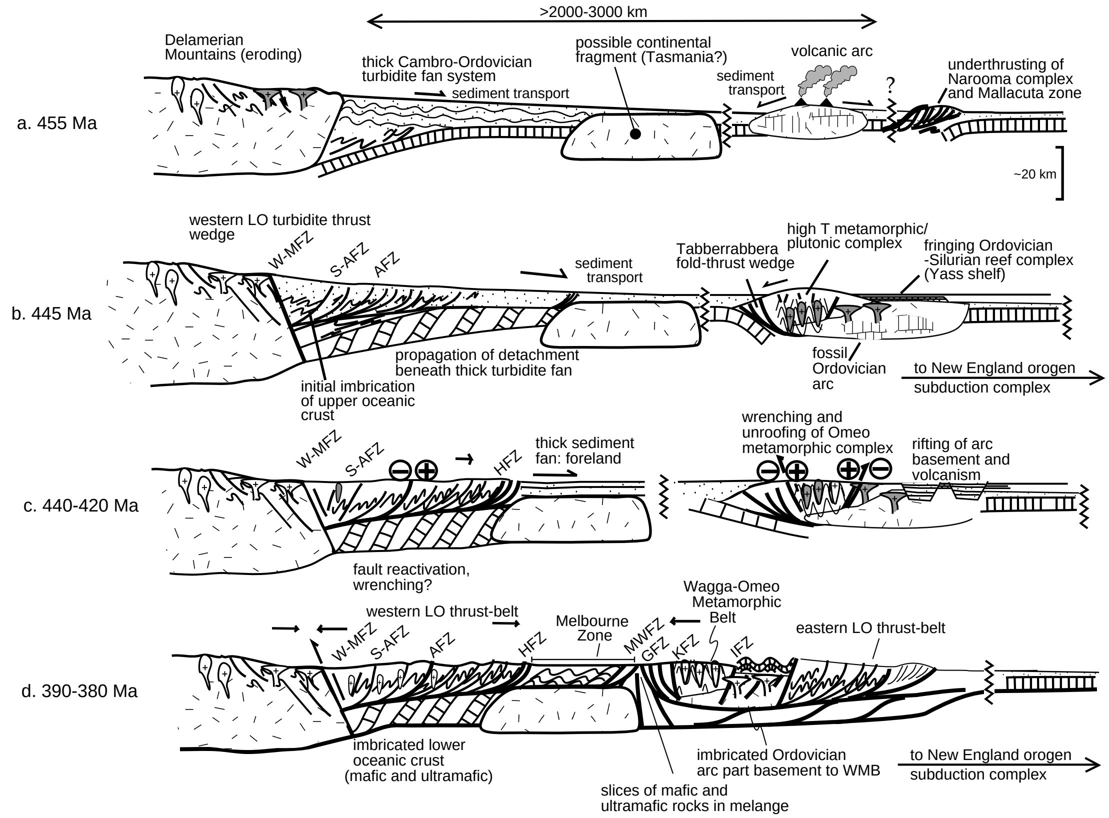

Figure 14 Plate tectonic model for 455–380 Ma incorporating a microplate in the eastern part of the western Lachlan.

(Powell et al 1994, Flöttmann et al 1994). North of the Kanmantoo Basin, the Delamerian Orogeny dominantly affected the Adelaidean platform sequences and Proterozoic cratonic basement in the Broken Hill Inlier (Hartley et al 1998).

A magmatic arc grew on the eastern side of the Delamerian Orogen starting at ~510–500 Ma and included plutons and volcanic rocks exposed just west of the Moyston fault (Foster et al 1998, Moore et al 1998). Shortly after major crustal thickening, the Delamerian belt began to extend rapidly. Evidence for extension includes: 1) the post-tectonic plutons with emplacement ages younger than ~490 Ma are dominantly A-type; 2) much of ~500 Ma Mount Stavely volcanic complex is developed within a rift; and 3) thermochronological evidence from the higher grade areas suggests relatively rapid cooling. Post-orogenic extension may have been caused by subduction rollback after the Delamerian, which could have also formed most of the oceanic (back arc) basement for the Lachlan turbidites deposited during the Late Cambrian and Ordovician. Most of the mafic metavolcanic rocks and plutons of the central Victorian basement give ages of ~500 Ma (Spaggiari et al 1999; Foster, unpublished data). Extension and rollback may have also rifted small continental fragments away from the Delamerian and distributed them within the back-arc basin.

