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Tectonic evolution of the Lachlan Orogen, southeast Australia: historical review, data synthesis and modern perspectives

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The Lachlan Orogen, like many other orogenic belts, has undergone paradigm shifts from geosynclinal to plate-tectonic theory of evolution over the past 40 years. Initial plate-tectonic interpretations were based on lithologic associations and recognition of key plate-tectonic elements such as andesites and palaeo-subduction complexes. Understanding and knowledge of modern plate settings led to the application of actualistic models and the development of palaeogeographical reconstructions, commonly using a non-palinspastic base. Igneous petrology and geochemistry led to characterisation of granite types into 'I' and 'S', the delineation of granite basement terranes, and to non-mobilistic tectonic scenarios involving plumes as a heat source to drive crustal melting and lithospheric deformation. More recently, measurements of isotopic tracers (Nd, Sr, Pb) and U–Pb SHRIMP age determinations on inherited zircons from granitoids and detrital zircons from sedimentary successions led to the development of multiple component mixing models to explain granite geochemistry. These have focused tectonic arguments for magma genesis again more on plate interactions. The recognition of fault zones in the turbidites, their polydeformed character and their thin-skinned nature, as well as belts of distinct tectonic vergence has led to a major reassessment of tectonic development. Other geochemical studies on Cambrian metavolcanic belts showed that the basement was partly backarc basin- and forearc basin-type oceanic crust. The application of ^{40}Ar–^{39}Ar geochronology and thermochronology on slates, schist and granitoids has better constrained the timing of deformation and plutonism, and illite crystallinity and b_o mica spacing studies on slates have better defined the background metamorphic conditions in the low-grade parts. The Lachlan deformation pattern involves three thrust systems that constitute the western Lachlan Orogen, central Lachlan Orogen and eastern Lachlan Orogen. The faults in the western Lachlan Orogen show a generalised east-younging (450–395 Ma), which probably relates to imbrication and rock uplift of the sediment wedge, because detailed analyses show that the décollement system is as old in the east as it is in the west. Overall, deformation in the eastern Lachlan Orogen is younger (400–380 Ma), apart from the Narooma Accretionary Complex (*ca* 445 Ma). Preservation of extensional basins and evidence for basin inversion are largely restricted to the central and eastern parts of the Lachlan Orogen. The presence of dismembered ophiolite slivers along some major fault zones, as well as the recognition of relict blueschist metamorphism and serpentinite–matrix mélanges requires an oceanic setting involving oceanic underthrusting (subduction) for the western Lachlan Orogen and central Lachlan Orogen for parts of their history. Inhibited by deep weathering and a general lack of exposure, the recent application of geophysical techniques including gravity, aeromagnetic imaging and deep crustal seismic reflection profiling has led to greater recognition of structural elements through the subcrop, a better delineation of their lateral continuity, and a better understanding of the crustal-scale architecture of the orogen. The Lachlan Orogen clearly represents a class of orogen, distinct from the Alps, Canadian Rockies and Appalachians, and is an excellent example of a Palaeozoic accretionary orogen.

KEY WORDS: backarc basin, Lachlan Orogen, plate tectonics, submarine fans, Tasman Orogen, thrusting.

INTRODUCTION

It has been long recognised (Schuchert 1916; Browne 1947; Rutland 1976; Crook 1980) that cratonisation of eastern Australia has involved an eastward progression of terminal deformation that caused stepwise addition of the Delamerian, Lachlan–Thomson and New England Orogens, respectively (Figure 1). However, controversy remains as to how, and in what tectonic environment(s), this occurred. The Lachlan Orogen perhaps remains the most enigmatic and most widely disputed part of the Tasman Orogenic system. Structural thickening took place during plate convergence in an oceanic setting along the eastern margin of Gondwana from *ca* 520 Ma through 340 Ma, with accretion of structurally thickened

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submarine fans, accretionary complexes, former volcanic arcs and oceanic crust, as well as possible micro-continents. The nature, causes and tectonic setting of this period of cratonisation have been hotly debated with arguments based on geochemistry, thermal regimes and regional structural architecture. Issues have included the mechanism for closing the marginal basin(s), an explanation for the variable thermal pattern expressed by metamorphism and magmatism, and as to how and why the orogenic system varied through time.

Most workers have argued that construction of the Lachlan Orogen was intraplate and inboard of a long-lived subduction system off Gondwana (Crook 1969, 1974; Scheibner 1972, 1973; Fergusson & Coney 1992a). But how did the system work? Powell (1983a) provided an insightful solution by changing the Tasmanide margin through time, from the hangingwall of a Marianas-type subduction system, to strike-slip along a transform plate boundary, to final Andean-type subduction. The final stages in the eastern Lachlan involve marked magmatism typical of the North American Basin and Range province (extensional environment) but as to whether Lachlan construction can be simply viewed as overall extension punctuated by brief contractional episodes (Collins 2002a, b), the Royden and Burchfiel (1989) 'retreating orogen' or Carpathian-type (Glen 1992), depends on the tectonic reference frame and the relative durations of extension versus contraction as expressed in the rock record. The presence of continental ribbons like the present day Lord Howe Rise and Campbell Plateau (e.g. Tasmania and the inferred Selwyn block extension underneath the Melbourne Zone, Victoria) have implications for the deformation patterns. Detailing cratonisation of eastern Australia requires fitting of the pieces of a tectonic jigsaw puzzle, but there is also a requirement of explaining how it works. The overall different geotherm in the western Lachlan (Offler *et al.* 1998a), coupled with the presence of serpentinite–matrix mélange incorporating blueschist knockers like the Franciscan of California (Spaggiari *et al.* 2002a, b), must also be considered. Clearly subduction was involved.

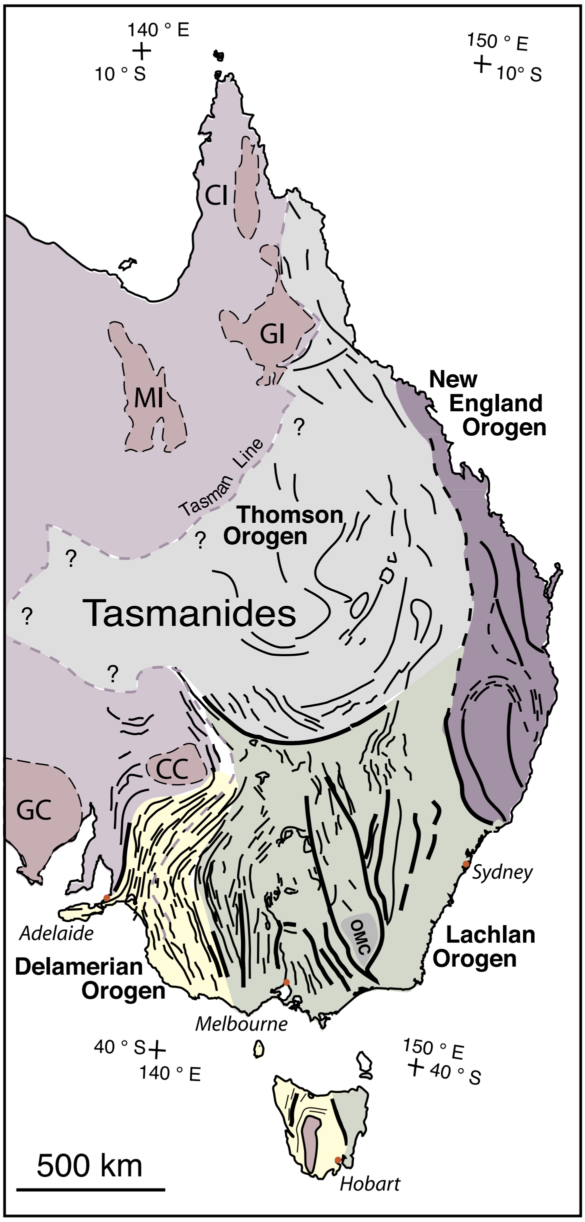


Figure 1 Map of eastern Australia with the composite Tasman Orogen (Tasmanides) showing the component Delamerian, Lachlan, Thomson and New England Orogens. Heavy lines are the major fault traces and the other lines are aeromagnetic trend lines. Precambrian cratons are: CI, Coen Inlier; GI, Georgetown Inlier; MI, Mt. Isa Inlier; CC, Curnamona Craton; GC, Gawler Craton.

Like most orogenic belts, studies on the Lachlan Orogen have been wide ranging and have undergone considerable change through time. Focus has included facies analysis, biostratigraphic and palaeogeographical analysis, granite studies, isotopic studies on the granites and host sedimentary successions, terrane subdivision, structural work on the folds and faults, sediment provenance studies utilising detrital zircon populations, and $^{40}Ar/^{39}Ar$ geochronology and thermochronology of the deformed turbidites. Depending on the locations of the research groups, many of the studies and thus, the derived views were either New South Wales-centric or Victoria-centric. This clearly led to different views on the orogen and to different opinions on how it developed. The recognisable Ordovician island arc occurs in New South Wales, whereas the greenstone belts occur in Victoria, and each has contributed in its own way to our understanding of the development of this orogenic belt. Likewise, Tasmania provides another view of orogen development with an inferred earlier obduction event (Berry & Crawford 1988; Crawford & Berry 1992). It is now clear that the orogenic belt is made up of different parts, the western part including central Victoria with the greenstone belts or ophiolitic slivers and the eastern part including the Ordovician island-arc rocks of central New South Wales.

After some 150 years of research on the Tasmanides, it is perhaps time for reflection and some historical perspective. Reviews by Fisher (1974) and Packham and Leitch (1974) for the Tasman Geosyncline volume in honour of Professor Dorothy Hill, provided a summary of both the geosynclinal approach and the application of the plate tectonic paradigm to the Lachlan Orogen, respectively. Rutland (1976) provided a review of the Lachlan Orogen as part of a more wide-ranging overview of the geology of the Australian continent to coincide with the Sydney International Geological Congress. Cas (1983) summarised the palaeography and reviewed the tectonics of the Lachlan Orogen in a Geological Society of Australia Special Publication. Coney *et al.* (1990) provided an excellent overview of the Lachlan Orogen, unaffected by Australasian idiosyncrasies and biases. More recently, Scheibner and Basden (1996, 1998) and Veevers (2000) have provided detailed discussion and review of Lachlan Orogen evolution in their respective *Geology of New South Wales* and *Billion-year Earth History of Australia and its Neighbours in Gondwanaland* volumes. Some 30 years after the introduction of plate tectonics, this paper attempts to document the historical sequence of ideas and tectonic scenarios proposed for the Lachlan Orogen, as well as providing a discussion and an overview on current hypotheses. It also looks at the evolution of eastern Australia from a modern perspective. This review attempts an approach which considers that the orogen as a 'whole is greater than its parts': the parts are important for their differences but are dealt with in the context of the whole orogen (Lacey 1976). As a result, we have steered away from the incredible detail

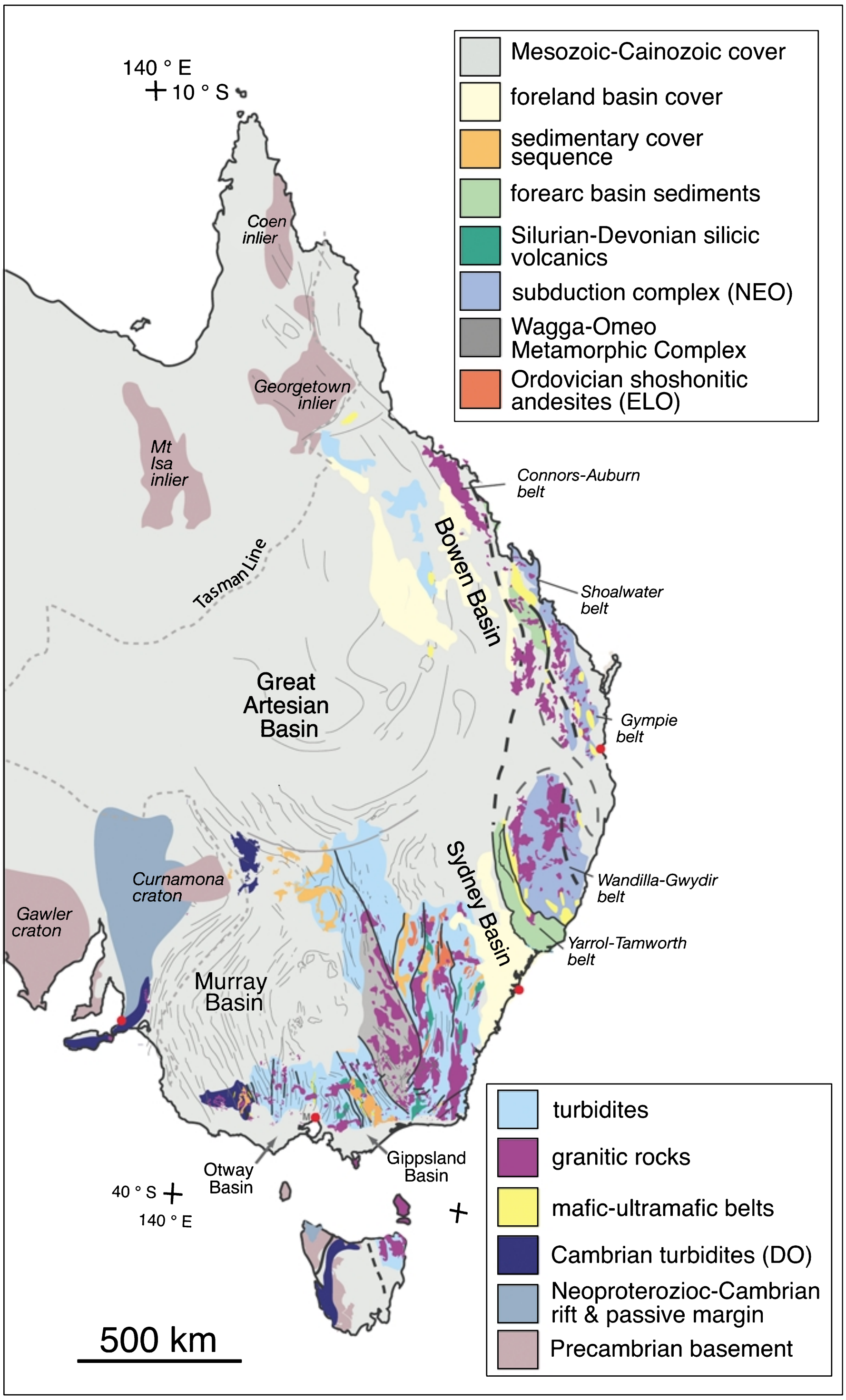


Figure 2 Geological map of the Tasman Orogen of eastern Australia showing the major lithotypes (based on the 1:1 000 000 scale geological map sheets of Victoria and New South Wales and the 1:5 000 000 geological map of Australia). DO, Delamerian Orogen; ELO, eastern Lachlan Orogen; NEO, New England Orogen.

and, therefore, apparent complexity of other reviews. In that sense, what we present here is clearly an overview, but within a historical perspective.

A review of this nature is essentially a personal view, clearly coloured by our respective biases, particularly towards structural geology and geochronology. As a consequence, it is different from the largely stratigraphic approach of Veevers (2000) and the combined stratigraphic–terrane–structure approach of Scheibner and Basden (1996, 1998). Because it is a personal view, our treatment of some research areas would be considered by some as superficial. We have attempted to present, what in our opinions, were the main research emphases, our opinions on their respective influences and a summary of what we think are the most important constraints for Lachlan Orogen tectonic evolution.

BACKGROUND

The Lachlan Orogen is a turbidite-dominated orogen that forms the central part of composite Palaeozoic Tasman Orogen (Scheibner 1978, 1987; Coney *et al.* 1990) along the eastern margin of Australia (Figure 1). Successive cratonisation from west to east included the Early Palaeozoic Delamerian Orogen (550–470Ma), the Middle Palaeozoic Lachlan Orogen (450–340 Ma) and the Late Palaeozoic to Early Mesozoic New England Orogen

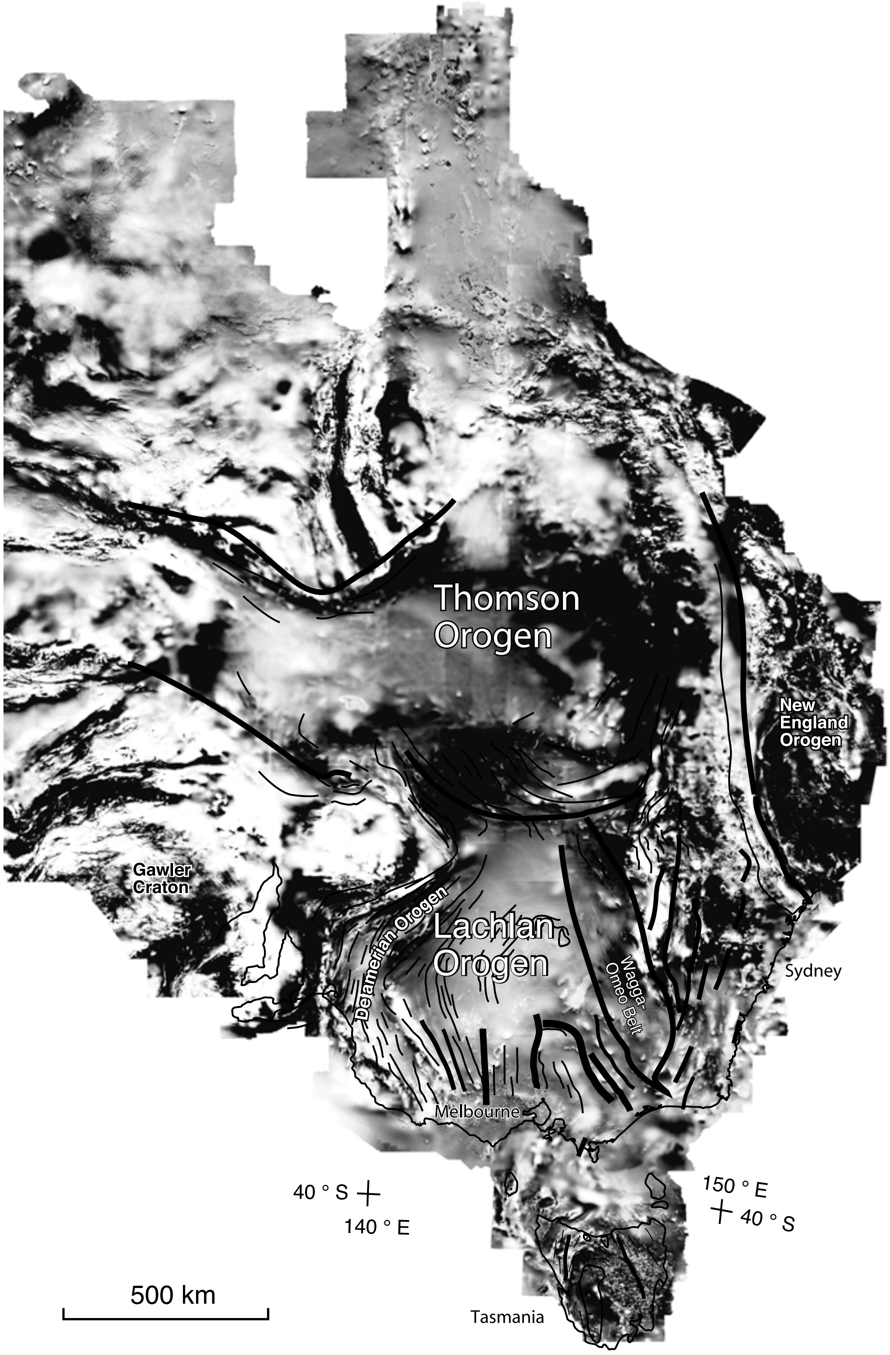


Figure 3 Aeromagnetic image of eastern Australia (from Kilgour 2002a) with superimposed major fault traces (bold lines), structural trends or form lines and aeromagnetic trend lines. Note the truncation of Lachlan trends by the Thomson Orogen and the apparent westwards extension of the Thomson Orogen towards the Musgrave–Arunta–Amadeus intracratonic orogenic belt of central Australia.

(310–210 Ma), with their respective peak deformations of Late Cambrian – Early Ordovician, Late Ordovician – Silurian and Permian–Triassic age (Foster & Gray 2000a). The Lachlan part is a Middle Palaeozoic orogen with a 200 million years history that occupies ~50% of the present outcrop of the Tasman Orogen.

Boundaries between the three orogens (Figure 1) are not generally exposed as they are mostly covered by younger sequences. The inner parts of the Tasman Orogen, including the Delamerian Orogen and the western part of the Lachlan Orogen, show pronounced curvature and structural conformity with what appear to be promontories and recesses in the old cratonic margin (Figure 2), redefined as the Tasman Line (Scheibner 1978). Outboard of this, the central and eastern parts of the Lachlan Orogen and the New England Orogen have more continuous north–south trends that appear to show no relationship to the form of the old cratonic margin (Figure 3).

The major feature of the Lachlan Orogen is the similarity of sedimentary facies (Figure 2) consisting of interbedded turbiditic sandstone and mudstone with minor chert and mafic metavolcanics typical of oceanic successions (Coney *et al.* 1990; Fergusson 2003; Spaggiari *et al.* 2003a, 2004a). As well, there is an overall structural style that is largely chevron folded cut by thin-skinned thrust systems (Gray & Willman 1991a, b; Gray & Foster 1998). The Lachlan clearly represents a class of orogen distinct from the Alps, Canadian Rockies and Appalachians, but is now recognised in other places as accretionary orogens, or Turkic-type orogens (after Sengor

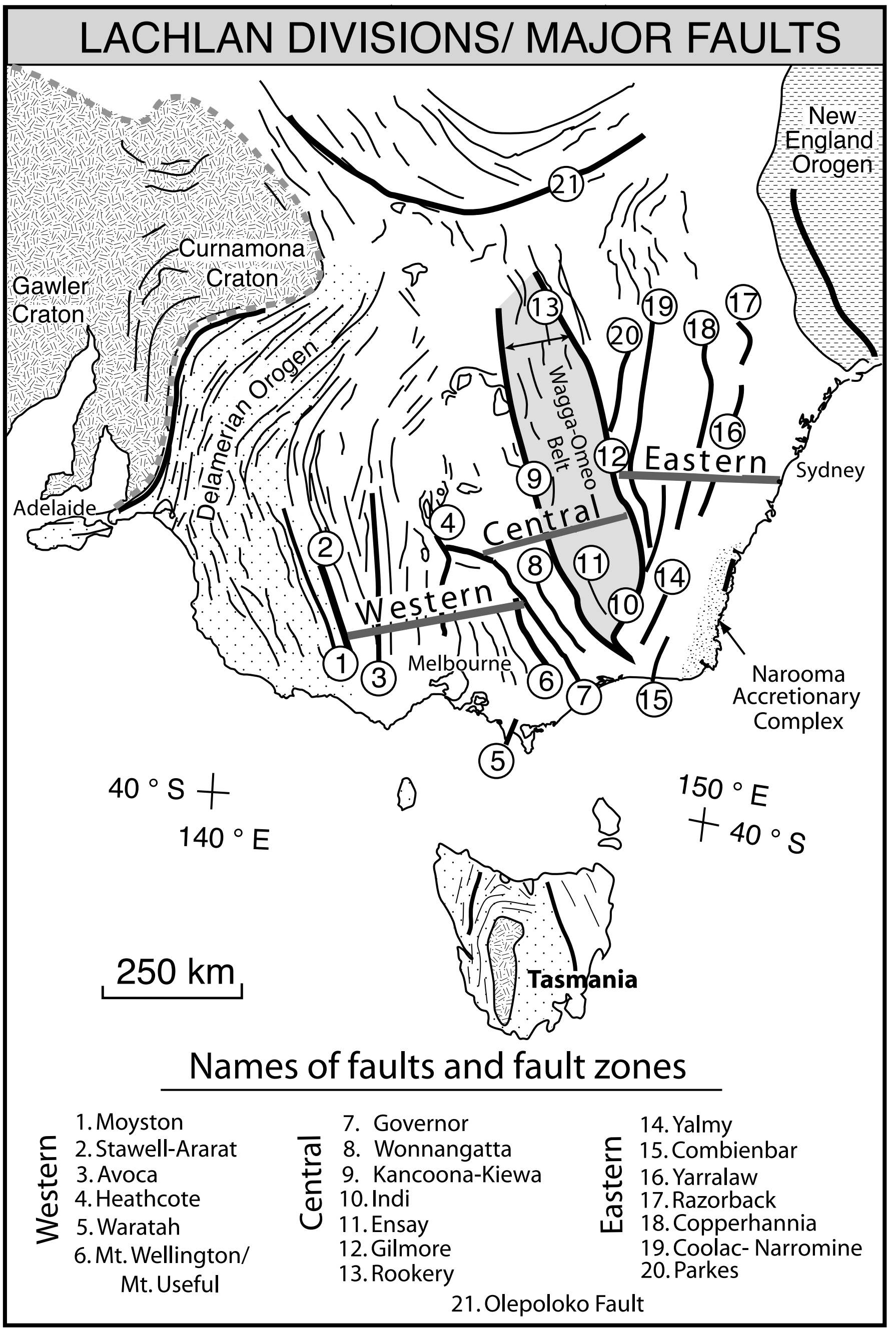


Figure 4 Simplified structural map of the Lachlan Orogen showing the defined subdivisions for the western, central and eastern parts (after Gray 1997), the traces (heavy lines) and names (circled numbers) of the major fault zones, and the structural form by aeromagnetic trend lines (finer lines). The positions of the Wagga–Omeo Metamorphic Belt and Narooma Accretionary Complex are shown.

