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Paleozoic crustal growth, structure, strain rate, and metallogeny in the Lachlan orogen, eastern Australia

David A. Foster
Department of Geological Sciences, University of Florida, Gainesville, Florida, 32611-2120, USA

David R. Gray
School of Earth Sciences, University of Melbourne, Melbourne, 3010, Victoria, Australia

ABSTRACT

Assembly of the Tasmanides of eastern Australia involved accretion of the Delamerian, Lachlan and New England orogens between ca. 520 and 260 Ma. The Lachlan orogen was constructed in an oceanic setting when subduction of paleo-Pacific plates alternated from slab rollback and backarc basin formation to intense shortening and basin closure. Lachlan accretion involved deformation of three thrust-systems that formed during shortening of a massive turbidite fan and island arc complex within a >1500 km wide marginal ocean basin. An east–verging fold-thrust wedge in the western Lachlan formed in two stages between 455-439 Ma and 410-395 Ma. In the central Lachlan a SW-propagating thrust wedge was active between 440-395 Ma in front of a 440-410 Ma magmatic arc. Final deformation in the Ordovician Macquarie volcanic arc of the eastern Lachlan is younger (400-340 Ma), although subduction began in the east before ca. 445 Ma. Extensional basins and inverted rifts are prominent in the central and eastern Lachlan orogen. Syn- and post-tectonic magmatism throughout the Lachlan reflects subduction geometries, areas of crustal thickening, basaltic underplating, periods of extension, and stabilization of the crust. Strain rates associated with tectonic shorting in the western Lachlan, defined by integrating $^{40}Ar/^{39}Ar$ and strain measurements, were about 10^{-14} s^{-1}. Metallogenic associations across the Lachlan orogen are correlated with tectonic setting and the geodynamics of evolving basins, magmatic arcs, forearcs, and accretionary prisms.

INTRODUCTION

The paleo-Pacific margin of Gondwana was a site of significant continental crust formation, regeneration, and cratonization between ca. 530 and 90 Ma (Fig. 1). The composite Tasmanides of eastern Australia show eastward younging in accretion of submarine fans, fragments of ocean crust, volcanic arcs and fore-arc basins from the Delamerian-Ross orogen through to New Zealand (e.g., Foster and Gray, 2000a; Cawood, 2005). The Tasmanides have not undergone a major collision with another continent or microcontinent, so they preserve an excellent example of accretion and crust formation during Paleozoic times. The Lachlan orogen (Fig. 2) in particular may be widely applicable as a template for understanding Circum-Pacific accretionary belts that are more highly deformed, or for predicting the ultimate fate of modern western Pacific basins.

In eastern Australia, accretion occurred in a stepwise fashion with an eastward decrease in age of final orogeny from the Cambrian through the Triassic, reflected by peak deformations of middle Cambrian, early Silurian to mid-Devonian, and Permian-Triassic age in the respective orogenic belts (Foster

e-mail: Foster: dafoster@ufl.edu; Gray: drgray@unimelb.edu.au

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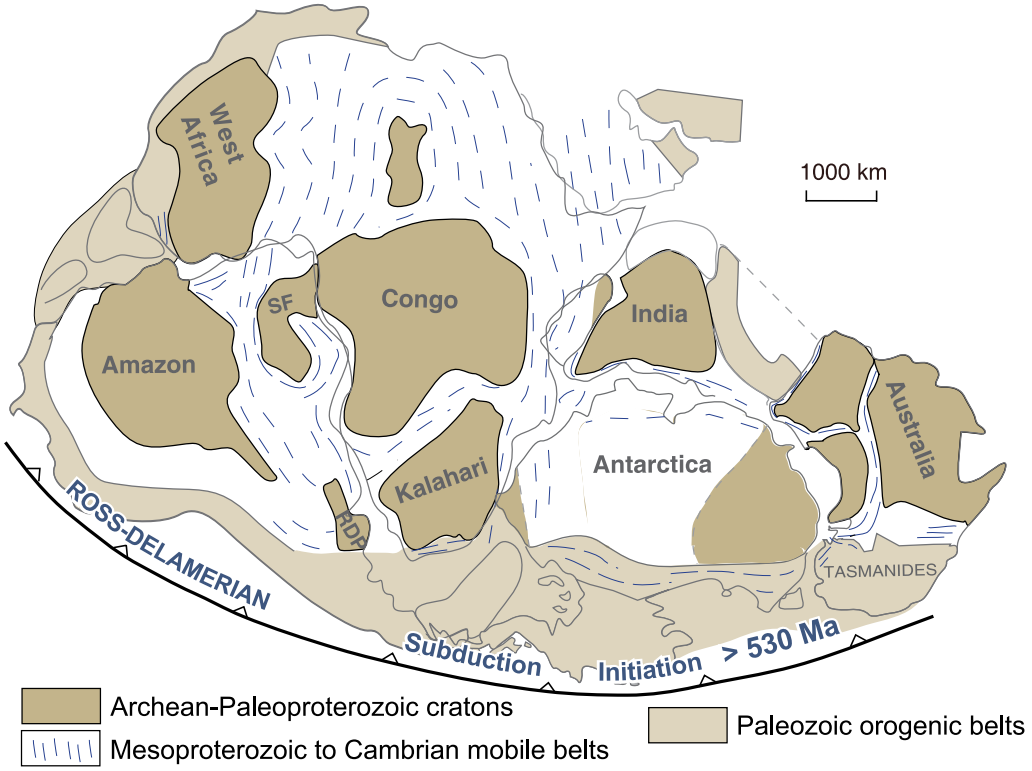

Figure 1. Map of Gondwana at about 530 Ma showing the location of the Tasmanides. SF, Sao Francisco craton, RDP, Rio de le Plata craton.

and Gray, 2000a; Gray and Foster, 2004). This involved deformation of Neoproterozoic platform and rift basin sequences (Delamerian orogen), a Cambrian-Ordovician composite turbidite submarine fan overlying Cambrian oceanic crust (Lachlan orogen), and Carboniferous-Permian arc, forearc, trench, subduction complex, and foreland basin sequences (New England orogen) (Gray and Foster, 2004; Cawood, 2005). Outboard of the Tasman orogen, the New Zealand continental landmass records sedimentation and accretionary prism development (Rakaia and Pahau Terranes; Bradshaw, 1989) in the hanging wall to a subduction system from Permian to Late Cretaceous times (Bradshaw, 1989; Mortimer, 2004).

THE LACHLAN OROGEN

Tectonic setting

The Paleozoic Lachlan orogen (Fig. 2), is a composite accretionary orogen that formed along the eastern margin of Gondwana during late Neoproterozoic through Paleozoic times. It is dominated by extensive Cambrian to Ordovician turbidites that formed a large submarine fan system that was comparable in size to the present day Bengal fan (Fergusson and Coney, 1992a). Detrital zircon (U-Pb) and muscovite ($^{40}Ar/^{39}Ar$) ages indicate that the turbidites were derived from the Ross-Delamerian and Pan-African orogenic belts throughout Gondwana (e.g., Turner and others, 1996; Foster and others, 1998; Squire and others, 2005).

