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Evolution of the southeastern Lachlan Fold Belt in Victoria

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The Benambra Terrane of southeastern Australia is the eastern, allochthonous portion of the Lachlan Fold Belt with a distinctive Early Silurian to Early Devonian history. Its magmatic, metamorphic, structural, tectonic and stratigraphic histories are different from the adjacent, autochthonous Whitelaw Terrane and record prolonged orogen-parallel dextral displacement. Unlike the Whitelaw Terrane, parts of the proto-Benambra Terrane were affected by extensive Early Silurian plutonism associated with high T/low P metamorphism. The orogen-parallel movement (north–south) is in addition to a stronger component of east–west contraction. Three main orogenic pulses deformed the Victorian portion of the terrane. The earliest, the Benambran Orogeny, was the major cratonisation event in the Lachlan Fold Belt and caused amalgamation of the components that comprise the Benambra Terrane. It produced faults, tight folding and strong cleavage with both east–west and north–south components of compression. The Bindian (= Bowning) Orogeny, not seen in the Whitelaw Terrane, was the main period of southward tectonic transport in the Benambra Terrane. It was characterised by the development of large strike-slip faults that controlled the distribution of second-generation cleavage, acted as conduits for syntectonic granites and controlled the deformation of Upper Silurian sequences. Strike-slip and thrust faults form complex linked systems that show kinematic indicators consistent with overall southward tectonic transport. A large transform fault is inferred to have accommodated approximately 600 km of dextral strike-slip displacement between the Whitelaw and Benambra Terranes. The Benambran and Bindian Orogenies were each followed by periods of extension during which small to large basins formed and were filled by thick sequences of volcanics and sediments, partly or wholly marine. Some of the extension appears to have occurred along pre-existing fractures. Silurian basins were inverted during the Bindian Orogeny and Early Devonian basins by the Tabberabberan Orogeny. In the Melbourne Zone, just west of the Benambra Terrane, sedimentation patterns in this interval, in particular the complete absence of material derived from the deforming Benambra Terrane, indicate that the two terranes were not juxtaposed until just before the Tabberabberan Orogeny. This orogeny marked the end of orogen-parallel movement and brought about the amalgamation of the Whitelaw and Benambra Terranes along the Governor Fault. Upper Devonian continental sediments and volcanics form a cover sequence to the terranes and their structural zones and show that no significant rejuvenation of older structures occurred after the Middle Devonian.

KEY WORDS: Benambra Terrane, Benambran Orogeny, Bindian Orogeny, Lachlan Fold Belt, Palaeozoic, stratigraphy, Tabberabberan Orogeny, tectonics, Victoria.

INTRODUCTION

Many subdivisions of the Lachlan Fold Belt are based on structural and stratigraphic features that are important in understanding the tectonic history of the belt in the Cambrian to Early Silurian interval, prior to the Benambran Orogeny (Glen 1992; Gray 1997). However, a different, but equally important, subdivision can be erected for the period following the onset of the Benambran Orogeny from the Early Silurian to Devonian. This paper describes the large-scale tectonism that affected the fold belt during this time and demonstrates that the Lachlan Fold Belt can be divided into two distinct parts, which had different stratotectonic histories (Powell *et al.* 1990; VandenBerg *et al.* 2000). We use the terminology of VandenBerg *et al.* (2000), who named the western part the Whitelaw Terrane and referred to the eastern part as the Benambra Terrane (Fergusson *et al.* 1986).

The fundamental differences between the two terranes can only be seen in Victoria, where an uninterrupted section is exposed across the whole Lachlan Fold Belt, including the boundary between them (Figure 1). Neither the Whitelaw Terrane nor the western part of the Benambra Terrane are exposed in New South Wales. In addition, the distinction between structures formed during the Benambran, Bindian and Tabberabberan Orogenies is more readily made in Victoria than in New South Wales, where structural trends for all the orogenies are mainly north–south. Structures formed by orogen-parallel movement are also best displayed in Victoria.

This paper describes the defining characteristics of the Benambra Terrane and the features that distinguish it from the Whitelaw Terrane, and examines its complex tectonic history from the Early Silurian to the Devonian. It focuses on the Victorian part of the terrane, which occupies the eastern part of the State and where recent extensive geological and geophysical mapping has been

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carried out by the Geological Survey of Victoria. The tectonic history forms a basis for linking structural, magmatic and depositional events that contributed to the construction of the Early Palaeozoic crust of the southeastern Lachlan Fold Belt. In particular, we examine the evidence for orogen-parallel transport and its significance for the movement history of terrane accretion.

