

American Journal of Science

NOVEMBER 1997

OROGENIC CONCEPTS—APPLICATION AND DEFINITION: LACHLAN FOLD BELT, EASTERN AUSTRALIA

DAVID R. GRAY* and DAVID A. FOSTER**
Australian Geodynamics Cooperative Research Centre

ABSTRACT. The orogenic framework for the Paleozoic Lachlan Fold Belt of southeastern Australia was based originally on local and/or regional unconformities in the rock record with the assumption that these reflected orogenic belt-wide tectonic events. Tectonic evolution was related to four main orogenic 'pulses' starting at approx 450 Ma and ending with stabilization by 340 Ma. Maximum thermal activity reflected by crystallization and cooling ages from granitic plutons was between 420 and 340 Ma with a peak at 400 to 410 Ma. $^{40}\text{Ar}/^{39}\text{Ar}$ geochronologic data from cleaved slates and mica-bearing quartz veins in the chevron-folded turbidites of the western subprovince show that deformation was diachronous and progressed from the west at 440 Ma to the east at 410 to 390 Ma. The end Ordovician-Silurian event is now recognized as being the most significant and most widespread orogenic event to affect the Lachlan Fold Belt. It occurred as two migrating waves of subduction-related west-to-east deformation within the western and eastern/central subprovinces respectively. The Middle Devonian event (approx 380-370 Ma), formerly considered to be the paroxysmal cataclysmic orogenic event for the Lachlan Fold Belt, has now markedly reduced significance and only represents limited deformation due to amalgamation of the western and central/eastern subprovinces of the fold-belt and attainment of freeboard at this time. Dating of mica growth during penetrative deformation, at low to medium metamorphic grades, can be used to constrain the timing and patterns of deformation during tectonic evolution of orogenic belts. The orogenic framework of the Lachlan Fold Belt must be redefined as continuous over the extent of the belt from Late Ordovician through to Late Devonian times. Apparent episodic events, which dominate the rock record as unconformities and facies changes, only reflect "local" instability due to changing accommodation mechanisms at the local to regional scale, and changing plate position with time.

INTRODUCTION

In an address as retiring President of the Geological Society of America in 1970 John Rodgers attacked the dogma that orogenies are sharp, discrete

* Department of Earth Sciences, Monash University, Melbourne, 3168 Australia.

** School of Earth Sciences, La Trobe University, Melbourne, 3083 Australia.

events punctuating the geologic record (Rodgers, 1971). Using the Taconic orogeny of the North American Appalachians as an example, Rodgers argued that this orogeny was really a complex series of orogenic episodes or climaxes spread over the larger part of the Ordovician period. It was not, as formerly defined, a single orogenic disturbance that occurred in eastern North America at the end of the Ordovician period. He showed that the Taconic orogeny included three long-lived and partly overlapping events: a disconformity in the external belt where carbonate was being deposited, gravity slides from internal uplifts into the external belt, and widespread deformation particularly in the internal belt. This example highlights the problems of recognizing "orogeny" in the rock record, in defining the timing and determining the duration of orogeny, as well as delineation of the extent and effects of orogeny across orogenic belts. This is particularly true of ancient orogenies where preservation of evidence for their deformation histories is incomplete.

Formerly synonymous with "mountain building," orogenic events have been wholly or in part defined by the accompanying processes of volcanism, plutonism, and metamorphism, as well as uplift and changes in sedimentary facies (Kent, Satterthwaite, and Spencer, 1969). Formal delineation of "orogeny" within most orogenic belts was originally based on the presence and/or recognition of unconformities (Harland, 1969); for example, Trumphy (1971, 1973) for the Alps, Rodgers (1971, 1982) for the Appalachians, and Armstrong (1968) for the Cordilleran Sevier orogenic belt. In the Appalachians, the classic Taconic unconformity is shown by strongly folded and cleaved slates unconformably overlain by Silurian and latest Ordovician conglomerate and sandstone (Rodgers, 1971, fig. 2). Delineated over a large area from Quebec, Canada, southward to Harrisburg, Pennsylvania (Rodgers, 1971, fig. 1), the Taconic unconformity itself can only be dated within broad limits between quite early in the Ordovician and some part of the Silurian. This illustrates a common problem in establishing the orogenic framework using erosional gaps in the rock record.

More recently, thermo- and geochronologic data on the timing of both thermal events including magmatism and metamorphism (Hatcher and Odom, 1980; Glover and others, 1981; Harrison, Spear, and Heizler, 1989; Spear and Harrison, 1989; Foster and others, 1992) and deformation (crystallization ages of metamorphic micas; for example, Liewig, Caron, and Clauer, 1981; Kligfield and others, 1986; Dunlap and others, 1991; West and Lux, 1993) have become important in understanding orogenic-belt evolution and providing time constraints on orogenic processes. Initially, the time lag between crystallization and cooling of metamorphic complexes through the closure temperatures of individual mineral phases led to differing or ambiguous interpretations of some thermochronological data. However, major advances in the understanding of the kinetics of argon diffusion in potassium-bearing phases (Harrison, 1981; Harrison, Duncan, and McDougall, 1985; Lovera, Richter, and Harrison, 1989; Lister and Baldwin, 1996) allow the thermochronologic data to be assessed with respect to deformation and metamorphism. Peaks on histograms of radiometric dates, particularly from

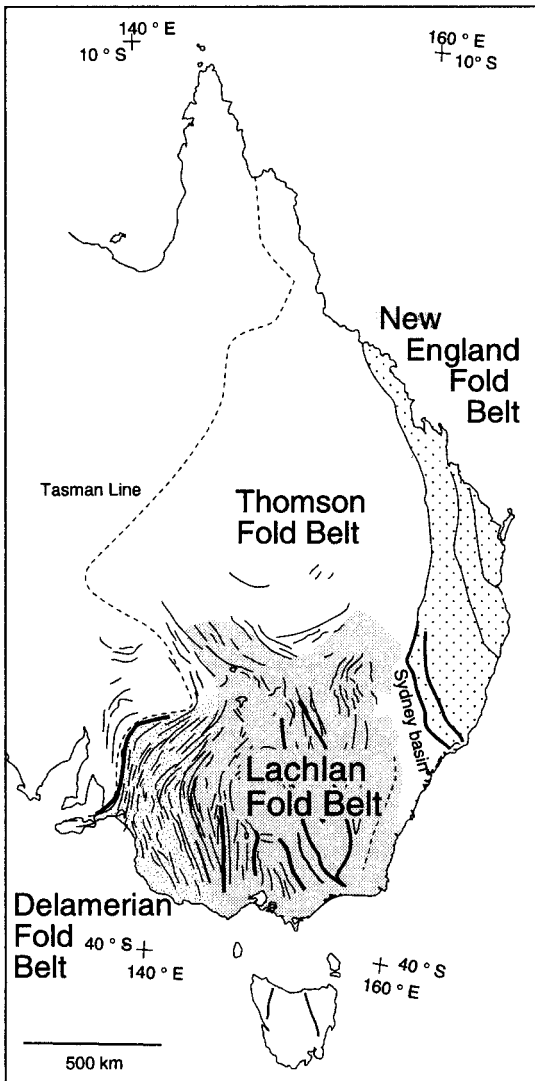


Fig. 1. Map of the Tasman Orogenic Belt showing the Early Paleozoic Delamerian Fold Belt (fine stipple pattern) adjacent to the old continental margin (Tasman Line: dashed line), the Middle Paleozoic Lachlan Fold Belt (shaded pattern), and the outboard Middle to Late Paleozoic New England Fold Belt (coarse stipple pattern). Faults and major structural boundaries are shown by heavy lines. Structural form lines (fine lines) are interpretations from gravity and aeromagnetic images.

granites, have been considered to record special events or "cycles" in the thermal evolution of orogenic belts, although in many cases these age peaks occur some time after the actual maximum thermal conditions.

This paper investigates the orogenic framework of the Lachlan Fold Belt of southeastern Australia, examines thermal and sedimentological aspects of the orogenic record, and summarizes recent geochronologic data from metamorphic micas on the timing of deformation across the fold belt. The paper uses this timing of deformation to re-evaluate the orogenic framework and to show the temporal and spatial relationships of deformation throughout the foldbelt. A major revision of the orogenic framework for the Lachlan Fold Belt is presented.

THE LACHLAN FOLD BELT

The Lachlan Fold Belt is part of a major Phanerozoic orogenic system that formed along the eastern margin of Gondwanaland in the Paleozoic (Coney and others, 1990). Occupying the central part of the composite

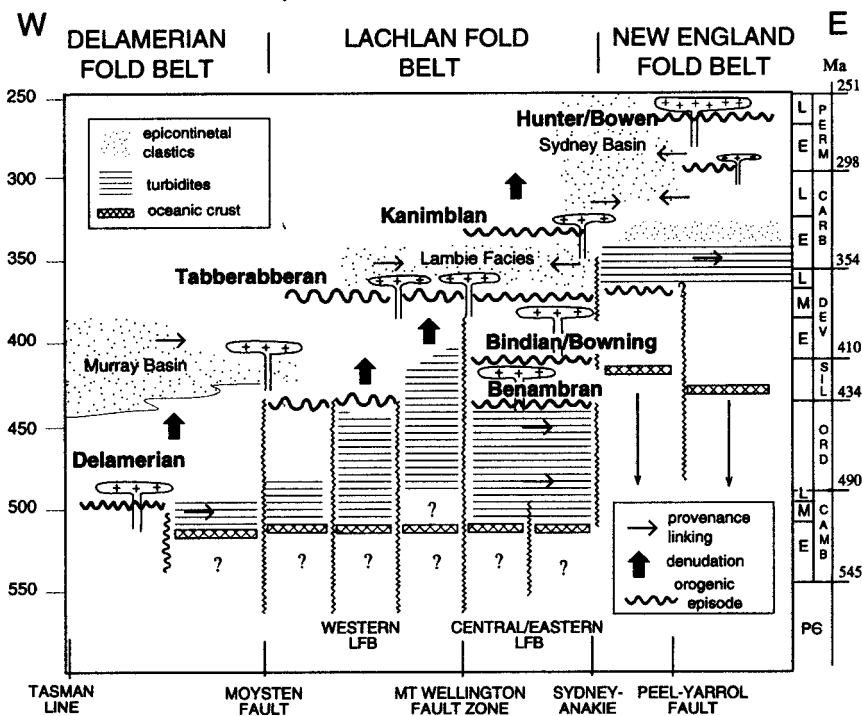


Fig. 2. Time-space diagram showing the chronology and relationships between sedimentation, deformation, metamorphism, and plutonism within the currently accepted orogenic framework for the Tasman Orogenic Belt (modified from Powell and others, 1990, fig. 2). Note there is a general younging in deformation, plutonism, and ages of sedimentary rocks from the Delamerian Fold Belt in the west to the New England Fold Belt in the east.