The Lachlan turbidite fan accumulated on Cambrian backarc basin and forearc crust (Fig. 3a), consisting of predominantly MORB to arc-tholeiite basalt and gabbro, boninite, and calc-alkaline arc volcanic rock (Crawford and Keays, 1987). Closure of the marginal ocean basin by subduction took place from ca. 460-340 Ma, with accretion of structurally thickened submarine fans, accretionary complexes, former volcanic arcs and oceanic crust, as well as the Tasmanian microcontinent (Fergusson and Coney, 1992b; Foster and others, 1999; Gray and Foster, 2004).

The Lachlan orogen comprises three thrust-belts that constitute the western, central and eastern parts, respectively (Fig. 2; Gray and Foster, 1997). The western Lachlan consists largely of an east-vergent thrust system with alternating zones of northwest- and north-trending structures. The central Lachlan is dominated by northwest-trending structures and consists of a southwest-vergent thrust belt linked to the high-T/low-P Wagga-Omeo metamorphic complex. The eastern Lachlan is dominated by a north-south structural grain and east-directed thrust faults, developed largely within the Ordovician Macquarie Arc (Glen and others, 2007). In the south-easternmost part, an east-vergent thrust system (Yalmy-Bungonia belt) lies above an older subduction-accretion complex (Narooma complex) (Fig. 3a).

A geodynamic setting involving backarc basin closure by subduction to form the western and central subprovinces

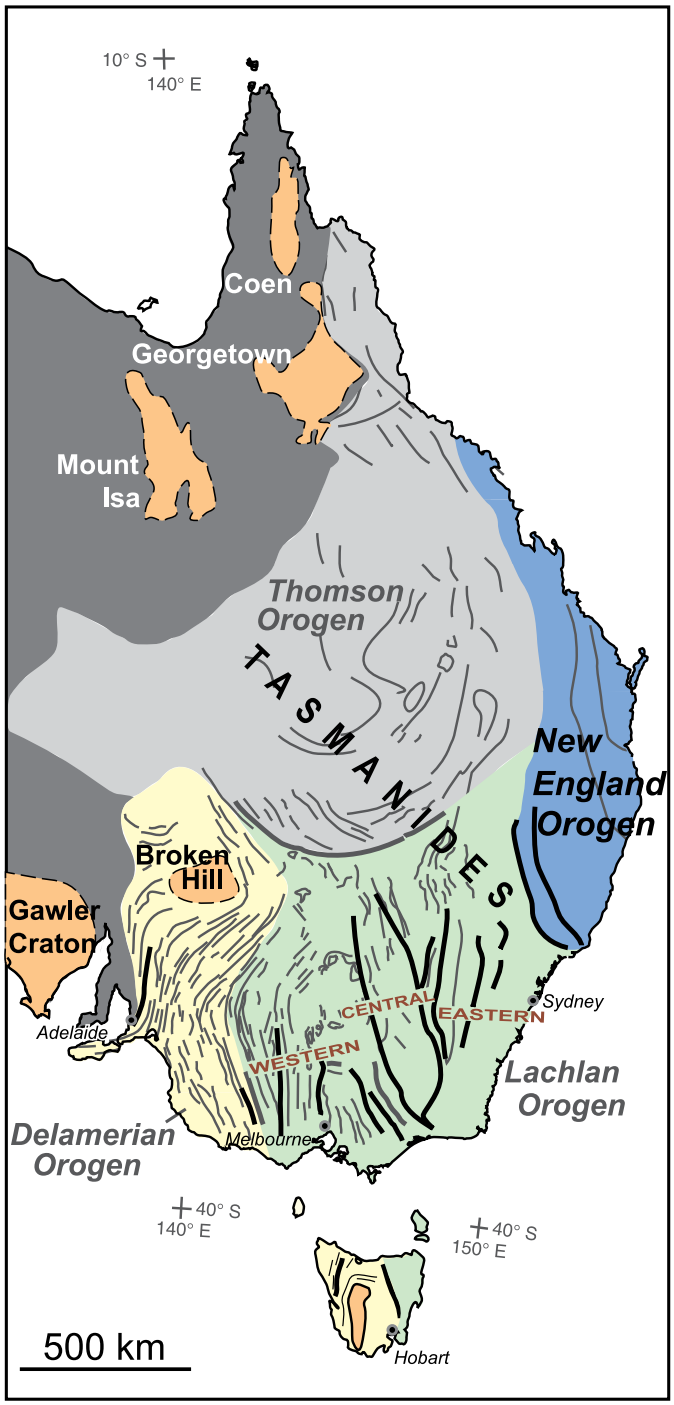

Figure 2. Map of eastern Australia showing the composite Tasmanides including the Paleozoic Lachlan orogen.

of the Lachlan orogen (Gray and Foster, 2004) is suggested by: (1) the presence of dismembered ophiolite slivers along some major fault zones (Spaggiari and others, 2003a, 2004), (2) the low-temperature, intermediate-pressure metamorphic conditions preserved in meta-sandstone/slate sequences of the western Lachlan and external part of the central Lachlan (Offler and others, 1998a; Spaggiari and others, 2003b), (3) the presence of broken formation in the central and eastern Lachlan (Miller and Gray, 1997; Watson and Gray, 2001), and (4) the presence of serpentinite-matrix mélange incorporating blueschist blocks similar to those in the Franciscan Complex of California (Spaggiari and others, 2002, 2003a).

Metamorphism

Turbidite sequences of the Lachlan orogen are generally of low metamorphic grade represented by greenschist (epizonal) and subgreenschist (anchizonal) conditions (Fig. 3b). Most of the turbidites are within the chlorite zone with localized development of biotite in contact aureoles of granitic plutons. High-T/low-P metamorphism is reflected by localized migmatites and K-feldspar-cordierite-sillimanite gneisses in the Wagga-Omeo Complex and Cooma, Cambalong, Jerangle and Kuark complexes of the Eastern metamorphic belt (Fig. 3). Peak metamorphic conditions in the Wagga-Omeo metamorphic complex and eastern metamorphic complexes were 700°C and 3-4 kbar (Morand, 1990; Collins, 2002a).

Turbidites from the low-grade parts of the Lachlan orogen show intermediate pressure metamorphism based on b0 measurements of phengitic micas (summarized in Gray and Foster, 2004). Intermediate-P metamorphism has also been inferred from co-existing chlorite and actinolite from metabasites (Offler and others, 1998a), as well as low-T/intermediate-P blueschist metamorphism of metabasalt blocks in serpentinite/talc-matrix mélanges within some major fault zones (Spaggiari and others, 2002). Amphibole compositions (winchite and glaucophane) give estimated pressures of ~5-6.5 kbar in the western Lachlan and ~6-7 kbar in the central Lachlan with temperatures <450°C (Spaggiari and others, 2002). This low-T/intermediate-P metamorphism occurred at 450-440 Ma during the regional deformation of the Lachlan orogen (Spaggiari and others, 2002, 2003a).