Lachlan Evolution

The complexity of deformation, sedimentation, and magmatic patterns in the Lachlan Orogen can be interpreted to reflect the interaction of oceanic microplates, a volcanic island arc, and multiple turbidite-dominated thrust systems (Gray & Foster 1997, 1998; Foster et al 1999). Differences among the deformational, metamorphic, and magmatic character of the western, central, and eastern subprovinces of the Lachlan Orogen reflect different tectonic positions and origins. The Lachlan Orogen developed as part of a greater Gondwanide oceanic accretionary system (Figure 12). However, the belt developed somewhat differently than the large accretionary systems that faced the open Pacific ocean, in that the Lachlan Orogen probably formed from the closing of a small ocean basin/arc system, inboard of a larger subduction zone. These basin systems closed behind—and in the back arc position to—a major long-lived Paleozoic subduction system now exposed in the New England Orogen (Fergusson et al 1993, Leitch et al 1994) (Figure 12); the total amount of subducted oceanic lithosphere was relatively small (<1000 km).

An oceanic thrust wedge model for the western subprovince of the Lachlan Orogen is supported by the presence of relict blueschist or transitional blueschist-greenschist facies metamorphism in the Cambrian metavolcanic rocks (Spaggiari et al 1999) and the high-P/low-T metamorphic field gradient in the Ordovician turbidites (Offler et al 1998a). A magmatic arc associated with the suggested west-dipping subduction zone of the western subprovince was not developed until late Silurian time—probably because subduction was of very shallow dip and the ocean basin that closed was relatively small, so the amount of subduction was limited. Shallow-dipping subduction is consistent with the moderately high metamorphic P/T ratios.

A plate tectonic model for early Paleozoic eastern Australia at different times, based on Foster et al (1999), is shown in Figure 13. During and following the Delamerian Orogeny (~500 Ma), a large turbidite fan grew offshore of the Ross-Delamerian mountain chain and spread onto the mafic crust of a marginal ocean. This marginal ocean basin formed by rollback of paleo-Pacific subduction at ~500 to 480 Ma. Subduction rollback also caused extension and collapse of the Delamerian Orogen and post-tectonic alkaline magmatism. Some thousands of kilometers offshore, Ordovician subduction in the oceanic plate led to the development of a volcanic arc complex, which is now represented by the Ordovician mafic to felsic arc volcanic rocks in the eastern Lachlan Orogen and an associated accretionary complex (Narooma complex). Shallow-angle subduction may have also initiated in the west and started to close a marginal basin under the backstop of the Delamerian Orogen by ~455 Ma, when major faults began forming in the western Lachlan Orogen.

By Late Ordovician-Silurian (~445–440 Ma) times, shallow-angle subduction and/or imbrication had closed a significant part of the marginal ocean basin in the west. (The amount of oceanic crust lost to the mantle may have been relatively small, with much of the present crustal thickness made up of imbricated mafic crust.) During this interval, sedimentation continued in the eastern part of the basin, the major fault zones of the western subprovince formed, and the basal décollement propagated eastward. Subduction in the eastern Lachlan orogen had probably stopped, and reefs were growing around the volcanic edifices. The major Gondwanide subduction zone probably stepped east (present coordinates), >1000 km (?) to what is now the New England Orogen. In the style of the Solomon or Molucca Sea, double convergence began along the western part of the central Lachlan, forming melange zones, a westward propagating wedge, and magmatism. Evidence from the eastern and northern Lachlan suggests that transtensional rifting dominated at ~420 Ma, and therefore the reactivation of faults documented throughout the western Lachlan may have been related to regional extension and not compression. Furthermore, the thickened crust was intruded in the west at ~400 Ma by granitic plutons that contain both mantle and crustal melt components. These magmas may have been generated by subduction processes or by post-thrusting extension/collapse or mantle delamination, as has been suggested for other orogenic belts (e.g. Dewey 1988). During the Middle Devonian, the last undeformed part of the marginal basin in the west had collided with the central subprovince, causing crustal thickening and deformation of the younger sediments in the Melbourne zone. Thrusting was also taking place in the eastern Lachlan thrust belts. Middle Devonian (~390–380 Ma) collision led to attainment of freeboard over most of the orogen, followed by widespread post-orogenic extension, basin-and-range style faulting, explosive volcanism, and high-level plutonism. This period of post-orogenic extension was dominated by bimodal volcanism and continental rift clastic sedimentation from the Late Devonian through Early Carboniferous (~370–360 Ma) times (Figure 13). The cause of extension is possibly related to the collapse of the previously thickened orogenic crust and/or delamination of part of the mantle lithosphere following thickening, rollback of the subduction system along the Gondwana margin, or transtension caused by oblique plate motions between Gondwana and the Pacific.