While the recognition of orogen-parallel movements in the Benambra Terrane can explain much of the complex geological history in the region, it is also important in understanding the history of the belt prior to the Early Silurian, when key plate-tectonic elements were active. These elements included a wide ocean basin receiving turbidites from the west and south (Powell 1983a; Fergusson & Colquhoun 1996), an intraoceanic mafic island arc (Glen *et al.* 1998), at least one large rifted fragment of continental crust (Scheibner & Basden 1998; Cayley *et al.* 2002) and subduction-related accretionary prisms (Miller & Gray 1997; Spaggiari *et al.* 2000). In the Benambra Terrane, much of the complexity that masks the original arrangement of these elements was imposed after their initial cratonisation in the Late Ordovician – Early Silurian Benambran Orogeny. Hence, by unravelling the Silurian to Middle Devonian history in Victoria we can provide some clues to the location of major tectonic elements in the Early Silurian.

The idea of large-scale strike-slip displacement of the Benambra Terrane is not new. Powell (1984) wrote that oblique plate convergence led to northwest–southeast dextral shear in the Late Ordovician followed by dextral transtension from the Silurian to Middle Devonian. Packham (1987) proposed large-scale sinistral transport between different outcrops of the Macquarie Arc. Fergusson *et al.* (1986) suggested that the Benambra Terrane was transported southward by dextral strike-slip movement along an ancestral fault (in place of the Mt Wellington Fault Zone) and was juxtaposed against the Melbourne Zone in a process beginning in the Silurian and culminating about the Middle Devonian. VandenBerg and Stewart (1992) favoured the model of Fergusson *et al.* (1986) because it is consistent with the distribution of lithofacies in Ordovician sediments in the Tabberabbera and Melbourne Zones. They suggested that a strike-slip reconstruction in the order of 400 km was needed to bring the Adaminaby and Castlemaine Groups along strike of each other, but VandenBerg *et al.* (2000) revised this estimate to approximately 600 km. Glen (1992) suggested that the Omeo Zone was transported southward in the Early Silurian and again in the Early Devonian. A part of Glen's model included northward transpressional insertion of the Melbourne Zone in the Early to Middle Devonian. However, we interpret the Melbourne Zone as a foreland basin to the uplifted Stawell and Bendigo Zones with only minor strike-slip displacement along the western margin of the Melbourne Zone after the Tabberabberan Orogeny (VandenBerg *et al.* 2000).

This paper is based on the model proposed by VandenBerg *et al.* (2000), who inferred a hypothetical fault