Lachlan orogen magmatism

Silurian-Devonian granitoids comprise about 20% of the present outcrop area of the Lachlan and up to 36% in eastern and central subprovinces (Fig. 3; e.g., Gray and Foster, 2004; Gray and others, 2007). Granitic intrusions include major batholiths with N-S and NNE orientations, roughly parallel to the structural grain, or isolated plutons (Chappell and others, 1988; Gray and Foster, 2004). Most of the plutons were emplaced at pressures ≤2 kbar within low-grade upper crustal rocks. The majority of plutons are post-tectonic and unmetamorphosed, although the older intrusions, such as those within the Wagga-Omeo metamorphic complex and Kosciusko batholith, are significantly foliated and were emplaced synkinematically at mid-crustal depths (e.g., Hine and others, 1978; Morand and Gray, 1991). Dacite to rhyolite dominated volcanic sequences are also widespread, and comprise ~15% of outcrop area in eastern Lachlan, large post-tectonic caldera complexes in western Lachlan, and other fields associated with shallow-level plutons. Older volcanic provinces (≥440

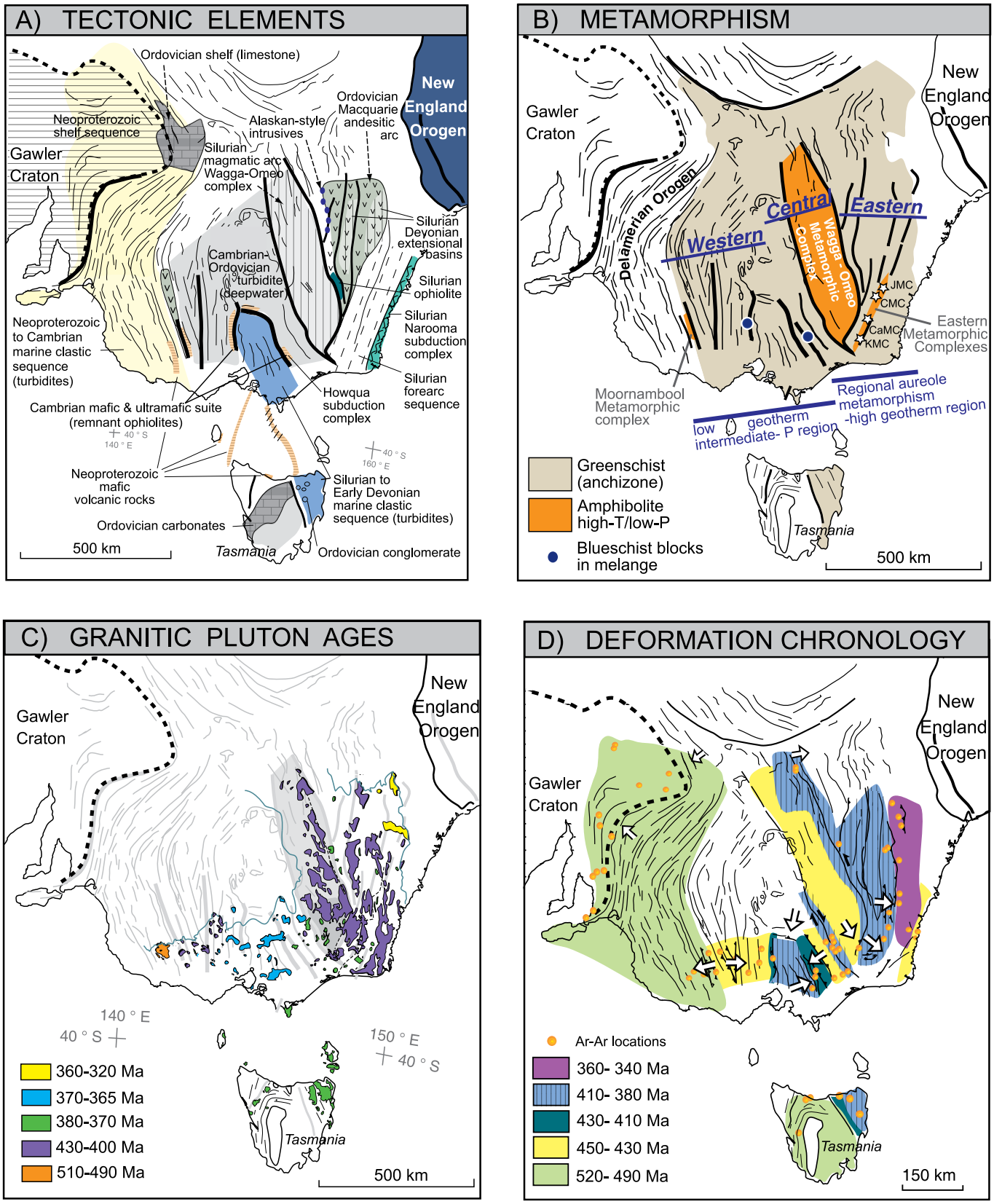

Figure 3. (a) Map showing the major tectonic elements important for understanding the tectonic setting of the Lachlan orogen (after Gray and Foster, 2004). The bold lines show locations of major faults and the finer gray lines show the orientation of the major structural grain. (b) Map showing the average grade of regional metamorphism across the Lachlan (after Gray and Foster, 2004). Eastern metamorphic complex abbreviations: CMC-Cooma, CaMc-Cambalong, JMV-Jerangle and KMC-Kuark (c) Map showing the age and location of major Paleozoic granitic plutons in the Lachlan (after Foster and Gray, 2000a). (d) Map showing the age of major deformation and metamorphism for different locations across the Lachlan (after Foster and others, 1999).

Ma) include basaltic to andesitic remnants of the Ordovician Macquarie Arc in the eastern Lachlan orogen (e.g. Glen and others, 2007).

K-Ar mica, $^{40}Ar/^{39}Ar$ mica and hornblende, and U-Pb zircon ages indicate that granitic plutonism within the Lachlan spanned between ca. 440 to 360 Ma (Fig. 3c), with two broad west-to-east younging trends in the eastern (ca. 430-370 Ma) and western (ca. 410-370 Ma) Lachlan orogen, respectively (reviewed in Veevers, 2000; Gray and others, 2002; Gray and Foster, 1997, 2004). Carboniferous (ca. 320 Ma) granites form a 100 km wide strip at the eastern edge of the Lachlan orogen; which are probably transitional to the Permo-Triassic granites of the New England orogen (Chappell and others, 1988).