Cayley & Taylor (1999) (also, Scheibner & Basden 1996) have suggested that a fragment of Proterozoic crust underlies the Melbourne zone in central Victoria. The proposed microcontinent is thought to be a continuation of crust exposed in Tasmania, and may have originated as a rifted portion of Australia or Laurentia during Neoproterozoic breakup. The existence of the fragment is suggested by geophysical data that shows trends apparently continuous with those across Bass Strait, as well as geological data from Cape Liptrap. Figure 14 shows a summary of the tectonic evolution of the southern Tasmanides that may have occurred if this fragment of Proterozoic crust exists within the Lachlan Orogen. The open folding and initial shortening of the western Lachlan belt at about 455 Ma was caused by the westward movement (current direction) of the microcontinent. By 445 to 440 Ma, much of the western belt, which was underlain by oceanic crust, had shortened to the point that the folds were very tight, and major thrusting occurred with the principle vergence direction to the east. During this interval, sedimentation continued in the Melbourne zone. By ~420 Ma, further westward motion of the Proterozoic crust caused the western Lachlan to be thrust westward over the Delamerian and eastward over the edge of the microcontinent. This eastward thrusting occurred on the Heathcote fault zone and caused the micro-continent to be depressed as a foreland basin. Rapid erosion of the uplifted thrust wedge in the west resulted in an eastward prograding sediment fan over the microcontinent. This thickened crust was intruded by plutons in the west at ~400 Ma, with mantle and crustal melt components that may have been generated by subduction east of the central Lachlan or post-orogenic extension/delamination in the west. At ~400–385 Ma, the east-vergent western subprovince came into close contact with the west-vergent central Lachlan. As in the previous discussion, the Late Devonian was dominated by the extension of the Ordovician to Middle Devonian orogen.

The Late Devonian to Carboniferous molasse-like overlap sequence of the Lachlan Orogen marks the emergence of the entire belt. The sediments were deformed over most of the Orogen during Late Carboniferous time, but with a highly variable intensity. Most of the deformation was concentrated in the north-east where the rocks were intensely cleaved and tightly folded. The Carboniferous event, known as the Kanimblan Orogeny, is probably related to the initial inter-action between the New England orogenic wedge and the Lachlan. Unfortunately, the exact timing and nature of the boundary between these two orogenic belts are not exposed and lie beneath the thick foreland basin sediments of the Sydney and Bowin Basins (Figures 2 and 4)

Although many aspects of the tectonic evolution of the Lachlan Orogen, the nature of the basement, and the thermal/magmatic processes that led to final accretion and cratonization of this orogen remain unclear, the summary provided here attempts to explain as much of the present data as possible.

ACKNOWLEDGMENTS

This review relies on the work of geoscientists who preceded us and of those presently working in the Tasmanides, as well as on our own work. We were unable to reference all of the previous work because of space limits, but we provide a framework of references that the reader can use to further investigate the Lachlan. Our work was influenced by interactions with many colleagues who we would like to thank; in particular: C Fergusson, A Gleadow, R Cas, C Gray, V Morand, C Willman, F VandenBerg, R Cayley, D Taylor, R Offler, C Wilson, D Moore, C Finn, G Price, R Korsch, P O'Sullivan, I Nicholls, W Collins, M Bucher, C Spaggiari, and J Miller. We thank S Zakowski, L Foster, and A Klein for assistance with the figures and K Burke for comments on the manuscript. Funding was provided by the Australian Research Council and Australian Geodynamics Cooperative Research Centre (AGCRC). This paper is published with the permission of the Director of the AGCRC, Dr. G Price.

LITERATURE CITED

Adams CJ, Kelley S. 1998. Provenance of Permain-Triassic and Ordovician metagraywacke terranes in New Zealand: evidence from $^{40}Ar/^{39}Ar$ dating of detrital mica. *Geol. Soc. Am. Bull.* 110:422–32

Arne DC, Bierlein FP, Keay S, Foster DA, McNaughton NJ. 1998. A dynamic model for gold mineralisation in the western Lachlan Fold Belt, central Victoria. *Geol. Soc. Aust. Abst.* 49:13

Aitchison JC, Ireland TR, Clarke GL, Cluzel D, Meffre S. 1998. Regional implications of U/Pb SHRIMP age constraints on the tectonic evolution of New Caledonia. *Tectonophysics* 299:333–43

Bucher M. 1998. *Timing of deformation, plutonism and cooling in the western Lachlan fold belt, southeastern Australia.* PhD thesis. La Trobe Univ. Melbourne, Australia.