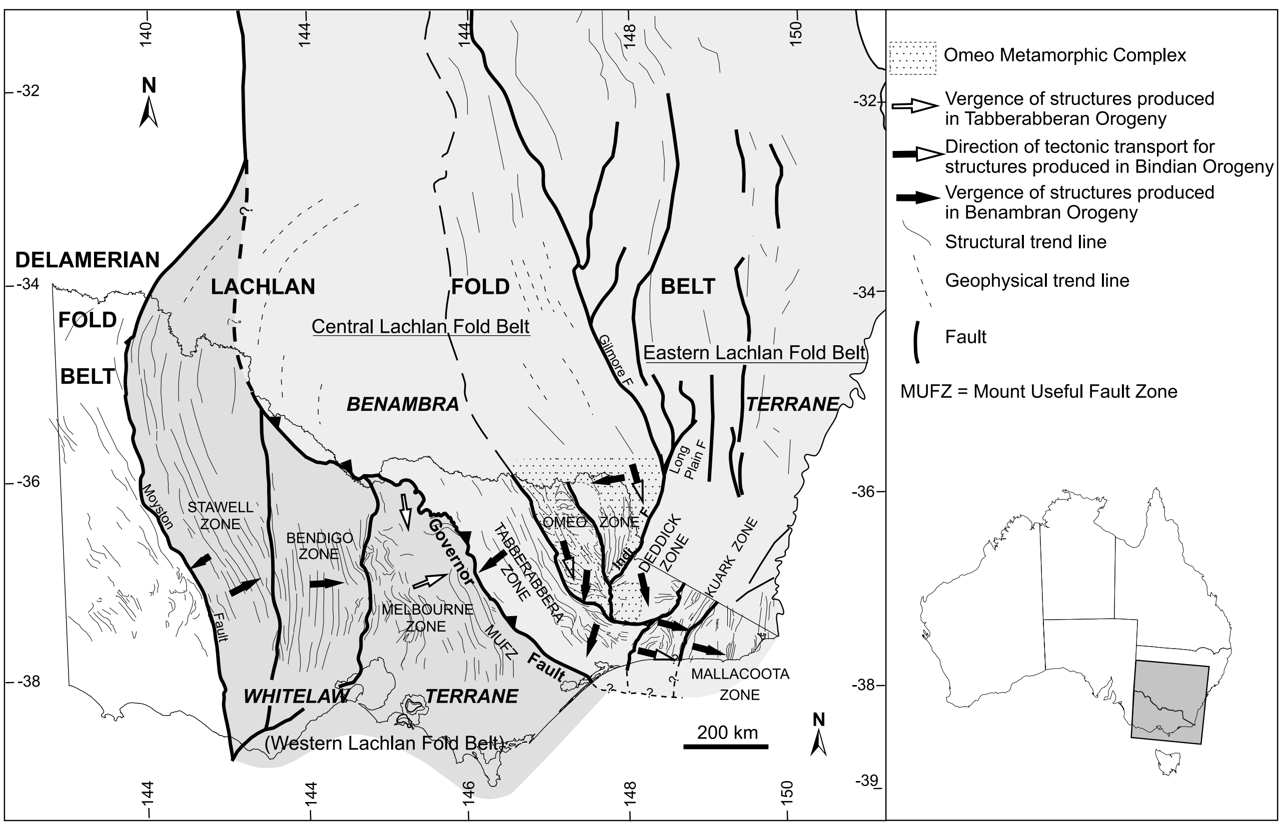


Figure 1 Structural subdivisions and terranes in Victoria and New South Wales showing vergence directions and dominant structural trends. New South Wales trends after Gray (1997). The Western, Central and Eastern Lachlan Fold Belts are subdivisions of the Lachlan Fold Belt after Gray (1997).

called the Baragwanath Transform, ancestral to the Governor Fault, that took up more than 600 km of orogen-parallel displacement between the terranes.

REGIONAL GEOLOGICAL SETTING

The Lachlan Fold Belt is one of the main components of the Tasman Fold Belt System in southeastern Australia. In Victoria it is approximately 700 km wide and its total strike length, including the New South Wales and Tasmanian portions, is approximately 1200 km.

There is a general consensus that the fold belt formed by protracted accretion of mainly oceanic crust against the Australian craton from the Late Ordovician to the Carboniferous (Cas 1983; Coney 1992; Gray 1997). The movement history of accretion was largely controlled by convergence orthogonal to the orogen, producing dominantly north–south structural trends, parallel to the Ordovician craton margin. In this environment, thin-skinned tectonics has been recognised as a dominant process across the belt (Glen & VandenBerg 1987; Cox *et al.* 1991; Gray & Willman 1991; Glen 1992). While many examples of orogen-parallel movement have also been documented, they are generally subordinate to orthogonal convergence (Glen 1992). The structural history is further complicated by distinct episodes of extension that separated the major contractional events (orogenies), and by protracted magmatism that produced migmatitic granites associated with regional metamorphism, syntectonic plutons within shear zones, and unfoliated post-tectonic granites.

This history presents a complex pattern of alternating extension, contraction and magmatism that was probably linked to a common and long-lived driving mechanism. Nevertheless, it is possible to distinguish four discrete deformation events in the terrane (cf. Gray 1997). These are the Benambran Orogeny (Late Ordovician to Early Silurian), Bindian (= Bowning) Orogeny (Silurian–Devonian boundary), Tabberabberan Orogeny (Middle Devonian) and the Kanimblan Orogeny (Early Carboniferous). The Benambran Orogeny was the most important cratonisation event, while the Kanimblan Orogeny was a relatively minor event in Victoria.

In the Benambra Terrane of eastern Victoria, exposed basement mainly comprises Ordovician to Lower Silurian deep-marine sedimentary rocks and their metamorphic equivalents. Underlying Cambrian volcanics are only exposed along and near the western margin of the terrane, although their presence in the Narooma area of southern New South Wales (Miller & Gray 1997) suggests that they may be widespread beneath the exposed (meta)sedimentary rocks. The central part of the Benambra Terrane in Victoria is dominated by high T/low P metamorphic rocks and associated S-type granites collectively known as the Omeo Metamorphic Complex. The Cambrian to Lower Silurian rocks were deformed by the Benambran Orogeny, which generated the Omeo Metamorphic Complex.