S-type granites comprise ~50% of the exposed plutons along with coeval volcanic rocks (e.g., Wyborn and others, 1981), and are concentrated in a NNW-trending belt along the center of the orogen. Compositions range from Mg-Fe-rich, cordierite-bearing granodiorites (e.g., Hine and others, 1978) to highly fractionated granite (e.g., Price and others, 1983). Felsic S-type granites (ca. 410-370 Ma) also occur in the western Lachlan, where several of the youngest (ca. 370 Ma) intrusions are associated with large caldera complexes (Phillips and others, 1981; Rossiter, 2003). I-type granites form a broad belt along the eastern coast (e.g., ca. 419-370 Ma Bega batholith), and are also abundant throughout the rest of the orogen. I-type volcanic rocks are locally preserved in grabens (Wyborn and Chappell, 1986). Medium- to high-K granodiorites and granites dominate the I-types, with lesser tonalite and rare gabbro-diorite (<1%).

Trace-element patterns in average I- and S-type granites are similar and have low Sr/Y ratios typical of sources with residual plagioclase (Wyborn and others, 1992), and plot in the volcanic-arc field on trace-element discrimination plots. Initial Sr and Nd isotope ratios ($^{87}Sr/^{86}Sr_i$ = 0.704-0.720; εNd_i = +4 to –11; e.g., McCulloch and Chappell, 1982; Maas and Nicholls, 2002) define a continuous hyperbolic trend on $^{87}Sr/^{86}Sr_i$ vs. εNd_i plots (e.g., Keay and others, 1997). I-type granites generally have lower $^{87}Sr/^{86}Sr_i$ and higher εNd_i than S-types, which trend towards the compositions of Paleozoic turbidites ($^{87}Sr/^{86}Sr_i$ = 0.715-0.730, εNd_i = -8 to -12; Adams and others, 2005), but there is significant overlap. Oxygen isotopes in the I-type ($\delta^{18}O$ = 5.5-10‰) and S-type ($\delta^{18}O$ = 9.2–12‰) granites of the eastern Lachlan orogen show correlations with Sr, Nd, and Hf isotope ratios consistent with mixing of high $\delta^{18}O$ crustal (including the Orodvician turbidites) and low $\delta^{18}O$ mantle components (McCulloch and Chappell, 1982; Kemp and others, 2007). Coupled $\delta^{18}O$ and εHf_i of zircons within I-type plutons also indicate derivation from partial melting of early Paleozoic sedimentary material mixed with juvenile mantle-derived basaltic magma (Kemp and others, 2007).

Inherited zircon in S-type granites of the eastern and central Lachlan and show dominate age populations at ca. 500 and 1000 Ma, with minor populations to as old as ca. 3.6 Ga, (Williams, 2001; Keay and others, 2000; Maas and others, 2001). The inherited zircon age populations are identical to detrital zircon populations in Early Paleozoic turbidites of the eastern Gondwana margin (Veevers, 2000). Inherited zircon in I-type granites is typically minor but of the same pattern as in the S-type granites (e.g. Chen and Williams, 1991; Williams, 1992). The Paleozoic turbidite-derived, detrital zircons in the granitoids indicate that partial melts of the Paleozoic sediments are one component in the source of the magmas, rather than the previously proposed Precambrian basement terranes (Foster and Gray, 2000a). The inherited zircon age populations and isotopic (Sr, Nd, Hf) compositions indicate that the Lachlan granitoids are hybrids of mafic mantle magmas and crustal magmas sourced by partial melting of Paleozoic turbidite along with Cambrian mafic volcanic basement (Gray, 1984, 1990; Collins, 1996; Kemp and others, 2007). Trace element data from mafic igneous rocks across the Lachlan suggest backarc to arc mantle signatures for the mantle-derived component (Bierlein and others, 2001b; Collins, 2002b). Post-orogenic magmatism (ca. 370-360 Ma) in the western Lachlan orogen and elsewhere is probably related to thickening of the crust during final collision of the eastern and western Lachlan (e.g., Soesoo and others, 1997).

Structural style

The western Lachlan orogen is characterized by chevron-folds cut by a series of linked fault-systems (e.g., Gray and Foster, 1998; Fig. 4). Chevron folding and thrusting resulted in massive shortening (~60-70%) and structural thickening (~300% vertical elongation) of the turbidite pile (e.g., Gray and Willman, 1991; Fergusson and Coney, 1992a; Gray and others, 2006a). The thrust wedge outside the fault zones has one phase of deformation, shown by a weak to moderately developed slaty cleavage which is parallel to the axial surface of upright, chevron-folds in the upper parts of thrust sheets (Gray and Willman, 1991). Major faults in the western Lachlan (Figs. 3a, 4) are spaced at 100 to ~120 km, have finite strike lengths on the order of 150 km (Gray and Foster, 1998; Gray and others, 2006b) and are zones containing slivers of the upper parts of a former Cambrian back-arc oceanic lithosphere (Gray and Foster, 1998). They contain dismembered Cambrian ophiolite slivers (Spaggiari and others, 2003a) as well as relicts of serpentinite and mud-matrix mélange incorporating blueschist blocks (Spaggiari and others, 2004). 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 of the large thrust wedges (Gray and Foster 1998; Spaggiari and others 2004). Major thrust fault zones are polydeformed zones characterized by transposition layering, crenulation cleavages, high, non-coaxial strains, intense mica fabrics, and isoclinal folds (e.g., Gray and Willman 1991; Gray and Foster 1998; Foster and Gray, 2007).

Relicts of accretionary complexes are preserved within the southwestern part of the central Lachlan (Howqua) and the southeastern part of the eastern Lachlan (Narooma) (Fig.