Tasman Orogenic Belt along the eastern margin of Australia (fig. 1) it consists predominantly of a large area of deformed deep-marine sedimentary rocks dominated by Ordovician quartz-rich turbidites (fig. 2). The Lachlan Fold Belt has an upper crustal framework of linked thrust-belts (Fergusson and Coney, 1992a; Glen, 1992; Gray, 1997), but the overall structural style is chevron folds cut by high-angle reverse faults (Gray and Willman, 1991a, b; Gray, 1997). Deep crustal seismic studies suggest that the steep faults at the present erosion surface flatten with depth and link into a common decollement (Gray, Wilson, and Barton, 1991; Leven and others, 1992).

Despite the overall similarity in sedimentary facies and structural style, there are differences in rock type, metamorphic grade, structural history, as well as geological evolution (table 1), which can be used to subdivide the Lachlan Fold Belt into three separate subprovinces (fig. 3) (Gray, 1997). The western and central subprovinces are dominated by a turbidite succession consisting of quartz-rich sandstones and black shales. The eastern belt consists of mafic volcanics, volcanoclastic rocks, and limestone, as well as quartz-rich turbidites and extensive black shale in the easternmost part (VandenBerg and Stewart, 1992). The large volume of turbidites must reflect a "Bengal fan" type submarine sediment dispersal system associated with uplift of the Delamerian-Ross Orogenic system along the Gondwana margin during the early Paleozoic (Fergusson and Coney, 1992b; Turner and others,

TABLE 1
Geological features of Lachlan Fold Belt subprovinces (see fig. 1)

	Western	Central	Eastern
Rock Succession	deep water, quartz-rich turbidite sequence	deep water, quartz-rich turbidite sequence	●platform carbonates and clastics with rhyolites and dacitic tuffs *chert, melange, basalt (South Coast, New South Wales)
Age of Range of Succession	Ordovician to Early Carboniferous	Ordovician to Late Silurian	●Ordovician to Early Carboniferous *Cambrian to Early Carboniferous
Oldest Stratigraphic Unit	Cambrian basic volcanics	Tremadocian chert ?Cambrian serpentinite	●Ordovician andesitic volcanics *Cambrian cherts, basalts and mudstones
Main Deformation Period	Late Ordovician to Late Silurian	Late Ordovician to Early Silurian	●mild Early Devonian with more intense Early Carboniferous phase *Early Silurian to Late Silurian
Main plutonism	Early Devonian Late Devonian	Late Silurian	Early Devonian

Solid circle refers to northern part of eastern subprovince; asterisk refers to southeastern part of eastern subprovince.

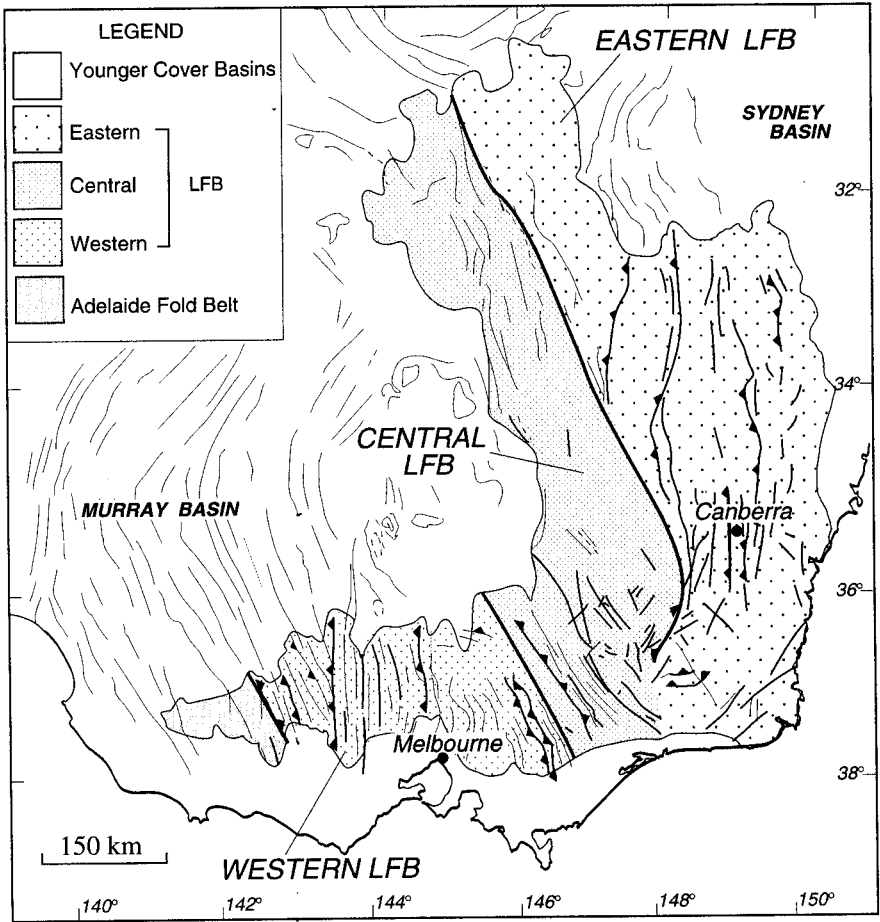


Fig. 3. Map of the Lachlan Fold Belt showing the western, central, and eastern geological subprovinces, the cover sequences of the Murray and Sydney basins, structural and aeromagnetic trend lines (medium lines), major faults (heavy lines with bars: contraction faults; heavy lines without bars: strike-slip faults).

1996). The nature of the basement to the turbidite succession is controversial. In the western belt Cambrian mafic volcanic rocks of oceanic affinities underlie the quartz-rich turbidite succession, whereas in the eastern belt the oldest rocks observed are Ordovician shoshonitic volcanics and a Late Cambrian/Early Ordovician chert/turbidite/mafic volcanic sequence.

Within the subprovinces there are a number of fault-bounded structural zones (fig. 4) which show differences in structural trends, the timing and nature of deformation, and tectonic vergence (fig. 5A, B). The fold belt in general is dominated by thrust-belts verging away from the craton (that is,

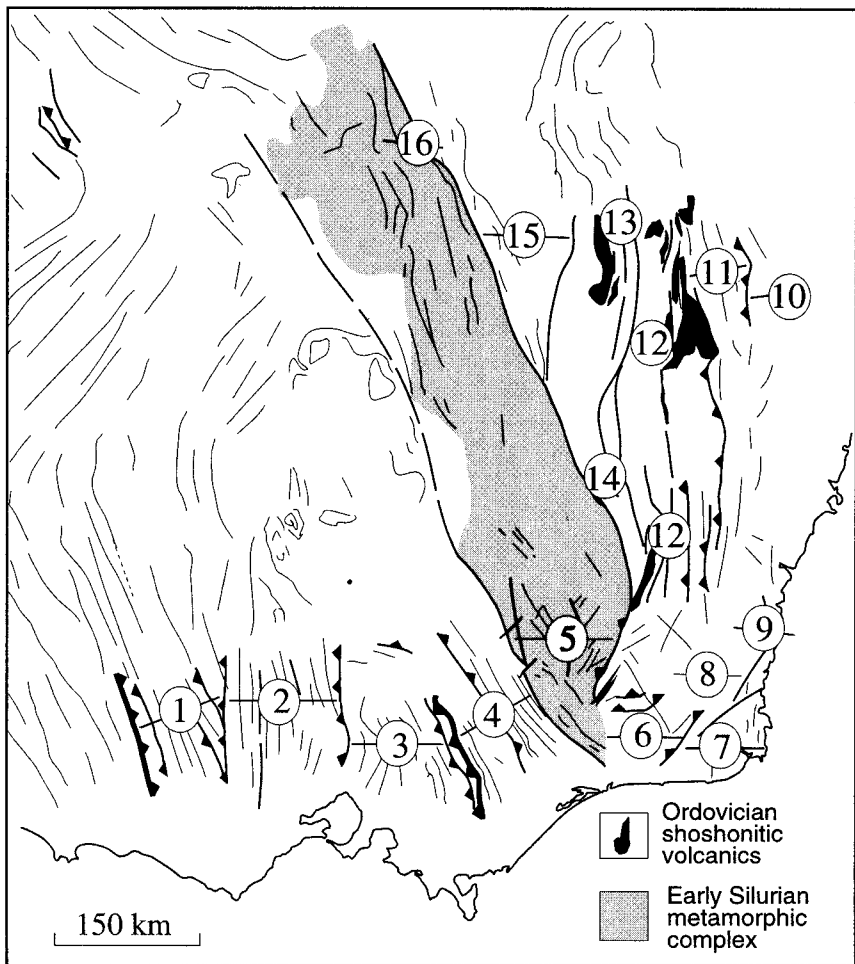


Fig. 4. Map of the Lachlan Fold Belt showing structural subzones (numbered), structural and aeromagnetic trends (thin lines), fault traces (heavy lines), the Wagga Metamorphic Belt (shaded region). (1) Stawell Zone; (2) Bendigo-Ballararat Zone; (3) Melbourne Zone; (4) Tabberabbera Zone; (5) Wagga-Omeo Zone; (6) Buchan Zone; (7) Mallacoota Zone; (8) Yalmy-Bungonia Zone; (9) South Coast Zone; (10) Capertee Zone; (11) Hill End Zone; (12) Orange-Molong Zone; (13) Yass-Cowra Zone; (14) Tumut Zone; (15) Giralambone-Goonambula Zone; (16) Cobar Zone.