Cas RAF. 1983. Palaeogeographic and tectonic development of the Lachlan Fold Belt of southeastern Australia. *Geol. Soc. Aust. Sp. Pub.* 10:104

Cas RAF, Powell CMcA, Crook KAW. 1980. Ordovician palaeogeography of the Lachlan Fold Belt: a modern analogue and tectonic constraints. *J. Geol. Soc. Aust*. 27:19–31

Cayley RA, Taylor DH. 1999. The Grampians and western Lachlan margin excursion, Halls Gap, Victoria—recent mapping supporting an intra-plate tectonic setting for the western Lachlan Fold Belt. *Specialist Group in Tectonics and Structural Geology Field Guide 8.* Geol. Soc. Australia, Sydney. 31 pp.

Chappell BW, White AJR, Hine R. 1988. Granite provinces and basement terranes in the Lachlan fold belt, southeastern Australia. *Aust. J. Earth Sci.* 35:505–24

Clemens JD. 1988. Volume and composition relationships between granites and their lower crustal sources: an example from central Victoria, Australia. *Aust. J. Earth Sci.* 35:445–49

Clemens JD, Wall VJ. 1988. Crystallisation and origin of some peraluminous (S-type) granitic magmas. *Can. Min.* 19:111–32

Collins WJ. 1996. Lachlan fold belt granitoids–-Products of three-component mixing. *Trans. R. Soc. Educ. Earth Sci.* 87:171–81

Collins WJ. 1998. Evaluation of petrogenetic models for Lachlan Fold Belt granitoids: implications for crustal architecture and tectonic models. *Aust. J. Earth Sci.* 45:483—500

Collins WJ. 1999. Heat sources and tectonic models for the east Lachlan fold belt: the basalt story. *Geol. Soc. Aust. Abstr. Ser.* 53:33

Coney PJ. 1992. The Lachlan fold belt of eastern Australian and Circum-Pacific tectonic evolution. *Tectonophysics* 214:1–25

Coney PJ, Edwards A, Hine R, Morrison F, Windrum D. 1990. The regional tectonics of the Tasman orogenic system, eastern Australia. *J. Struct. Geol*. 125:19–43

Cox SF, Wall VJ, Etheridge MA, Potter TF. 1991. Deformational and metamorphic processes in the formation of mesothermal vein-hosted gold deposits–examples from the Lachlan fold belt in central Victoria, Australia. *Ore Geol. Rev.* 6:391–423

Crawford AJ, Keays RR. 1978. Cambrian greenstone belts in Victoria: marginal seacrust slices in the Lachlan fold belt of southeastern Australia. *Earth Planet Sci. Let.* 41:197–208

Crawford AJ, Cameron WE, Keays RR. 1984. The association of boninite low-Ti andesite-tholeiite in the Heathcote Greenstone Belt, Victoria: ensimatic setting for the early Lachlan fold belt. *Aust. J. Earth Sci.* 31:161–76

Crook KAW. 1974. Cratonisation of west Pacific-type geosynclines. *J. Geol.* 87:24–36

Crook KAW. 1980. Fore-arc evolution and continental growth: a general model. *J. Struct. Geol.* 2:289–303

Curray JR, Emmel FJ, Moore DG, Raitt RW. 1982. Structure, tectonics and geological history of the northeastern Indian Ocean. In *The Ocean Basin and Margins, Vol. 6: The Indian Ocean*, ed. AEM Nairn, FG Stehli, pp. 399–450. New York: Plenum Press

Dadd KA. 1998. Incipient backarc magmatism in the Silurian Tumut Trough, New South Wales: an ancient analogue of the early Lau Basin. *Aust. J. Earth Sci.* 45:109–21

Dewey JF. 1988. Extensional collapse of orogens. *Tectonics* 7:1123–39

Farrell TR, Offler R. 1989. Greenschist facies metamorphism of a rift basin sequence, Breadalbane, N.S.W. *Aust. J. Earth Sci.* 36:337–49

Fergusson CL. 1987. Early Paleozoic back-arc deformation in the Lachlan fold belt, southeastern Australia: implications for terrane translations in eastern Gondwanaland. In *Terrane Accretion and Orogenic Belts Geodyn. Ser. vol. 19*, ed. EC Leitch, E Scheibner, pp. 39–56. Washington, DC: AGU

Fergusson CL. 1998. Cambrian-Silurian oceanic rocks, upper Howqua River, eastern Victoria: tectonic implications. *Aust. J. Earth Sci.* 45:633–44

Fergusson CL, Coney PJ. 1992a. Convergence and intraplate deformation in the Lachlan fold belt of southeastern Australia. *Tectonophysics* 214:417–39