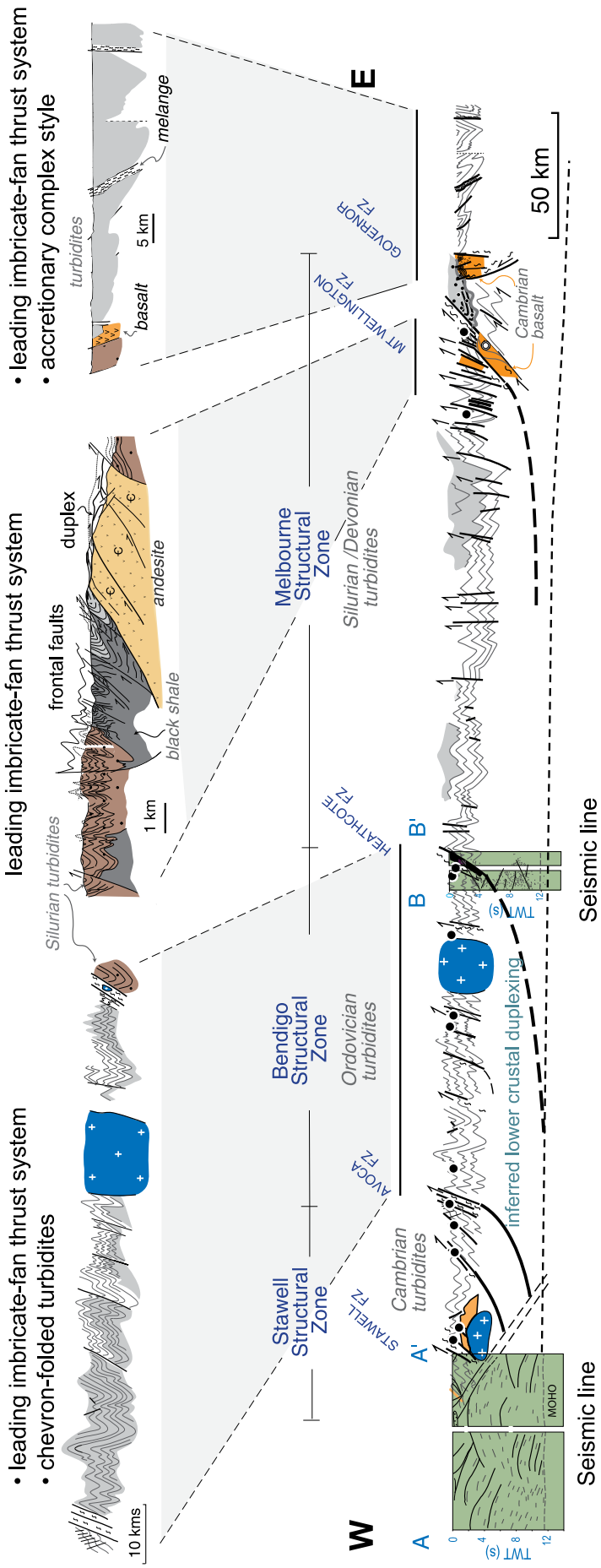

Figure 4. West to east structural cross-section of the western Lachlan orogen (after Gray and Foster, 1998; Gray and others, 2006b).

3a). In the Narooma accretionary complex large-scale imbrication is associated with chaotic block-in-matrix mélange, broken formation along high strain zones, early bedding-parallel cleavage, recumbent folds in turbidites, and structural complexity in cherts. This succession has been interpreted as the outer-arc slope and imbricated zone of an accretionary wedge that was part of a Late Ordovician-Silurian subduction zone (e.g. Powell 1983; Miller and Gray, 1997; Offler and others, 1998b; Fergusson and Frikken 2003). In the Howqua accretionary complex, an imbricated and chevron-folded, Late Ordovician-Silurian turbidite succession contains mud-matrix and serpentinite-matrix mélanges in the frontal fault zone (Spaggiari and others 2002, 2003b, 2004) as well as mud-matrix mélange along major faults within the wedge (Watson and Gray, 2001) and a possible detached seamount (Spaggiari and others 2004). These have been interpreted as part of a Late Ordovician-Silurian subduction accretionary wedge (Foster and Gray, 2000a; Fergusson, 2003).

The eastern Lachlan orogen is made up of several major, west-dipping fault zones that penetrate to the Moho (Glen and others, 2002; Gray and others, 2006b). The faults are crustal-scale imbrications of Ordovician volcanic arc rocks of the Macquarie Arc, inferred Cambrian oceanic crust and Silurian-Early Devonian platformal and basinal sedimentary rocks (Fig. 5). Major west-dipping thrust faults evolved from Silurian-Devonian normal faults that were inverted during the Silurian-late Early Devonian and the Carboniferous (Glen, 1992; Glen and others, 1992, 1994, 2002). As a consequence, the former extensional basins (e.g., Cowra and Hill End troughs) have west directed antithetic thrust faults defining their western margins. The crustal-scale faults are west dipping, but at shallow crustal levels there are both east and west dipping thrust fault systems.

Timing of deformation and strain rate

$^{40}Ar/^{39}Ar$ geochronologic and thermochronologic data interpreted along with other geological data indicate when specific regions in the Lachlan orogen underwent significant deformation, metamorphism, faulting and reactivation (Fig. 3d; Foster and others, 1999; Gray and Foster, 2004). Deformation initiated in the western part of the western Lachlan, the central Lachlan, and the eastern Lachlan between ca. 455 and 440 Ma (e.g., Foster and others, 1999). This interval is traditionally called the Benambran orogeny, although the timing and nature of this event are variable in different parts of the Lachlan (e.g., Gray and Foster, 1997; VandenBerg, 2000; Foster and Gray, 2000b). Metamorphism in the Wagga–Omeo meta-