& Natal'in 1996), with some similarities to retreating orogens (after Royden & Burchfiel 1989) although this concept does not apply to many features of the orogen. The features that set the Lachlan Orogen apart from the classic orogenic systems such as the Alps and the Appalachians, include: (i) the lack of sutures typical of continental collisional orogenic systems; (ii) no simple craton-directed thrusting, but juxtaposition of craton-verging and oceanwards-verging, marginal thrust systems; (iii) no metamorphic hinterland, but localised high-T–low-P metamorphic regions; (iv) no thrust slices or windows exposing Proterozoic basement, but major fault zones in the turbidite-dominated part contain slices of oceanic crust and blueschist blocks in serpentinite- and mud-matrix mélange; and (v) large volumes of granite (up to 30% exposed area) with complex age distributions (Coney *et al.* 1990; Powell *et al.* 1990; Fergusson & Coney 1992a; Gray 1997; Foster & Gray 2000a; Spaggiari *et al.* 2004a).

Tasmania provides another perspective on Lachlan Orogen evolution. The older core of Tasmania (the West Tasmania terrane of Burrett & Martin 1989) is an attenuated Mesoproterozoic and Neoproterozoic continental fragment, either a promontory or block that was outboard of the Gondwana margin (Elliott & Gray 1992; Berry & Burrett 2002; Bierlein *et al.* in press; Foster *et al.* in press). It provides evidence for inversion of the Neoproterozoic–Cambrian passive margin of East Gondwana, including obduction of mafic–ultramafic complexes as well as post-collisional continental rift magmatism and extension which continued as part of subduction rollback to form the Lachlan marginal backarc basin (Berry & Crawford 1988; Crawford & Berry 1992; Foster *et al.* in press).

Broad subdivisions of the Lachlan Orogen

Powell *et al.* (1990) split the orogen into eastern and western parts placing the boundary west of the Wagga–Omeo Metamorphic Belt (Powell *et al.* 1990 figure 1). Glen (1992) used a threefold subdivision, but placed the western boundary of the Lachlan Orogen at the Avoca Fault Zone on the western side of the Stawell Zone in Victoria (Gray *et al.* 1988, 2003). He also included the Tabberabbera Zone in the western Lachlan Orogen. Recent $^{40}Ar/^{39}Ar$ geochronology has placed the western boundary of the Lachlan Orogen at the Stawell–Ararat Fault Zone or Congee Fault rather than the Moyston Fault (after VandenBerg *et al.* 2000). This is because the Moornambool Metamorphic Complex west or inboard of the Stawell–Ararat Fault Zone has a partly overprinted Delamerian metamorphic signature (*ca* 500 Ma) and, therefore, partly pre-dates Lachlan Orogen evolution in terms of deformation and metamorphism (Foster *et al.* 1999; Phillips *et al.* 2002).

Structural considerations (Gray 1997; Fergusson 2003; Spaggiari *et al.* 2003b) require delineation of the orogen into a threefold subdivision (Figure 4), but as a consequence with boundaries different to those proposed by Glen (1992). These are: (i) Western Lachlan, including the Stawell Zone east of the Stawell–Ararat Fault Zone to the Mt Wellington Fault Zone – Mt Useful Fault Zone along the eastern side of the Melbourne Zone; (ii) Central Lachlan, which includes the Tabberabbera zone (Gray *et al.* 1988, 2003) and the Wagga–Omeo Metamorphic Belt; and (iii) Eastern Lachlan, which includes the Lachlan Orogen east of the Gilmore Fault Zone, the eastern shear zone delineating the Wagga–Omeo Metamorphic Belt.

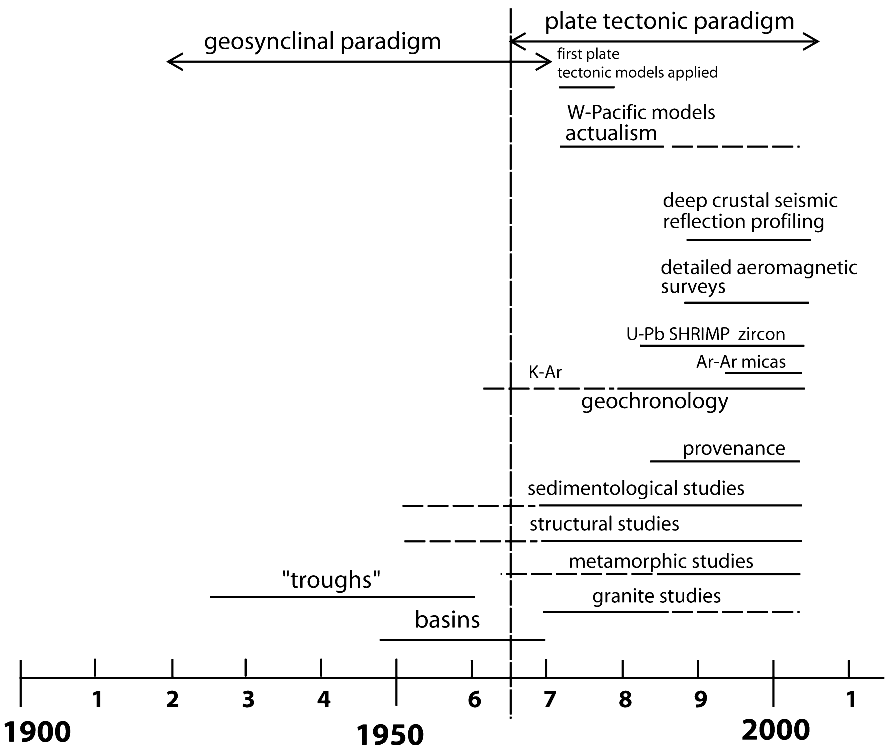


Figure 5 Time line showing the respective temporal influences of different approaches and techniques as applied to the Lachlan Orogen, as well as the timing of change from the geosynclinal to plate-tectonic paradigms.

REVIEW OF APPROACHES TO EASTERN AUSTRALIA TECTONIC EVOLUTION

Different approaches have been used over time to understand Lachlan Orogen tectonic evolution (Figure 5). Like other orogenic belts, the Lachlan Orogen has undergone a similar history of trends and approaches with the passage from the geosynclinal paradigm to that of plate tectonics.

Geosynclinal paradigm

The first half of the twentieth century was dominated by geosynclinal theory applied to the Lachlan Orogen (Figure 5) (Andrews 1938; Browne 1947; Voisey 1959). A historical overview of geosynclinal theory as applied to the Tasman Orogen is given in Fisher (1974). Schuchert (1916) first introduced North American geosynclinal concepts to eastern Australia. The orogen was subdivided into meridional depocentres that paralleled the cratonic margin. Implicit in this approach was repeated deposition of geosynclinal sediments in these depocentres followed by folding and uplift leading to continental growth with additions both east and northeast of the old craton, and subsequent migration of the depocentres eastwards (Andrews 1938; Browne 1947). Successive geanticlines marked the deformed and uplifted regions: the Benambran geanticline in the Ordovician, the Bowning geanticline in the Silurian, the Tabberabberan geanticline in the Early and Middle Devonian and the Kanimblan geanticline in the Late Devonian and Early Carboniferous (Browne 1947 figures 1–12). Outboard or to the east was an inferred landmass 'Tasmantis' (David & Sussmilch 1919).

One of the problems with geosynclinal theory was the reason or cause of the periodic forces acting from the Pacific that folded and elevated the geosynclinal sediments. These 'orogenic epochs . . . were marked by bathylithic injection and ore-deposition within the geanticlinal belts' and were correlated with worldwide orogenic episodes (Browne 1947 p. 636): for example, the Benambran orogeny with the Taconic of North America, the Bowning with the Caledonian of Great Britain and Europe, the Kanimblan with the Sudetic of Europe and so on.

As part of the geosynclinal approach, the Tasman Geosyncline was subdivided into a series of troughs and highs or rises (Figure 6) that clearly migrated in time and space (Brown *et al.* 1968; Webby 1976). Crook (1969, 1974, 1980) recognised similarities of lithofacies associations of eastern Australia with those of west Pacific settings and speculated on the tectonic process of formation of cratonic continental crust from oceanic terrains. He introduced the concept of the 'Pacific geosyncline' (Crook 1969) combining observations from modern Circum-Pacific forearc regions with interpretations of parts of the Tasman Orogen. This represented the first application of actualism to the Lachlan Orogen (see below), but it was done under the geosynclinal paradigm. Crook (1980) presented a generalised model with variants based on the thickness of the sediment prism in the forearc.

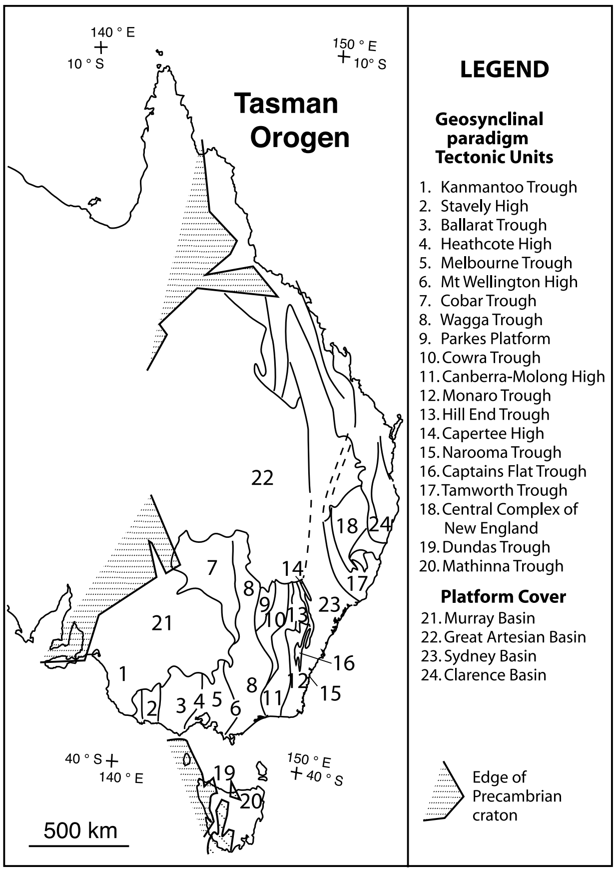


Figure 6 Tectonic-element map of the Tasman Orogen based on the geosynclinal paradigm showing the various troughs and intervening highs as well as the younger sedimentary cover basins (from Crook & Powell 1976).

Plate-tectonic paradigm

The first plate-tectonic interpretations were published in the early 1970s and placed eastern Australia in a typical modern west Pacific setting involving either a single subduction system (Oversby 1971; Solomon & Griffiths 1972) or multiple arc-subduction systems (Scheibner 1972, 1973, 1989). The early plate reconstructions were New South Wales-based and fitted aspects of Victorian geology (e.g. Melbourne Trough) clearly in a backarc position (Figure 7).

Erwin Scheibner (Geological Survey of New South Wales) had a significant influence on the early era of applying plate tectonics to eastern Australia. In the early 1970s, Scheibner struggled to pull eastern Australian geology toward this new paradigm, providing a new way of looking at Lachlan geology. In his papers, Scheibner (1972, 1973) described New South Wales geology in terms of actualistic plate-tectonic models with a series of reconstructions. Scheibner (1973 p. 409) was the first to invoke 'retrograde motion of the Benioff zone' (i.e. slab rollback) to create extension in the backarc region. In his models, the troughs were inter-arc or extensional basins consisting of oceanic crust separating the highs made up of either microcontinental blocks or newly formed volcanic arcs.

The evolution of plate models did not change significantly through the late 1970s and 1980s with various reconstructions by Scheibner (1978, 1987, 1989). However, in 1983 Chris Powell introduced a model where this part of the Gondwana margin changed through time (Powell 1983a).

From the initial setting in the upper plate of a Marianas-type subduction system, he argued (Powell 1983a, 1984a) that it evolved to strike-slip along a transform plate boundary, to final Andean-type subduction.

Actualism

Actualism involves matching key elements of modern orogenic systems with those preserved in the ancient rock record (Figure 8), or more simply, looking at the modern to provide analogues of the ancient (Jones 1976). It involved 'three dimensional character-by-character comparison' (Jones 1976 p.11). Within the Lachlan, comparisons were made with: (i) the Southwest Pacific (Crook 1969, 1974, 1980); (ii) the Andaman Sea (Cas *et al.* 1980; Powell 1984a); (iii) the Havre Trough – Lau Basin (Cas & Jones 1979); and (iv) the Bengal fan (Fergusson & Coney 1992b).

As an example, analogues in the Tonga–Kermadec arc system were applied to the Middle Silurian to Middle–Late Devonian Hill End Trough of the eastern Lachlan Orogen (Cas & Jones 1979 p. 71), where the Hill End trough was considered an 'embryonic inter-arc basin with a basement of continental or transitional, but not oceanic character'. It is characterised by silicic volcanism, epiclastic sediment partly of continental derivation, and submarine exhalative mineralisation (massive stratiform sulfide deposits) in a shallow-marine setting. The comparison implied a similar plate environment at the junction of a multiple arc system with a continental block. Evidence of basement with continental affinities in the northeastern Lachlan Orogen is perhaps lacking, but there is certainly agreement on the splitting of the old arc (Glen *et al.* 1998).

There was a fundamental difference between application of the actualism concept by Scheibner relative to other workers. Most fitted a modern analogue to a well-defined and delineated geology, whereas Scheibner described the geology in terms of actualistic plate models. In the latter case it is difficult to identify the factual data used to constrain the models.

Palaeogeographical approach

Outcrop distribution of time–rock units were used to construct palaeogeographical maps showing the migrations of seas and continental areas over time (e.g. Webby 1976 figure 6). This approach had been utilised since the earliest descriptions of the Tasman Orogen (Schuchert 1916; Andrews 1938; Browne 1947) but was adopted and re-invigorated in particular by the Macquarie University group (Veevers, Powell, Conaghan, Jones, Cas) in the 1970s, culminating in *Phanerozoic Earth History of Australia* (Veevers 1984), and subsequently by Ray Cas after moving to Monash University culminating in *A Review of the Palaeogeographical and Tectonic Development of the Palaeozoic Lachlan Fold Belt of southeastern Australia* (Cas 1983). Facies analysis was a prerequisite for palaeogeographical interpretation and was applied to the Lachlan Orogen as a series of maps for different time periods.

Many of these frameworks were based on the current positions of elements and were, therefore, non-palinspastic, ignoring the distances involved in the original tectonic setting and the fact that systems were deformed with up to 50–70% shortening (Gray & Willman

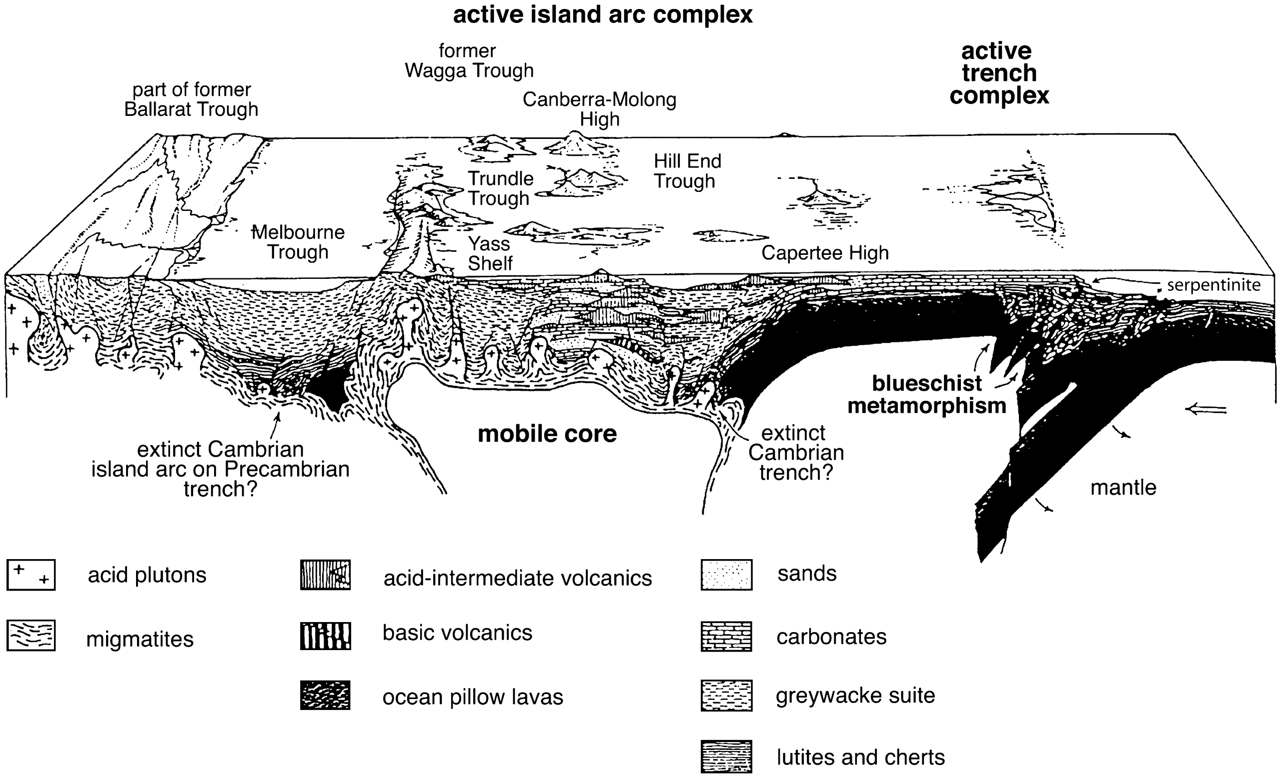


Figure 7 Plate-tectonic diagram of Oversby (1971), encapsulating elements of the plate-tectonic paradigm as applied to the Lachlan Orogen in the early 1970s.

1991a, b; Fergusson & Coney 1992a). Block diagrams were constructed incorporating stratigraphic and sedimentological data but without structural consideration. Despite these shortcomings, the approach led to greater understanding of the tectonic setting and evolution of the orogenic belt.

Basalt geochemistry and greenstone research

With the application of plate-tectonic models to the Lachlan Orogen, Crook and Felton (1975) pleaded for rigour and caution in defining ophiolite because of the implied tectonic significance. They argued that in west Pacific-type geosynclines, ophiolites *sensu stricto* were rare, whereas Alpine-type serpentinites were more common, and that the latter were '. . . most likely products of dismemberment of originally more complete ophiolites' (Crook & Felton 1975 p. 128). This required differences in structural style and tectonic development for west Pacific geosynclines (Spaggiari *et al.* 2004a).

Mapping, petrology and geochemistry were undertaken on the various belts of mafic and ultramafic rocks in the 1970s. The Colac Serpentinite Belt and related ophiolite in southern New South Wales was investigated by Ashley, Franklin and Ray in the 1970s (Ashley *et al.* 1971, 1979, 1983) and by the University of Technology group (Franklin, Basden and Marshall) in the 1980s and 1990s (Graham *et al.* 1996), with the original work suggesting that the geochemistry and sulfide occurrences in the mafic and ultramafic rocks were consistent with formation in a marginal sea or backarc basin (Ashley *et al.* 1979).

Mapping, petrological and geochemical work on the Victorian Cambrian greenstone belts in the late 1970s and early 1980s by the University of Melbourne group (Crawford, Keays) led to their recognition as disrupted ophiolite and arc rocks, and as basement to this part of the Lachlan Orogen (Crawford & Keays 1978; Crawford *et al.* 1984). Supporting geochemistry established the presence of boninites and low Ti andesites intruded by tholeiitic backarc-basin basalts, providing strong evidence for Cambrian island-arc development and a subduction-related origin for some parts of the ophiolites (Crawford *et al.* 1984; Nelson *et al.* 1984; Crawford & Cameron 1985; Crawford & Keays 1987). Despite alternative views of deep-seated linear rift-related basalts (Cas 1983) there is now general acceptance that these are faulted belts of former oceanic crust (Fergusson 2003; Spaggiari *et al.* 2003c; Foster *et al.* in press). The greenstone belts represent

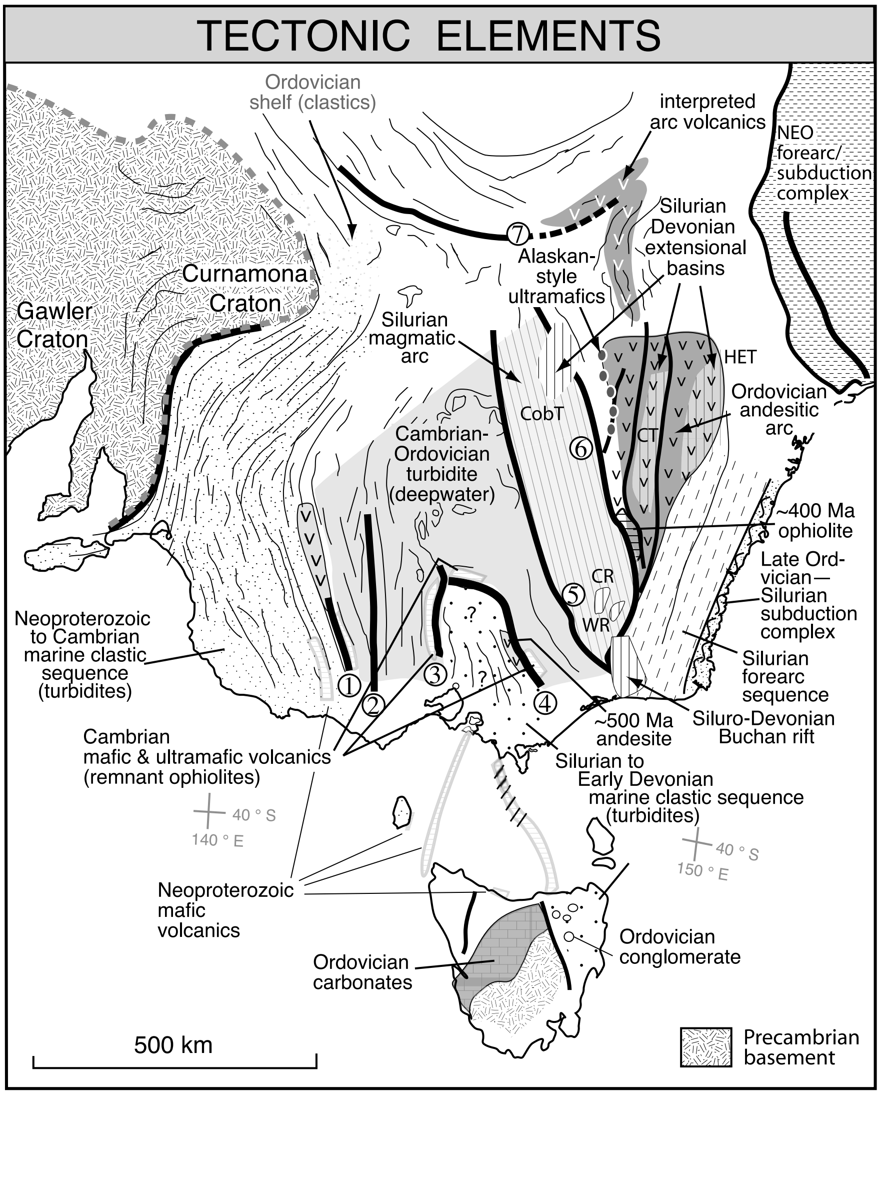


Figure 8 Major recognisable tectonic elements of the Lachlan Orogen that have been used to define Lachlan tectonic evolutionary scenarios. Structural trends (fine lines) are based on aeromagnetic imagery. NEO, New England Orogen; CobT, Cobar Trough; CT, Cowra Trough; HET, Hill End Trough; CR, Cowombat rift; WR, Wombat rift. Circled numbers represent faults (heavy lines): 1, Stawell–Ararat Fault Zone; 2, Avoca Fault Zone; 3, Heathcote Fault Zone; 4, Governor Fault Zone; 5, Kancoona–Kiewa Shear Zone; 6, Gilmore Shear zone; 7, Olepoloko Fault Zone.

slivers of dismembered ophiolite infaulted within the strongly deformed turbidite package, having similarities to Cordilleran ophiolites (Spaggiari *et al.* 2003c). Some may even represent truncated seamounts and/or remnants of oceanic transforms within the turbidite wedge (Spaggiari *et al.* 2003a, 2004a).

'Andesite' research

Despite the implied tectonic significance of the Ordovician 'andesitic' volcanic rocks in New South Wales (Scheibner 1973, 1989), the most detailed petrological and geochemical work on these rocks was undertaken in the 1990s (Wyborn 1992; Heithersay & Walshe 1995; Barron & Barron 1996; Glen *et al.* 1998), apart from Owen and Wyborn (1979) who argued that the volcanics were shoshonites with high K and low Ti signatures. Much of the research has been linked with the Cu–Au mineralisation that characterises this magmatic suite (Heithersay & Walshe 1995).

Granite research

Granites are a major component of the Lachlan Orogen (Figure 2) and have been studied by various groups at the Australian National University (Bruce Chappell and students), La Trobe University (Allan White, Chris Gray, Roland Maas and students) and Monash University (Ian Nicholls, Vic Wall and students). It is well recognised that the petrological and geochemical research of Allan White and Bruce Chappell and their students on these granites (White *et al.* 1974; White & Chappell 1983; Chappell *et al.* 1988; Chappell 1994) has had a major and profound impact on development of geological and plate-tectonic ideas for the Lachlan Orogen. However, after 25 years of I- and S-type granites (Allen 2001; Clemens 2003), there is doubt, first, on the applicability of the restite–unmixing model to explain chemical variation in granitic magmas (Clemens & Wall 1981; Gray 1984; Keay *et al.* 1997; Wall *et al.* 1987; Clemens 1989, 2003; Collins 1998), second, that granite geochemistry can be used to indicate source region, and third, that Precambrian basement underlies the Lachlan Orogen (Anderson *et al.* 1996; Anderson 1997; Handler & Bennet 2001; Maas *et al.* 2001). Unfortunately, the requirement of Precambrian crust beneath the Lachlan Orogen and the positions of I- and S-lines has placed unreasonable constraints on many of the proposed tectonic evolutionary models for the orogen over the last 20 years (Collins 1998).