Fergusson CL, Coney PJ. 1992b. Implications of a Bengal Fan-type deposit in the Paleozoic Lachlan fold belt of southeastern Australia. *Geology* 20:1047–49

Fergusson CL, VandenBerg AHM. 1990. Middle Paleozoic thrusting in the eastern Lachlan fold belt, southeastern Australia. *J. Struct. Geol*. 12:577–89

Fergusson CL, Gray DR, Cas RAF. 1986. Overthrust terranes in the Lachlan fold belt, southeastern Australia. *Geology* 14:519–22

Fergusson CL, Henderson RA, Leitch EC, Ishiga H. 1993. Lithology and structure of the Wandilla Terrane, Gladstone-Yeppoon District, central Queensland, and an overview of the Palaeozoic subduction complex of the New-England Fold Belt. *Aust. J. Earth Sci.* 40:403–14

Finn C, Damaske D, Mackey T, Moore D. 1998. The aeromagnetic connection: a new look at the Gondwana geology of Antarctica and Australia. *Geol. Soc. Aust. Abst.* 49:145

Finlayson DM, Collins CDN, Denham D. 1980. Crustal structure under the Lachlan Fold Belt, southeastern Australia. *Phys. Earth Plan. Int*. 21:321–42

Flöttmann T, Klinschmidt D, Funk T.1993. Thrust patterns of the Ross/Delamerian orogens in northern Victoria Land (Antartica) and southeastern Australia and their implications for Gondwana Reconstructions. In *Gondwana Eight, Assembly, Evolution and Dispersal*, ed. RH Findlay, R Unrug, HR Banks, JJ Veevers, pp. 131–39. Rotterdam: Balkema

Flöttmann T, Oliver R. 1994. Review of Precambrian-Palaeozoic relationships at the craton margins of southeastern Australia and adjacent Antarctica. *Precam. Res.* 69:293–306

Flöttmann T, James P, Rogers J, Johnson T. 1994. Early Palaeozoic foreland thrusting and basin reactivation at the palaeo-Pacific margin of the southeastern Australian Precambrian Craton: a reappraisal of the structural evolution of the Southern Adelaide Fold-Thrust Belt. *Tectonophysics* 234:95–116

Foster DA, Ehlers K. 1998. ^{40}Ar-^{39}Ar thermochronology of the southern Gawler Craton, Australia: implications for Mesoproterozoic and Neoproterozoic tectonics of East Gondwana and Rodinia. *J. Geophys. Res.* 103:10,177–93

Foster DA, Gleadow AJW. 1992. Reactivated tectonic boundaries and implications for the reconstruction of southeastern Australia and northern Victoria Land, Antarctica. *Geology* 20:267–70

Foster DA, Gray DR, Offler R. 1996. The western sub-province of the Lachlan fold belt, Victoria: structural style, geochronology, metamorphism, and tectonics. *Specialist Group in Geochemistry, Mineralogy, and Petrology Field Guide 1*. Geol. Soc. Australia, Sydney. 89 pp.

Foster DA, Gray DR, Kwak TAP, Bucher M. 1998. Chronology and tectonic framework of turbidite hosted gold deposits in the western Lachlan fold belt, Victoria: ^{40}Ar-^{39}Ar results. *Ore Geol. Rev.* 13:229–50

Foster DA, Gray DR, Bucher M, 1999. Chronology of deformation within the turbidite-dominated Lachlan orogen: implications for the tectonic evolution of eastern Australia and Gondwana. *Tectonics*. 18:452–85

Gibson G, Wesson V, Cuthbetson R. 1981. Seismicity in Victoria to 1980. *Geol. Soc. Aust. J.* 28:341–56

Gibson GM, Ireland TR. 1996. Extension of Delamerian (Ross) Orogen into western New Zealand; evidence from zircon ages and implications for crustal growth along the Pacific margin of Gondwana. *Geology* 24:1087–90

Glen RA. 1992. Thrust, extensional and strike-slip tectonics in an evolving Palaeozoic orogen of southeastern Australia. *Tectonophysics* 214:341–80

Glen RA, VandenBerg AHM. 1987. Thin skinned tectonics in part of the Lachlan fold belt near Delegate, southeastern Australia. *Geology* 15:1070–73

Glen RA, Watkins JJ. 1999. Implications of Middle Devonian deformation of the eastern part of the Hill End Trough, Lachlan Orogen, New South Wales. *Aust. J. Earth Sci.* 46:35–52

Glen RA, Dallmeyer RD, Black LP. 1992. Isotope dating of basin inversion–-The Palaeozoic Cobar Basin, Lachlan Orogen, Australia. *Tectonophysics* 214:249–68