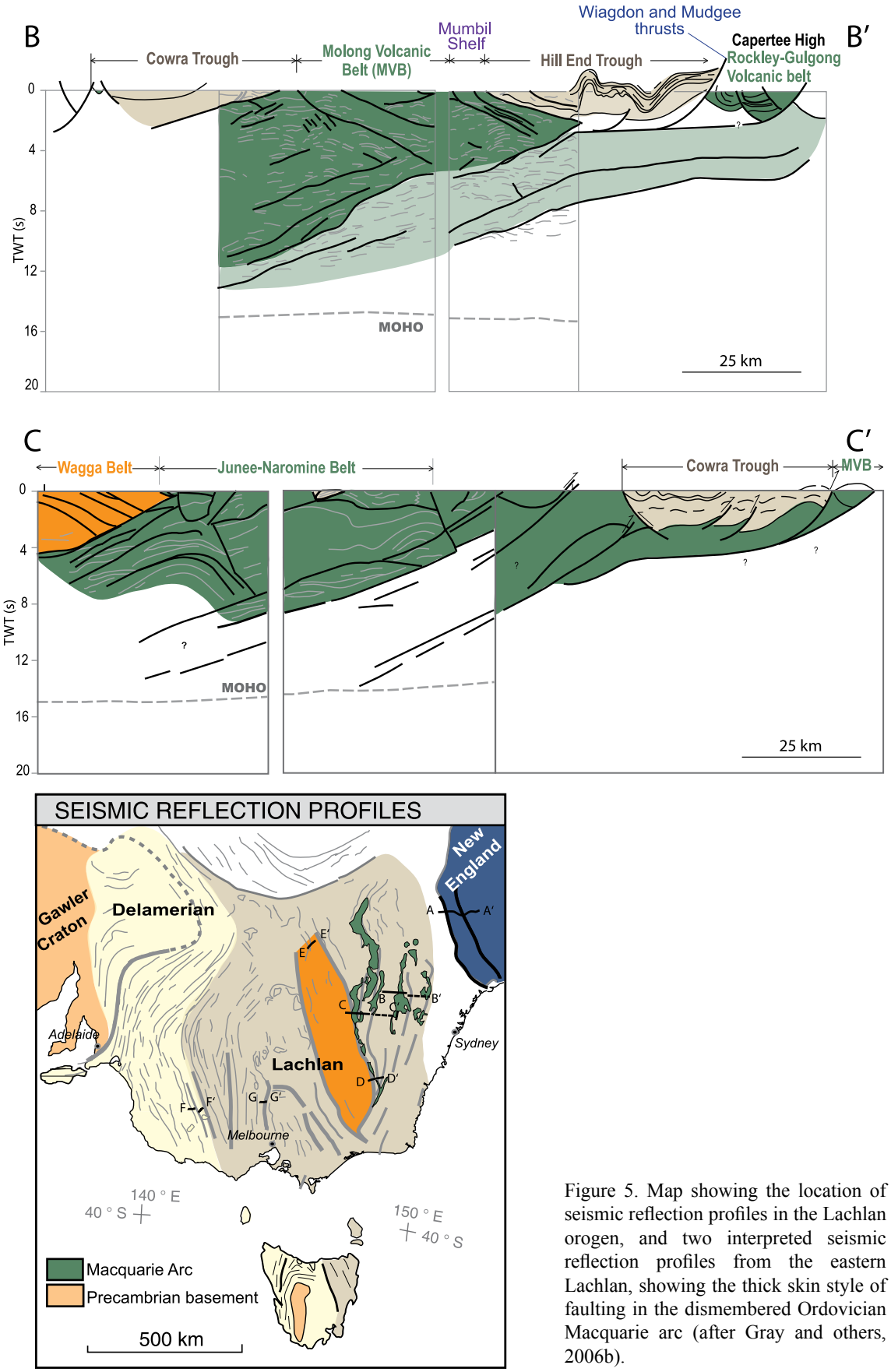

Figure 5. Map showing the location of seismic reflection profiles in the Lachlan orogen, and two interpreted seismic reflection profiles from the eastern Lachlan, showing the thick skin style of faulting in the dismembered Ordovician Macquarie arc (after Gray and others, 2006b).

morphic complex and in the Eastern metamorphic complexes (e.g., Cooma Complex) occurred at ca. 430 Ma (Maas and others, 2001; Williams, 2001). The interval between ca. 420-410 Ma was characterized by fault reactivation in the western Lachlan, strike-slip motion on the large boundary faults and mylonitic shear zones of the Wagga-Omeo metamorphic complex, along with significant exhumation (e.g., Foster and others, 1999). The eastern part of the western Lachlan and the central Lachlan provinces underwent significant deformation between ca. 400-385 Ma when they collided. This collision event is known as the Tabberabberan orogeny, and is the terminal crustal thickening interval for much of the Lachlan orogen. The inland parts of the eastern Lachlan are dominated by ca. 400–380 Ma deformation with a central and northeastern region of ca. 380–360 Ma deformation (Glen and others, 1992; Foster and others, 1999; Fig. 3d). Widespread Silurian extension and basin formation pre-dated this phase of shortening in the Macquarie arc. These events also overprinted the earlier fabrics in the eastern Lachlan such as the ca. 445-440 Ma fabrics in the Narooma accretionary complex. Although very widespread, intense Carboniferous deformation is focused in the northern part of the Lachlan orogen in the eastern province (Powell 1983; Glen 1992). Carboniferous deformation partly reflects the progressive eastward accretion of the Tasmanides and is probably related to amalgamation of the New England orogen.

The relatively low grade of regional metamorphism in the western Lachlan allows direct deformation dates to be determined from $^{40}Ar/^{39}Ar$ analyses of white mica from cleavage and syntectonic veins (Foster and others, 1998, 1999; Foster and Gray, 2007). After intensive sampling and $^{40}Ar/^{39}Ar$ analysis of deformed rocks from the western Lachlan there is now an excellent record of the chronology of deformation: early shortening and flexural folding of turbides began ca. 455 Ma. By ca. 445 Ma folds were tighter, cleavage started forming and early veins were folded. By ca. 440-439 Ma the folds achieved hinge angles of about 70 degrees in the hanging walls of regional thrust sheets in the Bendigo zone, developed strong cleavage, and deformation localized in the high strain zones. The best $^{40}Ar/^{39}Ar$ data set is from the thrust sheets in the western Lachlan where deformation took place over a period of about 16 million years (455–439 Ma) (Foster and Gray, 2007).

Retrodeformation for the Stawell and Bendigo zones of the western Lachlan gives a minimum shortening of ~310 km and a maximum of ~790 km (Gray and others, 2006a; Foster and Gray, 2007) over this 16 m.y. period. This gives an average displacement rate for the basal décollement between ~19 mm yr^{-1} (minimum) and ~50 mm yr^{-1} (maximum). The geochronology and strain data can also be used to calculate internal strain rates for the western Lachlan thrust wedges, where shortening of 66% occurred over 16 m.y., giving a strain rate equal to 1.3 x 10^{-15} s^{-1}. The abundance of $^{40}Ar/^{39}Ar$ mica ages from veins and cleavage of ca. 443–439 Ma suggests that most deformation in the thrust sheets occurred over a shorter interval of more rapid deformation. The fact that most of the cleavage development occurred ca. 441–440 Ma, and the veins intruding thrusts in fold hinges give ages of ca. 440–439 Ma, suggest that most deformation ended by ca. 439 Ma. Given the errors in the analyses and ranges of ages, a pulse of deformation lasting about 2 m.y. probably resulted in much of the 66% shortening, and the strain rate was on the order of 1 x 10^{-14} s^{-1}. This strain rate is within the range of modern plate tectonic rates in backarc settings, like those of the western Pacific (e.g., McCaffrey, 1996).

Lachlan tectonic evolution

The Lachlan orogenic cycle was initiated after the extensional collapse of the Ross-Delamerian orogen and the proto-Lachlan backarc basin opened between ca. 505 and 495 Ma (Foster and others, 2005; Fig. 6). Most of the resulting marginal basin was floored by oceanic crust although some continental ribbons were probably rifted from Gondwana such as the Delamerian-aged crust in New Zealand (Gibson and Ireland, 1996) and the proposed continental block under the Melbourne zone of the southern Lachlan (Cayley and others, 2002). Extensive turbidite fan deposition took place in the developing basin off the Gondwana margin between ~490 Ma and 470 Ma. Most of the turbidite fan was derived from along the Gondwana margin in the Ross orogen (Squire and others, 2005). On the outer part of this margin basin, 1000's of km away from the Australian continent ocean, arc volcanism in the Macquarie arc was initiated at ca. 485 Ma due to subduction of the paleo-Pacific (Glen and others, 2007). At ca. 460 Ma, inboard of the Macquarie arc, subduction initiated along both sides of Lachlan backarc basin similar to the modern Mollucca Sea (Gray and Foster, 1997, 2004; Soesoo and others, 1997; Foster and Gray, 2000a). In this scenario, multiple oceanic thrust-systems were active in both the eastern and western parts of the basin from about 455-439 Ma, which eventually developed into the current central and western Lachlan, respectively (Fig. 6; Foster and others, 1999). Structural thickening of the turbidites in the western thrust system led to erosional exhumation and sediment output into the yet undeformed center of marginal basin (Melbourne "trough") during the interval 439-410 Ma (Foster and others, 1998, 1999; Foster and Gray, 2000a).