Most recent interpretations of the granites, based on isotopic and geochemical data, argue for magma mixing or mingling mechanisms (Elburg 1996; Rossiter & Gray 1996) with components derived from subduction-generated melting in the mantle and secondary melting of crustal materials including the Cambrian metavolcanic rocks and Ordovician metasediments (Keay *et al.* 1997). Multiple-component mixing models can explain the I- and S-type granite geochemical variations (Gray 1984; Rossiter & Gray 1996; Keay *et al.* 1997; Collins 1998). Current ideas on granite evolution are more in line with the plate-tectonic paradigm and there is no need to invoke a special character for the Lachlan Orogen, such as involving mantle plumes. Models to explain high heat flow for the Lachlan Orogen should only be applied to the eastern and central Lachlan Orogen (Collins & Hobbs 2001).

Granite emplacement mechanisms have also been studied, particularly in the central and eastern Lachlan Orogen (Paterson *et al.* 1990; Tobisch & Paterson 1990; Fowler & Lennox 1992; Morand 1992). Overall, the western Lachlan Orogen has post-tectonic granites that are largely undeformed with narrow contact aureoles, whereas some granites in the central and eastern Lachlan Orogen show high-T deformation fabrics in bounding shear zones suggesting that they must be in part syntectonic (Paterson *et al.* 1990; Tobisch & Paterson 1990).

Mafic rocks (basaltic and andesitic dykes) associated with granites

The first studies on the more mafic to intermediate Palaeozoic rocks of the Lachlan Orogen have been undertaken only recently (Soesoo & Nicholls 1999; Bierlein *et al.* 2001a). Alvaar Soesoo showed that the Early Devonian basaltic to andesitic dykes and plutons had primitive mantle-normalised trace-element abundance patterns with negative Nb and Ti anomalies typical of island arcs, indicating a subduction influence on mantle magma sources for the central Lachlan Orogen (Soesoo & Nicholls 1999). Similar geochemical data were obtained by Bierlein *et al.* (2001a) from Silurian and Early Devonian mafic dykes for the western Lachlan Orogen. In contrast, the chemistry of the Late Devonian mafic rocks confirmed the switch to a continental rift–extensional setting (Soesoo & Nicholls 1999; Soesoo 2000).

Sedimentary facies and sedimentology research

Biostratigraphic investigations by Talent (1965) in Victoria, and Packham (1969a, b, 1987), Webby (1976; Webby 1987) and Crook *et al.* (1973) in New South Wales, established the gross stratigraphic framework of the Lachlan Orogen (see also Talent *et al.* 1975). Recognition and delineation of unconformities was an important part of this approach, and these were used to define orogenic periods that produced the Lachlan Orogen (for review see Gray *et al.* 1997).

Subsequent lithofacies approaches by Powell and coworkers, Fergusson and coworkers, Glen, and VandenBerg and Stewart (Powell 1984a; Glen & VandenBerg 1987; Fergusson *et al.* 1989; Glen 1992; VandenBerg & Stewart 1992; Fergusson & VandenBerg 2003) have led to a generalised stratigraphy for the central Lachlan Orogen and southeastern Lachlan Orogen, of Cambrian mafic volcanics, overlain by bedded chert, overlain by Lower to Middle Ordovician turbidites with abundant sandstone (Adaminaby Group) and incorporating a thin-bedded chert unit (Numerella Chert) in the easternmost parts, overlain by mudstone dominant turbidites (Sunlight Creek Formation), overlain by Upper Ordovician black shale (Warbisco Shale; Fergusson & Fanning 2002 figure 2).

DEPOSITIONAL FRAMEWORK – SUBMARINE FAN SYSTEM

Fergusson and coworkers have demonstrated that the Ordovician strata of the Lachlan Orogen constitute a palinspastically restored turbidite succession that must have rivaled the modern-day Bengal Fan with approximate dimensions of $1200 \times 800 \times 3$ km (Fergusson & Coney 1992b). Palaeocurrent and sandstone provenance data suggest derivation from the northern part of the Ross–Delamerian Orogen (Ireland *et al.* 1998; Fergusson & Fanning 2002). Significant longitudinal sediment dispersal parallel to this mountain chain is perhaps suggestive of deposition as one major turbidite fan (Fergusson & Tye 1999), although Fergusson and Fanning (2002) have argued that development of subduction zones in the Late Ordovician marginal sea may have restricted sediment supply to the eastern part of the marginal sea (cf. Carter *et al.* 1996). The width of the fan has been questioned by VandenBerg and Stewart (1992) who, on stratigraphic grounds, argued for strike-slip duplication to give the ~1200 km restored width.

PALAEOCURRENT ANALYSIS

Linked palaeocurrent and provenance studies undertaken by Powell and coworkers in the 1970s and 1980s led to a new approach in understanding Lachlan Orogen tectonism, by looking at the sedimentary response (Powell 1984a). Powell undertook detailed analysis of palaeocurrent markers (cross-bedding, sole marks and cross-laminations) in the Lambie facies units throughout New South Wales, as well as parts of the Ordovician and Siluro-Devonian sequences of the Melbourne Trough (Powell *et al.* 2003) and Mathinna Group of northeast Tasmania (Powell *et al.* 1993). The early work was integrated with sedimentary facies and was presented as a series of palaeogeographical maps that reflected the structural thickening, metamorphism, and eventual cratonisation across the developing Lachlan Orogen (Powell 1984a figures 207, 209, 210, 211, 212, 221 and 222).

Using a similar approach, the Ordovician sequences of Victoria were investigated in the Bendigo Zone in central Victoria by Cas and coworkers (Cas and VandenBerg 1988), and in the Ordovician–Silurian sequences of the Tabberabbera Zone (Fergusson *et al.* 1989). Palaeocurrents were directed generally east or northeast from the Ordovician onwards (Figure 9).

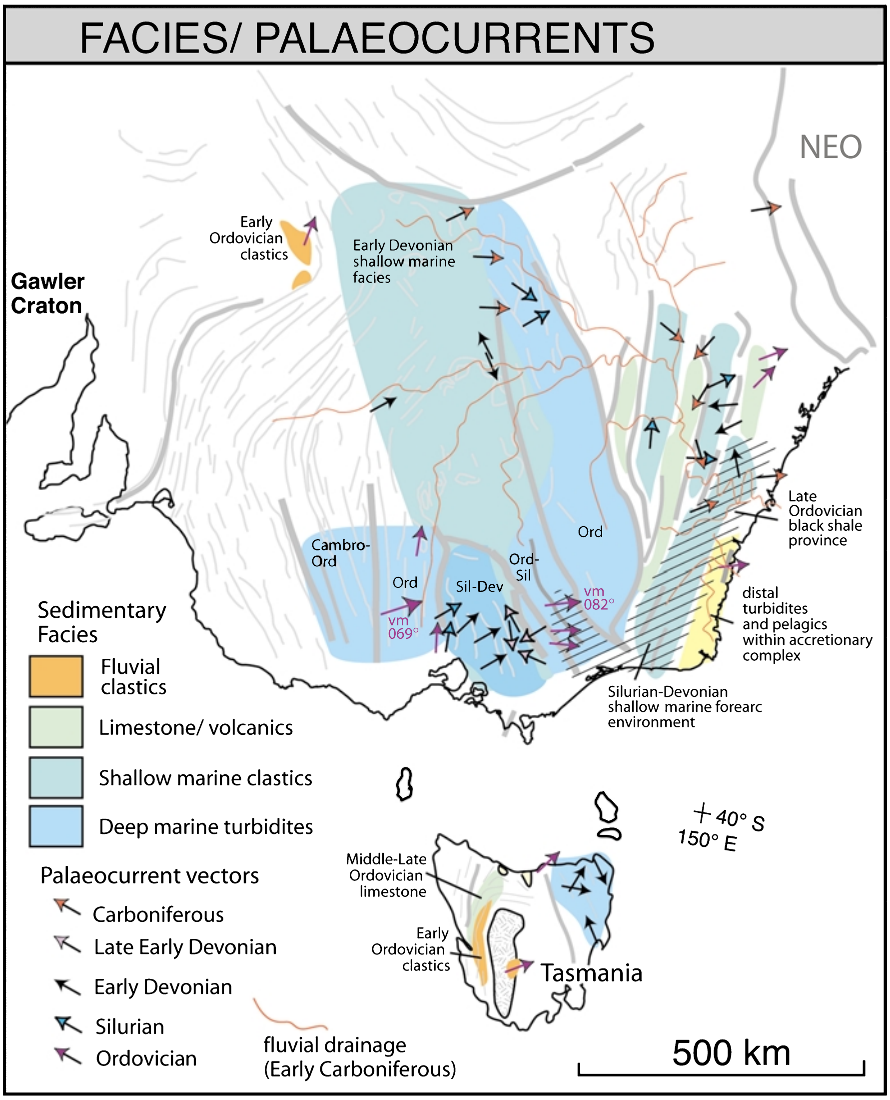


Figure 9 Simplified sedimentation map of the Lachlan Orogen showing the distribution of sedimentary facies and published palaeocurrent data. Data for the Ordovician from Powell (1983a, 1984a), Cas and VandenBerg (1988), Fergusson *et al.* (1989), VandenBerg and Stewart (1992), Colquhoun *et al.* (1999), and Fergusson and VandenBerg (2003). Data for the Silurian, Devonian and Early Carboniferous from Powell (1983a, 1984a) and Powell *et al.* (2003). The diagonal lines depict the Late Ordovician black shale province (from VandenBerg & Stewart 1992; Colquhoun *et al.* 1999). Lithofacies distribution maps by VandenBerg and Stewart (1992) provide the most comprehensive picture of Early and Late Ordovician lithofacies.

PROVENANCE

Provenance studies on the Ordovician fan-package have included zircon provenance studies (Williams *et al.* 1991, 1994; Fergusson & Fanning 2002), strontium isotopes (Gray & Webb 1995), as well as the more traditional petrographic approaches utilising sandstone clast composition (Colquhoun *et al.* 1999; Fergusson & Tye 1999). Detrital zircon U–Pb age populations from the Ordovician turbidite sandstones are relatively uniform over the present outcrop extent and include a dominant 700–500 Ma grouping with lesser concentrations of 1300–1000 Ma (Fergusson & Fanning 2002). The Australian National University research group described detrital zircon age groupings of 650–450 Ma, 1200–700 Ma and >1200 Ma (Williams *et al.* 1994).

Sandstone compositions are dominated by monocrystalline quartz, with lesser feldspar, polycrystalline quartz, metamorphic rock fragments and mica, indicative of a low-grade metamorphic source terrain (Fergusson & Tye 1999). Lower Silurian sandstones show similar composition but contain less feldspar, suggesting derivation from uplifted portions of the Ordovician turbidite package. This is supported by detrital mica ages (Foster *et al.* 1999). In the eastern Lachlan Orogen there is a change in the Late Ordovician from the quartz-rich facies to a volcanolithic facies derived from the Ordovician calc-alkaline basaltic volcanics (Colquhoun *et al.* 1999).

Structural research

The adoption of modern structural analysis (based on Turner & Weiss 1963) led to localised studies throughout the orogen (Hobbs 1962, 1965; Stauffer & Rickard 1967; Williams 1971; Hopwood 1977). Much of this early work was undertaken in New South Wales, although there were local studies in Victoria (Beavis 1962; Beavis & Beavis 1968). However, there were problems with regional correlation of structural elements. In some instances this was related to the fact that in many parts of the orogen, the major fault zones are regions of higher strain and localised polydeformation (Gray *et al.* 1988, 2003; Gray & Foster 1998). Since 1988, there has been greater realisation that the regional application of designated structural events centred on such fault zones is problematical and, in particular, fault-zone-determined deformation chronologies cannot be applied across structural zones, and

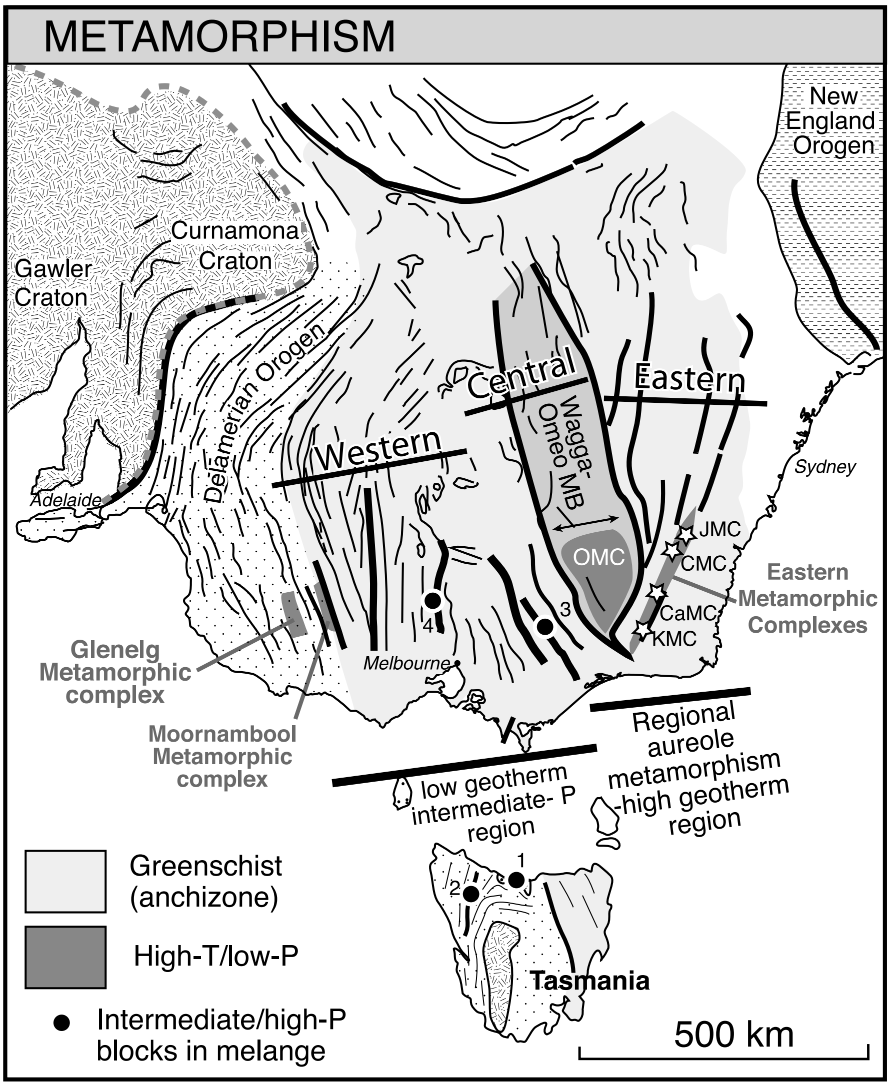


Figure 10 Simplified metamorphic map of the Lachlan Orogen showing the areas of high-T regional aureole-style metamorphism (grey regions), the known occurrences of blueschists representing low-T intermediate-P metamorphism (black dots), and the overall distribution of the background intermediate-P, lower geotherm metamorphism recorded by the low-grade slates (see Figure 11). Blueschist localities are: 1, Port Sorell mélange; 2, Arthur Lineament; 3, Howqua mélange; 4, Heathcote mélange. Eastern metamorphic complexes (depicted by stars) are: JMC, Jerangle Metamorphic Complex; CMC, Cooma Metamorphic Complex; CaMC, Camblong Metamorphic Complex; KMC, Kuark Metamorphic Complex; OMC, Omeo Metamorphic Complex.

especially across the orogen proper. Regions away from fault zones generally have only one fabric element suggesting that they have only seen one deformational event (Gray & Foster 1998).

Structural work, particularly in the 1980s and 1990s, led to a greater recognition and delineation of the major faults in the Lachlan Orogen (Fergusson *et al.* 1986; Fergusson 1987a, b; Glen & VandenBerg 1987; Begg *et al.* 1988; Burg & Wilson 1988; Fergusson & VandenBerg 1990; Cox *et al.* 1991a; Gray & Willman 1991a, b; Glen 1992; Wilson *et al.* 1992; Gray 1995; Gray & Foster 1998; Gray *et al.* 1999; VandenBerg *et al.* 2000; Spaggiari *et al.* 2003b, 2004a). Major fault traces (Figure 4) define structural zones in the Lachlan Orogen (Gray *et al.* 1988; VandenBerg *et al.* 2000; Gray *et al.* 2003). The concept of tectonic vergence based on overall regional fault dip and changes in chevron-fold geometry approaching major faults (Gray & Willman 1991b) led to the definition of major regional-scale vergence belts (Gray 1997; Gray & Foster 1998; Foster & Gray 2000a) that have bearing on the tectonic evolution of the Lachlan Orogen.

Through the 1980s, the application of modern structural techniques and concepts (e.g. thrust belt geometry and vergence) led to the realisation that the Lachlan Orogen consisted of a system of linked, upper crustal thrust-belts (Fergusson *et al.* 1986; Glen & VandenBerg 1987; Gray *et al.* 1991; Fergusson & Coney 1992a; Glen 1992; Gray 1997), where the overall structural style was chevron folds cut by steep thrust faults (Fergusson 1987a; Fergusson & VandenBerg 1990; Cox *et al.* 1991a; Gray & Willman 1991a, b; Gray 1997), although Glen (1992) has adopted a different geometry in New South Wales due to differing lithologies (Glen 1992 figures 10, 11). The overall thin-skinned geometry of the Lachlan Orogen upper crust is exemplified by the profiles of Fergusson and Coney (1992a figure 11) and Glen (1992 figure 13a). A review of the style of deformation, the nature of the faults zones and the different vergence belts for the Lachlan orogen are presented in Gray and Foster (1998).

Metamorphic research

The systematic study of regional metamorphism in the Lachlan Orogen began with the work of Howitt (1889) in the Omeo Metamorphic Complex (Figure 10) of the central Lachlan Orogen. Subsequent studies by Tattam (1929), Joplin (1947), Vallance (1967), Guy (1968), Rogerson (1976), Fagan (1979) and Morand (1990) have established the Wagga–Omeo Metamorphic Belt (Figure 2) as a classic example of low-pressure series metamorphism. This north–northwest-trending zone of greenschist to upper amphibolite facies-grade metamorphic rocks is the main locus of Palaeozoic low-pressure metamorphism in the Lachlan Orogen. A smaller, discontinuous north–south belt to the east is centred on Cooma (Figure 10) and was termed the Eastern Metamorphic Belt by Vallance (1969). In both belts, the peak temperatures of ~700°C and pressures of ~350 MPa, implying a P–T gradient of 65°C/km, caused partial melting of the Ordovician metasediments to produce migmatites and large bodies of S-type granite (Flood & Vernon 1978).

Most studies on the low-grade slates away from these low-P metamorphic regions has been relatively recent with the first study undertaken by Smith (1969) in the Hill End region of the eastern Lachlan. In the 1980s, Offler and students at the University of Newcastle undertook studies of low-grade metamorphism in various parts of the eastern Lachlan Orogen (Offler & Prendergast 1985; Brill 1988; Farrell & Offler 1989). More recently, illite crystallinity and b_0 measurements in Lachlan Orogen slates by Offler, McKnight, and Morand (Offler *et al.* 1998a) in the western Lachlan Orogen, Offler *et al.* (1998b) in the Narooma accretionary complex of the eastern Lachlan Orogen, and Spaggiari *et al.* (2003b) in the Tabberabbera Zone of the

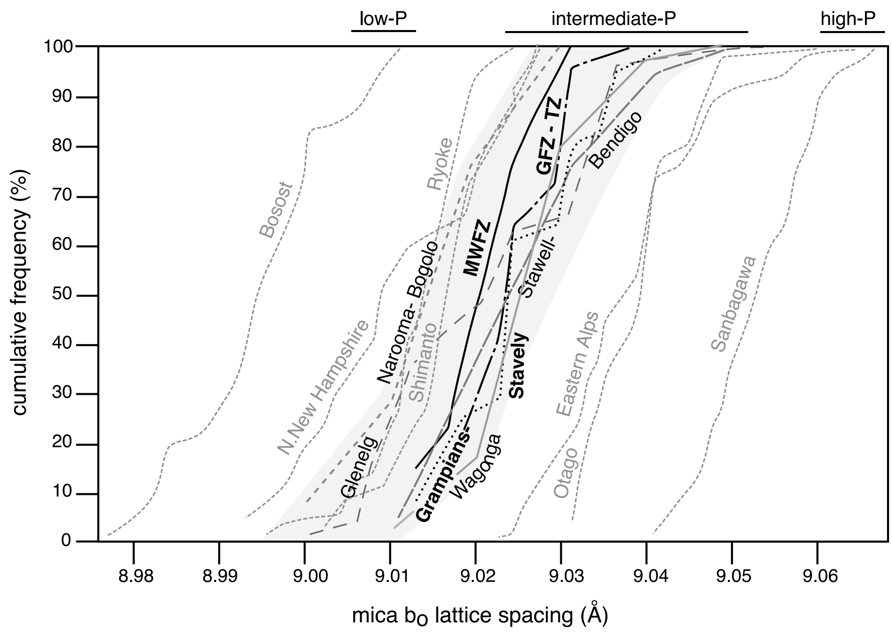


Figure 11 Cumulative frequency (%) plot of mica b_0 data from the Lachlan Orogen showing that the slates record a metamorphic background of intermediate pressure (grey region). Data curves are shown for the western Lachlan Orogen Stawell–Ballarat–Bendigo Zones (data from Offler *et al.* 1998a) and the Mt Wellington Fault Zone (MWFZ curve; data from Spaggiari *et al.* 2003b), the eastern Lachlan Orogen Narooma Accretionary Complex (Narooma–Bogolo and Wagonga curves; data from Offler *et al.* 1998b) and the central Lachlan Orogen [Governor Fault Zone and Tabberabbera Zone curve (GFZ-TZ); data from Spaggiari *et al.* 2003b]. Curves for Delamerian Orogen slates are also included (Glenelg and Grampians–Stavely; S. McKnight unpubl. data). Curves for different P–T regimes are shown for comparison (data from Sassi & Scolari 1974), including the Bosot (low-P), N. New Hampshire (P at the Al_2SiO_5 triple point), Ryoke, Shimanto, Eastern Alps, Otago (intermediate-P), and Sanbagawa (high-P).

central Lachlan have shown that the background metamorphic field gradient is intermediate pressure – low temperature (Figure 11).

Terrane research

The application of terranes to the Lachlan Orogen (Scheibner 1985; Leitch and Scheibner 1987; Scheibner & Basden 1996, 1998; VandenBerg *et al.* 2000; Willman *et al.* 2002) in some instances has led to incredible complexity that makes tectonic understanding difficult, although Coney *et al.* (1990) introduced the term Lachlan superterrane because of the similarity of the lithofacies both along and across the orogen, referring to the 'Lachlan mudpile'. The terrane concept was based on the terrane as a fault-bounded geological entity that has a different history to its neighbours, and involved the concepts of stitching plutons, provenance linking, cover sequences and exotic, far-travelled terranes (Jones *et al.* 1983). Powell *et al.* (1990) and Li *et al.* (1990) argued that palaeomagnetic data were needed to constrain inferred lateral translations between various terranes proposed for the Tasman Orogen, but few reliable poles have been determined from pre-Carboniferous rocks of the Lachlan part (Li *et al.* 1990).

Most recently, Geological Survey of Victoria publications (VandenBerg *et al.* 2000; Willman *et al.* 2002) split the Lachlan Orogen into the Whitelaw Terrane (western Lachlan Orogen of Gray 1997) and the Benambra Terrane (includes the central and eastern Lachlan Orogen of Gray 1997). Gray (1997), Gray *et al.* (1988, 2003) and Gray and Foster (1998) advocated the use of structural zones rather than terrane terminology, where a structural zone is defined as a fault-bounded region that shows differences in either structural trends, timing and style of deformation, and/or tectonic vergence, and in some cases in the age and nature sedimentation. In general, the broad tripartite nature of the Lachlan Orogen (Figure 4) is supported by the three thrust systems that have clearly operated during tectonic evolution of this orogen (see below).

Geophysical research

DEEP-CRUSTAL SEISMIC REFLECTION PROFILING

Extensive deep-crustal seismic reflection profiling (Figure 12) in New South Wales (Pinchin 1980; Korsch *et al.* 1986, 1993, 1997; Leven *et al.* 1992; Glen *et al.* 1994, 2002; Finlayson *et al.* 2002), as well as limited surveys in

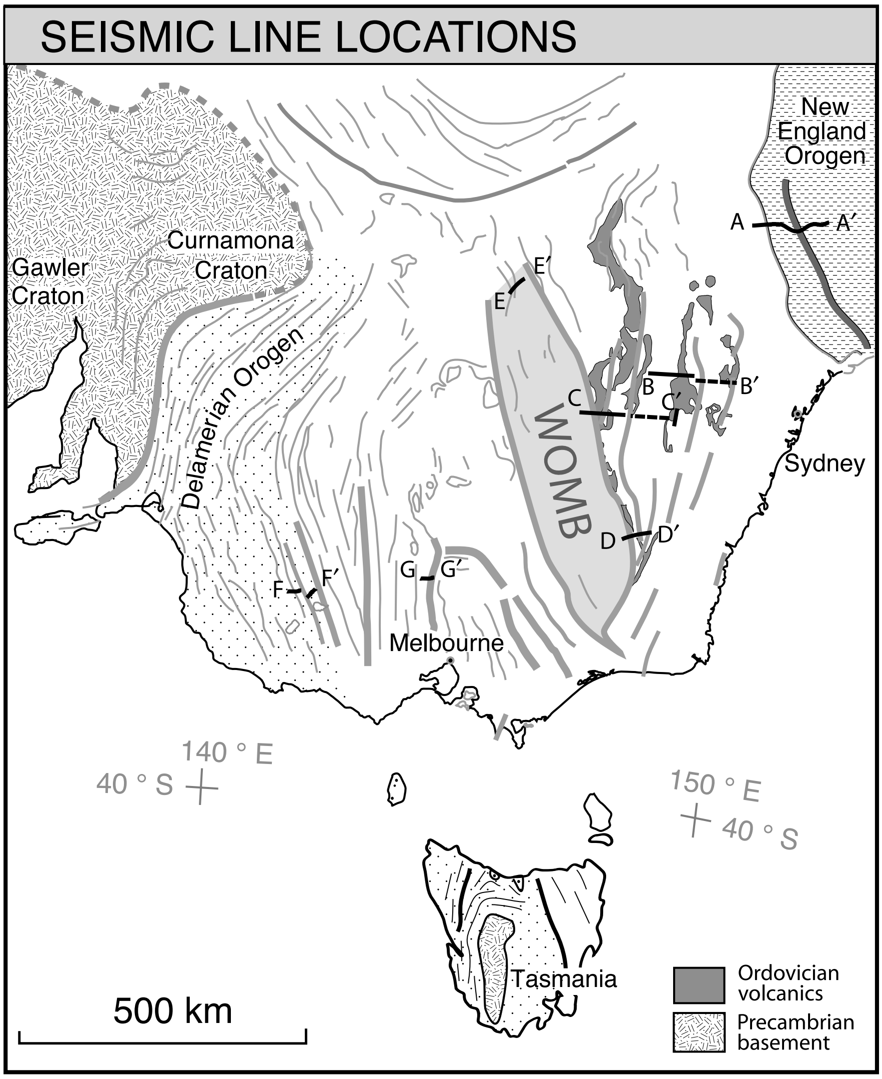


Figure 12 Location map for deep crustal seismic reflection profiling undertaken in the Lachlan Orogen. Line A–A′, southern New England profile; Line B–B′, Molong High – Hill End Trough profile; Line C–C′, Wagga Metamorphic Belt to Cowra Trough; Line D–D′, Tumut Trough traverse; Line E–E′, Cobar Basin; Line F–F′, Grampians traverse; Line G–G′, Heathcote Fault Zone traverse. Actual profiles shown in Figure 13. Darker grey areas, Ordovician volcanics of the segmented Macquarie volcanic arc; stippled region, Delamerian Orogen; dashed horizontal lines, New England Orogen.