Glen RA, Drummond BJ, Goleby BR, Palmer D, Wake-Dyster KD. 1994. Structure of the Cobar basin, New South Wales, based on seismic reflection profiling. *Aust. J. Earth Sci*. 41:341–52

Glen RA, Walshe JL, Barron LM, Watkins JJ. 1998. Ordovician convergent-margin volcanism and tectonism in the Lachlan sector of Gondwana. *Geology* 26:751–54

Gray CM. 1990. A strontium isotopic traverse across the granitic rocks of southeastern Australia: petrogenetic and tectonic implications. *Aust. J. Earth Sci*. 37:331–49

Gray DR. 1988. Structure and tectonics. In *Geology of Victoria*, ed. JG Douglas, JA Ferguson, pp. 1–36. Victorian Div., Geol. Soc. Australia, Melbourne. 2nd edition.

Gray DR. 1997. Tectonics of the southeastern Australian Lachlan fold belt: structural and thermal aspects. In *Orogeny through Time*, ed. JP Burg, M Ford, *Geol. Soc. Spec. Pub*. 121:149–77

Gray DR, Foster DA. 1997. Orogenic concepts–-application and definition: Lachlan fold belt, eastern Australia. *Am. J. Sci*. 297:859–91

Gray DR, Foster DA. 1998. Character and kinematics of faults within the turbidite-dominated Lachlan orogen: implications for the tectonic evolution of eastern Australia. *J. Struct. Geol.* 20:1691–1720

Gray DR, Foster DA, Bucher M. 1997. Recognition and definition of orogenic events in the Lachlan Fold Belt. *Aust. J. Earth Sci*. 44:489–501

Gray DR, Willman CE. 1991a. Deformation in the Ballarat Slate Belt, Central Victoria and implications for the crustal structure across SE Australia. *Aust. J. Earth Sci.* 38:171–201

Gray DR, Willman CE. 1991b. Thrust-related strain gradients and thrusting mechanisms in a chevron-folded sequence, southeastern Australia. *J. Struct. Geol*. 13:691–710

Gray DR, Wilson CJL, Barton TJ. 1991. Intracrustal detachments and implications for crustal evolution within the Lachlan fold belt, southeastern Australia. *Geology* 19:574–77

Gray DR, Foster DA, Gray C, Cull J, Gibson G. 1998. Lithospheric structure of the southeast Australian Lachlan fold belt along the Victorian Global Geoscience Transect. *Int. Geol. Rev.* 40:1088–1117

Griffin WL, O'Reilley SY. 1987. Is the continental Moho the crust-mantle boundary? *Geology* 15:241–44

Hartley MJ, Foster DA, Gray DR, Kohn BP. 1998. ^{40}Ar-^{39}Ar and apatite fission track thermochronology of the Broken Hill Inlier: implications for the Mesoproterozoic to Recent tectonics. *Aust. Geol. Surv. Org. Rec*. 25:46–49

Hendrix M. 1999. The I-S line: a thrust sheet boundary in eastern Victoria. *Geol. Soc. Aust. Abst.* 53:101–2

Hoffman PF. 1991. Did the breakout of Laurentia turn Gondwanaland inside out? *Science* 252:1409–12

Hoffman PF. 1988. United plates of America, the birth of a craton: Early Proterozoic assembly and growth of Laurentia. *Annu. Rev. Earth Planet. Sci.* 16:543–603

Jenkins RJF, Sandiford M. 1992. Observations on the tectonic evolution of the southern Adelaide Fold Belt. *Tectonophysics* 214:27–36

Keay S, Collins WJ, McCulloch MT. 1997. A three-component Sr-Nd isotopic mixing model for granitoid genesis, Lachlan fold belt, eastern Australia. *Geology* 25: 307–10

Keay S, Steele D, Compston W. 1998. Identifying granite sources by SHRIMP U-Pb zircon geochronology: an application to the Lachlan fold belt. *Contrib. Min. Petrol*. In press

Korsch R, Barton T, Gray DR, Owen AJ, Foster DA. 1999. Structural interpretation of a deep seismic reflection transect in the vicinity of the Grampians, Victoria. *Geo. Soc. Aust. Abst.* 53:139–41

Leitch EC, Fergusson CL, Henderson RA, Morand VJ. 1994. Ophiolitic and metamorphic rocks in the Percy Isles and Shoalwater Bay region, New England fold belt, central Queensland. *Aust. J. Earth Sci.* 41:571–79

Leven JH, Stuart-Smith PG, Musgrave RJ, Rickard MJ, Crook KAW. 1992. A geophysical transect across the Tumut Synclinorial Zone, N.S.W. *Tectonophysics* 214:239—48