eastward in present geographic coordinates), unlike other orogenic systems (for example, Appalachians: Price and Hatcher, 1983, fig. 5; and Canadian Cordillera: Price and Hatcher, 1983, fig. 6). The western subprovince consists of an east-vergent thrust system with alternating zones of northwest- and north-trending structures. The central subprovince is dominated by northwest-

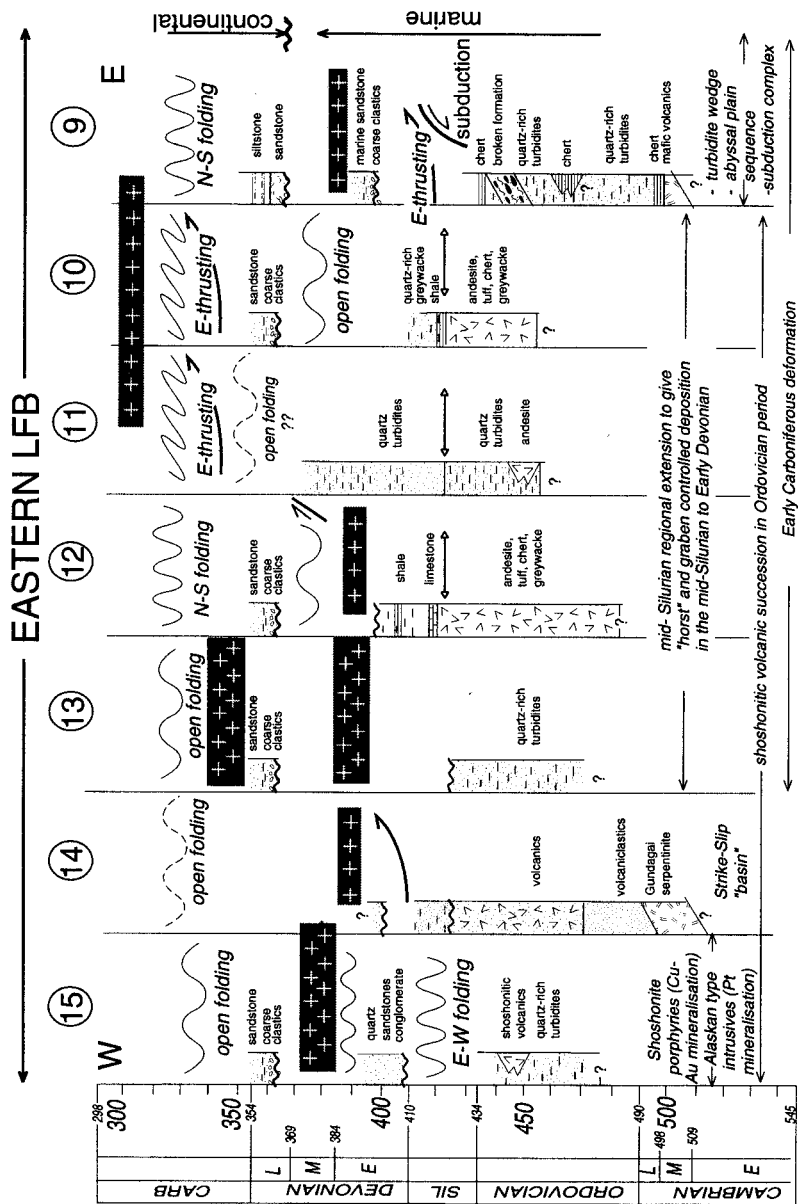


Fig. 5(B) Time-space plot showing the relationships between sedimentation, deformation and plutonism for the eastern Lachlan Fold Belt. Subdivisions are the major geological zones of New South Wales arranged from west to east (see fig. 4). Ages and the nature of sediments, directions of thrusting, times of extension, and age ranges of granitic intrusives are shown. Granite geochronology (black regions with white crosses) from Richards and Singleton (1981) and Gray (1990). Geological time scale based on Young and Laurie (1996).

trending structures and consists of a southwest vergent thrust-belt linked to a fault-bounded metamorphic complex (Morand and Gray, 1991). The eastern subprovince is dominated by a north-south structural grain and east-directed thrusting which caused inversion of extensional basins in the west. In the south and in the easternmost part an east-vergent thrust system links into a subduction-related accretionary complex (Fergusson and VandenBerg, 1990; Miller and Gray, 1996, 1997).

Metamorphism is greenschist facies or lower across the Lachlan Fold Belt, except in the fault-bounded Wagga-Omeo and several smaller (Cooma, Cambalong, Jerangle, and Kuark) metamorphic complexes in the eastern subprovince (for locations, see Glen, 1992, fig. 9; and Gray and Cull, 1992, fig. 1), where high temperature-low pressure metamorphism is characterized by andalusite-sillimanite assemblages (Morand, 1990). Such assemblages are typical of thermal metamorphism, but here they occur on a regional scale and are associated with "regional aureole" granites (White and Chappell, 1983), migmatites, and K-feldspar-cordierite-andalusite-sillimanite gneisses. Regional metamorphism and felsic magmatism throughout the central/eastern subprovinces of the fold belt took place under very little cover, suggesting a shallow to mid-crustal heat input for melting. Here granites constitute up to 36 percent of the exposed Lachlan Fold Belt. In the western subprovince most of the granites are post-tectonic and have narrow (1-2 km wide) contact aureoles. Some of these are subvolcanic granites associated with rhyolites and ash flows of similar composition.

^ OROGENIC FRAMEWORK

The presently accepted orogenic framework of the Lachlan Fold Belt (fig. 6) is largely based on the presence of unconformities in the rock record (Powell, 1983; Coney and others, 1990; Glen, 1992; Fergusson and Coney, 1992a; Gray, Foster, and Bucher, 1997). Associated with this is the particular problem of establishing timing in a fold belt dominated by interbedded sandstones and mudstones. Approaches to orogenesis in such a turbidite-dominated fold belt have been by "dating" of unconformities, interpretation of facies changes (Cas, 1983; Powell, 1983, 1984), and palaeocurrent changes (Powell, 1983, 1984).

In the Lachlan Fold Belt unconformities in the rock record were attributed to major deformational events, and the erosional breaks were correlated and extrapolated throughout the Lachlan Fold Belt (fig. 7) to define the present orogenic framework of six orogenic "events" (see table 2; Gray, Foster, and Bucher, 1997). These range over more than 100 Ma extending from approx 450 to 340 Ma (fig. 6). The evidence for the earliest "orogenesis" in the Lachlan Fold Belt was a change in sedimentation at the end of the Ordovician (see Cas, 1983, fig. 24) as well as an unconformity between polydeformed metamorphic rocks of the Wagga-Omeo metamorphic belt (zone 5, fig. 4) and folded and cleaved Silurian volcanics. This deformation, characterized by early east-west trending folds and a pronounced northnorthwest-trending structural grain, was largely restricted to

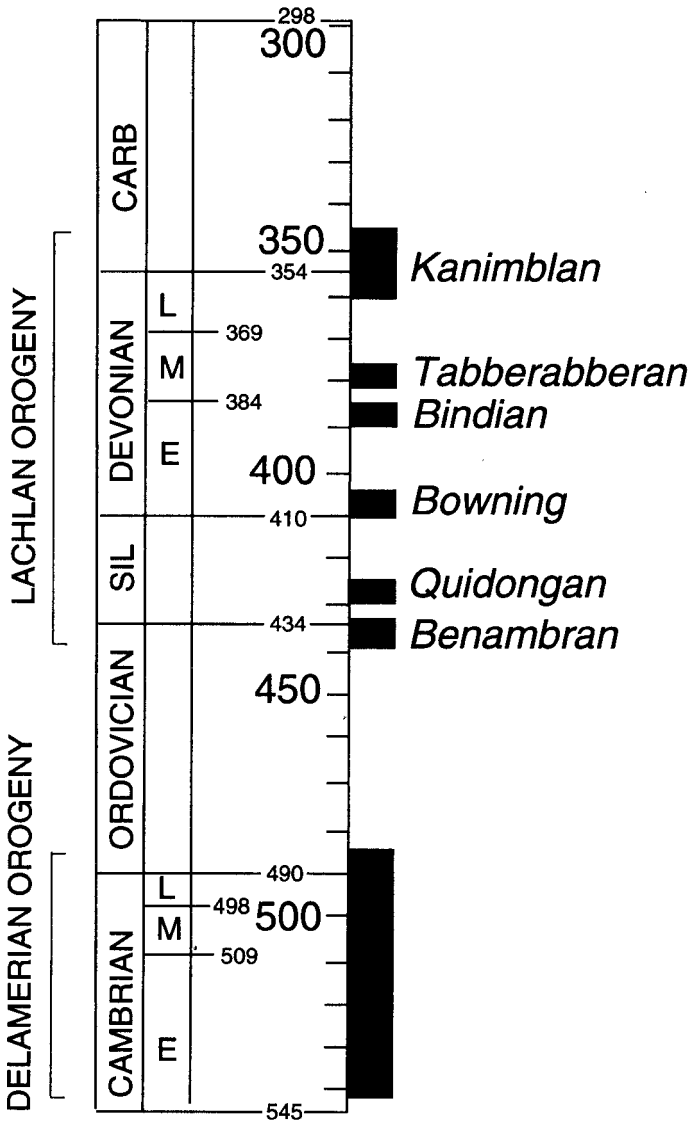


Fig. 6. Geological time scale based on Young and Laurie (1996) showing the existing orogenic framework of the Lachlan Fold Belt (modified from Crook and Powell, 1976, table 3). Recognition of localized unconformities in the rock record led to an orogenic scheme with 6 orogenic "pulses" over 80 Ma. The Delamerian Orogeny (540-485 Ma, Turner and others, 1996) formed the Early Paleozoic Delamerian-Ross Fold Belt.