Victoria (Gray *et al.* 1991; Korsch *et al.* 2002), has provided an image of the Lachlan Orogen lithospheric structure (Figure 13). These studies have shown that most major fault zones dip to the west, that steeply dipping faults at the present erosion surface tend to flatten with depth, and that regions between major faults sometimes show a complex intersecting networks of both east- and west-dipping faults and shear zones.

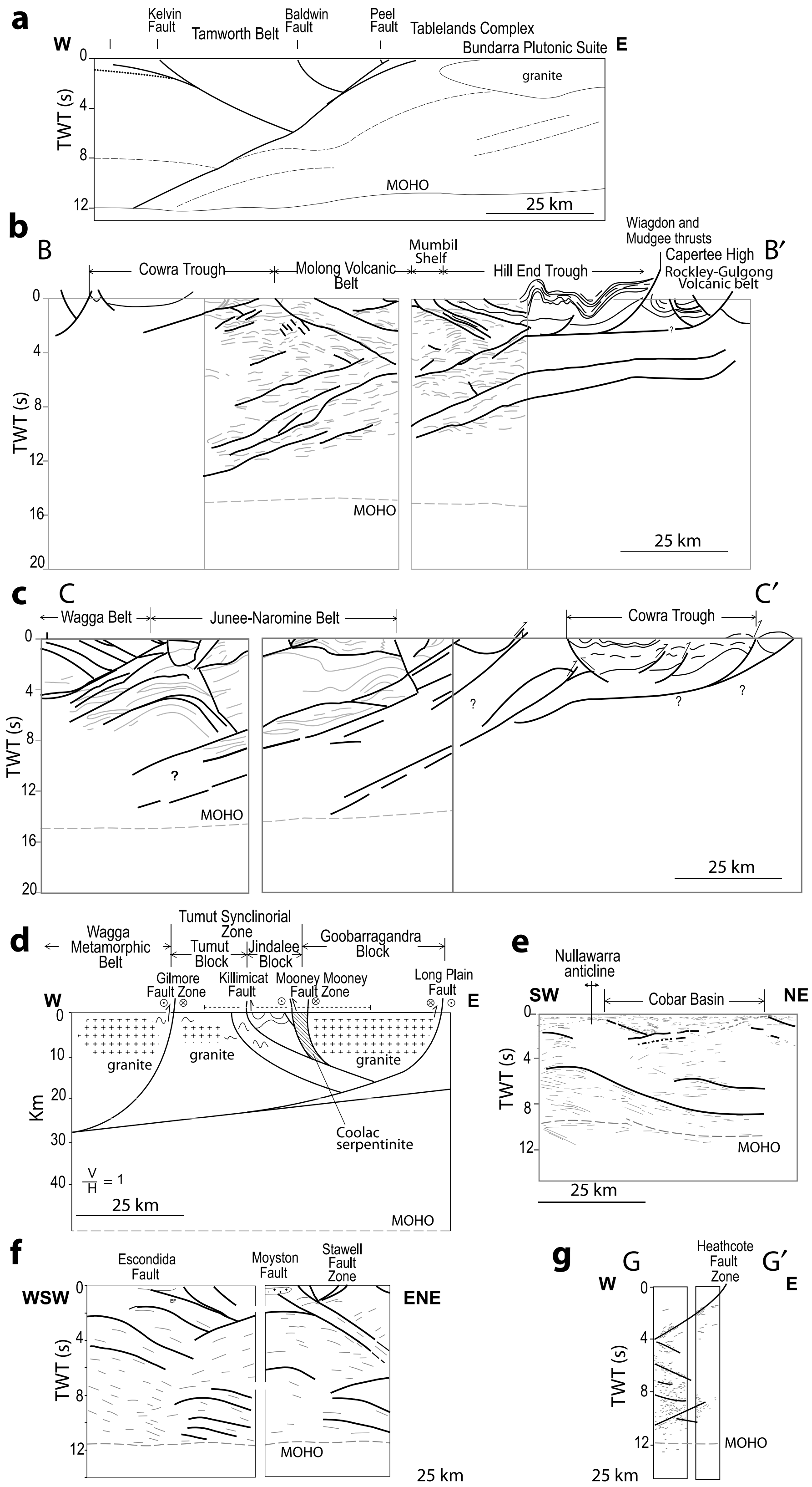


Figure 13 Deep crustal seismic reflection profiles of the Lachlan Orogen. (a) Southern New England profile (from Korsch *et al.* 1993, 1997). (b) Molong High – Hill End Trough profile (from Glen *et al.* 2002). (c) Wagga Belt to Cowra Trough (from Glen *et al.* 2002). (d) Tumut Zone traverse (from Leven *et al.* 1992). (e) Cobar Basin profile (from Glen *et al.* 1994). (f) Grampians profile; Delamerian and Lachlan Orogen boundary (from Korsch *et al.* 2002). (g) Heathcote Fault Zone profile (from Gray *et al.* 1991).

AEROMAGNETIC IMAGING

The Geological Surveys of New South Wales, Victoria and Tasmania in collaboration with Geoscience Australia undertook detailed aeromagnetic studies during the late 1980s (Brown *et al.* 1988; Wellman 1988, 1995) and 1990s (VandenBerg *et al.* 2000). This has provided an important window into the subsurface (Figure 3), particularly in regions of poor exposure and those that are covered by younger basinal sedimentary successions, that is much of southeastern Australia (Kilgour 2002a). The strongly magnetic elements are the I-type granites, the Ordovician shoshonitic volcanics of New South Wales and the Victorian Cambrian greenstone belts, whereas the S-type granites are magnetically quiet but are commonly rimmed by magnetic highs, due either to magnetite in the contact aureoles or to I-type compositional rims of granite.

GRAVITY STUDIES

The Lachlan Orogen is only covered by broadly-spaced gravity data, but computer-generated maps and images (Wellman 1988, 1995; Murray *et al.* 1989; Kilgour 2002b) particularly of the short wavelength (<50 km) Bouguer gravity anomalies, define gross structural trends by the domain patterns of gravity lows versus gravity highs (Wellman 1995 figure 4).

Geochronology

K–Ar AND Rb–Sr RESEARCH

The first detailed age determinations of the Lachlan granitic rocks was undertaken in the 1960s by Everden and Richards (1962), followed by a more extensive study by Richards and Singleton (1981) and Gray (1984, 1990). These early K–Ar and Rb–Sr studies identified the first age groupings of granitoids and demonstrated a complex pattern of crystallisation ages (Figure 14). Cas *et al.* (1976) undertook the first K–Ar studies of metamorphism by dating slates in the Hill End Trough.

^{40}Ar/ ^{39}Ar GEOCHRONOLOGY/THERMOCHRONOLOGY RESEARCH

The first application of ^{40}Ar/^{39}Ar geochronology to Lachlan Orogen slates, was undertaken by Glen *et al.* (1992a) in a study in the Cobar region of the central Lachlan Orogen.

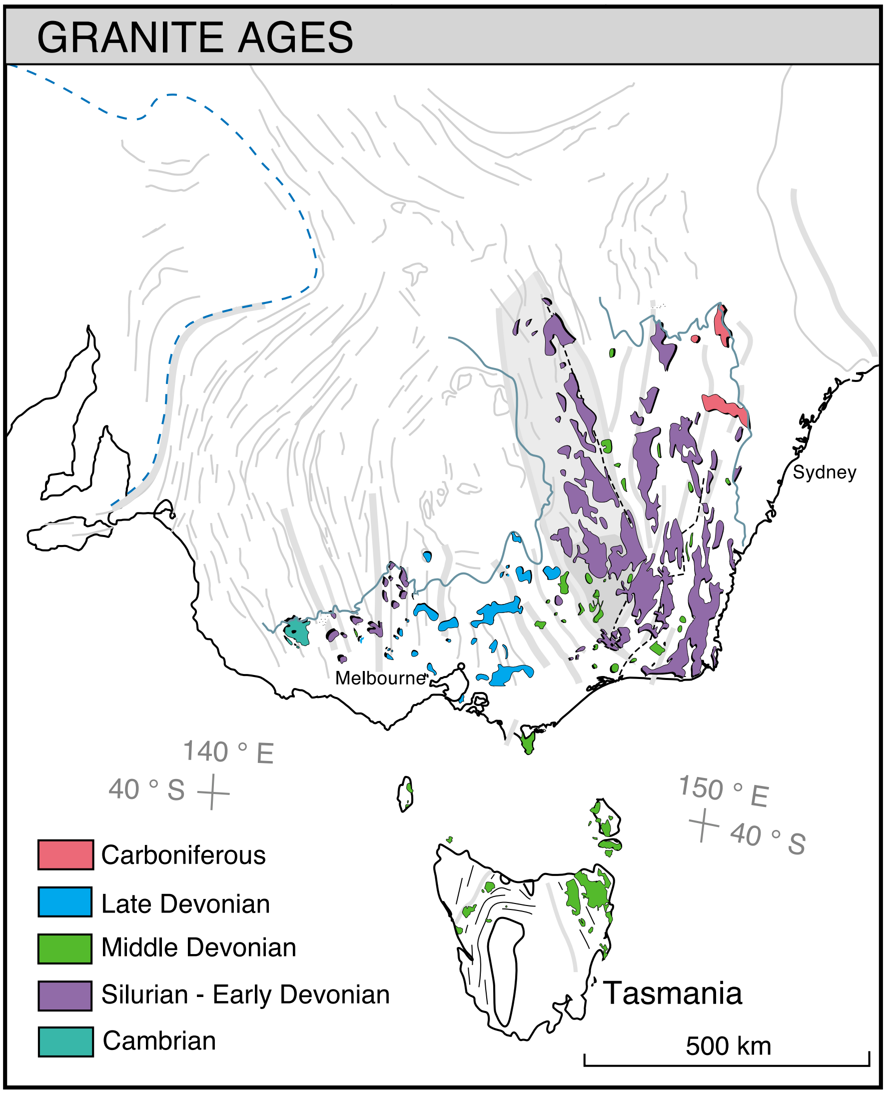


Figure 14 Granite age map for the Lachlan Orogen showing the distribution and ages of granites. Based on data from Everden and Richards (1962), Richards and Singleton (1981), Gray (1990) and Shaw *et al.* (1992). Granites that have not been isotopically dated have no fill.

Subsequently, detailed studies of the white micas in the slates and sandstones, as well as in quartz veins, of the Lachlan Orogen were undertaken by Foster and coworkers in the early 1990s (Foster *et al.* 1996, 1998, 1999; Lu *et al.* 1996; Bucher 1998) followed by Bierlein and coworkers (Bierlein *et al.* 2001a) and Fergusson and Phillips (2000). It is only since the application of the $^{40}Ar/^{39}Ar$ technique that a better understanding of the timing of deformation has been obtained (Figure 15). Previously, this was only loosely constrained on stratigraphic grounds.

SHRIMP ZIRCON GEOCHRONOLOGY RESEARCH

Research groups largely based at the Australian National University involving Ian Williams have undertaken a two-pronged approach, firstly studying zircon populations in the granites and enclaves (Williams *et al.* 1991, 1994; Keay *et al.* 2000; Williams 2001) along with work at La Trobe University (Anderson *et al.* 1998; Maas *et al.* 2001) and Monash University (Elburg 1996), and at Geoscience Australia by Lance Black (Black *et al.* 1997; Turner *et al.* 1998), and secondly, determining zircon populations in the sedimentary successions (Williams *et al.* 1991, 1994; Ireland *et al.* 1998; Fergusson & Fanning 2002).

This research has shown similar zircon age grouping in the granitic suites, the enclaves within the granites and the Ordovician sediment that constitutes most of the Lachlan Orogen. Zircon age groupings of 650–450 Ma, 1200–700 Ma and >1200 Ma occur in the Ordovician turbidites (Williams *et al.* 1994) as well as in the enclaves within the granites (Anderson *et al.* 1998; Maas *et al.* 2001).

Williams (2001; Chen & Williams 1991) and other workers (Arne *et al.* 1998; VandenBerg *et al.* 2000; Bierlein *et al.* 2001b) have also utilised the ion probe to directly determine crystallisation ages of many of the plutons in the Lachlan Orogen, as well as the timing of metamorphism.

Metallogenesis

Much of the research on Lachlan Orogen mineral deposits has been related to genesis of individual deposits (Edwards 1953; Walshe *et al.* 1995), with links between metallogenesis and tectonics rarely considered. Research groups at the

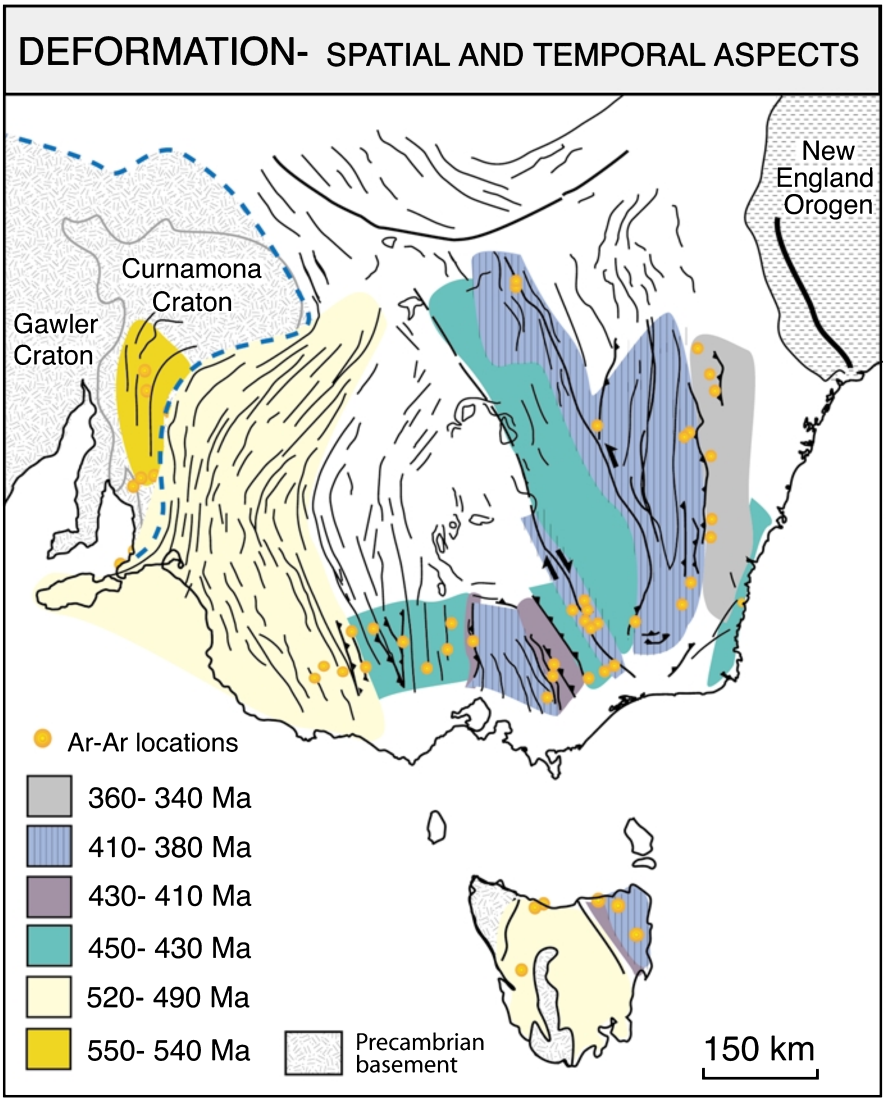


Figure 15 Deformation map for the Lachlan Orogen based on Ar–Ar slate whole-rock and white mica crystallisation ages in the low-grade rocks and cooling ages in the high-grade rocks. Data from Foster *et al.* (1996, 1998, 1999), Offler *et al.* (1998b), Bierlein *et al.* (1999), Fergusson and Phillips (2000) and Spaggiari *et al.* (2002a, b, 2003b).

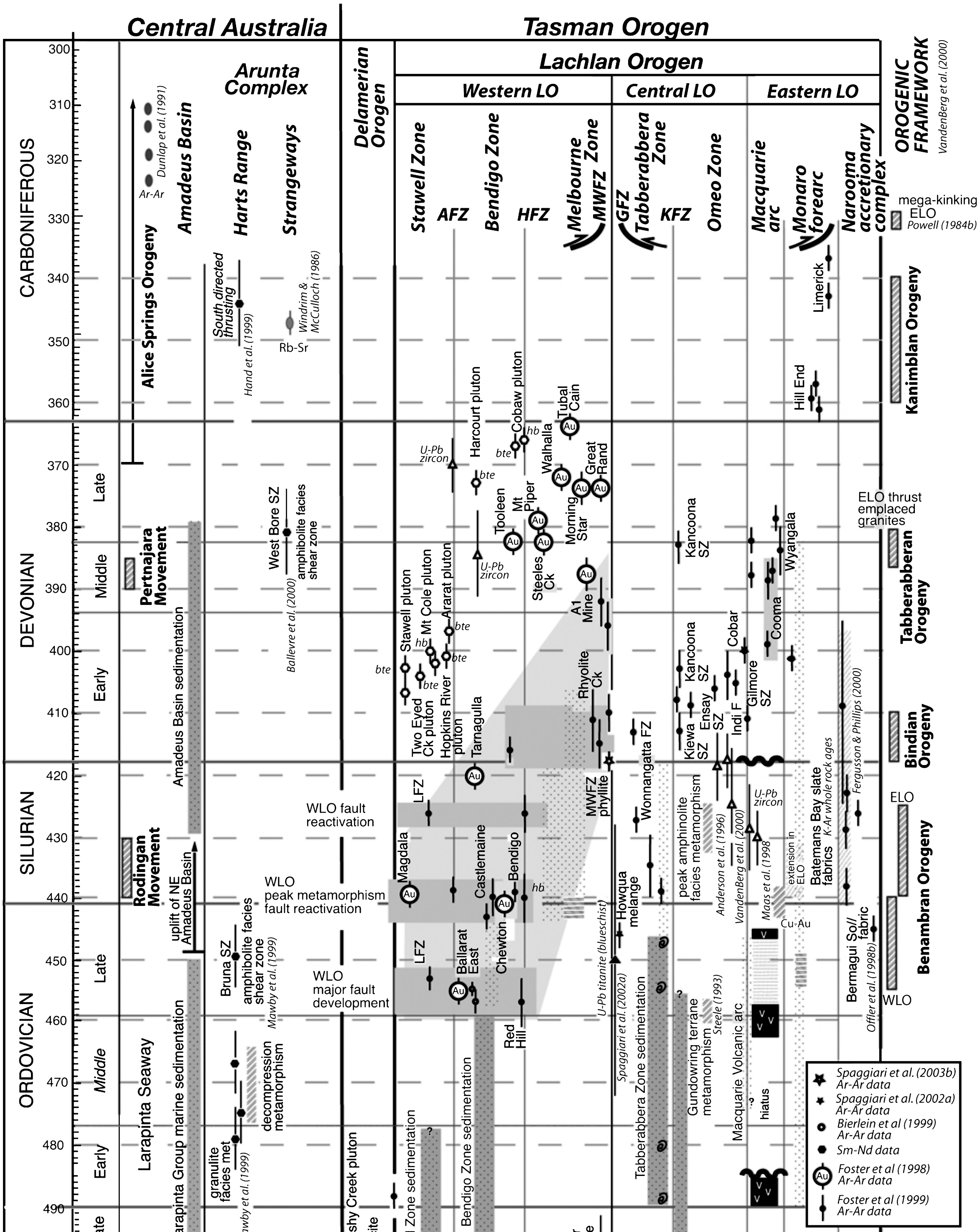


Figure 16 Time–space plot attempting to link tectonic events between central Australia and the Tasman Orogen for the period 520 Ma to 310 Ma. Major datasets are from $^{40}Ar-^{39}Ar$, Sm–Nd and U–Pb SHRIMP zircon geochronology. Data sources are shown.

University of Tasmania led by Ross Large, and at the Australian National University led by John Walshe have undertaken much of this research, in Tasmania and New South Wales, respectively, with Reid Keays (formerly University of Melbourne), Teunis Kwak (formerly La Trobe University), Ross Ramsay, Frank Bierlein, Dennis Arne and Martin Hughes (formerly University of Ballarat), Neil Phillips (formerly James Cook University), Chris Wilson and students (University of Melbourne) and Stephen Cox (formerly Monash University, and now at the Australian National University) working on Victorian gold deposits through the 1980s and 1990s (Sandiford & Keays 1986; Cox *et al.* 1991b; Gao & Kwak 1995; Phillips & Hughes 1996; Ramsay *et al.* 1998; Bierlein *et al.* 1998).

REVIEW OF OROGENIC FRAMEWORK FOR THE LACHLAN OROGEN

Lachlan Orogen tectonic evolution has been related to four main orogenic pulses (Crook & Powell 1976; Cas 1983; Gray & Foster 1997; VandenBerg 2000; VandenBerg *et al.* 2000), starting at *ca* 450 Ma and ending with stabilisation by 340 Ma (Figure 16). Local and/or regional unconformities (Figure 17) in the rock record were used to establish the original orogenic framework (Talent 1965), with the assumption that these reflected orogenic belt-wide tectonic events. In the 1980s, tectonic effects on sedimentation, including changes in facies (Cas 1983; Powell 1983a, 1984a) and palaeocurrent flow patterns (Powell 1983a, 1984a) were examined within this framework (see above).

The present framework: (i) defines each orogeny as an orogen-wide event and does not necessarily allow for either localised or wide-ranging, diachronous deformations (VandenBerg 2000); and (ii) was set up on a non-palinspastic base where widely separated parts (>1000's km) were undergoing supposedly simultaneous deformation/metamorphism (Fergusson & Coney 1992a). This convention was challenged by Rutland (1976 p. 176) and then by Powell *et al.* (1977), who were the first to argue that localised unconformities in the Lachlan Orogen do not necessarily reflect orogen-wide major deformational events.

Powell (1984a) showed that the orogenic episodes were neither synchronous nor uniform in their effects across the Lachlan Orogen. We still maintain (Gray & Foster 1997) that there are problems with the spatial configurations of deformation, metamorphism and magmatism across the

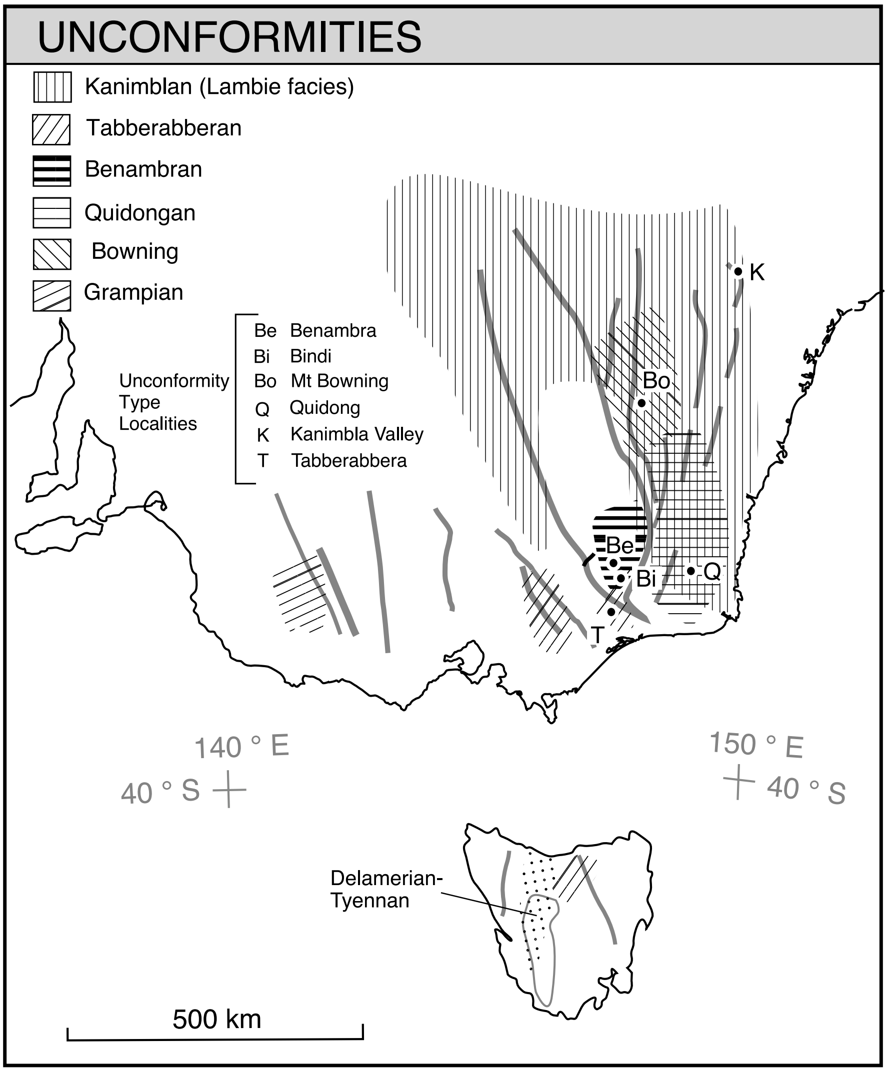


Figure 17 Lachlan Orogen map showing the approximate areal extents of the major unconformities that have been used to establish the Lachlan orogenic framework. Unconformity type localities, with their specific erosional hiatuses that constrain the timing of each orogenic pulse, are shown by the black dots (see Gray *et al.* 1997 and Gray & Foster 1997 for discussion, and VandenBerg *et al.* 2000 for more detail).

orogen, and how these link to the causes of orogeny in the plate-tectonic setting. There is no doubt that in the modern context, orogeny, where possible, should be defined by a combination of unconformities, generation of metamorphic fabrics, rock deformation, plutonism, sedimentation, and exhumation (Gray & Foster 1997; Foster & Gray 2000b).