Li ZX, Powell CmcA. 1993. Late Proterozoic to early Paleozoic paleomagnetism and formation of Gondwanaland. *Gondwana Eight Assembly, Evolution, and Dispersal*, ed. RH Findlay, R Unrug, MR Banks, JJ Veevers, AA Balkema, pp. 9–21. Rotterdam: Balkema

Li ZX, Powell CMcA, Thrupp GA. 1990. Australian Palaeozoic palaeomagnetism and tectonics, II: a revised apparent polar wonder path and palaeogeography. *J. Struct. Geol.* 12:567–75

McCulloch MT, Chappell BW. 1982. Nd isotopic characteristics of S- and I-type granites. *Earth Plan. Sci. Lett.* 58:51–64

Miller JMcL, Gray DR. 1996. Structural signature of sediment accretion in a Palaeozoic accretionary complex, southeastern Australia. *J. Struct. Geol.* 18:1245–58

Moore DH, VandenBerg AHM, Willman CE, Magart APM. 1998. Palaeozoic geology and resources of Victoria. *AGSO J. Aust. Geol. Geophys*. 17:107–122

Morand VJ. 1990. Low-pressure regional metamorphism in the Omeo Metamorphic Complex, Victoria, Australia. *J. Met. Geol*. 8:1–12

Morand VJ, Gray DR, 1991. Major fault zones related to the Omeo Metamorphic Complex, northeastern Victoria. *Aust. J. Earth Sci.* 38:203–21

Offler R, Prendergast E. 1985. Significance of illite crystallinity and b_o values of K-white micas in low-grade metamorphic rocks, North Hill End Synclinorium, New South Wales, Australia. *Miner. Mag.* 49:357–64

Offler RL, McKnight S, Morand V. 1998a. Tectono-thermal history of the western Lachlan fold belt, Australia: insights from white mica studies. *J. Met. Geol.* 16:531–40

Offler R, Miller JMcL, Gray DR, Foster DA, Bale R. 1998b. Crystallinity and b_o spacing of K-white micas in a Paleozoic accretionary complex, eastern Australia: metamorphism, paleo-geotherms and structural style of an underplated sequence. *J. Geol.* 106:495–509

O'Halloran GJ, Cas RAF. 1995. Evidence for syndepositional deformation from the Late Devonian of the Mansfield Basin, east-central Victoria. *Aust. J. Earth Sci*. 42:581–96

O'Halloran GJ, Rey P. 1999. Isostatic constraints on the central Victorian lower crust: Implications for the tectonic evolution of the Lachlan Fold Belt. *Aust. J. Earth. Sci.* In press.

Oversby B. 1971. Palaeozoic plate tectonics in the southern Tasman geosyncline. *Nat. Phys. Sci*. 234:45–47

Packham GH. 1999. Radiometric evidence for Middle Devonian inversion of the Hill End trough. *Aust. J. Earth Sci*. 46:23–33

Pinchin J. 1980. Intracrustal seismic reflections from the Lachlan Fold Belt near Canberra. *BMR J. Aust. Geol. Geophys.* 5:305–9

Powell CMcA. 1983. Tectonic relationship between the Late Ordovician and Late Silurian palaeogeographies of southeastern Australia. *J.Geol Soc. Aust.* 30:353–73

Powell CMcA. 1984. Uluru regime. In *Phanerozoic Earth History of Australia. Oxford Geol. Sci. Series, Vol. 2*, ed. JJ Veevers, pp. 290–337. Melbourne: Oxford Univ. Press

Powell CmcA, Preiss WV, Gatehouse CG, Krapez B, Li ZX. 1994. South Australian record of a Rodinian epicontinental basin and its mid-Neoproterozoic breakup to form the Paleo-Pacific Ocean. *Tectonophysics* 237:113–40

Richards JR, Singleton OP. 1981. Palaeozoic Victoria, Australia: igneous rocks, ages and their interpretation. *J. Geol. Soc. Aust.* 28:395–421

Royden LH. 1993. The tectonic expression of slab pull at continental convergent Boundaries. *Tectonics* 12:303–25

Sandiford M, Powell R. 1986. Deep crustal metamorphism during continental extension: modern and ancient examples. *Earth Planet. Sci. Lett.* 19:151–58

Sandiford, M, Foden J, Zhou S, Turner S. 1992. Granite genesis and the mechanics of convergent orogenic belts with application to the southern Adelaide Fold Belt. *Trans. R. Soc. Educ. Earth Sci.* 83:83–93

Scheibner E. 1974. A plate tectonic model of the Palaeozoic history of New South Wales. *J. Geol. Soc. Aust.* 20:405–26

Scheibner E, Basden H. 1996. *Geology of New South Wales–Synthesis.* Vol. 1, *Structural Framework,* Geol. Surv. of New South Wales, Sydney, 295 pp.