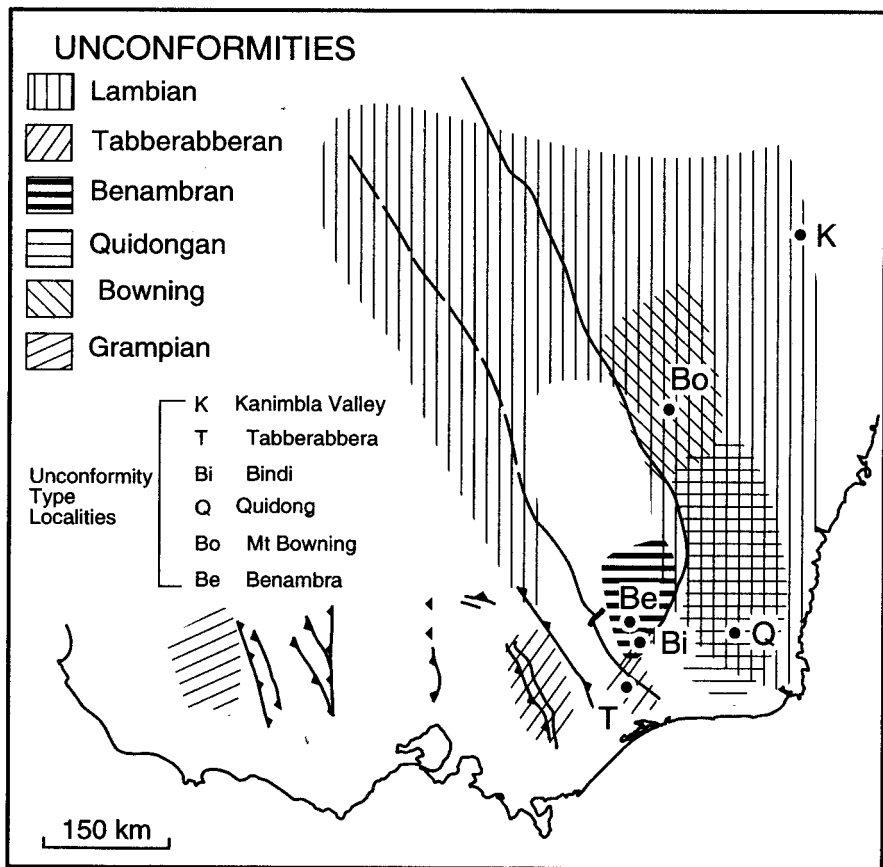


Fig. 7. Lachlan Fold Belt map showing the type localities for the unconformities used to define the existing orogenic framework. The "Lambian" unconformity, defined by the base of the Lambie-type continental fluvial/transitional marine sequences in New South Wales (vertical slash pattern), equates with the Tabberabberan unconformity of Victoria. The Bindian unconformity is very locally developed at Bindi (Bi) (see table 2). The Grampian unconformity involves Silurian Grampians Group sandstones sitting unconformably on rocks of the Delamerian Fold Belt.

the central part of the Lachlan Fold Belt (Fergusson and Coney, 1992a, fig. 4; Glen, 1992, fig. 6); it has been called the Benambran Orogeny.

The effects and extent of the "Quidongan" and "Bowning" events have been questioned (Rutland, 1976; Bolger, 1982). In Victoria, the "Benambran" hiatus extends across the time period of the "Quidongan" event and over most of the fold-belt they cannot be distinguished. The "Bowning" Orogeny is also defined by "local" unconformity between Upper Silurian and Lower Devonian strata (zone 12, fig. 4), but there is conformity between the Upper Silurian and Lower Devonian over much of the fold-belt. The

TABLE 2

Summary of Lachlan Fold Belt "orogenic" events

Orogeny	Type Locality	Geological Constraints	Age	Time
Benambran (Early Silurian)	Mitta-Mitta River and Wombat Creek, Victoria (Talent, 1965)	Unconformity: folded Silurian volcanics and Wenlockian sedimentary rocks overlie polydeformed and metamorphosed Ordovician rocks	Llandoveryian between Bolindian and Ludlovian	~439-435 Ma
Quidongan (late Early Silurian)	Quidong, New South Wales (Crook and others, 1973)	Unconformity: Late Silurian Quidong Limestone overlies Early Silurian Merriangah Siltstone	Wenlockian between late Llandovery and late Wenlock-Ludlow	~430-424 Ma
Bowning (Late Silurian-Early Devonian)	Mt Bowning, Yass New South Wales (Brown, 1954)	Unconformity: Early Devonian strata overlies Late Silurian strata with low angular discordance	Lochkovian	~409-396 Ma
Bindian (Early Devonian)	Bindi, Victoria (Bolger, 1975; VandenBerg and others, 1982)	Unconformity: weakly deformed Early Devonian Snowy River Volcanics overlie strongly foliated Silurian volcanics	Emsian	~390-386 Ma
Tabberabberan (Middle Devonian)	Tabberabbera, Victoria (Brown, 1930; Talent, 1965)	Unconformity: Flat lying Late Devonian redbeds overlie folded and Devonian rocks	Givetian between Pragian and Givetian-Early Frasnian	~381-377 Ma
Kanimblan (Early Carboniferous)	Kanimbla Valley, N.S.W. (Sussmilch, 1914, p. 80)	Unconformity: between Permo-Triassic sandstones and Upper Devonian strata deformation predates Bathurst Granite (312 ± 4 and 322 ± 10 Ma)	Early Visean	~360-340 Ma

"Bindian" and the "Bowning" events in Victoria cannot be differentiated and have been equated (Bindian Orogeny = Bowning Orogeny in New South Wales; compare VandenBerg and Wilkinson (1982, p. 47). Typically the "Tabberabberan-Lambian" event is considered to be a major period of regional deformation in the evolution of the Lachlan Fold Belt (Coney and others, 1990; Fergusson and Coney, 1992a; Glen, 1992; Gray, 1997). It is marked by a major unconformity known as the "Tabberabberan" unconformity in Victoria and the "Lambian" unconformity in New South Wales, which is the most regionally extensive and most widely recognized unconformity across the Lachlan Fold Belt. It is also considered to represent the major climactic deformational event responsible for a change to non-marine conditions (Cas, 1983).

The Early Carboniferous "Kanimblan" deformation is widespread but is a generally weak deformational event whose effects vary across the fold-belt (see Powell, 1984, fig. 222B). In the western and central subprovinces, the

Upper Devonian-Lower Carboniferous cover sequences are folded into broad, open folds. Stronger localized deformation, involving tight folds and reticulate cleavage, is associated with reactivation of some older faults. In the northeast part of the eastern Lachlan Fold belt (fig. 4, zone 10), folds in the cover sequence are close to tight and have tightness similar to that of the older rocks. These folds have overturned limbs and contain moderate to strong cleavage. The "Kanimblan" event was the last major Palaeozoic deformation to affect the Lachlan Fold Belt and represents the final stage in orogenic evolution.

The present framework defines each orogeny as a fold-belt wide event (see fig. 2) and does not necessarily allow for either localized or wide-ranging, diachronous deformations. Exceptions to this tendency are Rutland (1976, p. 176) and Powell and others (1977) who first recognized that localized unconformities in the Lachlan Fold Belt do not necessarily reflect fold-belt wide major deformational events and challenged the conventional approach. Powell (1984) has shown that the Lachlan Fold belt orogenic episodes were neither synchronous nor uniform in their effects across the belt (compare with fig. 5A, B).

Complexity in the timing of deformation is shown across the geological zones of figure 4, where "deformation" is constrained by the age of the youngest sedimentary rocks and the ages of granitic intrusions (see fig. 5A, B). Each zone has undergone a different history, particularly with respect to timing of deformation and plutonism, indicating a complexity not conveyed in the current orogenic framework (fig. 6). In the western subprovince the age of sedimentation and the timing of deformation is diachronous and young to the east (fig. 5A, zones 1, 2, 3). The central province is made up of the Early Silurian high-grade metamorphic complex (zone 5, fig. 5A). This is rimmed by a southwest-verging, very low-grade belt of turbidites and tectonic melange and a more strongly deformed chevron folded sequence of turbidites to the east (fig. 5A, zone 4). The eastern subprovince shows eastward tectonic vergence and an eastward change from turbidites through to chert, mafic volcanics, and turbidites (fig. 5A, zones 6, 7). In the northeastern part, much of the deformation is considered to be Carboniferous (see Powell and others, 1977), but it is preceded by mid-Silurian extension of an Ordovician shoshonitic volcanic succession (fig. 5B, zones 10-13). Formation of a Silurian strike-slip extensional basin (fig. 5B, zone 14) is also part of this event (Stuart-Smith and others, 1992). In the southeast (fig. 4, zone 9) east-directed thrusting is associated with a Silurian subduction zone (Miller and Gray, 1996, 1997). Plutonism is generally Late Silurian-Early Devonian (fig. 5B, zones 12-15), but it is Carboniferous in the north and east (fig. 5B, zones 10, 11).

THERMAL CONSTRAINTS FOR OROGENESIS

With the refinement of geochronologic and thermochronologic techniques to date thermal events there has been a shift toward defining tectonothermal events in orogenic belts (Hatcher and Odom, 1980; Glover and

others, 1983). Fold-belt evolution can be linked to a series of tectonothermal events which can be correlated over large parts of the fold-belt.

Granites.—Major thermal pulses within orogenic systems are reflected in the ages of granitic and volcanic rocks. In the Lachlan Fold Belt K-Ar biotite ages are generally a reasonable estimate of the timing of crystallization because the plutons tend to be high level and rapidly cooled (Richards and Singleton, 1981; Bucher, Foster, and Gleadow, 1995). In the large number of examples where plutons are dated by a combination of methods including U/Pb zircon, $^{40}\text{Ar}/^{39}\text{Ar}$, K-Ar, and Rb/Sr, the K-Ar biotite ages lag behind the crystallization ages by only about 1 to 5 Ma, except in the highest grade terrains and for a small proportion of the oldest plutons where the lag may be up to 10 Ma (Chappell, White, and Williams, 1991; Bucher, Foster, and Gleadow, 1995). A plot of K-Ar biotite ages from granitic rocks from the entire Lachlan Fold Belt (fig. 8) indicates that magmatism occurred mainly over an interval from 440 to 340 Ma peaking between 410 and 380 Ma (~Early Devonian period).