Over this same interval of time, west-directed shortening took place in northeast Tasmania and the mineralized Dundas belt was deformed in western Tasmania (Bierlein and others, 2005). Widespread post-orogenic magmatism in the western part of the western Lachlan at ca. 400 Ma was followed by final closure of the marginal basin at ca. 390 Ma (Foster and others, 1999). The collision between the western Lachlan accretionary-style thrust belt and the central Lachlan accretionary complex and magmatic arc was accompanied by localized strong to intense north-south folding and regional, meridional crenulation cleavage development in the central Lachlan orogen (Morand and Gray, 1991). Collision also

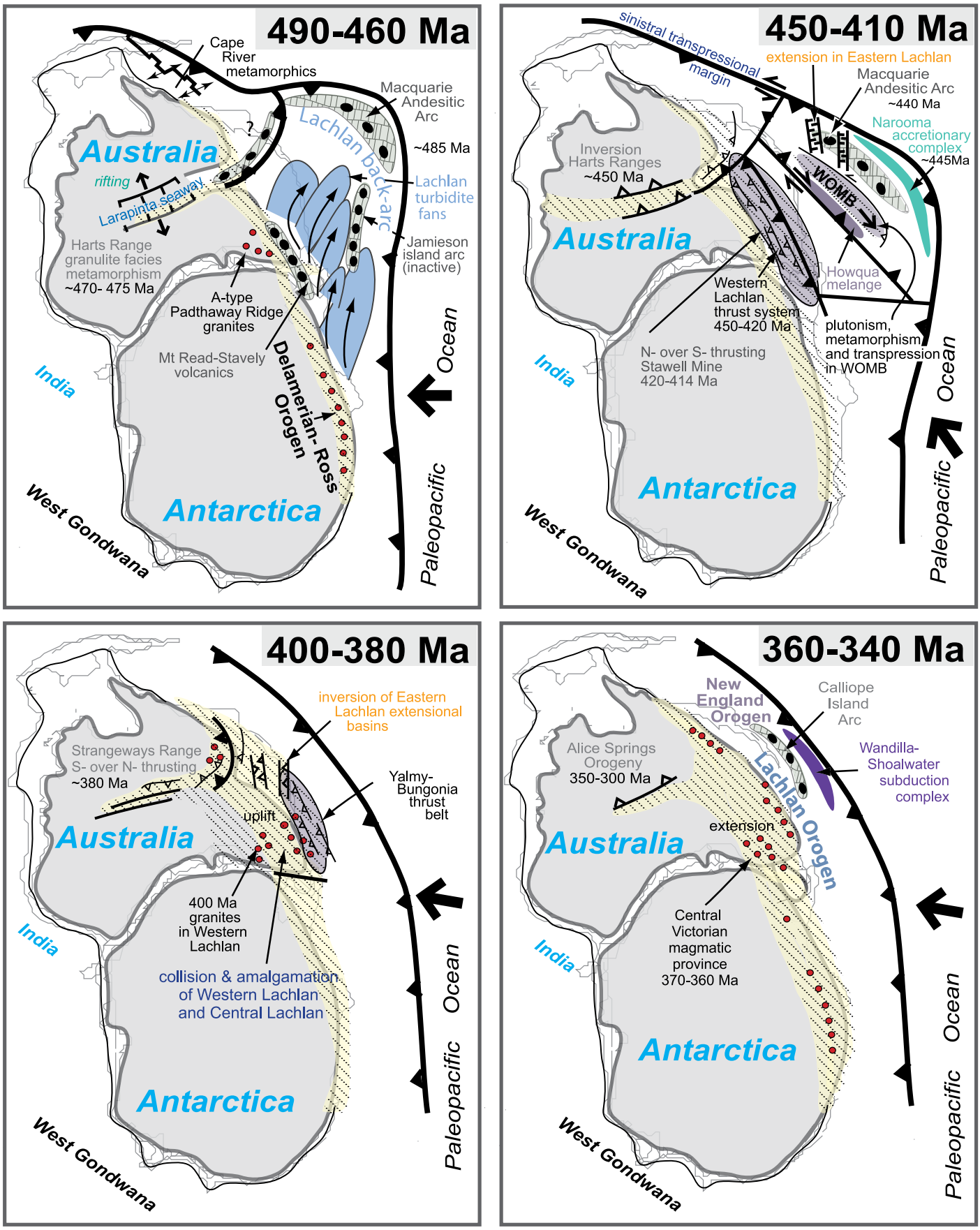

Figure 6. Reconstructions of the tectonic evolution of the Lachlan orogen (after Foster and Gray, 2000; Gray and Foster, 2004). The diagonal pattern and yellow shading indicate areas undergoing active orogenesis.