Sengor CAM, Natal'in BA. 1996. Turkic-type orogeny and its role in the making of the continental crust. *Annu. Rev. Earth Planet. Sci.* 24:263–337

Solomon M, Griffiths JR. 1972. Tectonic evolution of the Tasman Orogenic zone, eastern Australia. *Nat. Phys. Sci.* 237:3–6

Smith RE. 1969. Zones of progressive regional burial metamorphism in part of the Tasman Geosyncline, eastern Australia. *J. Petrol.* 10:144–63

Spaggiari CV, Gray DR, Foster DA. 1999. Occurrences and significance of Franciscan-like melange and blueschist metamorphism in Lachlan Orogen fault zones. *Geol. Soc. Austr. Abst.* 53:248–49

Stuart-Smith PG. 1991. The Gilmore fault zone–The deformation history of a possible terrane boundary within the Lachlan fold belt, New South Wales. *BMR J. Aust. Geol. Geophys.* 12:35–50

Talent JA. 1965. The stratigraphic and diastrophic evolution of the central and eastern Victoria in Middle Palaeozoic times. *Proc. R. Soc. Vic.* 79:179–95

Turner SP, Foden JD, Morrison RS. 1992. Derivation of some A-type magmas by fractionation of basaltic magma: an example from the Padthaway Ridge, South Australia. *Lithos* 28:151–79

Turner SP, Adams CJ, Flöttmann T, Foden JD. 1993. Geochemical and geochronological constraints on the Glenelg River complex, western Victoria. *Aust. J. Earth Sci.* 40: 275–92

Turner S, Sandiford M, Flöttmann T, Foden JD. 1994. Rb/Sr dating of differentiated cleavage from the upper Adelaidean metasediments at Hallett Cove, southern Adelaide fold belt. *J. Struct. Geol.* 16:1233–41

Turner SP, Kelley SP, VandenBerg AHM, Foden JD, Sandiford M, Flötmann T. 1996. Source of the Lachlan fold belt flysch linked to convective removal of the lithospheric mantle and rapid exhumation of the Delamerian-Ross fold belt. *Geology* 24:941–44

VandenBerg AHM. 1988. Silurian-Middle Devonian. In *Geology of Victoria*, ed. JG Douglas, JA Fergusson. Geological Society Australia, Victorian Division, Melbourne. pp. 103–46. 2nd ed.

VandenBerg AHM, Stewart IR 1992. Ordovician terranes of the southeastern Lachlan fold belt: stratigraphy, structure and palaeogeographic reconstruction. *Tectonophysics* 214: 159–76

VandenBerg AHM, Willman CE, Hendrix M, Bush MD, Sands BC. 1995. *The geology and prospectivity of the 1993 Mount Wellington Airborne Survey area. VIMP Rep. 2*. Geol. Surv. of Victoria, Melbourne. p. 165

Veevers JJ, Powell CMcA, Roots SR. 1991. Review of seafloor spreading around Australia. I. synthesis of the patterns of spreading. *Aust. J. Earth Sci.* 38:373–89

White AJR, Chappell BW. 1983. Granitoid types and their distribution in the Lachlan Fold Belt, southeastern Australia. *Geol. Soc. Am. Mem.* 159:21–34

Williams IS. 1992. Some observations on the use of zircon U-Pb geochronology in the study of granitic rocks. *Trans. R. Soc. Educ.: Earth Sci*. 83:447–58

Williams IS, Compston W, Chappell BW. 1983. Zircon and monazite U-Pb systems and the histories of I-type magmas, Berridale Batholith, Australia. *J. Petrol.* 24:76–97

Wilson CJL, Will TM, Cayley RA, Chen S. 1992. Geologic framework and tectonic evolution in western Victoria, Australia. *Tectonophysics* 214:93–127

Wilson CJL, Gray DR, Foster DA, Morand VJ, Schaubs PM, Spaggiari C, 1999. The great southern transect I: an overview of the geology of the eastern, central, and western sub-provinces of the Lachlan Fold Belt; Mallacoota to Halls Gap, Victoria: *Specialist Group in Tectonics and Structural Geology Field Guide No. 5*. Geol. Soc. of Australia, Sydney. 123 pp.

Yang X, Gray DR. 1994. Strain, cleavage and microstructure variations in sandstone: implications for stiff layer behaviour in chevron folding. *J. Struct. Geol.* 16:1353–65