Granite cooling ages clearly vary however, across the Lachlan Fold Belt but define five major regions of plutonism (fig. 9). In the central and eastern

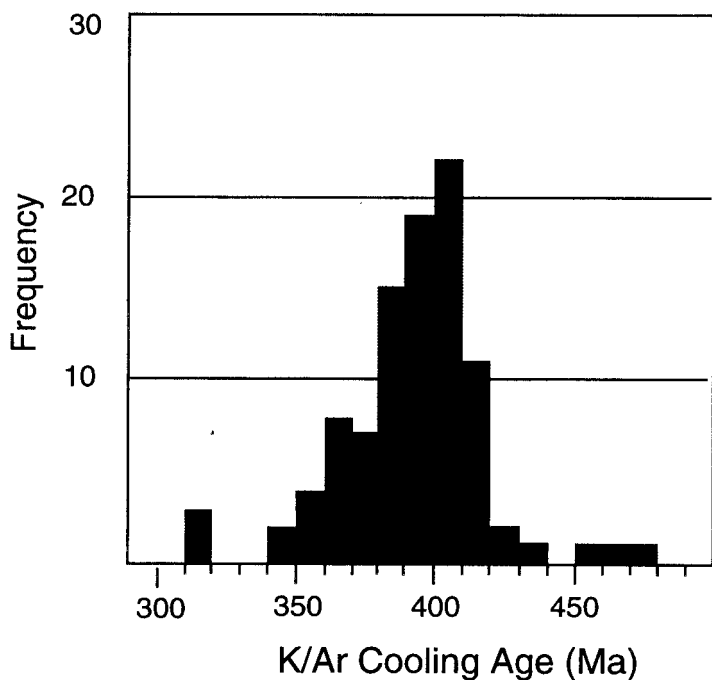


Fig. 8. Histogram of K-Ar cooling ages for biotite in Lachlan Fold Belt granitic rocks. Age data recalculated from Evernden and Richards (1962), Brooks and Leggo (1972), and Richards and Singleton (1981), Gray (1990), Chappell, White, and Williams (1991), Bucher, Foster, and Gleadow (1995).

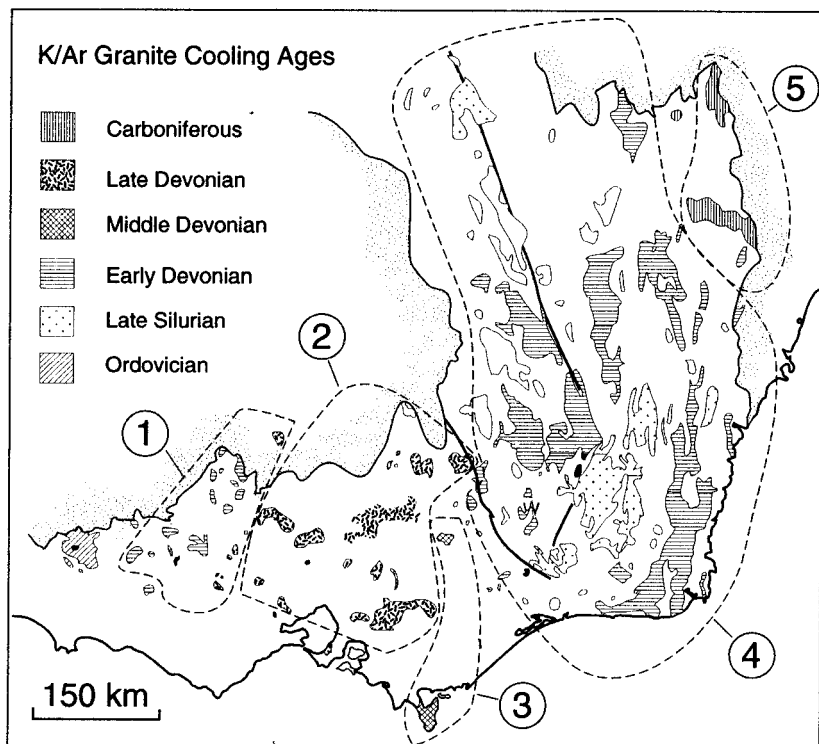


Fig. 9. Granite age map showing the distribution and ages of granites for the Lachlan Fold Belt. Age data from Evernden and Richards (1962), Brooks and Leggo (1972), Richards and Singleton (1981), Gray (1990), Chappell, White, and Williams (1991); Bucher, Foster, and Gleadow (1995). The map shows the five main age regions of plutonism.

subprovinces biotite K-Ar cooling ages are predominantly Early Silurian to Early Devonian (fig. 9, region 4), whereas the western subprovince shows two main periods of granitic magmatism: Early Devonian in the west (fig. 9, region 1) and Late Devonian in the east (fig. 9, region 2). The Late Devonian granites in the western subprovince (fig. 9, region 2) are post-tectonic and associated with volcanic cauldron complexes and ignimbrite flows. Many of the granitoids in the central and eastern subprovinces are syntectonic with emplacement along thrust-faults (Paterson, Tobisch, and Morand, 1990). In the southern part of the eastern subprovince granitoids show an eastward younging in the age of plutonism (Powell, 1983, fig. 9). In the central subprovince granitic magmatism is dominantly Late Silurian with some emplacement in strike-slip fault zones (Morand, 1992). A small zone of mid-Devonian, post-tectonic, magmatic activity (fig. 9, region 3) coincides with the boundary between the western and central subprovinces. The youngest plutonism in the Lachlan Fold Belt, in the extreme northeast (fig. 9, region 5), is post-tectonic and Carboniferous in age.

Metamorphism.—Timing of metamorphism throughout the foldbelt, excluding obvious contact metamorphism around plutons, is based on limited geochronological and thermochronological data (Cas, Flood and Shaw, 1976; Glen, Dallmeyer, and Black, 1992; Lu and others, 1996; Foster, Gray and Offler 1996; Foster, Gray, and Bucher, 1997). Within the Wagga-Omeo Metamorphic Belt, the centrally located and largest belt of high-grade metamorphism in the Lachlan Fold Belt (fig. 4, zone 5), greenschist to upper amphibolite-facies metamorphism is limited by stratigraphic relationships to be Late Ordovician-Early Silurian (Morand, 1990; see fig. 5A). This is consistent with recent geochronology (Anderson, 1996; Foster and Gray, unpublished). Erosional unroofing of the metamorphic complex in the Middle-Late Silurian occurred during southeastward movement of a crustal “wedge” in the Late Silurian to Early Devonian. This movement, by combined wrenching on the northwest-trending marginal shear zones and thrusting along the leading edge of the “wedge” (see Morand and Gray, 1991, fig. 13), exposed the deepest levels of the metamorphic complex in the south.

Timing of the sub- to low greenschist facies metamorphism in other parts of the fold belt is constrained by isotopic, structural, and petrologic data. Recent $^{40}\text{Ar}/^{39}\text{Ar}$ geochronologic data have defined timing of mica growth in cleaved slates where the mica has grown well below its closure temperature (Glen, Dallmeyer, and Black, 1992; Bucher, Foster, and Gray, 1996; Foster, Gray, and Offler, 1996; Foster and others, 1997). A distinct mica preferred orientation (White and Johnston, 1981; Yang and Gray, 1994, fig. 4C, E, F; Tan, Gray, and Stewart, 1995, fig. 2C) is related to cleavage formation late in folding (Yang and Gray, 1994), coincident with attainment of maximum structural thickening and the thermal maximum. The age of deformation and growth of metamorphic phases can therefore be bracketed by the isotopic ages of these rocks.

Mica crystallisation ages.—Deformation in the northern part of the eastern subprovince of the Lachlan Fold Belt was first constrained in the Hill End Zone (fig. 4, zone 11). The deformation was shown to be Early Carboniferous from biotite K-Ar analysis giving ages of 338 ± 10 and 349 ± 10 Ma (Cas, Flood, and Shaw, 1978). More recent $^{40}\text{Ar}/^{39}\text{Ar}$ dating of metamorphic biotite in this belt gives an age of 360 ± 2 Ma for regional metamorphism, (Lu and others, 1996). Strong deformation and cleavage formation in the eastern and northern parts of the Early Devonian Cobar “basin” (fig. 4, zone 16) is shown to be Early Devonian in age by $^{40}\text{Ar}/^{39}\text{Ar}$ plateau ages of 398 to 405 Ma (Glen, Dallmeyer, and Black, 1992). Data from intensely cleaved rocks in a high-strain zone adjacent to the major Rookery Fault zone gave consistent K-Ar ages of 402 ± 8 , 402 ± 8 , and 405 ± 8 Ma (Glen, Dallmeyer, and Black, 1992).

In the western subprovince of the Lachlan Fold Belt regional metamorphism is sub-greenschist facies to greenschist facies with metamorphic grade tending to increase near large thrust faults, where deeper levels of the sedimentary pile are exposed (Offler, McKnight, and Morand, 1996; Foster, Gray, and Offler, 1996; Foster and others 1997). Higher grades of metamorphism are restricted to the contact zones of large granitic plutons. $^{40}\text{Ar}/^{39}\text{Ar}$

whole-rock dating of strongly cleaved slates and phyllites, with metamorphic micas being the only K-bearing phase, shows that cleavage development in the west (fig. 4, zone 1) began in Late Ordovician to Early Silurian time (Bucher, Foster, and Gray, 1996; Foster, Gray and Offler, 1996; Foster and others 1997). $^{40}\text{Ar}/^{39}\text{Ar}$ data from the four major sheet-bounding (structural zone) thrust faults indicates an eastward progression of imbrication and unroofing from an inferred deep-level, basal detachment. Polydeformed and strongly cleaved slates and phyllites from the Landsborough (fig. 4, within zone 1), Avoca, Heathcote, and Mount Wellington Fault Zones give well constrained plateau ages of 453 ± 2 , 440 ± 2 , 426 ± 4 , and 410 to 395 Ma, respectively (Foster, Gray, and Offler, 1996; Foster and others 1997). Identical ages are obtained from separates of sericite from syntectonic quartz veins within thrust sheets (Foster, Gray, and Offler, 1996; Foster and others 1997). These results reveal a progression of the main deformation front from west to east across the western Lachlan Fold Belt from Late Ordovician through Late Silurian-Early Devonian times.