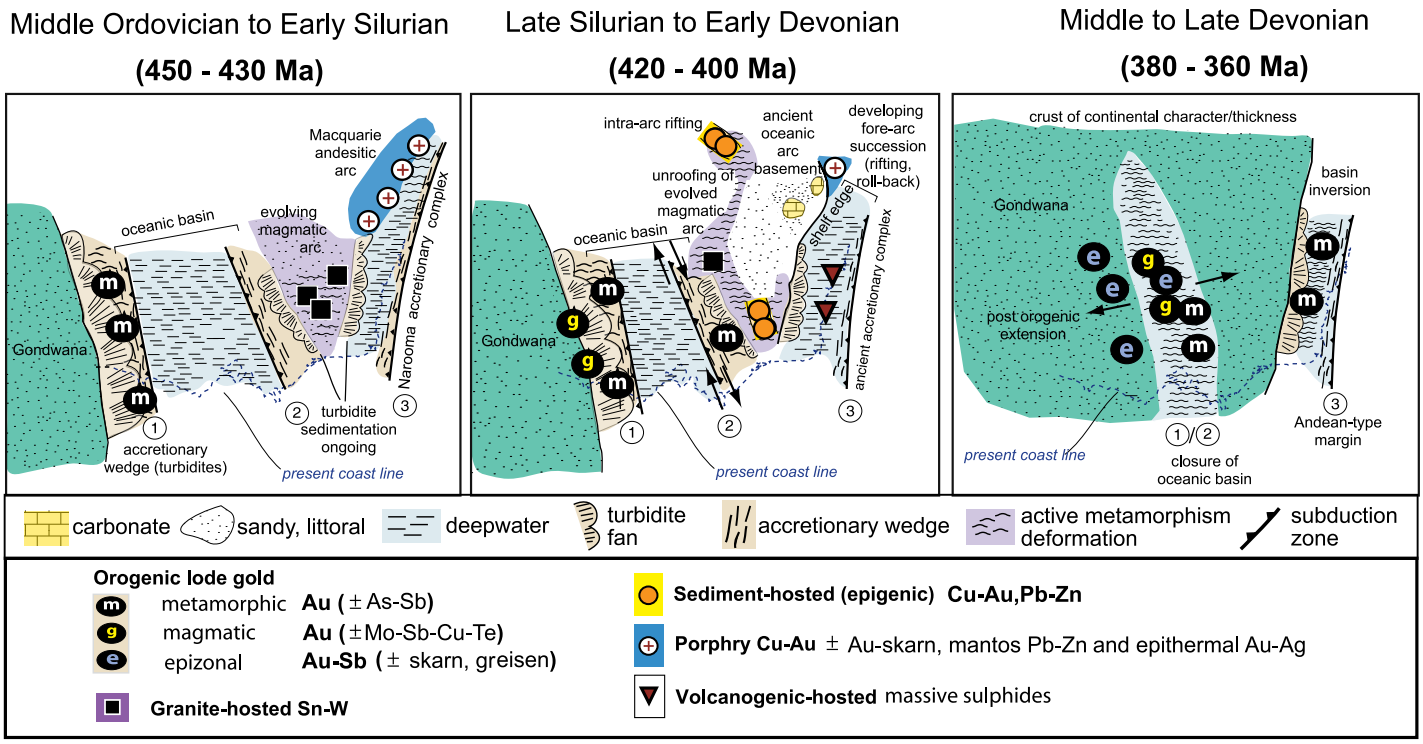

Figure 7. Cartoon showing the location and timing of mineral deposits in the Lachlan with respect to the evolving tectonic settings (after Bierlein and others, 2002).

caused reactivation of shear zones in the Delamerian orogen and Precambrian basement massifs (Mt. Painter, Broken Hill and Tyennan of Tasmania). This structural thickening and amalgamation of the western and central Lachlan belts led to cratonization of the inner Lachlan (Foster and Gray, 2000).

In the eastern Lachlan orogen intermittent east-directed thrusting and extension was associated with high-temperature metamorphism and syn-deformational magmatism (e.g. Cooma Complex) in the interval ca. 440-435 Ma (Fergusson and VandenBerg, 1990; Collins, 2002b). Periods of shortening in the eastern Lachlan separated longer intervals of extension and extension-related volcanism above the outer subduction zone between ca. 440 and 420 Ma (Zen, 1995; Collins, 2002b). Closure of Early Devonian extensional basins formed within the older Macquarrie arc occurred between 410 and 390 Ma (Cobar basin: Glen and others, 1992) and again between 360 and 340 Ma (Hill End basin: Foster and others, 1999). Post-orogenic magmatism in the eastern part of the western Lachlan orogen (central Victorian magmatic province) occurred at ca. 370-360 Ma, while east-directed thrusting in the eastern Lachlan caused inversion of former basin bounding normal faults, and was followed by post-orogenic magmatism. Cratonization of the Lachlan orogen was complete by ca. 330 Ma.

Metallogeny

Remarkable spatial and temporal relationships between tectonic setting and mineral deposits characterize the Lachlan orogen (Fig. 7; Bierlein and others, 2002; Gray and others, 2002). Large Ordovician orogenic gold deposits, including the Bendigo, Ballarat and Stawell districts of western Victoria, formed within thrust sheets in the western Lachlan. These deposits formed in an accretionary setting involving subduction, which generated of large volumes of metamorphic fluids derived during devolatization of a hydrated succession within the internally heated, thickened crust (Bierlein and others, 2002). The lode gold deposits predated granitic magmatism and a secondary phase of gold mineralization and remobilization by about 50 m.y. (Bierlein and others, 2001a). The majority of the gold deposits in the western Lachlan are unrelated to the plutons, but there is close association of the orogenic lode gold deposits with metasedimentary rocks above oceanic crust.

Pb-isotopic data from western Victoria gold province indicate that the ores were derived from a homogenized crustal source (Bierlein and McNaughton, 1998). Stable isotope data indicate that the large veins are locally derived from the host turbidites and, therefore, the gold is largely enriched from the sedimentary host rocks (Gray and others, 1991). These data are consistent with the hypothesis that early Paleozoic strata are enriched in gold due to the unique chemistry of the global ocean at that time (Titley, 1991).

At the same time as the Ordovician orogenic gold lode deposits formed in the western Lachlan, porphyry Cu-Au deposits like Copper Hill, Parks, Peak Hill and Lake Cowal formed in the northern part of the eastern Lachlan. These deposits are associated with the dismembered Ordovician calc-alkaline Macquarie arc (Bierlein and others, 2002). Primitive lead isotopic signatures indicate a largely mantle-derived source for these ores and their corresponding host rocks (Carr and others, 1995). Sn-W-Mo-bearing granites of the high-temperature/low-pressure Wagga-Omeo belt represent the deeper, more chemically differentiated levels of a supra-subduction environment (Bierlein and others, 2002). The deposits of the Wagga tin belt, like Ardlethan, are associated with Early to Late Silurian granitoids within the central Lachlan.

Late Silurian and Early Devonian regional extension and intra-arc rifting associated with magmatic flare-ups, produced the sediment-hosted Cu-Pb-Zn mineralization in rifts like the Cobar Basin (Glen, 1995). Deposits formed in these rift basins include Wilga, Currawong, Cobar and Clarkes Reef (Bierlein and others, 2002). Rifting in the southern and central parts of the eastern Lachlan was related to oblique convergence at ca. 410-400 Ma (Foster and others, 1999), and produced crustal-scale normal faults and rapid subsidence within the old forearc region. Late Silurian to Devonian stratabound Kuroko-style volcanogenic-exhalative Pb-Zn-Ag sulphide mineralization (Carr and others, 1995), like the Woodlawn deposit appear to be related to large the normal faults (Bierlein and others, 2002).

CONCLUSIONS

In the western and central Lachlan orogen accretion occurred by thickening and imbrication of extensive and thick submarine fans, including the underlying oceanic (including backarc and forearc) lithosphere, in a Mollucca Sea-style (see Hall, this volume) double divergent subduction system. In this scenario subduction zones were initiated on the opposing sides of a Cambrian-Ordovician marginal ocean basin. Low-angle underthrusting in the western Lachlan orogen resulted in marked shortening (~65-70%) by chevron folding, cleavage development and thrust imbrication of the turbidites. Subduction along the eastern side of the marginal basin, represented by the Howqua accretionary complex, produced large elongate composite batholiths within a shear zone-bounded, northwest-trending magmatic arc, as well as the associated high-T/low-P metamorphism. The eastern Lachlan orogen, which is dominated by crust composed of the fragmented Ordovician Macquarie arc, was periodically rifted and then shortened above an outboard subduction zone. Mafic to felsic magmatism throughout the Lachlan was generated by a variety of processes over time including subduction, extension, crustal thickening, and post-orogenic extension. Mineralization events are strongly correlated in space and time with tectonic setting and magmatism throughout the evolution of the Lachlan orogen.

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