Most workers today still think within the old orogenic framework and present deformed state (i.e. the present map pattern) and not the undeformed state (Fergusson & Coney 1992a) where the belt was potentially a marginal ocean basin that was 2000–3000 km in width. Despite criticisms (Rutland 1976; Powell *et al.* 1977, 1983; Powell 1983a, 1984a; Gray & Foster 1997; Gray *et al.* 1997), the old orogenic framework is like a 'security blanket' providing an established framework on which to hang our concepts of orogeny.

Linked with this is another debate relating to the relative role of extension versus contraction in the evolution of accretionary-style orogens. Collins (2002a, b) has argued that tectonic evolution of the Lachlan is characterised by protracted extension caused by slab-rollback, punctuated by short (>10 million years), sharp orogenic pulses (i.e. the orogenies of the orogenic framework). This concept relates to the eastern Lachlan Orogen, particularly the Silurian–Devonian magmatic episode, and is not necessarily applicable to the orogen as a whole (see discussion below). There is clear evidence for both shortening and extensional deformational components, particularly in the central and eastern Lachlan Orogen (Gray 1997 figure 18; Collins 2002b). We note, that in Tasmania the switch from obduction and shortening to oceanic backarc basin extension started a cycle of alternating convergent and divergent dynamics along the Pacific margin of Australia that formed crust of the Lachlan Orogen and parts of the New England Orogen (Foster & Gray 2000a; Collins 2002b; Foster *et al.* in press).

LACHLAN OROGEN: WIDELY ACCEPTED FACTS

(1) Structural thickening in the Lachlan Orogen took place during plate convergence in an oceanic setting along the eastern margin of Gondwana from *ca* 450 Ma through 340 Ma, with accretion of structurally thickened submarine fans, accretionary complexes, former volcanic arcs and oceanic crust, as well as the Tasmania microcontinent (Fergusson & Coney 1992a; Gray 1997; Foster *et al.* 1999).

(2) The Lachlan deformation pattern involves three thrust systems that constitute the western, central and eastern parts, respectively. The western Lachlan Orogen consists largely of an east-vergent thrust system with alternating zones of northwest- and north-trending structures (Cox *et al.* 1991a; Gray & Willman 1991a, b). The central Lachlan Orogen is dominated by northwest-trending structures and consists of a southwest-vergent thrust-belt linked to a fault-bounded metamorphic complex (Fergusson 1987a; Morand & Gray 1991). The eastern Lachlan Orogen is dominated by a north–south structural grain and east-directed thrusting which caused inversion of extensional basins in the west (Glen 1992). In the south and in the easternmost part, an east-vergent thrust system overrides an older, subduction-related accretionary complex (Fergusson & VandenBerg 1990; Miller & Gray 1996, 1997; Offler *et al.* 1998b; Fergusson & Phillips 2000).

(3) The presence of dismembered ophiolite slivers along some major fault zones (Spaggiari *et al.* 2003a), the lower T, intermediate-P metamorphic conditions preserved in metasandstone–slate sequences of the western Lachlan Orogen and external part of the central Lachlan Orogen (Offler *et al.* 1998a; Spaggiari *et al.* 2003b) and the presence of serpentinite–matrix mélange incorporating blueschist knockers like the Franciscan Complex of California (Spaggiari *et al.* 2002a, b, 2003a) requires an oceanic setting involving oceanic underthrusting (subduction) for the western and central Lachlan Orogen for parts of their history.

(4) Extensional basins (e.g. Silurian Tumut, Yass and Captains Flat basins and Cowombat and Wombat Creek rifts; Siluro-Devonian Cobar, Cowra and Hill End basins; and the Devonian Buchan rift) and evidence for basin inversion are largely restricted to the central and eastern Lachlan Orogen (Glen 1992; Gray 1997; Gray & Gregory 2003).

(5) The final stages in the evolution of the Lachlan Orogen involve extension and marked magmatism typical of the Basin and Range extensional environment of the western USA (Cas 1983; Zen 1995; Gray 1997; Collins & Hobbs 2001; Collins 2002a, b), that is, the margin becomes an Andean- or Cordilleran-type margin with effects seen mostly in the central and eastern Lachlan Orogen.

DATA SYNTHESIS

Current data are summarised in a series of simplified maps of the Lachlan Orogen. The aim here is to provide an overview, rather than detail that can lead to complexity and difficulty in understanding of Lachlan Orogen systematics. The diagrams are an attempt to present an up-to-date summary of elements and constraints that control, or are important for, Lachlan Orogen tectonic evolution.

Key tectonic elements

Key tectonic elements (Figure 8) include the: (i) Ordovician andesitic arc (calc-alkaline and shoshonitic volcanics of the eastern Lachlan Orogen); (ii) Late Ordovician – Early Silurian Narooma subduction complex (eastern Lachlan Orogen); (iii) Cambrian dismembered ophiolitic fault slivers (western Lachlan Orogen); (iv) thick deformed turbidite sedimentary wedges (western Lachlan Orogen); (v) Late Ordovician – Silurian subduction complex (Tabberabbera Zone, central Lachlan Orogen); (vi) Silurian metamorphic complex (central Lachlan Orogen); and (vii) Early Silurian extensional system (eastern Lachlan Orogen).

Cambrian age mafic to ultramafic rock of ophiolitic affinities are preserved as slivers along major faults (Figure 2), particularly in the western Lachlan Orogen (Spaggiari *et al.* 2003a, 2004a). The mafic rocks are predominantly MORB tholeiitic pillow basalts and dolerites with some andesitic and boninitic volcanics (Crawford &

Keays 1978; Crawford *et al.* 1984). They are generally associated with hemipelagic black shales and cherts supporting the notion of oceanic basement for the turbidites (Fergusson 1998, 2003).

Subduction-related elements include the following.

(1) *Arc-related rocks.* The eastern Lachlan Orogen contains a number of possible formerly contiguous Ordovician volcanic belts, including the Fifield–Nyngan Pt-rich mid-crustal zoned, Alaskan-type intrusive complexes (Suppel & Barron 1986), the high-level porphyry Cu/Au intrusive complexes of the Parkes–Narromine and Orange–Wellington–Kiandra belts, and the easternmost Sofala–Rockley volcanic belt (Glen *et al.* 1998). Based on geochemistry and phenocrysts, these volcanic rocks have been designated as shoshonites by Wyborn (1992), or high-K lavas with low field strength elements that are not related to subduction but to mantle-derived magmatism due to lithospheric heating or mantle overturning.

Contrasting tectonic interpretations for the New South Wales Ordovician volcanic rocks relate to differences in recorded geochemistry. However, Glen *et al.* (1998) more recently presented further geochemical data arguing that: (i) the New South Wales Ordovician volcanic rocks show variations between normal shoshonites to calc-alkalic to low-K calc-alkalic compositions; (ii) the shoshonites are dominantly Late Ordovician in age; and (iii) the volcanics have a clear subduction-related signature. The New South Wales Ordovician volcanic rocks most likely represent remnants of an intraoceanic island arc system developed on Cambrian oceanic crust (Squire & Miller 2003).

(2) *Accretionary complex rocks.* Interbedded sandstone and mudstone, as well as disrupted sandstone and mudstone, in the Batemans Bay – Narooma–Bermagui area of the south coast of New South Wales (eastern Lachlan Orogen) have been interpreted as the outer-arc slope and imbricated zone of an accretionary wedge that was part of a Late Ordovician – Silurian subduction zone (Powell 1983a, b, 1984a; Bischoff & Prendergast 1987). More recently, structural investigations on chaotic block-in-matrix mélange, broken formation along high-strain zones associated with the large-scale imbrication, early bedding-parallel cleavage, recumbent folds in turbidites, and structural complexity in cherts have supported this interpretation (Miller & Gray 1996, 1997; Fergusson & Frikken 2003). This belt of rocks is now referred to as the Narooma Accretionary Complex (Figure 4).

The Tabberabbera Zone of Victoria (central Lachlan Orogen) has also now been largely accepted as an imbricated and chevron-folded, Late Ordovician – Silurian accretionary wedge (Gray & Foster 1997; Fergusson 2003). It is designated by mud–matrix and serpentinite–matrix mélanges in the frontal part of the wedge (Spaggiari *et al.* 2002a, b, 2003b, 2004a), mud–matrix mélange along major faults within the wedge (Fergusson 1987a; Watson & Gray 2003), and a possible detached seamount (Spaggiari *et al.* 2003c).

(3) *Blueschist metamorphic blocks in serpentinite–matrix mélange.* Blocks of blueschist metamorphics, with similarities in occurrence and metamorphic assemblages to those in the subduction-related Franciscan Complex of California, have been located along the major Heathcote and Governor Fault Zones (Figure 10) of the western Lachlan Orogen and central Lachlan Orogen, respectively (Spaggiari *et al.* 2002a,2002b). These have ages of *ca* 455–440 Ma and *ca* 450 Ma in the Heathcote and Governor Fault Zones, respectively (Spaggiari *et al.* 2002a, b).

Sedimentation, flow patterns and provenance

Major changes occurred in sedimentary facies and depositional environments from the Ordovician, which was dominated by deep-marine turbidite submarine fans, into the Silurian, which in turn was dominated by more isolated sedimentation in restricted sedimentary basins (e.g. Melbourne and Cobar Troughs, and the Cowra and Hill End Troughs) through to the Late Devonian – Early Carboniferous continental facies sedimentation (Cas 1983; Powell 1983a, 1984a). Flow patterns were always from the west and/or southwest (Figure 9). These relationships are best exemplified in the facies maps of Powell (1983a, 1984a).

Provenance studies have shown little variation in composition and, therefore, source region over the vast extent of the Ordovician turbidites (Fergusson & Fanning 2002).

Major faults

Major fault zones spaced at ~100–120 km contain dismembered Cambrian ophiolite slivers, particularly in the western Lachlan Orogen (Spaggiari *et al.* 2004a). In the western Lachlan Orogen, these include the Avoca, Heathcote and Mt Wellington Fault Zones and the Governor Fault Zone in the central Lachlan Orogen (Figure 4). These fault zones have widths up to 4–5 km in plan view, and have duplex-like character where interconnecting faults link with bounding faults that define the fault zone proper (Gray & Foster 1998; Spaggiari *et al.* 2004a). Major thrust fault zones occur in the deformed turbidite package of the Lachlan Orogen (Figure 4). These are polydeformed zones characterised by transposition layering and crenulation cleavages (Gray & Willman 1991a,1991b; Morand *et al.* 1995; Gray & Foster 1998). Groupings of these reverse faults define three thrust systems of distinct tectonic vergence (Gray 1997; Gray & Foster 1998). Overall, the thrust systems in the western and central Lachlan Orogen are characterised by leading imbricate-fan geometry (Gray & Foster 1998), where maximum throw occurs on the frontal or leading fault.

Strike-slip shear zones bound the Wagga–Omeo Metamorphic Complex and consist of mylonite zones containing shear bands and S–C fabrics (Stuart-Smith 1990a, b; Morand & Gray 1991; Gray & Foster 1998). Calculated and measured shear displacements are less than 100 km for these strike-slip shear systems (Sandiford *et al.* 1988; Morand & Gray 1991; Gray & Foster 1998).

Timing of deformation and metamorphism

Deformation in the Lachlan Orogen was initiated between *ca* 450 and 430 Ma (Foster *et al.* 1999; Foster & Gray 2000a) in the three vergence belts (see above): the western Lachlan Orogen where it migrated eastward, the central Lachlan Orogen where it migrated to the southwest, and the eastern Lachlan Orogen where it migrated eastwards from *ca* 400 Ma, apart from older deformation (*ca* 445–440 Ma) preserved in the Narooma Accretionary Complex (Figure 15).

Metamorphism in the Wagga–Omeo Metamorphic Belt (Figure 10) and in the Eastern Metamorphic Complexes (e.g. Cooma Complex) occurred at *ca* 430 Ma (Maas *et al.* 2001 p. 1445; Williams 2001), although an age of *ca* 460 Ma has been argued for peak metamorphism in the Gundowring terrane of the Omeo Metamorphic Complex (Steele 1993). The youngest deformation is in the Hill End Zone with mica crystallisation ages of 360–340 Ma (Lu *et al.* 1996).

Metamorphism

Metamorphism is generally greenschist facies or lower across the Lachlan Orogen, but high-T–low-P metamorphism occurs in the centrally located Wagga–Omeo Metamorphic Belt of the central Lachlan Orogen and in several smaller metamorphic complexes (Cooma, Cambalong, Jerangle and Kuark complexes) of the eastern Lachlan Orogen (Figure 10). Peak conditions are 700°C and 300–400 MPa (Morand 1990). This high-T–low-P metamorphism is recorded by localised migmatites and K-feldspar–cordierite–sillimanite gneisses. Most of the turbidites are within the chlorite zone with localised development of biotite in contact aureoles around granites. The turbidites show intermediate pressure series metamorphism (Figure 11) based on b_0 measurements of phengitic micas (Offler *et al.* 1998a, b; Spaggiari *et al.* 2003b). Moderately high-P metamorphism has been inferred from coexisting chlorite–actinolite from metabasites from one of the major fault zones (Offler *et al.* 1998a). Low-T–intermediate-P blueschist metamorphism is recorded by blueschist blocks (knockers) in serpentinite–talc–matrix mélanges that occur within the Heathcote and Governor Fault Zones (Spaggiari *et al.* 2002a, b). Winchite (blue Na–Ca amphibole) and/or glaucophane (blue Na amphibole)–actinolite assemblages give estimated pressures of 600–700 MPa and 500–650 MPa, respectively, with temperatures <450°C (Spaggiari *et al.* 2002a, b).

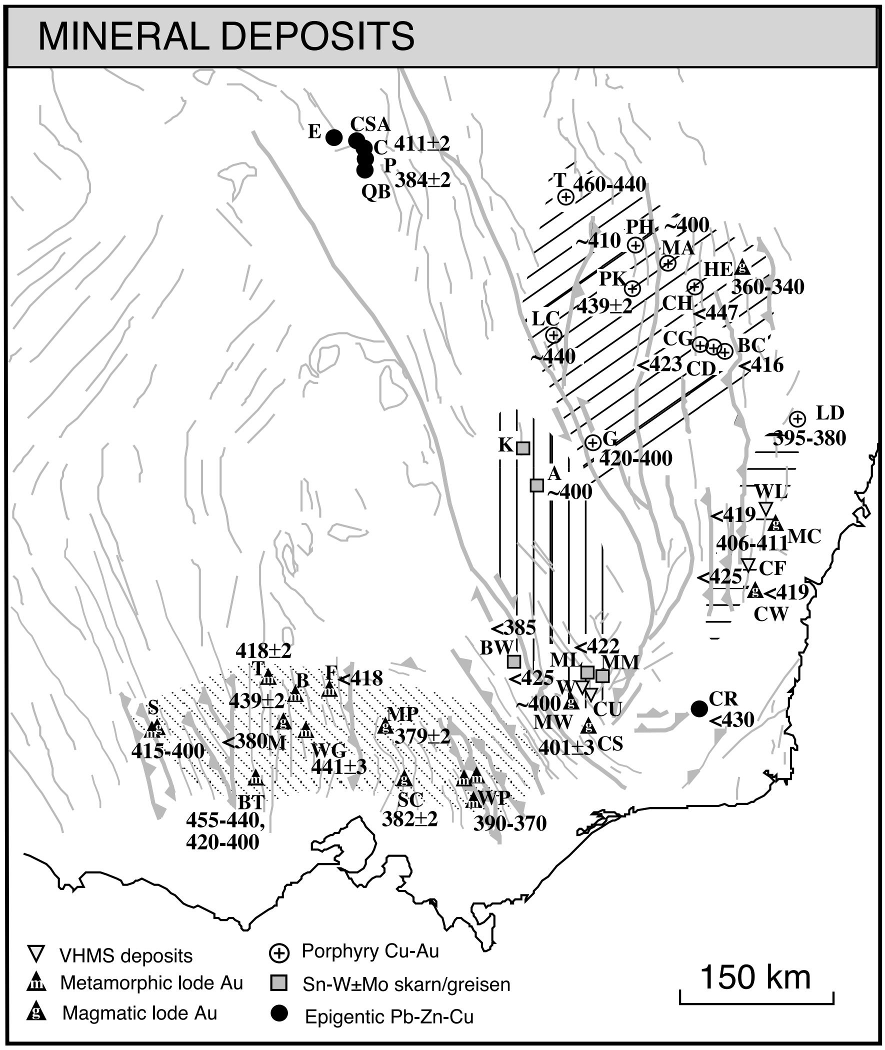


Figure 18 Mineral deposit locality map for the Lachlan Orogen showing the distribution of deposit types and formation ages (based on Bierlein *et al.* 2002 and Gray *et al.* 2003). Deposit age data are from Richards and Singleton (1981), Carr *et al.* (1995), Perkins *et al.* (1995), Foster *et al.* (1998, 1999), and Bierlein *et al.* (1999). For a more detailed explanation and description of deposits see Bierlein *et al.* (2003). The line patterns delineate the regional distribution of deposit types: vertical lines, Sn–W ±skarn, greisen deposits; horizontal lines, volcanogenic massive sulfide deposits; dotted diagonal lines, orogenic lode gold deposits; diagonal lines, porphyry Cu–Au deposits. Deposits: A, Ardlethan; B, Bendigo; BC, Browns Creek; BT, Ballarat; BU, Buchan; BW, Beechworth; CA, Castlemaine; C, Cobar; CD, Cadia; CF, Captains Flat; CG, Cargo; CH, Copper Hill; CR, Clarkes Reef; CSA, CSA deposit, Cobar; CS, Cassilis; CU, Currawong; CW, Cowarra; E, Elura; F, Fosterville; G, Gidginbung; HE, Hill End; K, Kikoira; LC, Lake Cowal; LD, Lucky Draw; M, Maldon; Ma, Mt Aubrey; ML, Mammoth Lode; MM, Mt Murphy; MP, Mt Piper; MW, Mt Wills; MC, Majors Creek; N, Nagambie; P, Peak (Cobar); PK, Parkes; PH, Peak Hill; QB, Queen Bee deposit; SC, Steels Creek; S, Stawell; T, Tottenham; W, Walhalla; WI, Wilga; WL, Woodlawn; WP, Woods Point; WTB, Wagga Tin Belt; WL, Woodlawn.

Granites

Distinct pulses of magmatism are recorded by Silurian–Early Devonian, Late Devonian and Carboniferous granitoid bodies of the Lachlan Orogen (Figure 14). These tend to be large (up to 10 000 km^2), commonly elongated bodies subparallel to the structural grain that occur in distinct belts, as shown by the north–northwest-trending granites of the Wagga–Omeo Metamorphic Belt of the central Lachlan Orogen and the more north-trending granites of the eastern Lachlan Orogen (Gray 1997; Foster & Gray 2000a). Granites include regional aureole, contact aureole and subvolcanic field associations, as well as S- I- and A-types based on geochemistry and mineralogy (Chappell *et al.* 1988).

Regional aureole types are associated with the high-T–low-P metamorphism, migmatites and K-feldspar–cordierite–sillimanite gneisses (e.g. Wagga–Omeo, Cooma, Cambalong and Kuark belts: Figure 10). Subvolcanic granitic plutons emplaced at shallow (<4 km) crustal levels with associated rhyolites and ash flows make up the Central Victorian Magmatic Province of the western Lachlan Orogen (Clemens 1988). These are largely post-tectonic with narrow (<2 km wide) contact aureoles. Some granitic plutons in the Wagga–Omeo Metamorphic Belt and the eastern metamorphic complexes of the Lachlan Orogen (Figure 10) are coeval with regional deformation. In the eastern Lachlan Orogen, some granites coincident with deformation were emplaced along major west-dipping shear zones (Paterson *et al.* 1990; Tobisch & Paterson 1990).

Metallogeny

The Lachlan Orogen shows five distinct metallogenic associations (Figure 18) including turbidite-hosted orogenic lode Au (±As–Sb; e.g. western Victoria), sediment-hosted (epigenetic) Cu–Au and Pb–Zn (e.g. western New South Wales), granite-hosted Sn–W (+skarn–greisen; e.g. central New South Wales), porphyry Cu–Au (+Au–skarn, Mantos Pb–Zn and epithermal Au–Ag; central northern New South Wales) and volcanogenic-hosted massive sulfides

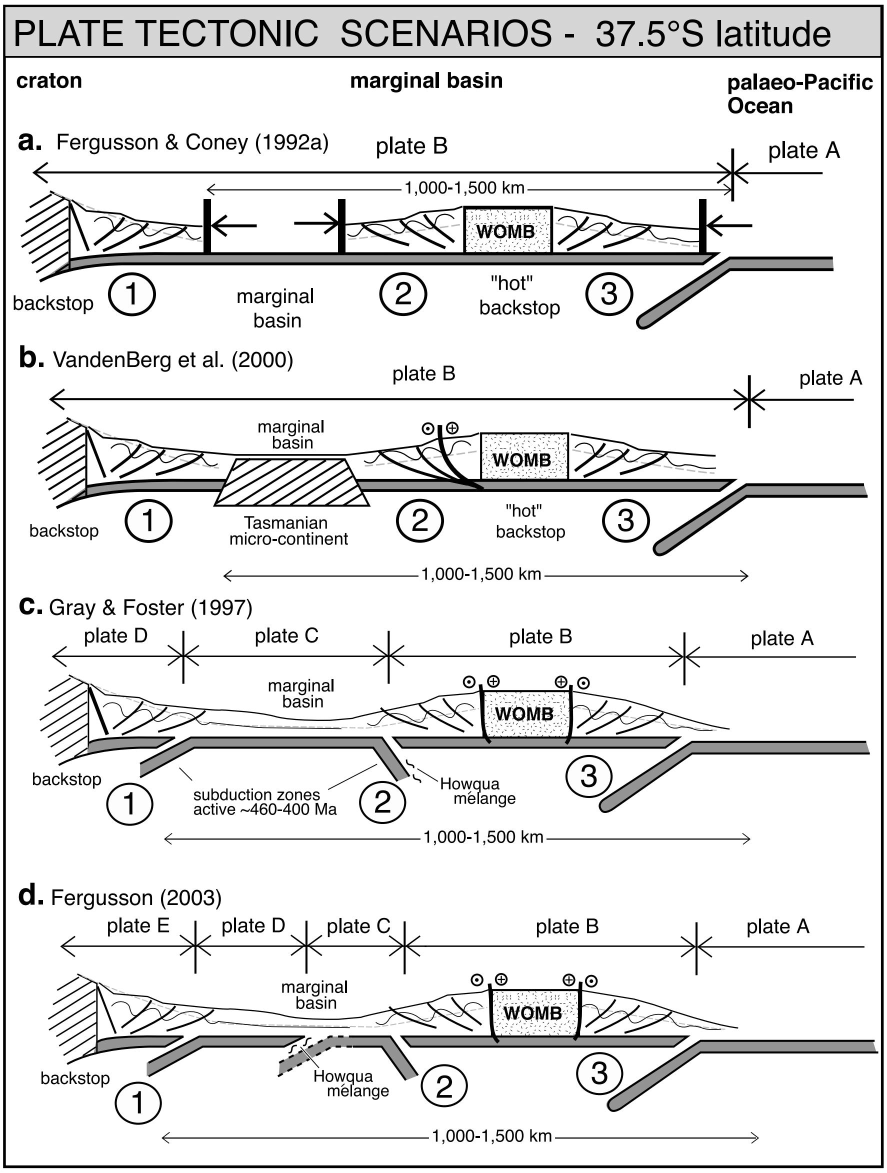


Figure 19 Variants in proposed mid-Silurian (*ca* 430 Ma) plate-tectonic scenarios for the southern Lachlan Orogen (present-day 37.5°S latitude). (a) Intraplate model after Fergusson and Coney (1992a). (b) Intraplate model incorporating a Tasmania micro-continent (Selwyn Block) after VandenBerg *et al.* (2000). (c) Multiple subduction zone model after Gray and Foster (1997), Gray *et al.* (1997), Soesoo *et al.* (1997) and Foster and Gray (2000a). (d) Multiple subduction zone model after Fergusson (2003). The circled numbers 1, 2 and 3 indicate the locations of the three thrust systems that operated to produce the Lachlan Orogen architecture. WOMB, Wagga–Omeo Metamorphic Belt.