Rocks from intra-zone faults, such as the Whitelaw Fault (fig. 4, within zone 2), give ages similar to those from the sheet-bounding faults (Foster, Gray, and Offler, 1996). Reactivation occurred within the thrust sheets and along the bounding faults in the west, during periods of unroofing in the east. For example, reactivation in the Stawell and Bendigo-Ballararat Zones occurred at about 420 and 410 Ma, when deformation took place within the Heathcote and Mount Wellington Fault Zones (Foster, Gray, and Offler, 1996). Dates up to 10 to 15 Ma older than those from the fault zones are given by metamorphic mica structurally higher in the thrust sheets (Bucher, Foster, and Gray, 1996; Foster, Gray, and Offler, 1996; Foster and others 1997). These presumably reflect diagenesis/metamorphism prior to imbrication in the major thrust zones. Detrital mica, preserved in the less deformed areas and in sandstones, give ages between 490 and 520 Ma (Delamerian) in the Stawell and Bendigo-Ballararat Zones, and about 500 and 450 to 430 Ma in the Melbourne Zone (Turner and others, 1996; Foster, Gray, and Offler, 1996; Foster and others 1997).

The sedimentary record.—The Lachlan Fold Belt sedimentary record shows two major effects of orogeny: First, a marked change at the end of the Ordovician period where relatively deep marine environments, widespread during the Ordovician and Cambrian, were significantly reduced in extent and replaced by greater facies diversity and palaeogeographic complexity (see Cas, 1983, fig. 24). Second, a major regional unconformity overlain by Late Devonian/Early Carboniferous continental successions reflects the final emergence of the orogen. This period was marked by subaerial environments, graben-controlled sedimentation, and bimodal volcanism typical of modern continental rift environments (Cas, 1983).

In the western subprovince the major effects in sedimentation are shown by a progradation from the west to the east (Early Ordovician to late Early Devonian): Stawell Zone (unfossiliferous Cambrian to Early Ordovician turbidites, intruded locally by Early Ordovician plutons: Foster and others, 1997); Bendigo-Ballararat Zone (Early Ordovician graptolite faunas); Mel-

bourne Zone (Silurian to late Early Devonian turbidites, mudstones and reworked sandstones, with detrital mica ages consistent with derivation from the Stawell and Bendigo-Ballararat Zones (Bucher, Foster, and Gray, 1996). Burial prior to crustal thickening must range between 5 and 10 km based on the thickness of the sediment pile (Cas and VandenBerg, 1988), with uplift (<10 km) in the Middle to Late Devonian (Offler, McKnight, and Morand, 1996; Foster, Gray, and Offler, 1996) causing a change from deep marine to continental fluvial facies sedimentation (Cas and VandenBerg, 1988). In the Melbourne Zone (fig. 4, zone 3), after the late Early Devonian (Emsian) there was a change from deep marine sedimentation to terrestrial conditions. This was associated with a marked reduction in the volume of relatively deep-water facies across the fold belt (see Cas, 1983, fig. 24). These effects have been related to the Middle Devonian "Tabberabberan" orogenic event.

The Melbourne Zone (fig. 4, zone 3) contains a thick, unbroken Silurian-Lower Devonian sedimentary succession but shows progradation from west to east (VandenBerg, 1988, table 4.1). In the west there is a thicker basal Silurian to Pragian sequence (9-10 km thick in Darraweit Guim province) than in the east (2.2 km thick in Mount Easton province: Ramsay and VandenBerg, 1986, p. 225; VandenBerg, 1988). The Lower Devonian successions are marked by shallowing in the west and turbidite deposition (>5 km) in the east. Sedimentation was terminated after deposition of 2 to 4 km thick late Early Devonian (Frasnian) to mid Devonian (Eifelian) Cathedral Beds (VandenBerg and Wilkinson, 1982). $^{40}\text{Ar}/^{39}\text{Ar}$ analyses on weakly to strongly cleaved samples from the eastern Melbourne Zone give dates of 450 to 430 Ma for the inherited detrital mica components (Bucher, Foster, and Gray, 1996), reflecting the Late Ordovician or Early Silurian deformation of the Early Ordovician quartz-rich turbidites in the zones to the west (fig. 4, zones 1 and 2). This suggests cannibalization of the deformed terrains to the west and a general progradation in sedimentation from west to east across the belt.

In part of the eastern subprovince of the Lachlan Fold Belt (fig. 4, zone 6), the sedimentary record shows a marked change from black shale to turbidites at the Ordovician-Silurian boundary (VandenBerg and Stewart, 1992), but in the easternmost part (fig. 4, zone 7) there is no break between Late Ordovician and the late Llandovery Yalmy Group (VandenBerg and Stewart, 1992). In southern New South Wales (fig. 4, zone 9) there are marked unconformities between Early and Late Silurian strata and a change from deeper water quartz-turbidite submarine fans in the Ordovician to shallow water successions including subaerial acid volcanism with stratiform metalliferous deposits and limestone in the Late Silurian (Crook and others, 1973, figs. 9, 10, 11). Widespread Silurian deformation led to marked crustal thickening across the fold-belt and caused a change from open-ocean deep-marine conditions along the Gondwana continental margin in the Ordovician to a mixed continental-shallow-deep marine basin with parts emergent in the late Silurian-Devonian. By the Late Devonian much of the fold-belt was emergent and was undergoing continental-facies sedimentation and bimodal volcanism with cauldron complexes (Cas, 1983; Powell, 1983).

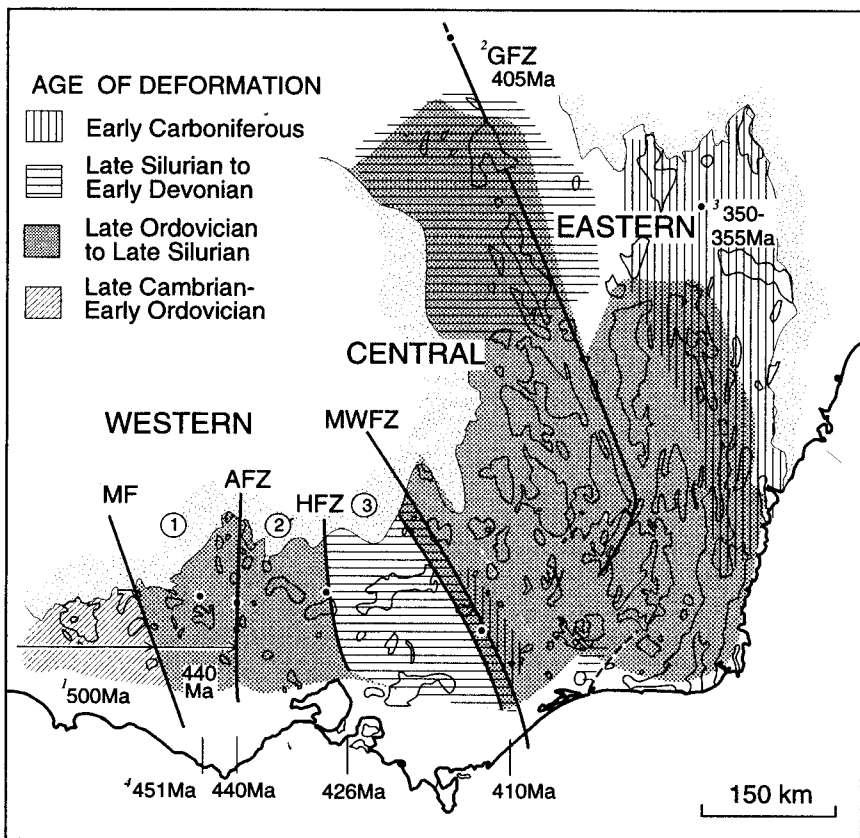


Fig. 10. Age-of-deformation map for the Lachlan Fold belt showing the temporal and spatial relationships of the major deformational events in the western, central and eastern subprovinces. Deformation ages were previously poorly constrained to time periods of 10 to 40 Ma (see fig. 6) largely by ages of the post-tectonic granites, ages of the youngest sedimentary rocks affected by the deformation, and local to regional unconformities. Deformation age data include; (1) Bucher, Foster, and Gleadow 1995; (2) Glen, Dallmeyer, and Black 1992; (3) Lu and others; and (4) Foster, Gray, and Offler 1996. Circled numbers are: (1) Stawell Zone; (2) Bendigo-Ballarat Zone; and (3) Melbourne Zone. MF: Moyston Fault Zone; AFZ: Avoca Fault Zone; MWFZ: Mount Wellington Fault Zone; GFZ: Gilmore Fault Zone.

The major regional unconformity is overlain by the Late Devonian-Early Carboniferous "Lambie" facies redbed sandstones and siltstones.

DISCUSSION

Orogenic concepts have changed because of the plate-tectonic paradigm which assumes first, that deformation on a plate scale is gradual and continuous involving slow rates of deformation, and second, that initiation of orogenic events is associated with reorganization of crustal plate motions and

poles of rotation. In detail, orogenic belts are largely "thin-skinned" tectonic elements and must involve diachronous deformation with variations in structural complexity in both space and time.

Traditional thinking of "orogenic events" and tectonic phases is based on definition of orogeny as occurring in sharply delimited pulses with orogenic belt evolution considered as a series of such spasms, events, phases, or episodes (Rodgers, 1971; Cebull, 1973). Many orogenic events have now been redefined over longer periods and do not represent brief, singular events (<10 Ma duration) but rather prolonged episodes or sequences of events that lasted at least over a geological period (Taconic orogeny: Rodgers, 1971; Acadian Orogeny: Williams, 1993, p. 125).

Ideas of orogeny, particularly in the Australian context (Rutland, 1976; Powell, 1984), range from "episodic" orogeny involving short time periods (epochs) separated by much longer epochs of rest or negative movements, where unconformities are evidence for orogenic deformation, to "climactic" orogeny, involving a major deformational pulse that leads to a stabilized, subaerial orogen ("Tabberabberan" of the Lachlan Fold Belt). More recently, arguments for more "continuous" deformation, associated with the gradual and approximately linear displacements of lithospheric plates in the plate-tectonic paradigm (Hsu, 1981), led to concepts of 'megascale' orogeny with >100 Ma duration. In the Lachlan Fold Belt, Cas (1983) argued that the short-lived, "deformational" events previously assigned orogeny status are better viewed as parts of a larger scaled "Lachlan Orogeny" which extended over the lifespan of the orogenic belt. These events did not affect the whole belt synchronously nor uniformly everywhere.