(eastern New South Wales) with overprinting minor post-tectonic granite-related magmatic Au (±Mo–Sb–Cu–Te) mineralisation (Walshe *et al.* 1995; Bierlein *et al.* 2002; Gray *et al.* 2002).

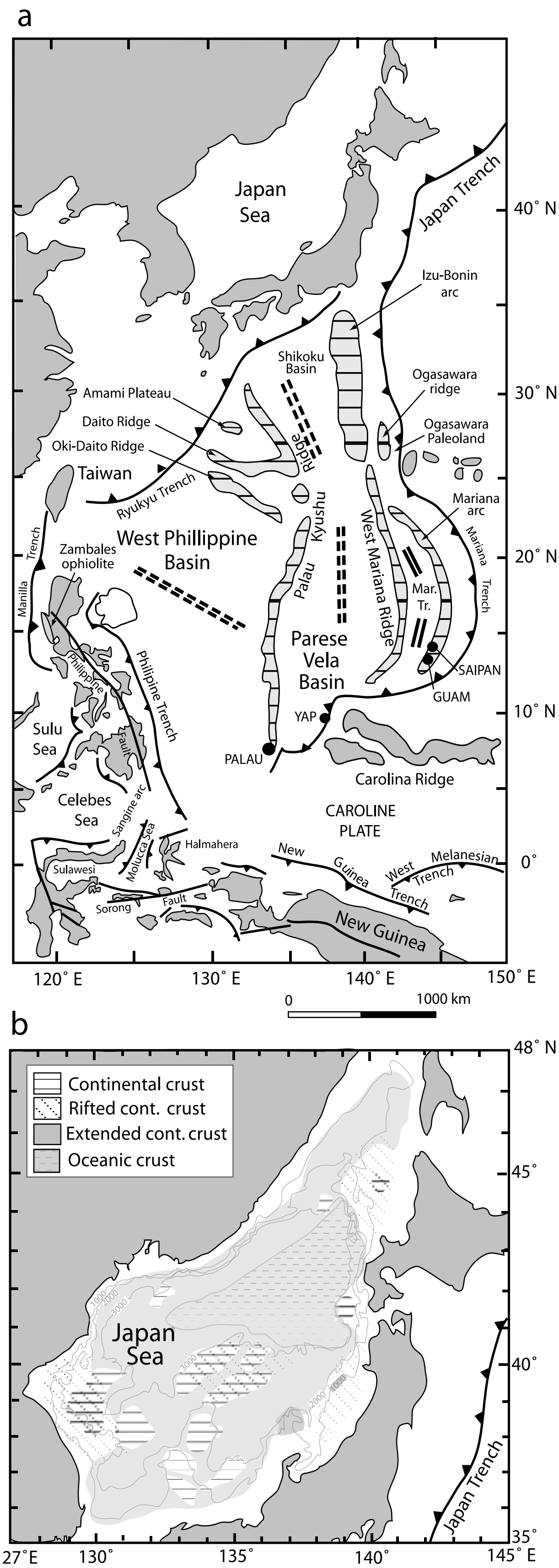


Figure 20 Map of the west Pacific margin showing the geometry of subduction systems, the positions and extent of volcanic arcs and the nature and sizes of the various marginal basins including those dominated by oceanic crust with relict and active arcs (e.g. Philippine Basin) and those dominated by attenuated continental crust (e.g. Japan Sea). Map compiled from Bloomer *et al.* (1995 figure 1) and Hall 1996 figure 1). (b) A more detailed map of the Japan Sea region showing the complex distribution of attenuated continental crust, rifted crust and oceanic crust (modified from Tamaki 1995 figure 11.4).

PROPOSED TECTONIC EVOLUTIONARY SETTINGS AND MODELS FOR THE LACHLAN OROGEN

In the 1980s and early 1990s, most models for Lachlan Orogen tectonic evolution were within an intraplate setting (Figure 19a), involving a marginal ocean basin behind a long-lived subduction zone (i.e. an intraplate backarc setting) that was present along the margin of Gondwana throughout the Palaeozoic (Powell 1983a, 1984a; Fergusson & Coney 1992a). In this setting, the marginal basin could either be a Philippine Sea-type basin (Figure 20a), involving a multiple subduction environment dominated by oceanic crust but with smaller embedded continental fragments as well as remnant arcs (Figure 19b), or a Japan Sea-type backarc basin (Figure 20b), that is, a marginal basin dominated by extended and attenuated continental crust. It is highly probable that continental as well as volcanic-arc ribbon-fragments occurred in the Lachlan Orogen backarc basin oceanic crust. For example, aeromagnetic data of Bass Strait has been interpreted by Cayley *et al.* (2002) to indicate that Neoproterozoic oceanic crust on King Island (Grassy Group volcanics) extends northwards under central Victoria as part of an inferred micro-continental block, that is, the Selwyn block of VandenBerg *et al.* (2000) and Cayley *et al.* (2002). The presence of fault-bounded segments of a Late Cambrian Licola andesitic arc in the northeastern part of the Melbourne Zone (Spaggiari *et al.* 2003c), however, may complicate this interpretation.

Since the late 1990s, more complex scenarios have evolved involving multiple subduction systems in a marginal ocean setting (Figures 19c, d) behind the major, long-lived subduction system (Gray *et al.* 1997; Collins 1998; Soesoo *et al.* 1997; Foster & Gray 2000a; Fergusson 2003; Spaggiari *et al.* 2003a), although intraplate tectonic scenarios still persist (Li & Powell 2001; Willman *et al.* 2002; Squire & Miller 2003; Braun & Pauselli 2004).

The multiple subduction system proposed by Gray and Foster (1997) was a short-lived, complex west Pacific-type setting localised in the Tasmanide part of the Gondwana margin from *ca* 460 Ma through 380 Ma (Table 1). The apparently complex model was required to explain: (i) the underthrusting requirements of the three major thrust systems of the Lachlan Orogen; (ii) the distinct magmatic trends reflected by northwest granitoid elongation of the central Lachlan Orogen Silurian Wagga–Omeo

Metamorphic Belt and the north–south trends of the eastern Lachlan Orogen magmatic belt; (iii) the intermediate-P, lower geotherm environment shown by the phengites in the turbidites (now defined in the western, central and eastern Lachlan Orogen); (iv) the presence of blueschist knockers in serpentinite–matrix mélange of the major fault zones now in the western and central Lachlan Orogen; and (v) the presence of the Narooma Accretionary Complex in the eastern Lachlan Orogen.

The complexity shown in the present-day west Pacific (Figure 20) reflects the potential complexity of the Palaeozoic Gondwana margin. Marginal basins exist within extensional regions of backarc spreading (e.g. Philippine Sea and Lau Basin) and of thin, attenuated, continental crust (Japan Sea). Subduction zone traces are commonly isolated and have finite lengths (Philippine and Manilla Trenches), with some showing pronounced curvature (e.g. Mariana and West Melanesian Trenches). They are associated with discontinuous arcs (e.g. Sangine, Halmahera and Mariana Arcs), coupled arcs and subduction accretion wedges (e.g. Taiwan, Japan), linked subduction zones defining triple junctions (e.g. Ryuku–Nankai trough system with the Izu Bonin –Marianas trough system, and the developing intersection of the New Guinea and West Melanesian Trenches) and complex multiple subduction systems involving strike-slip faults/transforms (e.g. Philippine Fault, Philippines and the Sorong Fault, New Guinea) and divergent double subduction zones (e.g. Molucca Sea).

RECENT ISSUES

Role of subduction

The number of subduction zones is still debated (Fergusson 2003; Squire & Miller 2003; Braun & Pauselli 2004; Spaggiari *et al.* 2004b). The presence of serpentinite–matrix mélanges containing blueschist blocks associated with fault-bounded, ophiolitic slivers (Spaggiari *et al.* 2002a, b, 2003a, b, c, 2004a) provides the major constraint for the multiple subduction scenario proposed for the western and central Lachlan Orogen in particular. Serpentinite–matrix and mud–matrix mélanges are diagnostic of subduction environments and are clearly linked to faults in both modern and ancient accretionary wedges, that is, in the hangingwalls to descending slabs (Pickering *et al.* 1988; Fryer *et al.* 1999)

Table 1 Lachlan Orogen subduction zone parameters.

	Western Lachlan Orogen Subduction Zone	Central Lachlan Orogen Subduction Zone	Eastern Lachlan Orogen Subduction Zone
Age of sediment	Cambrian to Ordovician	Cambrian to Silurian	?Neoproterozoic to Early Devonian
Depositional environment	Composite submarine fan	Submarine fan/pelagic sediment	Distal fan/ pelagic sediments
Nature of sediment	Turbiditic sandstone and mudstone overlying chert and basalt	Turbiditic sandstone and mudstone overlying chert and basalt possible overlying chert and basalt	Turbiditic sandstone and mudstone olistostromal horizons
Sediment thickness	>5 km	<1 km (W of Wonnangatta Fault) ~2–3 km (E of Wonnangatta Fault)	<1 km (Narooma Accretionary Complex)
Time of subduction initiation	Middle Ordovician *ca* 460 Ma	Middle Ordovician *ca* 460 Ma	Early Ordovician <485 Ma
Duration of subduction	~70 million years (*ca* 460–390 Ma)	~ 70 million years (*ca* 460–390 Ma)	~160 million years (*ca* 490–330 Ma)
Magmatic arc: nature and (trend)	None recognised	Wagga–Omeo Metamorphic Complex: regional aureole granites; large composite batholiths (NW–SE)	Cordilleran style batholiths; large composite batholiths (N–S)
Metamorphism (wedge): grade and timing	Greenschist: *ca* 455–440 Ma (Stawell–Bendigo Zone); *ca* 410–390 Ma (east Melbourne Zone)	Greenschist high-T: *ca* 430 Ma	Greenschist: *ca* 445–440 Ma
Wedge b_o values	9.022 A (Offler *et al.* 1998a)	9.026 A (Spaggiari *et al.* 2003b)	9.024 A (Offler *et al.* 1998b)
Main magmatism	*ca* 405–400 Ma; *ca* 370–365 Ma	*ca* 440–420 Ma	*ca* 405–400 Ma
Rollback	limited ?	limited ?	6 mm/year east migration
Basal fault zone	Heathcote Fault Zone; Mt Wellington Fault Zone	Governor Fault Zone	None recognised
Blueschist metamorphism: age, P, T	Heathcote mélange: ca 455–440 Ma, ~600–700 MPa, ~450°C	Howqua mélange: ca 450 Ma, ~400–450 MPa, 450°C	None recognised
Low-grade slate/phyllonite fabric (basal fault zone)	*ca* 419 Ma (Spaggiari *et al.* 2003b)	*ca* 446 ± 2 Ma ($^{40}Ar/^{39}Ar$, whole-rock (Spaggiari *et al.* 2002b)	*ca* 445 (Offler *et al.* 1998b)
Ophiolite remnant: lithotype; age	Metabasalts, boninites; Cambrian	Metabasalts (Howqua) Cambrian	Metabasalts (Narooma); ?Neoproterozoic–Cambrian

Most recently, numerical modelling by Braun and Pauselli (2004) of Lachlan Orogen tectonic evolution has argued that a single subduction zone scenario can explain the observed deformation, metamorphic and magmatic patterns. Such a model may be plausible but must also explain the serpentinite–matrix mélanges in the fault zones of the western Lachlan Orogen and central Lachlan Orogen. The same arguments apply to speculative models utilising collisions of seamounts and variable rates of slab retreat along a single outboard subduction system (Squire & Miller 2003).

Despite the lack of a recognised magmatic arc in the western Lachlan Orogen (Soesoo *et al.* 1998), geochemical studies of the more mafic to intermediate Palaeozoic rocks of both the western and central Lachlan Orogen (Soesoo & Nicholls 1999; Bierlein *et al.* 2001a) have shown that Early Devonian basaltic to andesitic dykes and plutons have primitive mantle-normalised trace-element abundance patterns with negative Nb and Ti anomalies typical of island arcs and consistent with a subduction influence on mantle magma sources.

Problem of the basement

Several approaches have been used to fingerprint the basement beneath the Lachlan Orogen. Originally, Bruce Chappell and Allan White (Chappell *et al.* 1988) argued that granite geochemistry provided the clues, supporting the notion of basement terranes made up of attenuated Proterozoic crust beneath the Lachlan Orogen. Concepts of multiple-component mixing for granitic magma generation have, however, changed attitudes towards this (Collins 1996, 1998; Keay *et al.* 1997). In addition, U–Pb SHRIMP dating of zircons from granites and their enclaves has shown they have similar populations to the Ordovician turbidite detrital zircon populations, suggesting that they have a common source (or sources) and, therefore, do not necessarily require a continental substrate (Williams *et al.* 1994; Keay *et al.* 1997; Williams 2001). Zircon inheritance studies on the high-grade gneisses of the Wagga–Omeo Metamorphic Belt suggest that this belt is also not underlain by Proterozoic crust (Anderson *et al.* 1996; Anderson 1997; Maas *et al.* 2001).

Sm–Nd geochemistry of the granites (McCulloch & Chappell 1982) was also used in support of continental crust beneath the Lachlan Orogen, as well as Re–Os geochemistry on mantle xenoliths in basalts of the Western Districts, southwest Victoria (McBride *et al.* 1996; Handler & Bennet 2001). The mantle xenoliths indicate Proterozoic model ages for lithospheric mantle beneath the western part of the western Lachlan Orogen (McBride *et al.* 1996), but this does not necessarily imply crust of the same age (Handler & Bennett 2001).

In another approach using a comparison of tectonothermal histories, Gibson (1992) argued that western New Zealand Fiordland sillimanite-grade schists and gneisses provided a window into basement rocks beneath the Lachlan Orogen, and that basement was likely to be of Delamerian age and signature. This was argued on the basis of similar metamorphic characteristics, detrital zircon populations as well as the magmatic history of Glenelg Zone, western Victoria rocks with those of former, lower crustal rocks now exposed in Fiordland (Gibson 1992; Gibson & Ireland 1996).

By 2000, however, debate over the nature of the basement to the Tasman Orogen evolved to general consensus for an oceanic setting largely involving oceanic lithosphere (Foster & Gray 2000a; Fergusson 2003). Significant magmatic underplating has to be part of crustal evolution, particularly in the central and eastern Lachlan Orogen (see next section). Isostatic considerations clearly require a dense (>2.9 g/cm^3) lower crust (O'Halloran & Rey 1999) matching the observed lower crustal P-wave velocities of >6 km/s (Finlayson *et al.* 1979, 1980; Gibson *et al.* 1981).

Granite problem and high heat flow

The regional aureole style of metamorphism of the central and eastern Lachlan Orogen implies high temperatures at shallow crustal levels, requiring a mechanism to facilitate the intrusion of large volumes of hot, mafic to intermediate mantle-derived magma to shallow levels in the crust (White *et al.* 1974; Chappell *et al.* 1988). The voluminous granitic magmatism, particularly in the eastern Lachlan Orogen, has been explained by a number of different tectonic scenarios, including lithospheric delamination due to structural thickening (Loosveld & Etheridge 1990; Cox *et al.* 1991a; Collins 1994; Collins & Vernon 1994), anomalous thermal behaviour in the mantle (Chappell *et al.* 1988), lithospheric extension (Cas 1983; Sandiford & Powell 1986; Zen 1995), shear-heating and internal strain-heating during crustal thickening (Gray & Cull 1992) and multiple subducting slabs (Collins & Vernon 1992; Gray 1997; Foster & Gray 2000a).

Lachlan Orogeny and relative durations of extension versus compression

The Lachlan Orogen has been interpreted as a retreating orogen or Carpathian-type (after Royden and Burchfiel 1989; Glen 1992), where construction can be simply viewed as overall extension punctuated by brief contractional episodes (Collins 2002a, b). Rollback along the outer, long-lived subduction zone that mantled Gondwana separating it from the Palaeo-Pacific ocean has clearly played an important role in the formation of the Lachlan Orogen substrate or basement (Foster *et al.* 1999; Spaggiari *et al.* 2003a; Foster *et al.* in press), and also in the development of the Basin and Range style magmatic province in the Late Silurian – Early Devonian for the eastern Lachlan Orogen (Collins & Hobbs 2001).

Most recently, the magmatic character, particularly of the eastern Lachlan Orogen, has been argued to justify a new class of orogen, the 'extensional accretionary orogen' (Collins 2002b). This is somewhat misleading, as the western and central Lachlan Orogen have undergone a distinctly different structural–tectonic–metamorphic evolution to the eastern Lachlan Orogen (see above). The western Lachlan Orogen is dominated by Late Ordovician – Silurian thrusting, chevron folding, and imbrication of oceanic sequences in an intermediate-P, lower geotherm environment and does not fit the criteria for 'retreating orogen' status. All the illite crystallinity and mica b_0 work done to date on the low-grade slates throughout the orogen, indicates that the background metamorphism is intermediate-P and low geotherm. The requirement that '. . . the orogen remains hot, despite repeated thickening events, because of ongoing extension, which promotes advective heat transfer into the crust . . .' (Collins 2002b p. 1024) does not hold. The conditions and model described by Collins (2002a, b) are applicable to the eastern Lachlan Orogen extensional magmatic province for the Late Silurian – Early Devonian (Cas 1983; Zen 1996).

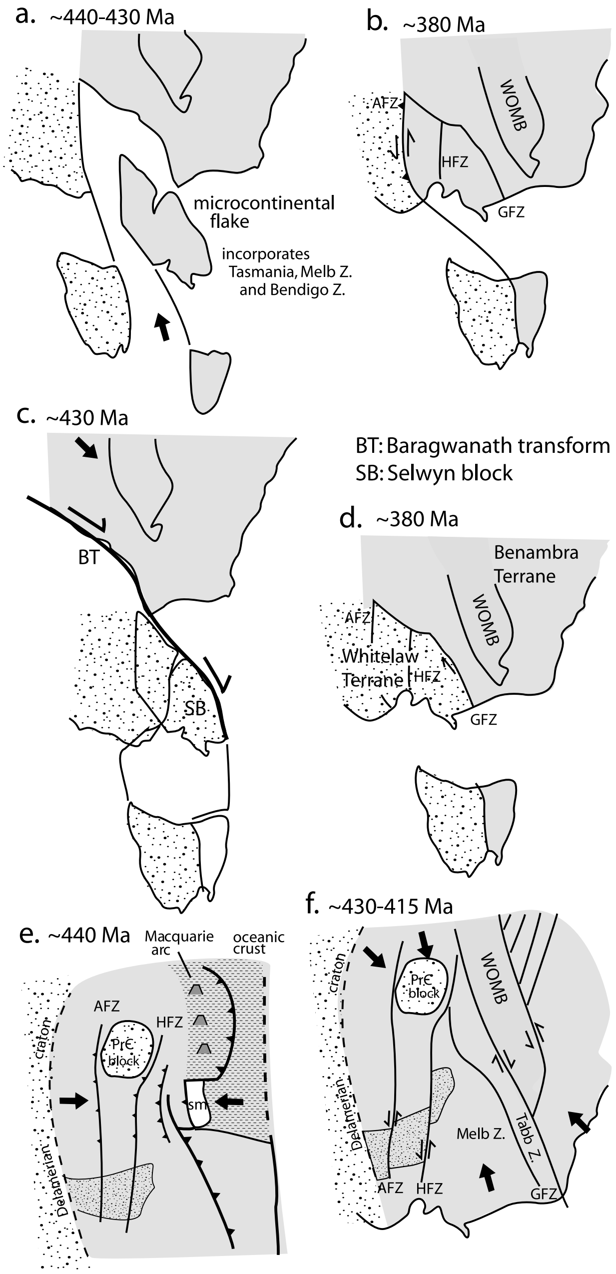


Figure 21 Strike-slip models of Lachlan Orogen evolution. (a, b) 'Flake escape' scenario of Glen *et al.* (1992b). (c, d) Baragwanath transform model of the Victorian Geological Survey (VandenBerg *et al.* 2000; Willman *et al.* 2002). (e, f) Partitioned strike-slip model of Squire and Miller (2003). sm, seamount; stippled pattern, Upper Ordovician conglomerate facies (Sunbury Group); AFZ, Avoca Fault Zone; HFZ, Heathcote Fault Zone; GFZ, Governor Fault Zone; WOMB, Wagga–Omeo Metamorphic Belt; Tabb Z, Tabberabbera Zone; PrC, Precambrian.

Role of transpressional deformation

Oblique convergence and transpressional and/or strike-slip deformation (Figure 21) have been considered important in Lachlan Orogen plate-tectonic evolution (Powell 1983a; Packham 1987; Li & Powell 2001). Arguments for transpressional deformation have been linked to: (i) apparent clockwise rotation of Gondwana relative to the magnetic pole between 430 and 400 Ma to produce dextral strike-slip margin (Powell 1983a, 1984a; Li *et al.* 1990; Li & Powell 2001); (ii) east–west-trending Benambran folds in the Wagga–Omeo Metamorphic Belt and other parts of the Lachlan Orogen (Powell 1983a, 1984a; Fergusson 1987a, b; Stuart-Smith 1990a, b); (iii) offset in the Macquarie Arc due to inferred sinistral movement on major faults segmenting the former arc with movements >350 km (Packham 1987); (iv) interpretation of the Tumut basin as a strike-slip pullapart basin Powell (1983a figure 2b) due to Late Silurian dextral strike-slip fault motion (Stuart-Smith 1990a, b; Stuart-Smith *et al.* 1992); (v) interpretation of the Cobar Basin as a strike-slip pullapart basin (Glen 1992); tissue-paper modelling of strike-slip deformation of the Cobar Basin (Smith 1992) suggested that basin formation with development of *en échelon* extensional faults was due to sinistral transtension, whereas basin inversion was related to dextral transpression along the north-trending boundary faults (e.g. Rookery Fault of Glen 1990); (vi) interpretation of the north–south-trending extensional basins of central northern New South Wales (Powell 1983a); (vii) interpretation of the Bendigo, Melbourne and Mathinna terranes as part of a crustal flake that migrated northwards relative to the Australian craton and the outboard parts of the developing Lachlan Orogen (Glen *et al.* 1992b); and (viii) changes in facies of the turbidite succession between the western Lachlan Orogen and central Lachlan Orogen (VandenBerg & Stewart 1992) with large-scale movement (~400–600 km) along an inferred transform fault (Baragwanath Transform: VandenBerg *et al.* 2000; Willman *et al.* 2002).

Certainly in the period 410–400 Ma (Emsian), the Wagga–Omeo Metamorphic Belt moved southwards as a wedge, but the amount of lateral translation on the marginal shear zones was probably <100 km (Sandiford *et al.* 1988; Morand & Gray 1991). Distributed shear strain in the backarc is more apparent east of the Wagga–Omeo Metamorphic Belt (e.g. Tumut, Cobar Basins as strike-slip pullaparts and the Cowra and Hill End Troughs as transtensional basins), whereas there is less evidence for distributed shear strain in the western and central Lachlan Orogen (Spaggiari *et al.* 2003b). On structural grounds, Gray and Foster (1998) have argued that evidence for large-scale strike-slip movement in the Lachlan Orogen is lacking, with both observed and calculated shear displacements on faults and shear zones generally <50 km. There is no structural evidence from currently recognised structures for a major, dominant strike-slip fault, such as the Alpine Fault in New Zealand (Norris *et al.* 1990) or the Puross Mylonite Zone in the transpressional Kaoko belt of Namibia (Goscombe *et al.* 2002), despite arguments for the inferred Baragwanath transform (VandenBerg *et al.* 2000).

East–west versus north–south contractional deformation

North–south shortening (generally <5%) and south-directed thrusting have been recognised in parts of the Lachlan Orogen (Powell 1984b), suggesting that north–south shortening was interactive with east–west shortening throughout Lachlan Orogen evolution. Regional structural relationships clearly indicate, however, that overall east–west shortening is responsible for the major structural grain of the Lachlan Orogen. Overprinting structures related to orogen-scale, north–south shortening pulses appear to be temporally linked with major shear zone development and reactivation in central Australia (Figure 3) (Powell 1984b; Miller *et al.* 2001). In the Lachlan Orogen, pulses of north–south shortening have occurred at *ca* 420–414, *ca* 390–380 and *ca* 330Ma.

In the eastern Lachlan Orogen, kinking and megakinking reflects approximate north–south shortening at mid-Carboniferous time (*ca* 330 Ma), as the megakinks overprint the regional Early Carboniferous folds but predate the latest Carboniferous basinal sediment of the Sydney Basin (Powell 1984b; Powell *et al.* 1985). These structures were equated with the north–south shortening of the Alice Springs Orogeny in central Australia (Powell 1984b). Similar kinks and timing relationships have been observed in northern Tasmania (Goscombe *et al.* 1994).

In the western Lachlan Orogen, effects of north–south shortening have been recognised in the Melbourne Zone (Gray & Mortimer 1996; Morand *et al.* 1997; Edwards *et al.* 1998) and in the Stawell Zone (Miller *et al.* 2001). Fold interference patterns and intersecting cleavages indicate that parts of the Melbourne Zone have undergone two deformational events during the Late Silurian – Middle Devonian period (Gray & Mortimer 1996; Morand *et al.* 1997). Gray and Mortimer (1996) argued that the overprinting relationships require mutually interfering, contemporaneous and diachronous north–south and northeast–southwest shortening deformations; F_1 folds in the north are east–west folds overprinted by northwest–southeast folds and cleavage (D_2 deformation), whereas F_1 folds to the south are northwest–southeast folds that have curvilinear axial traces due to effects of east–west folds and overprinting by east–west cleavage (D_2 deformation). Other interpretations were that these were separate and discrete events (Morand *et al.* 1997; Edwards *et al.* 1998).

Miller *et al.* (2001) have identified west–northwest-trending brittle faults with top to the south–southwest shear sense that have offset the gold lodes in the Stawell Mine of western Victoria. They argued that overprinting relationships along with sedimentation changes in the Melbourne Zone requires these fault structures to have developed in the Middle to Late Silurian (*ca* 420–414 Ma).

Presence of microcontinental ribbons

The nature of the basement to the Lachlan Orogen has been contentious for some time (see above), with opinions ranging from attenuated Proterozoic continental crust (Rutland 1976; Chappell *et al.* 1988) to oceanic crust with embedded continental ribbons or microcontinents or oceanic plateau like the present-day Lord Howe Rise and Campbell Plateau (Scheibner 1987, 1989; Scheibner & Basden 1996, 1998). Scheibner (1987, 1989) has argued for a Victorian microcontinent distinct from Tasmania, whereas the Selwyn Block inferred by the Geological Survey of Victoria represents an extension of Tasmanian Precambrian crust underneath the Melbourne Zone of the western Lachlan Orogen (VandenBerg *et al.* 2000; Cayley *et al.* 2002).

Collision of an oceanic plateau has been speculated to be important in shutting off magmatism in the Macquarie Arc from the Middle to Late Ordovician (*ca* 475–468 Ma; Glen *et al.* 1998; Squire & Miller 2003) and also for generation of hydrothermal activity causing the influx of Au into the western Lachlan Orogen at *ca* 440 Ma (Squire & Miller 2003), but there is a question as to whether such a plateau is preserved within the present-day orogen. At this stage, there are no known or interpreted exotic fragments, and/or observed collision-induced structural complexities, in the exposed part of the eastern Lachlan Orogen.

Tasman Line and Lachlan Orogen

The nature and form of the Tasman Line has major implications for the age distribution of the Neoproterozoic–Cambrian oceanic crustal substrate beneath the Lachlan Orogen. Originally defined as the boundary between the Palaeozoic Tasman Orogen and the older Precambrian craton (Figure 1), the mapped position, form and significance of this contact has varied considerably (for a review see Direen & Crawford 2003; Kennett *et al.* 2004).

An interpreted rectilinear form of the Tasman Line has been related to the breakup of the former Rodinia supercontinent, where the linear northwest- and northeast-trending segments were interpreted as rift and transform components of the margin, respectively (Veevers & Powell 1984; Scheibner & Basden 1996, 1998; Li & Powell 2001). Most recently, Crawford *et al.* (2003) have argued that the northwestern margin of Western Australia is a modern analogue for this Neoproterozoic margin, and that the spreading centre segments were northwest–southeast-trending, as defined by the *ca* 600 Ma rift tholeiitic pillow basalts of the Koonenberry belt of New South Wales, the southeast coast of King Island, and the magnetic belt of western Victoria (Direen & Crawford 2003 figure 4).

Most ages for the fault-bounded ophiolitic slivers in Victoria are around *ca* 505–500 Ma (Spaggiari *et al.* 2003a, b), with older ages of *ca* 530 Ma from the New England Orogen (Aitchison *et al.* 1992) and 560–550 Ma from Tasmania (S. Meffre pers. comm. 2004).

IMPLICATIONS OF THOMSON OROGEN STRUCTURE

The Thomson Orogen is considered to be coeval with, as well as the possible northern continuation of, the Lachlan Orogen (Murray & Kirkegaard 1978; Coney *et al.* 1990). Mostly hidden under cover of the younger sedimentary basins that make up the Great Artesian Basin, geophysical aeromagnetic imagery (Figure 3) shows that it has east-trending structural trends that truncate Lachlan Orogen trends. Drill samples and limited surface exposures have shown that the Thomson Orogen consists of low metamorphic grade, turbiditic sandstone and mudstone lithologies similar to the Lachlan Orogen, and like the Lachlan it is intruded primarily by Silurian and Devonian granites (Murray & Kirkegaard 1978; Thalhammer *et al.* 1998).

Regional structural interpretation is largely based on the regional gravity and aeromagnetic databases (Wellman 1988; Murray *et al.* 1989; Glen *et al.* 1996; see Kilgour 2002a, b for the latest datasets). Structural grain in the aeromagnetic imagery is overall northeast-trending, but becomes east–west with arcuate form in the south where structures have a concave-to-the-north form (Figures 3, 22). The Olepoloko fault/shear zone is the major boundary with the Lachlan Orogen (Figure 4) and truncates features such as the northwest-trending grain of the Wagga–Omeo Metamorphic Belt (Crawford *et al.* 1997 figure 1). An inferred north dip on this shear zone has implied south-directed thrusting of the Thomson Orogen over the Lachlan Orogen (VandenBerg *et al.* 2000; Willman *et al.* 2002). Structures in the Thomson Orogen immediately north of this shear zone either merge with it, or are truncated by it at a low angle, suggestive of a sinistral transpressive deformation component, but this is not reflected in the Lachlan Orogen. Merging of aeromagnetic highs with similar intensity aeromagnetic trends (Figures 8, 22), matching the interpreted northern extension of volcanic rocks of the now-segmented Macquarie Arc (Glen *et al.* 1996), suggests that the Olepoloko structure may have been part of an east-trending subduction interface in the Ordovician (see below).

Linking the Lachlan and Thompson Orogens with central Australian intra-cratonic orogens

Apart from the structural work of Powell (1984b), the linking of eastern Australian crustal evolution with that in central Australia has been largely done through the sedimentation history of the major regional sedimentary basins of cratonic Australia (Veevers 1984; Shaw *et al.* 1991). Utilising Australia-wide palaeogeographical facies maps incorporating the central Australian basins, basin depositional hiatuses were matched with orogenic movements across the Australian craton (Veevers 1984; Shaw *et al.* 1991). Links through palaeogeographical maps have also been made by Veevers (2000) and Li and Powell (2001), and the implications of the Alice Springs Orogeny for Tasman Orogen evolution were discussed in detail by Betts *et al.* (2002). Geochronological data (Figure 16) from Shaw *et al.* (1991, 1992), Dunlap *et al.* (1991, 1995), Dunlap and Teyssier (1995), Mawby *et al.* (1999) Hand *et al.* (1999, 2001), Ballèvre *et al.* (2000), and Biermeier *et al.* (2003a, b) have placed greater constraints on shear-zone reactivation and structural evolution both prior to, and during, the Alice Springs orogeny. These

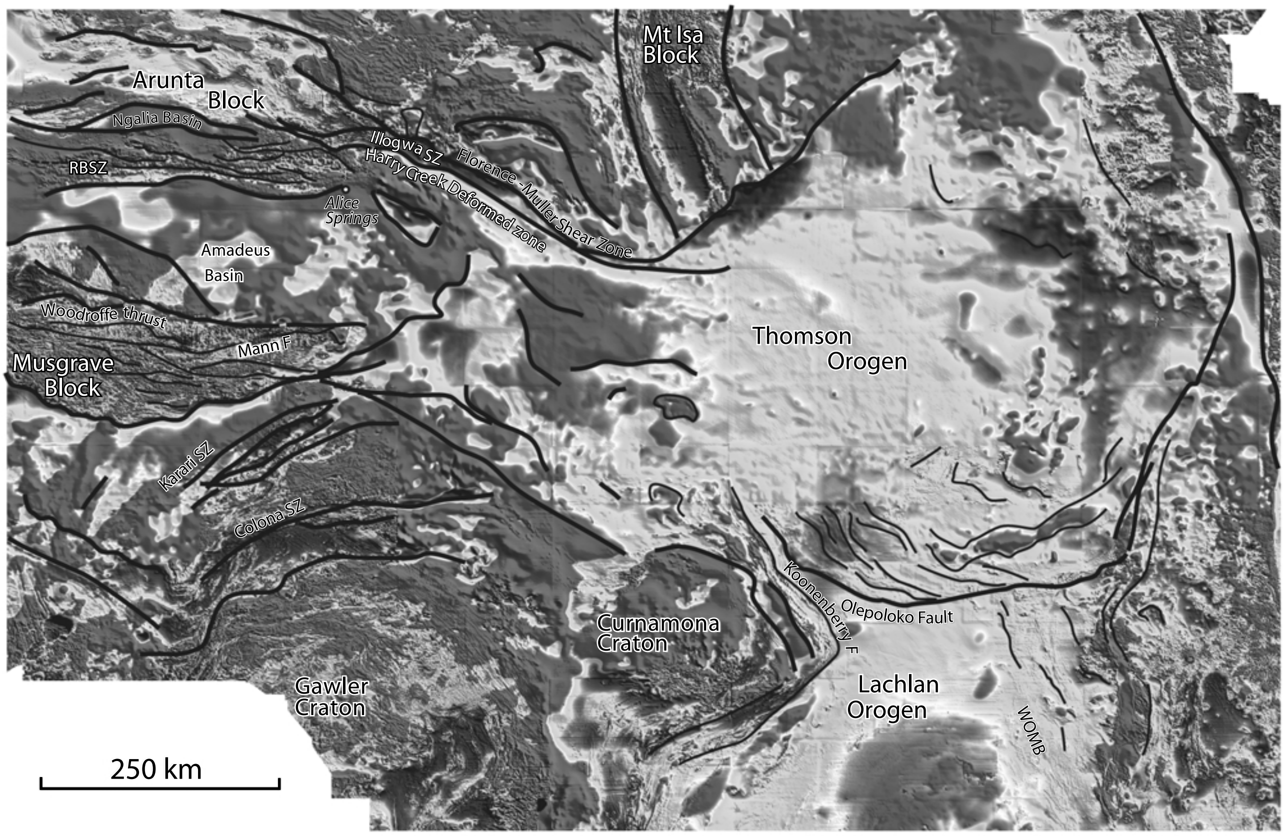


Figure 22 Interpreted aeromagnetic image of the southern Thomson Orogen and the Arunta region of central Australia (enlarged segment from Kilgour *et al.* 2002a). Black lines represent structural interpretation of the image. Shear zone names, orogen names and cratonic block names are shown. RBSZ, Redbank Shear Zone.

data can be compared with the geochronological and thermochronological datasets from eastern Australia (Figure 16).

A contractional thrust-belt was concentrated at the northern margin of the Amadeus Basin from *ca* 400–300 Ma (Dunlap *et al.* 1991, 1995; Shaw *et al.* 1991; Dunlap & Teyssier 1995; Biermeier *et al.* 2003a), but the major Proterozoic shear zones have been reactivated through the 500–400 Ma period as well (Figure 16). The major Redbank, West Bore, Harry Creek and Illgowa shear zones of the Arunta Complex form an interconnecting, anastomosing shear zone array that may extend eastwards, as part of reactivated structures joining with the east-trending structures of the Thomson Orogen. Such structures must have been important for the north–south shortening effects seen in the developing Lachlan part of the Tasman Orogen (see above) and were probably responsible for thrusting of the Thomson Orogen over the northern Lachlan Orogen.

CAUSES OF LACHLAN OROGENY

The diachroneity of deformation and migration of orogeny in time and space has been related to a number of different causes (Figure 23).

(1) *Plutonism induced orogeny* (‘surge tectonics’ after Hollister & Crawford 1986) where deformation centred about meridional batholiths was thermally activated (thermal softening) and migrated away from a magmatic–metamorphic core (Figure 23a) or the transitory axis of an ancient mature magmatic arc (White *et al.* 1974; Rutland 1976 p. 176; Collins & Vernon 1992). This implied plutonism-induced deformation occurred in a neutral stress regime, where migration of a deformation front was controlled by heat focusing in the mid-crust. Heat focusing has been related to mantle plumes, delamination, crustal extension and/or magmatic underplating with each mechanism bringing hot asthenosphere to shallower levels (Gray & Cull 1992).

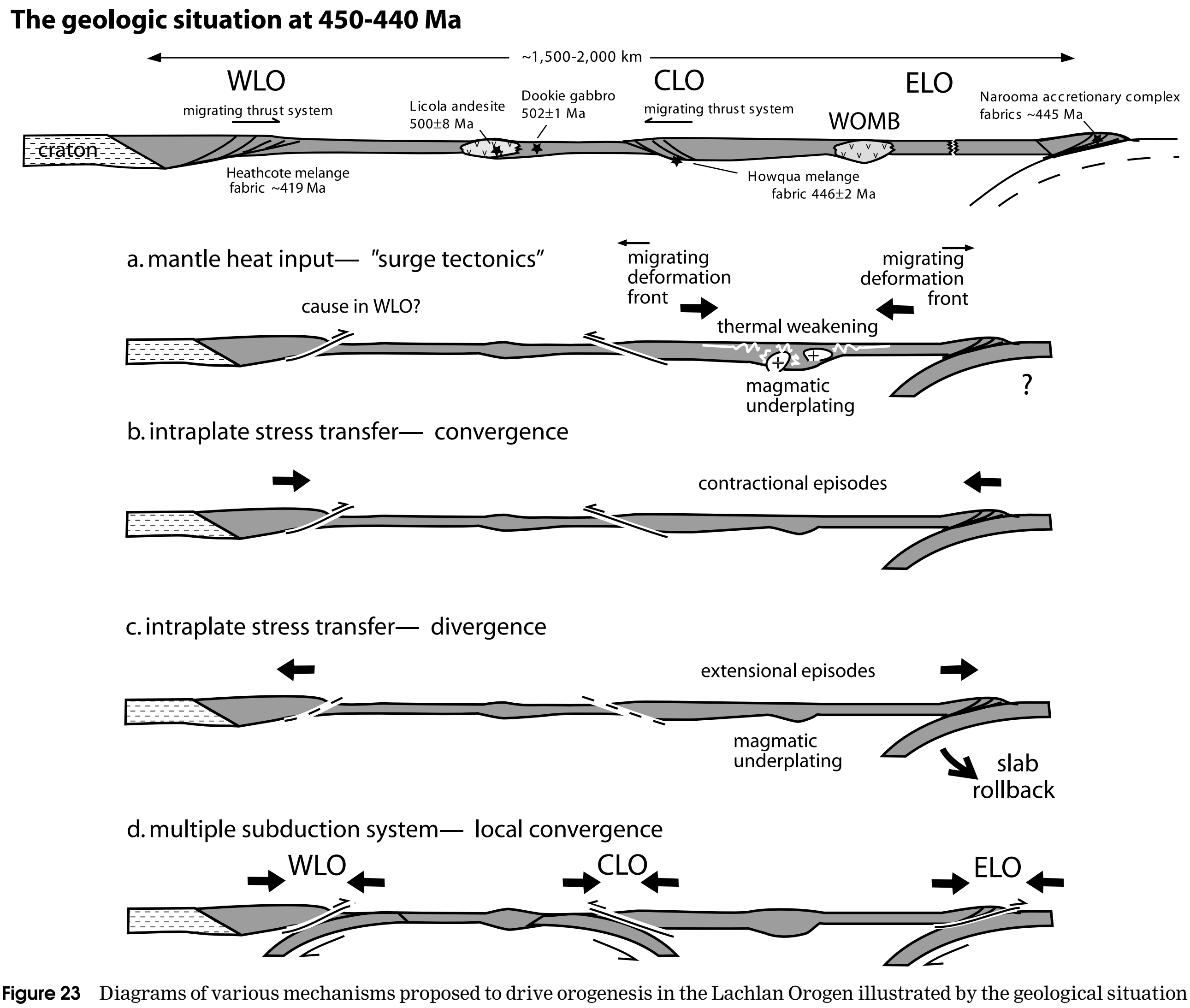


Figure 23 Diagrams of various mechanisms proposed to drive orogenesis in the Lachlan Orogen illustrated by the geological situation at 450–440 Ma (modified from Fergusson 2003; Spaggiari *et al.* 2004b). (a) Plutonism-induced thermal weakening (Collins & Vernon 1994). (b) Intraplate slab forces involving a single subduction zone (after Fergusson & Coney 1992a; Braun & Pauselli 2004). (c) Slab rollback and extensional retreat (Collins & Hobbs 2001; Collins 2002a, b). (d) Slab forces and multiple subduction zones (Gray & Foster 1997; Gray *et al.* 1997; Soesoo *et al.* 1997). WLO, western Lachlan Orogen; CLO, central Lachlan Orogen; ELO, eastern Lachlan Orogen.

(2) *Intraplate convergence* (Fergusson & Coney 1992a; Braun & Pauselli 2004) where intraplate deformation took place inboard of, and as a consequence of, continuous subduction along a single outboard subduction zone (Figure 23b).

(3) *Slab rollback and extensional retreat* was first invoked by Scheibner (1972). This is another variant on continuous subduction along a single subduction zone (Figure 23c), but where prolonged, overall slab retreat is interspersed with rapid switches to episodic short-lived contractional events (Collins 2002a, b).

(4) *Multiple subducting slabs* (Collins & Vernon 1992, 1994; Gray & Foster 1997, 1998; Soesoo *et al.* 1997, 1998; Foster & Gray 2000a; Collins & Hobbs 2001; Spaggiari *et al.* 2004b) where deformation is linked to multiple subduction systems, in particular linked to accretionary prism-style thrust systems in their respective upper plates (Figure 23d).

LACHLAN OROGEN EVOLUTION: DATA AND TIME SLICES

The historical evolution is presented as a series of non-palinspastic maps of southeastern Australia (Figure 24a–f) showing the relationships between sedimentation, deformation, metamorphism and magmatism over the time interval from 550 to 340 Ma. The major tectonic intervals are discussed below.

Post Rodinia breakup: 550–526 Ma (Figure 24a)

From *ca* 550–540 Ma (Offler *et al.* 1999; Gray *et al.* 2000), the Neoproterozoic cover sequence in the northern Flinders Ranges underwent Jura-style disharmonic folding above a basal décollement (Clarke & Powell 1989; Miller 1994). An older, pre-Kanmantoo Group deformation is supported by a Rb/Sr date of 531 ± 32 Ma on differentiated cleavage from the upper Adelaidean metasediments at Hallets Cove (Turner *et al.* 1996b). This deformational event was followed by outboard extension and pullapart basin development accompanied by Kanmantoo Group sedimentation *ca* 532–526 (Ma) along this rifted margin resulting from Rodinia breakup (Flöttmann *et al.* 1994; Flöttmann & Cockshell 1996).

Major deformation and backarc spreading: 520–495 Ma (Figure 24b)

High-T metamorphism and deformation at *ca* 520–505 Ma in the southern Delamerian Orogen (Mt Lofty Ranges: Foden *et al.* 1999) was superimposed on the earlier fold structures and caused reactivation of shear zones in the Precambrian basement massifs (e.g. Broken Hill block of the Curnamona craton: Gray *et al.* 2000; Hartley 2000).

This was accompanied by obduction of oceanic crust from *ca* 520–515 Ma in Tasmania along with significant deformation and metamorphism at *ca* 514 Ma (e.g. Ulverstone Metamorphics, Forth Metamorphic Complex), followed by exhumation of the metamorphic complexes from *ca* 500–490 Ma (e.g. Forth Metamorphic Complex), high-P metamorphism in rocks in the Arthur Lineament (*ca* 510 Ma), and Mt Read volcanism in the Dundas trough (Meffre *et al.* 2003; Foster *et al.* in press).

Post-orogenic extension in the Delamerian Orogen from *ca* 505–495 Ma is suggested by: (i) the dominantly alkaline and extension-related nature of the Padthaway Ridge post-tectonic plutons (intrusion ages younger than about 490 Ma); (ii) the inferred rift setting of the Mt Stavely and Mt Read volcanic complexes; and (iii) thermochronological data indicating relatively rapid cooling of the higher grade areas (Foster *et al.* in press).

At this time (*ca* 505–495 Ma), there was a major growth of oceanic crust off the Gondwana margin in a complex southwest Pacific-style oceanic setting. This formed the oceanic basement to the Lachlan Orogen (e.g. Dookie, Howqua, Dolodrook MORB, boninites, ultramafics; Licola and Jamieson intra-oceanic island-arc andesites; Mt Stavely andesites). Oceanic crustal growth was accompanied by turbidite fan deposition in the westernmost part (Stawell Zone of the western Lachlan Orogen: Spaggiari *et al.* 2003a, 2004a).

Cratonisation of Delamerian Orogen and turbidite deposition in Lachlan backarc basin: 490–460Ma (Figure 24c)

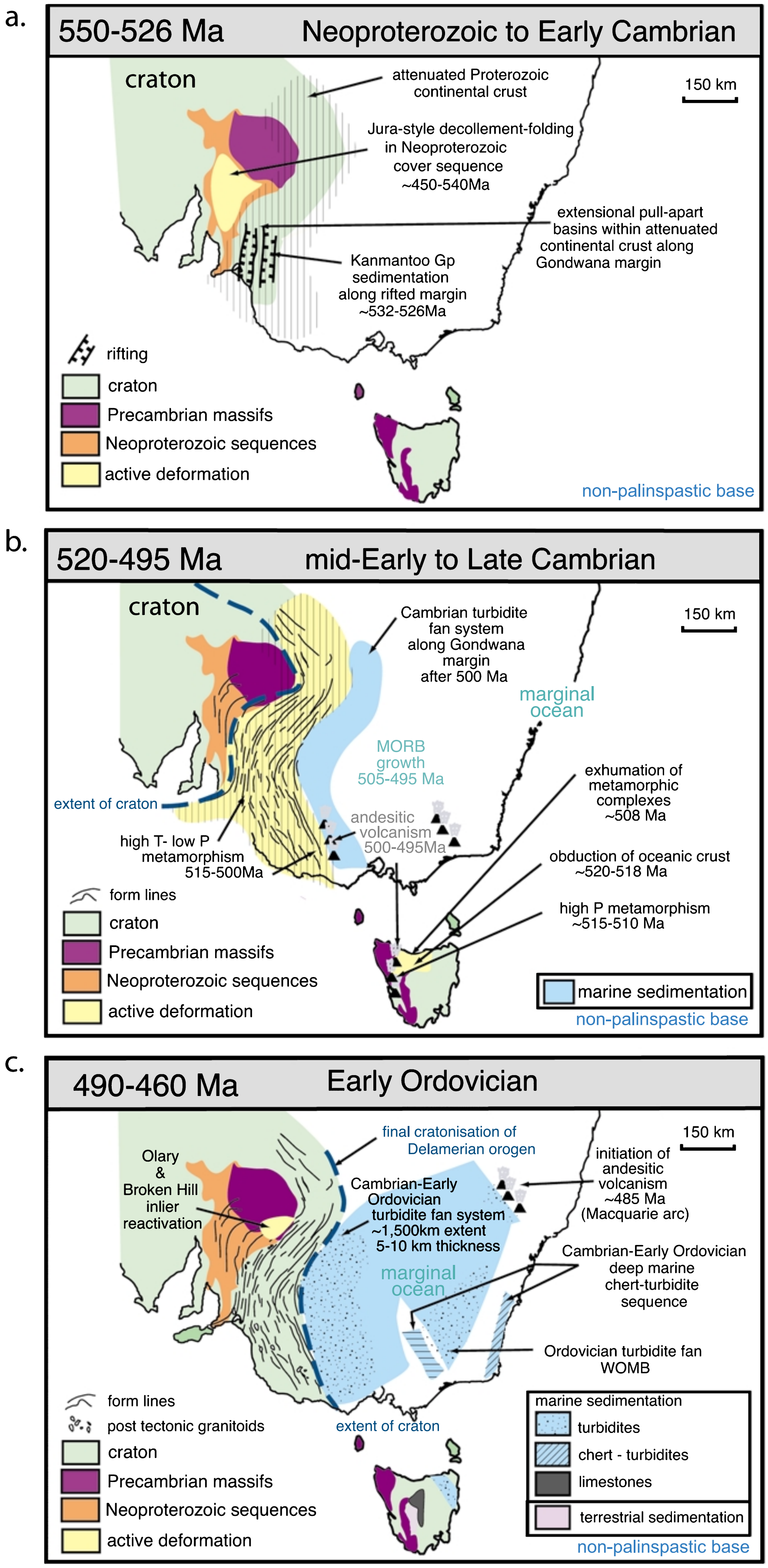
Extensive turbidite fan deposition took place in a marginal basin off the Gondwana margin between *ca* 490 and 470 Ma, with large turbidite fans spreading out onto the newly formed oceanic crust of the developing marginal basin. Turbidite deposition was occurring at the same time as post-orogenic magmatism, cooling and erosional exhumation inboard in the Delamerian Orogen from *ca* 490–480 Ma (Turner *et al.* 1996a; Foden *et al.* 1999).

Outboard subduction-related arc volcanism was initiated at *ca* 485 Ma in the oceanic plate some thousands of kilometres away (based on retrodeformation of the western and central Lachlan Orogen), leading to the development of the Macquarie volcanic arc complex (Glen *et al.* 1998). At *ca* 460 Ma inboard of the arc and this older, long-lived subduction zone, subduction was initiated along both sides of the marginal backarc basin (Gray *et al.* 1997; Soesoo *et al.* 1997; Foster & Gray 2000a).

Backarc basin closure: 450–410Ma (Figure 24d)

The Lachlan marginal backarc basin began to close due to Woodlark basin-style double divergent subduction (Gray *et al.* 1997; Soesoo *et al.* 1997). Multiple oceanic thrust systems operated in both the eastern and western parts of the basin, that is the central Lachlan Orogen and western Lachlan Orogen, respectively, causing duplexing of oceanic crust, imbrication and chevron folding in the overlying turbidite wedge (Spaggiari *et al.* 2004a, b). Structural thickening of the turbidites in the western thrust system led to erosional exhumation and sediment output into the prograding marginal basin (Melbourne trough: Foster *et al.* 1998; Foster & Gray 2000a).