Orogeny may occur and appear in the rock record as episodic pulses with time-scales of a few million years simply because of changes in accommodation mechanisms on the orogenic and plate scale. Examples of this in modern orogenic belts include the record of the collision of India with Asia. Initial collision occurred at 60 to 55 Ma (Klootwijk and others, 1992, 1994), and the accommodation to this collision has changed several times during Paleogene and Neogene times (Tapponnier, Peltzer, and Armijo, 1985; Molnar and Tapponnier, 1975; Harrison and others, 1992). The change from dominantly continental escape to shortening on the various major thrusts appears episodic in the uplift, sedimentation, and geochronologic data; however, on the scale of the entire orogenic system convergence has continued at a relatively constant rate (Koolwijk and others, 1994; Molnar and Tapponnier, 1975; Harrison and others, 1992).

In the modern context, orogeny should be defined by a combination of unconformities, generation of metamorphic fabrics, rock deformation, plutonism, sedimentation, and exhumation. More than one of these manifestations of orogeny should be used to define an "orogeny." For example, unconformities must be considered significant indicators of orogeny, but they do not necessarily reflect orogenic belt-wide tectonic events. Dating of mica growth in relatively low-grade rocks and of other dateable minerals with higher closure temperatures at higher grades (for example monazite; Kingsbury and others, 1993) has the potential to record discrete events related to a

thermal maximum coincident with maximum burial and structural thickening. However, the geochronology cannot be considered alone.

In this light, the orogenic framework of the Lachlan Fold Belt needs to be completely revised. Cleavage in the chevron-folded sandstones and mudstones of the Lachlan Fold Belt developed late in the folding sequence (Gray and Willman, 1991b; Yang and Gray, 1994). Syntectonic mica growth was associated with an approximately axial-planar grain-alignment cleavage that overprints an earlier formed, fanning spaced cleavage (see Yang and Gray, 1994, fig. 9). It is how these mica growth events vary temporally and spatially across the orogenic belt that determines the significance of the old orogenic framework. The $^{40}\text{Ar}/^{39}\text{Ar}$ dates from the metamorphic mica for the western subprovince of the Lachlan Fold Belt show a diachronous, transgressive deformation extending over 40 Ma at rates consistent with modern plate movements (Bucher, Foster, and Gray, 1996; Foster, Gray, and Offler, 1996). These data highlight the Silurian as a period of marked tectonism in this western belt and probably throughout the foldbelt as a whole.

Linked with the definition of orogenic events is the question of the time scale over which orogeny occurs. This can be highly variable depending upon the type of plate interaction responsible for the orogenic event. A summary of pre-1981 orogenic data suggested that most named orogenies have defined or constrained durations of <10 Ma (see Pfiffner and Ramsay, 1981, fig. B1). Continent-continent collisional orogenies can last over 100 Ma (the Grenville Orogeny: Rankin and others, 1993; and the East African Orogeny: Stern, 1989). In the Himalayan collisional belt orogenesis has already lasted over 60 Ma, but individual movements to define separate "events" have not been separated out. India is inferred to have started colliding with Asia at 65 to 55 Ma (Klootwijk and others, 1992, 1994), but the first evidence for major crustal thickening was at 27 to 23 Ma shown by movement on the Gandise Thrust (Yin and others, 1995). Geochronology shows a progressive southward younging of major periods of fault-zone movements with 24 to 18 Ma on the Main Central thrust and 11 to 4 Ma on the Main Boundary thrust (Harrison and others, 1992; Meigs, Burbank, and Beck, 1995; Yin and others, 1995). The first evidence for widespread uplift was at 20 to 15 Ma, with a narrow but high mountain belt formed between 27 to 22 Ma (Copeland and others, 1987; Harrison and others, 1993). Orogenies in continental-margin situations involving subduction are also documented to occur over time scales of millions of years (the Sevier/Laramide Orogeny of western North America: Miller and others, 1992).

We propose that the orogenic cycle in the Lachlan Fold Belt be expanded to comprize evolving deformation/sedimentation and magmatism from Late Ordovician-Early Silurian to Late Devonian times, the Silurian being the major period in the tectonic evolution of the belt, particularly with respect to deformation, metamorphism, and plutonism. Carboniferous deformation is separated because it is presumably related to tectonic processes farther east and may be related to New England orogenic events (Coney and others, 1990). The time from what was previously defined as Benambran to Tabberabberan is redefined as one progressive orogenic episode that we now

call the Lachlan Orogeny after Cas (1983) (see fig. 6). The process of orogeny in the Lachlan Fold Belt was partly cyclical involving sedimentation, folding, structural thickening, imbrication, uplift, erosion, and resedimentation, in a prograding "thrust-system" which generally migrated away from the Australian Precambrian craton. This prograding deformation is similar to thickening in an accretionary wedge above a subduction complex (Byrne, Wang, and Davis, 1993; Wang and Davis, 1996). In the western subprovince the end of the long-lived progression of orogeny is related to the termination of subduction and closing of the ocean basin (that was called the "Tabberabberan" event). The eastward progression observed is recorded by the $^{40}\text{Ar}/^{39}\text{Ar}$ mica dates that reflect mica growth in the high-strain zones of the turbidite wedges above imbricated oceanic crust.

Collisional belts appear to display ordered diachronous deformation fronts, which may or may not be related directly to plate-convergence directions or processes. Differences in the preserved rock record and modes of deformation are highlighted by modes of accommodation (for example, extrusion via strike-slip faulting, wedge shortening, thrust faulting, and imbrication). In the Appalachians, the Taconic, Acadian, and Alleghanian orogenies represent different "docking" events in the Appalachian tectonic history. The Taconic event, which lasted over 50 Ma, is due to docking of an island arc and attendant closure of an ocean basin (Stanley and Ratcliffe, 1985). The Acadian and Alleghanian events reflect collision of Avalonia and continent-continent collision between Africa and North America with closure of the Iapetus Ocean (Rast, 1988). The tectonic evolution of the Lachlan Fold Belt can be subdivided into two main Taconic-like "events", the earlier episode dominating the Silurian represents the closure of a small ocean basin in the western subprovince, and the Carboniferous episode related to convergence between the Lachlan and New England Fold Belts.

SIGNIFICANCE FOR OROGENESIS IN OCEANIC SYSTEMS

The Lachlan Fold Belt shows evidence for subduction-related transitory and diachronous deformation. The apparent complexity of deformation patterns (Coney and Fergusson, 1992a; Glen, 1992; Gray, 1997; Gray, Foster, and Bucher, 1997) reflects the interaction of microplates and three subduction systems in a relatively complex oceanic setting in the Silurian period (figs. 11, 12). Differences between the deformational, metamorphic, and magmatic character of the western, central, and eastern subprovinces of the Lachlan Fold Belt reflect their different tectonic positions. Exposure of rocks deformed under higher temperature conditions in the east (for example "hot" thrusts: Glen, 1992) relate to deformation in the arc and forearc position, whereas lower heat input in the west relates to accretionary-complex-style deformation in a small marginal ocean basin and/or back arc basin (fig. 12). Some of the previous tectonic models called for Precambrian continental crust to underlie the Lachlan Fold Belt to explain the source of the granitoid plutons (Chappell, White, and Hine, 1988). This interpretation is based only

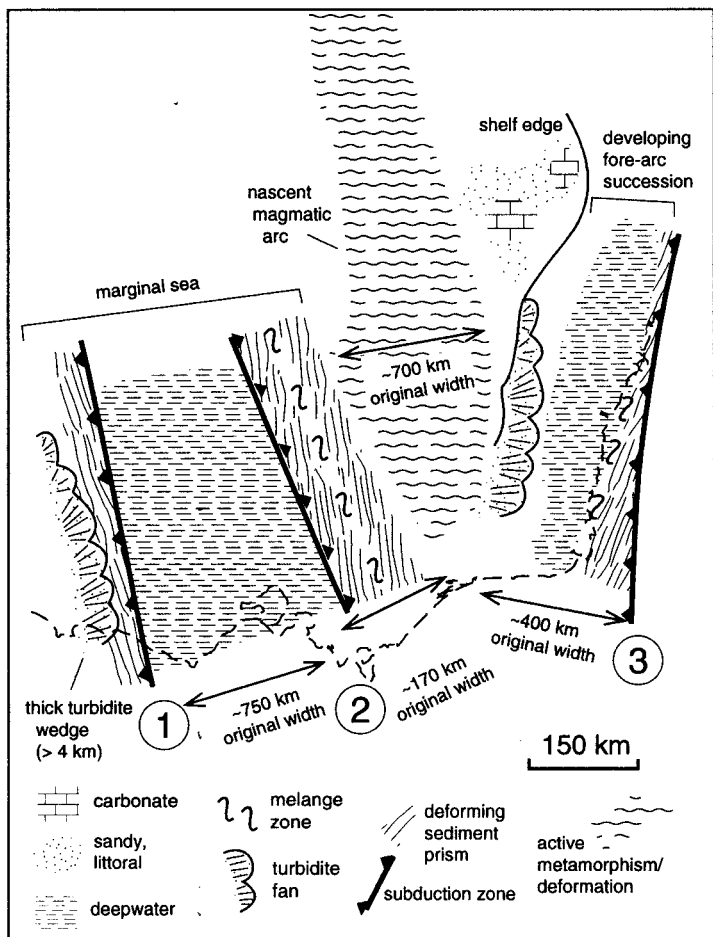


Fig. 11. Tectonic synthesis map showing the positions of the three subduction zones within a complex southwest-Pacific-style oceanic setting in the Early Silurian (map base modified from Powell, 1983, fig. 2a). Early Silurian metamorphic and key paleogeographic elements are also shown. Distances between tectonic elements represent restored shortenings after retrodeformation of the chevron-folded and faulted sedimentary successions (Gray and Willman, 1991a, fig. 10). The positions of the subduction zones are not fixed but migrate with respect to each other and the geographic template over time. For example, the marginal sea (Melbourne "trough") closes due to convergence of subduction zones 1 and 2 in the late Early Devonian to mid-Devonian (see Soesoo and others, 1997).

on restite models for granitoid genesis and is not consistent with the fact that Precambrian crust does not crop out east of the Tasman Line (see fig. 1). More recent isotopic and geochemical data as well as the structural and tectonic style of the belt as discussed here indicate that only oceanic crust is needed, because the granitoid chemistry can be explained in terms of mixing

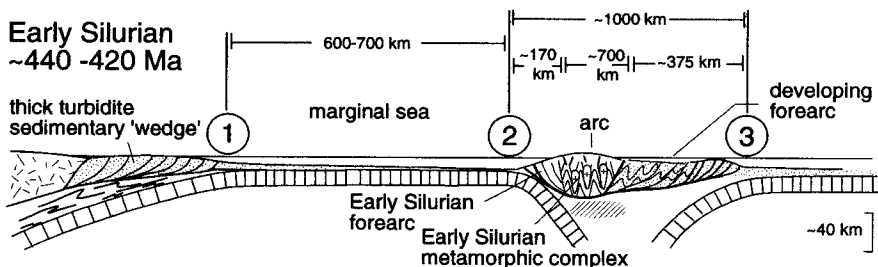


Fig. 12. Plate setting for the Early Silurian period based on the geology at 37.5° S latitude showing configuration of the three subduction zones in fig. 11. Circled numbers refer to the inferred subduction zones (see text for discussion). Distances (km) represent restored shortenings after retrodeformation of the chevron-folded and faulted sedimentary successions. This gives a palinspastic restoration of approximately 1500 to 2000 km between subduction zones 1 and 3 (see fig. 11). The marginal sea between the Delamerian Orogen and the developing Wagga-Omeo Metamorphic belt was up to 600 to 700 km wide.

between mantle and crustal components (Gray, 1990; Collins, 1996; Ehlberg, 1996; Rossiter and Gray, 1996; Keay, Collins, and McCulloch, 1997).