At the same time, west-directed collisional shortening was taking place in northeast Tasmania (Mathinna Supergroup), and deformation of the mineralised Dundas belt was occurring in western Tasmania. Shear-zone reactivation was taking place in the Delamerian Orogen with


a.
550-526 Ma
Neoproterozoic to Early Cambrian
craton
attenuated Proterozoic continental crust
150 km
Jura-style decollement-folding in Neoproterozoic cover sequence ~450-540Ma
extensional pull-apart basins within attenuated continental crust along Gondwana margin
Kanmantoo Gp sedimentation along rifted margin ~532-526Ma
rifting
craton
Precambrian massifs
Neoproterozoic sequences
active deformation
non-palinspastic base
b.
520-495 Ma
mid-Early to Late Cambrian
craton
Cambrian turbidite fan system along Gondwana margin after 500 Ma
150 km
marginal ocean
MORB growth 505-495 Ma
exhumation of metamorphic complexes ~508 Ma
extent of craton
andesitic volcanism 500-495Ma
high T- low P metamorphism 515-500Ma
obduction of oceanic crust ~520-518 Ma
high P metamorphism ~515-510 Ma
form lines
craton
Precambrian massifs
Neoproterozoic sequences
active deformation
marine sedimentation
non-palinspastic base
c.
490-460 Ma
Early Ordovician
final cratonisation of Delamerian orogen
150 km
Olary & Broken Hill inlier reactivation
Cambrian-Early Ordovician turbidite fan system ~1,500km extent 5-10 km thickness
initiation of andesitic volcanism ~485 Ma (Macquarie arc)
marginal ocean
Cambrian-Early Ordovician deep marine chert-turbidite sequence
Ordovician turbidite fan WOMB
form lines
post tectonic granitoids
extent of craton
craton
Precambrian massifs
Neoproterozoic sequences
active deformation
marine sedimentation
turbidites
chert - turbidites
limestones
terrestrial sedimentation
non-palinspastic base

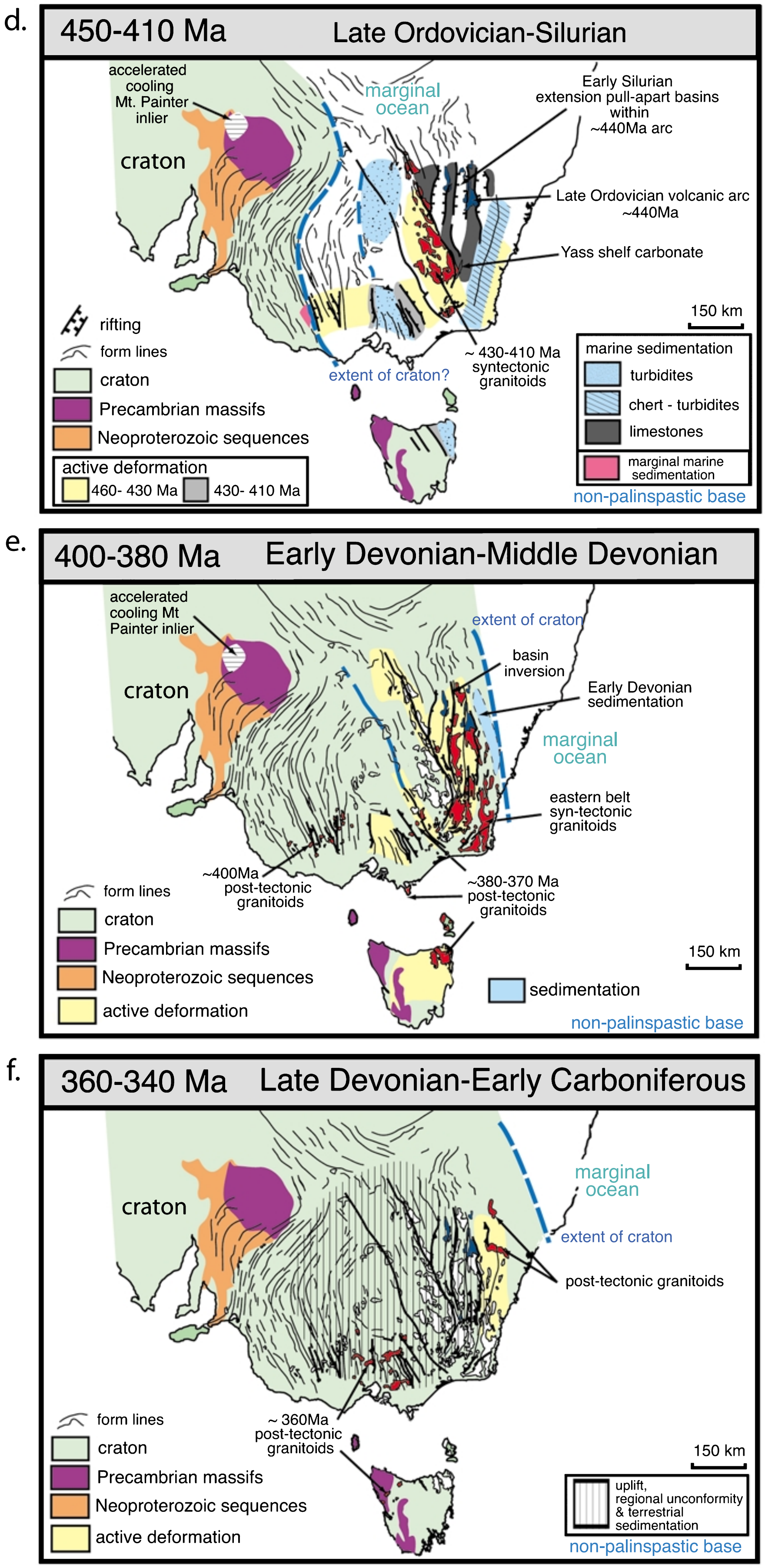


Figure 24 Non-palinspastic reconstructions showing snapshots of the progressive evolution of the Lachlan Orogen part of the Gondwana margin from 550 to 340 Ma. Depositional environments, metamorphic, deformational and magmatic events are shown.

continued exhumation of the belt (Offler *et al.* 1999; Gray *et al.* 2000).

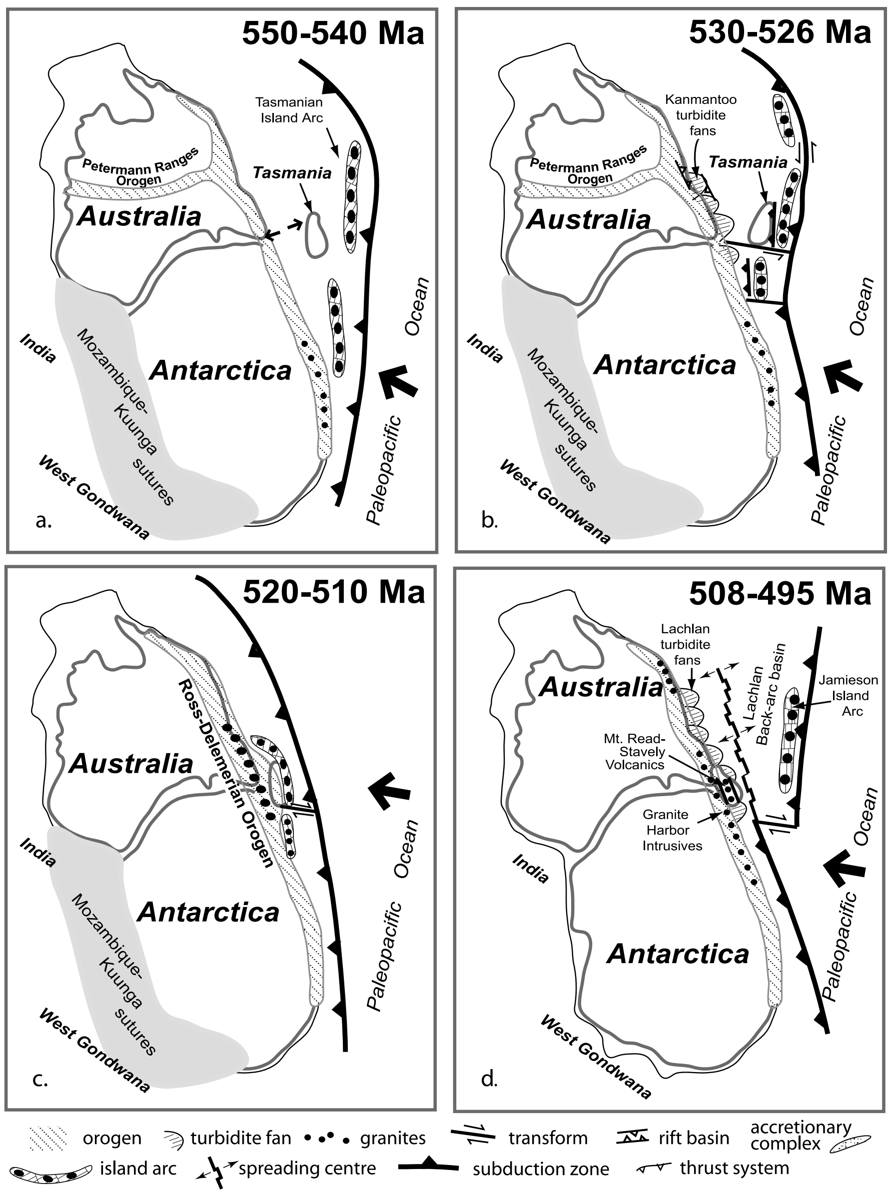
Docking, cratonisation of western and central Lachlan Orogen, Andean-type margin for the eastern Lachlan Orogen: 400–380Ma (Figure 24e)

Post-orogenic magmatism in the western Lachlan Orogen at *ca* 400 Ma was followed by final closure of the marginal basin (Melbourne Trough) at *ca* 390 Ma. This structural thickening and amalgamation of the western Lachlan Orogen and central Lachlan Orogen led to cratonisation of the inner Lachlan (Gray 1997; Foster & Gray 2000a). The collisional event was accompanied by localised strong to intense north–south folding (e.g. Mitchell syncline; Fergusson & Gray 1989) and regional, meridional crenulation cleavage development in the central Lachlan Orogen (Morand & Gray 1991), as well as causing reactivation of shear zones in the Delamerian Orogen and Precambrian basement massifs (Mt Painter, Broken Hill and Tyennan of Tasmania: Gray *et al.* 2000).

Outboard in the eastern Lachlan Orogen, syndeformational magmatism and high-T metamorphic belts (e.g. Cooma Complex) formed during intermittent east-directed thrusting and periods of extension-related volcanism (Snowy River and Boyd Volcanics) as part of a Cordilleran or Andean-type margin (Zen 1996).

Rollback and Gondwana margin post-orogenic extension: 360–320Ma (Figure 24f)

Post-orogenic magmatism in the eastern part of the western Lachlan Orogen (central Victorian magmatic province) occurred at *ca* 370–360 Ma (Gray 1990), while east-directed thrusting deformation in the eastern Lachlan Orogen (e.g. inversion of former extensional basin faults defining the Hill End and Cowra Troughs) was followed by post-orogenic magmatism (e.g. Bathurst



granite). Cratonisation of the Lachlan Orogen was completed by *ca* 330 Ma (Powell 1983a, 1984a).

LACHLAN OROGEN TECTONIC EVOLUTION: A GONDWANA-WIDE PERSPECTIVE

The Lachlan Orogen during the Palaeozoic was part of a greater Gondwanide oceanic accretionary system that began during the Late Neoproterozoic with initial rifting between cratonic Australia and Laurentia (North America) in the proposed supercontinent of Rodinia. For most of its history, the Lachlan Orogen has been inboard of a single, long-lived subduction system off Gondwana (Figure 25a–e). From the Late Cambrian to the Early Ordovician (*ca* 508–495 Ma), rollback on this subduction zone led to spreading and formation of a Marianas-style or Japan Sea-style marginal ocean basin floored largely by oceanic crust but containing active island arcs (e.g. Jamieson arc: Figure 25d) and microcontinental fragments (e.g. Tasmania: Foster *et al.* in press). The Ordovician was a period of major turbidite fan deposition with sediment sourced primarily from the Antarctic part of the Delamerian–Ross Orogen that had been constructed from *ca* 520–510 Ma (Figure 25c). In the Early Ordovician (*ca* 485 Ma), the Macquarie island arc was initiated outboard of the developing Bengal Fan-scale, turbidite fans with episodic volcanism through to *ca* 460 Ma (Figure 25e). To the north, in the developing Thomson Orogen, a curved, more east–west-trending subduction system splay produced similar age volcanic arc rocks, and linked into the shear systems of the older established intracratonic central Australian orogens (Figure 25e). Marine conditions extended into central Australia as part of the Larapinta seaway that had developed within an intracratonic rift by *ca* 480 Ma extension (Mawby *et al.* 1999).

In the Late Ordovician (*ca* 450 Ma), the Lachlan marginal basin began to close by underthrusting of oceanic crust along both the craton- and ocean-ward sides, leading to a complex, Woodlark Basin-style, double-divergent

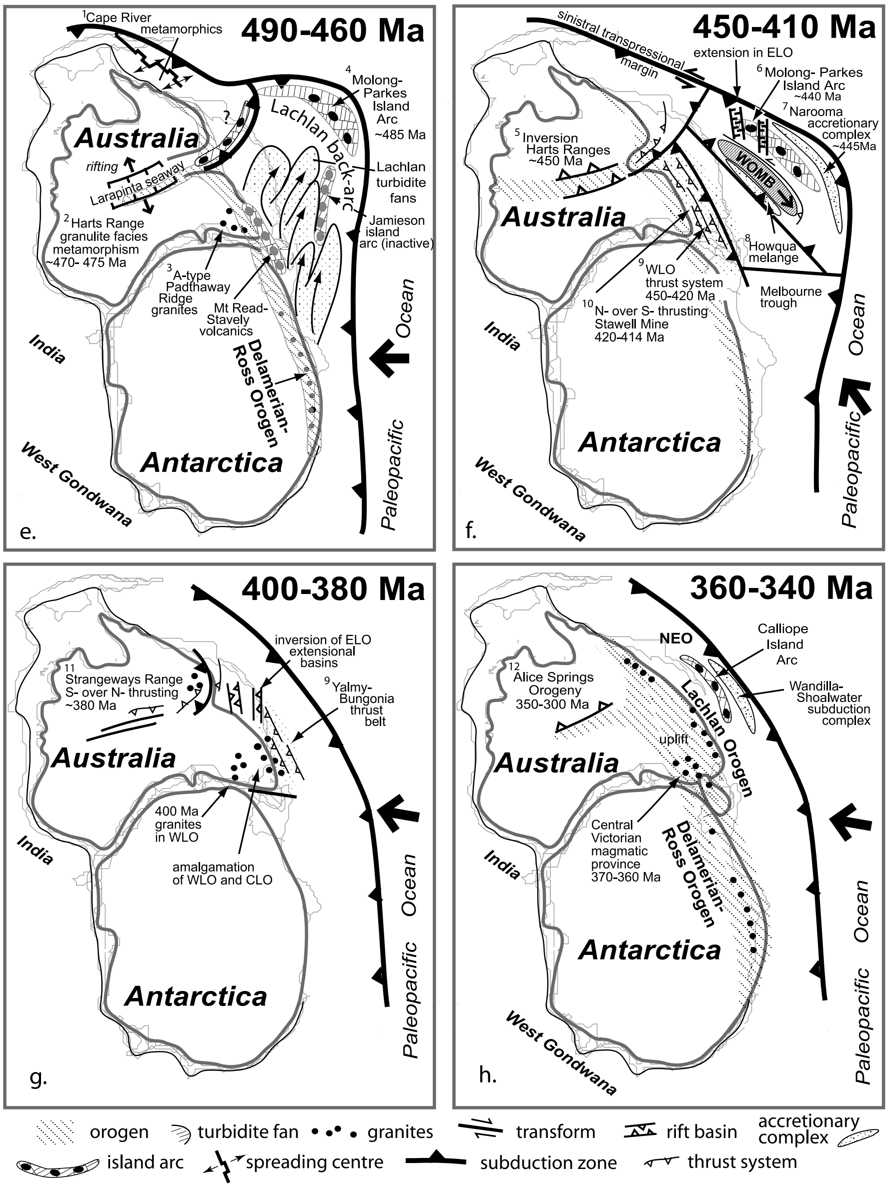


Figure 25 Speculative tectonic evolution for the Australia–Antarctica part of the Gondwana margin shown as a series of approximately restored palinspastic maps from 560 to 340 Ma. The Late Ordovician – Silurian time period (450–420 Ma) is based on the multiple subduction scenario of Gray and Foster (1997), Soesoo *et al.* (1997), Foster and Gray (2000a) and Spaggiari *et al.* (2003b) (see Figure 5c). Data sources: 1, Fergusson *et al.* (2004); 2, Mawby *et al.* (1999); 3, Turner *et al.* (1992); 4, Butera *et al.* (2001); 5, Mawby *et al.* (1999); 6, Perkins *et al.* (1995); 7, Offler *et al.* (1998b); 8, Spaggiari *et al.* (2002a); 9, Foster *et al.* (1999); 10, Miller *et al.* (2001); 11, Ballèvre *et al.* 2000); 12, Dunlap *et al.* (1991, 1995) and Shaw *et al.* (1991).

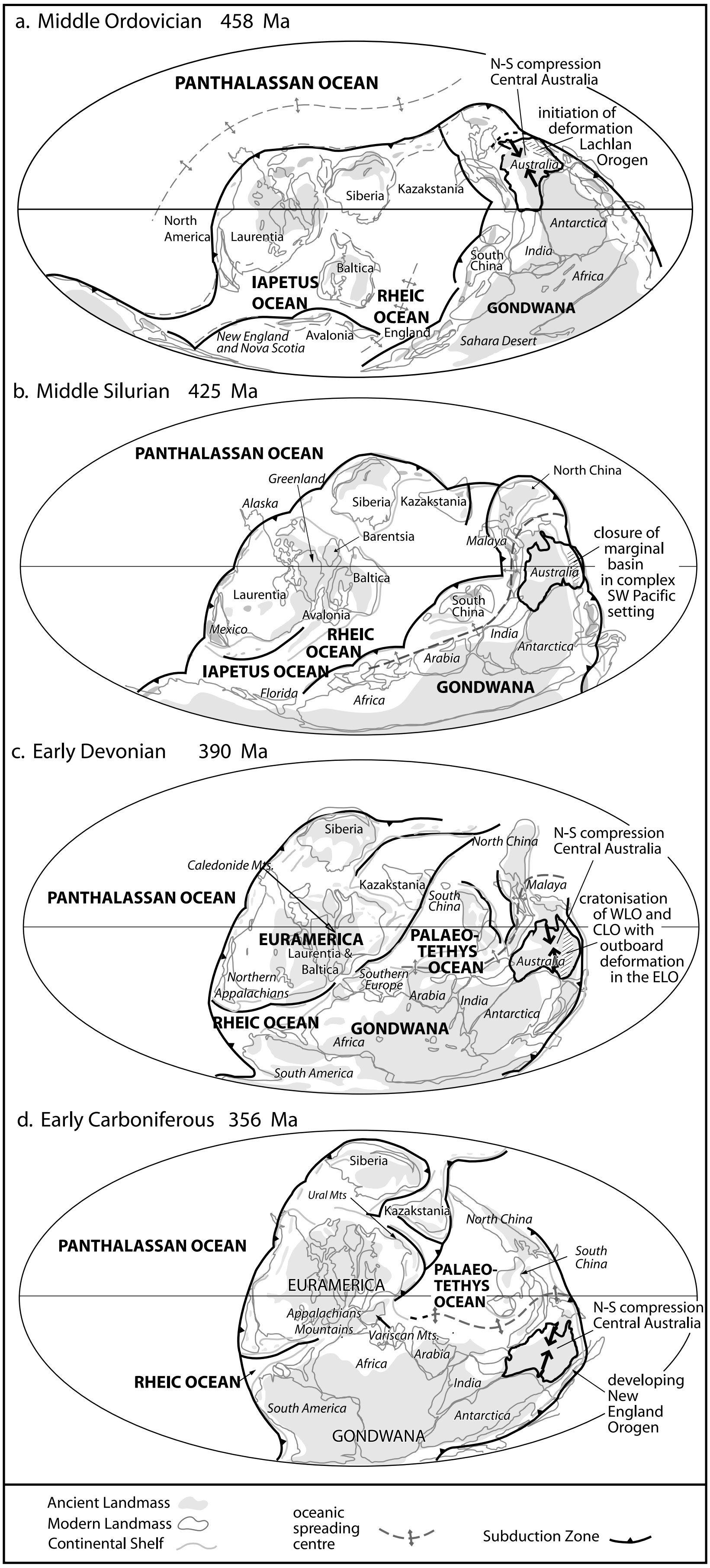


Figure 26 Modified global reconstructions (after Scotese 2001) for (a) Middle Ordovician, (b) Middle Silurian, (c) Early Devonian and (d) Early Carboniferous, showing the position of Australia in Gondwana and the changing plate configurations within the Panthalassan Ocean. Changes to the nature and configuration of the Gondwana margin were made using the data available from the Lachlan Orogen, as well as Palaeo-Tethys tectonic reconstructions by Stampfli and Borel (2004).

subduction system through 410 Ma (Figure 25f). On the Gondwana continent-margin side, an ocean-vergent, oceanic thrust system dramatically shortened (~60% by chevron folding) and structurally thickened the Cambro-Ordovician turbidite fans resulting in interleaving of remnants of oceanic crust (Figure 25f). At *ca* 440 Ma, lock-up of this thrust wedge led to peak metamorphism, liberation and deposition of Au to form the major Au deposits in the western Lachlan Orogen. At the same time, continued subduction in the central Lachlan Orogen led to shortening and thickening of the outboard, smaller accretionary wedge and development of the Chugach-style (Hudson & Plafker 1982; James *et al.* 1989), high-T, low-P metamorphic belt (WOMB of Figure 25f) in the backarc basin behind the Macquarie Arc. Collision of the Licola island arc – Selwyn Block with this trench at *ca* 420 Ma led to reactivation of thrusts in the western Lachlan Orogen, shallow-level deformation in the Melbourne Trough part, with thrusting of the marginal basin sediments over the relict island arc. At this time, oblique convergence on the outboard subduction system led to shallow-crustal level, sinistral transpressional deformation in the Macquarie Arc part of the marginal basin with development of Early Silurian extensional basins in the arc and strike-slip pull-apart basins associated with limited southwards translation of the metamorphic belt. Part of this movement is registered inboard on the craton by inversion and shear-zone reactivation in the central Australian Harts Ranges (Arunta) at *ca* 450 Ma (Mawby *et al.* 1999) (Figure 25f).

By the late Early Devonian (*ca* 390 Ma), the marginal basin had fully closed, leading to inversion of the eastern Lachlan Orogen extensional basins and development of the Yalmy–Bungonia thrust system (Fergusson & VandenBerg 1990) behind the outboard subduction zone (Figure 25g), with eventual thrusting of the Monaro forearc sediments (Fergusson 1998) over the ancient accretionary complex (Narooma Accretionary Complex). At this time, oceanwards-directed thrusting led to emplacement of syntectonic granitoids and localised high-T metamorphic complexes to shallower crustal levels. Movements in central Australia reflecting a component of north–south shortening are recorded by shear-zone reactivation in the Strangways Range (Arunta) at *ca* 380 Ma (Ballèvre *et al.* 2000) (Figure 25g).

By *ca* 380–370 Ma, continental facies sedimentation and bimodal volcanism dominated the cratonised part of the Gondwana margin. From *ca* 400 Ma, the Lachlan part of the Gondwana margin had become an Andean-type margin displaying elevated heat flow, extensive magmatism and fluctuating periods of compressional and extensional deformation in what is now largely preserved as the eastern Lachlan Orogen (Cas 1983; Zen 1996; Collins & Hobbs 2001; Collins 2002a, b). In the Late Silurian – Early Devonian, continued subduction along the outboard subduction zone led to renewed island-arc volcanism (Calliope Arc) and development of the Wandilla–Shoalwater subduction complex (Murray *et al.* 1987). By *ca* 340 Ma, deformation (Figure 25h) had migrated outboard to the developing New England Orogen and the Lachlan part of the Gondwana margin tectonic history had effectively finished, although north–south shortening related to the intracratonic Alice Springs Orogeny led to megakinking in the eastern Lachlan Orogen at *ca* 330 Ma (Powell 1984b) (Figure 25h).

TASMANIDE MARGIN OF GONDWANA IN THE GLOBAL CONTEXT

The position of Australia within Gondwana and the nature of the Tasmanide part of the Gondwana margin relative to subduction systems in the Palaeo-Pacific or Panthalassan Ocean has been investigated or speculated upon previously (Li *et al.* 1990; Coney 1992; Foster & Gray 2000a; Li & Powell 2001). Retreat or advance of the Gondwana margin relative to the Palaeo–Pacific Ocean has important consequences for orogenic contractional episodes, as well as do collisions with continental fragments and oceanic plateaux (Nur & Ben-Avraham 1983; Coney 1992). For example, it is speculated that collision of Gondwana with North America in mid-Carboniferous time may have been responsible for the intraplate Alice Springs Orogeny (Coney *et al.* 1990; Coney 1992).

Concomitant Palaeozoic north–south shortening in central Australia and east–west shortening in the Lachlan Orogen, however, requires plate-boundary processes along the northern and eastern margins of the Tasmanide part of Gondwana at that time and, therefore, similar plate-boundary stresses to those occurring today (Betts *et al.* 2002). This is supported by thin-plate thermomechanical numerical modelling of Palaeozoic deformation of the Australian lithosphere undertaken by Braun and Shaw (2001). By invoking in-plane driving forces generated at the plate margins, they derived similar velocity fields to those of the present day. Within-plate stresses relate to ridge-push effects from the Southern Ocean spreading ridge transferred across the Australian Plate, coupled with collision arc–continent along the leading northern edge of the Australian plate seen in Papua New Guinea, and transpressional deformation due to oblique convergence along the eastern margin, seen in New Zealand.

This indicates that Scotese PalaeoMap-type global tectonic reconstructions (Li & Powell 2001; Scotese 2001) need modification to accommodate this concomitant north–south and east–west shortening in the Australian continent (Figure 26). There is a requirement of tectonic forces acting on separate but adjacent and almost orthogonal parts of the Gondwana margin from *ca* 450 Ma through 300 Ma. North–south-trending within-plate compressional forces along the northern Gondwana margin are most easily related to ridge-push effects from a spreading ridge initiated at *ca* 450 Ma (Stampfli & Borel 2004 figure 3.1), associated with the opening of the Palaeo-Tethys ocean (Figure 26).

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