Deformation in such oceanic settings, like the modern southwest Pacific (Hamilton, 1979; Hall and Blundell, 1996), differs from, and does not always leave evidence of a classic suture typical of, continent-continent collisions (for example Indus-Yarlung Tsangpo suture, Himalayan orogen: Searle and others, 1987). Based on the western Lachlan Fold Belt, ophiolites may occur in former oceanic settings as remnants along major faults preserved within the turbidite wedges. The ophiolite remnants are a product of thrust imbrication and detachment within the upper part of the former oceanic crust. These thrust systems develop as leading imbricate fans, associated with tiered detachment systems by duplexing in the oceanic crust and imbrication in the overlying turbidite wedge (Gray, 1995). The $^{40}\text{Ar}/^{39}\text{Ar}$ data indicate that this occurs diachronously by migration of a deformation front above a decollement, linked in some way to subduction processes. Deformation occurs within the structurally thickening wedge by chevron folding, cleavage development, and imbricate thrusting. Recycling of metamorphic mica into younger sediments indicates that contraction is simultaneous with sedimentation outboard in the oceanic sediment wedge. The subduction model is supported by the presence of relict blueschist facies metamorphism in the Cambrian metavolcanic rocks (Nicholls, 1965; Wilson and others, 1992, p. 123) and the intermediate pressure/low temperature metamorphic field gradient shown by white micas in slates of the Ordovician turbidite sequence (Offler, McKnight, and Morand, 1996; Foster, Gray, and Offler, 1996). A magmatic arc associated with the proposed west-dipping subduction zone of the western subprovince (figs. 11, 12, subduction zone 1) was not developed during Silurian time probably because subduction was of very shallow dip, and the ocean basin that closed was relatively small, so that the amount of subduction was therefore limited.

The other subduction zones (figs. 11, 12, subduction zones 2 and 3) have been inferred to explain the spatial and temporal distribution of structures, metamorphism, and plutonism in the central and eastern subprovinces of the Lachlan Fold Belt. Previously, diachroneity of deformation and migration of orogeny in time and space, particularly in the eastern Lachlan Fold Belt, had been related to the migration of a deformation front controlled by heat focusing in the mid-crust. Deformation was proposed to be caused by plutonism in a neutral stress regime. Orogeny, it was argued, was centered around meridional batholiths with deformation due to thermally controlled (thermal softening) migration from a magmatic/metamorphic core or the transitory axis of an ancient mature magmatic arc (Rutland, 1976, p. 176; White, Chappell, and Clearly, 1974; Collins and Vernon, 1992). The extensive granites in the eastern belt have been explained by anomalous thermal behavior in the mantle (Chappell, White, and Hine, 1988), lithospheric delamination due to structural thickening (Looseveld and Etheridge, 1990; Cox and others, 1991; Collins, 1994; Collins and Vernon, 1994), lithospheric extension (Cas, 1983; Sandiford and Powell, 1986; Zen, 1995), and multiple subducting slabs (Collins and Vernon, 1992; Gray, 1997; this paper). Most recent interpretations based on isotopic and geochemical data argue for magma mixing mechanisms, 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, Collins, and McCulloch, 1997).

The southwest-directed thrusting in the Tabberabbera Zone (fig. 4, zone 4) and the high temperature/low pressure metamorphism and elongated, northwest-trending Late Silurian to Early Devonian granitoids of the Wagga-Omeo Metamorphic Complex (fig. 4, zone 5) have been related to an northwest-trending, east-dipping subduction zone beneath the Wagga Omeo Zone (figs. 11, 12, subduction zone 2). The subduction model implies that the Tabberabbera Zone is a Silurian accretionary complex. This is supported by the strong development of bedding-parallel fabrics in the turbidites of the Tabberabbera Zone (Gray, Miller, and Gregory, 1996), a 2-km-wide zone of melange/broken formation (Wonnangatta Fault Zone) separating polydeformed Ordovician rocks to the northeast (inferred rear of prism) from poorly cleaved, weakly metamorphosed, simply folded Silurian rocks to the west (inferred frontal part of prism) (Fergusson, 1987; Fergusson and Gray, 1989; Fergusson personal communication, 1996). Younging of the deformed sediment wedge in the direction of imbrication is typical of modern accretionary complexes (Scholl, Marlow, and Cooper, 1977; Von Huene, 1984).

Evidence for the easternmost subduction zone (figs. 11, 12, subduction zone 3) occurs on the south coast of New South Wales where an imbricated turbidite, chert, basalt sequence of mid-Cambrian to Late Ordovician age is associated with chaotic block-in-matrix melange, broken formation, early bedding-parallel fabrics in turbidites, and planar-linear fabrics (prolate strain ellipsoids) in the structurally lowest units (Miller and Gray, 1996, 1997). A "coastal" belt with dominant early bedding-parallel fabric, isoclinal recum-

bent folding, poly-deformation, and differentiated layering in the quartz-rich turbidites, shows a strain-dependent transition into an "inland" belt of chevron-folded turbidites cut by high-angle reverse faults. We argue that this subduction zone was north-trending and west-dipping and caused the magmatism responsible for the extensive, north-trending, elongated granitoids in the eastern subprovince of the Lachlan Fold Belt. An easterly younging in these granitoids probably relates to slab rollback during the mid-Late Silurian through the Early Devonian (Coney and Reynolds, 1977). Implied rollback rates are $\sim 6\text{mm/yr}$ (Powell, 1983, fig. 9) for subduction zone 3 (figs. 11, 12).

Subduction-controlled deformation of the Cambrian to Middle Ordovician basin was operative in both the western and central/eastern Lachlan Fold Belt during the Late Ordovician to Silurian (figs. 11, 12, subduction zones 1 and 2). This phase in the tectonic evolution was terminated in the late Early Devonian by closure of a marginal basin or back-arc basin in the western subprovince with docking of an island arc/forearc system (central/eastern subprovinces). The effects have been previously related to the climactic "Tabberabberan" orogenic event which preceded the development of the major regional, fold-belt-wide angular unconformity. However, the regional extent of this unconformity suggests that it must rather reflect a morphogenic phase of "mountain building", where relatively rapid uplift with unroofing of granitoid plutons is the follow-up of the compressional phase of orogenic evolution (Gansser, 1982). The causes of such uplift (for example, crustal flexure, crustal thickening, lithospheric delamination, thermal expansion, isostatic compensation) are still being debated in most orogenic belts. The oldest apatite fission-track ages, with corresponding long mean track lengths, from high elevations and down-faulted blocks in the Lachlan Fold Belt reveal relatively rapid cooling and denudation during the late Early Devonian (Moore and others, 1986; Foster and Gleadow, 1992, 1993). This is also the time that the Early Devonian plutons in the western subprovince cooled through final closure to argon loss in K-feldspar, associated with erosional unroofing (Bucher and others, 1995).

The Lachlan Fold belt typifies orogenic systems that develop when "Bengal-type" turbidite fan systems along former continental margins encounter and clog-up subduction zones (compare with "Turkic type" of Sengor and Natal'in, 1996). Orogenesis occurs in such oceanic settings by deformation within structurally thickening sedimentary wedges, which prograde and migrate in front of the subducting plate. Large volumes of eroded sediment that were part of such fan deposits on the ocean floor eventually become incorporated into new 'continental' crust by the processes of deformation, metamorphism, and magmatism, in a manner not unlike continental growth described by Crook (1980). Crustal thicknesses approach 35 km, due to structural thickening and additions of magma into the lower crust during subduction-related magmatic-underplating episodes. This type of accretion is characterized by chevron-folded turbidite sequences, fault-bounded remnants of oceanic crust, and large proportions of granitoids (up to 36 percent surface area).

ACKNOWLEDGMENTS

Ideas in this paper have evolved over a number of years and have benefited from interactions with Chris Powell, Ray Cas, Chris Fergusson, Robert Gregory, Ian Nicholls, Chris Gray, Gordon Lister, Lynn Glover III, Fred Read, Krishna Sinha, Nick Woodward, Vince Morand, Colleen Elliot, Andrew Gleadow, and Martin Bucher. Impetus for the paper came from the results of $^{40}\text{Ar}/^{39}\text{Ar}$ dating of slates and plutonic rocks by Bucher and Foster. The work was supported by the Australian Geodynamics Cooperative Research Centre (AGCRC) and was a collaborative project between the VIEPS Departments of La Trobe and Monash Universities under the auspices of the AGCRC. We thank Chris Mawer (Project Leader) and Barry Drummond (Program Leader) for their support during the course of the research. The paper was published with permission of the Director, Australian Geodynamics Cooperative Research Centre. We thank Sylvia Zakowski for help with drafting, manuscript preparation, and literature search, Bob Gregory for comments on the manuscript, and Evan Leitch and John Rodgers for review and editorial comments.

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