A major unconformity separates all these rocks from Upper Silurian extensional basin fills, which contain silicic volcanic rocks and sedimentary rocks that are mostly marine. This period of extension affected much of the Benambra Terrane and in some cases basins developed by transtension along existing strike-slip faults (Glen 1990). In eastern Victoria, the Bindian Orogeny inverted these basins in an event characterised by orogen-parallel movement largely facilitated by strike-slip faults. This was associated with widespread Early Devonian magmatism that generated predominantly I-type granites, some of which intruded active fault zones.

After the Bindian Orogeny, a second period of extension resulted in the deposition of Lower Devonian rift sequences. The Tabberabberan Orogeny deformed these in the Middle Devonian, but otherwise its effects were generally mild in the Benambra Terrane. Nevertheless, the orogeny was an important event that amalgamated the Whitelaw and Benambra Terranes and strongly deformed the Melbourne Zone.

Deposition of the volcanic and sedimentary rocks of the Avon Supergroup began during the Tabberabberan Orogeny and continued during post-orogenic extension in the (Mt) Howitt Province in central Victoria, continuous with the East Gippsland Province (O'Halloran & Cas 1995; VandenBerg *et al.* 2000). The Kanimblan Orogeny gently faulted and folded these rocks.

Table 1 Comparison of structural subdivisions in the southern Lachlan Fold Belt.

<table>
<tr><th></th><th>Victorian structural zones (VandenBerg et al. 2000)</th><th>Main subdivisions of the southern Lachlan Fold Belt (VandenBerg et al. 2000)</th><th>Main subdivisions of the southern Lachlan Fold Belt (Gray 1997)</th><th>Main subdivisions of the southern Lachlan Fold Belt (Glen 1992)</th></tr>
<tr><td>West</td><td colspan="4">Moyston Fault</td></tr>
<tr><td></td><td>Stawell</td><td rowspan="3">Whitelaw Terrane</td><td rowspan="3">Western Lachlan Fold Belt</td><td rowspan="3">Southwestern Belt</td></tr>
<tr><td></td><td>Bendigo</td></tr>
<tr><td></td><td>Melbourne</td></tr>
<tr><td></td><td colspan="4">Governor Fault</td></tr>
<tr><td></td><td>Tabberabbera</td><td rowspan="5">Benambra Terrane</td><td rowspan="2">Central Lachlan Fold Belt</td><td>Western Belt</td></tr>
<tr><td></td><td>Omeo</td><td>Central Belt</td></tr>
<tr><td></td><td>Deddick</td><td rowspan="3">Eastern Lachlan Fold Belt</td><td rowspan="3">Eastern Belt</td></tr>
<tr><td></td><td>Kuark</td></tr>
<tr><td>East</td><td>Mallacoota</td></tr>
</table>

WHITELAW AND BENAMBRA TERRANES

The Lachlan Fold Belt in Victoria has been divided into eight structural zones, each characterised by differences in structural trend and geological history, and bounded by regional-scale faults (Gray *et al.* 1988; VandenBerg *et al.* 2000). In several different schemes structural zones have been grouped into belts or terranes (Table 1). Powell *et al.* (1990) defined the West and East Lachlan Fold Belts separated by the Mt Wellington Fault Zone (Mt Useful Fault Zone). The Whitelaw and Benambra Terranes of VandenBerg *et al.* 2000) coincide with these except that their boundary lies a little farther northeast, along the Governor Fault. We include much of the Lachlan Fold Belt in New South Wales in the Benambra Terrane because it has a similarly complex history to the Benambra Terrane in Victoria (Figure 1).

It is important to understand that in our view, the Benambra Terrane did not exist before the Early Silurian. The terrane is a composite formed as a result of accretionary processes involving the Central and Eastern Lachlan Fold Belts that occurred in the Benambran Orogeny. We use the term proto-Benambra Terrane to collectively describe these components prior to their amalgamation in the Early Silurian.

Subdivision of the Lachlan Fold Belt into two terranes is based on the recognition that the structural and geological histories of structural zones on either side of the Governor Fault are quite different (Fergusson *et al.* 1986; Powell *et al.* 1990; VandenBerg & Stewart 1992; VandenBerg *et al.* 2000). In this paper we highlight the profound differences that emerged during and after the Benambran Orogeny. Prior to this, we consider that the western part of the Benambra Terrane was contiguous with the Whitelaw Terrane and hence they have a shared stratotectonic Cambrian to Early Silurian history. However, the central and eastern parts of the Benambra Terrane have some features not shared with the Whitelaw Terrane during this period. Some of the main differences and similarities between the Whitelaw and Benambra Terranes in Victoria

Table 2 Similarities and differences between the Whitelaw and Benambra Terranes after VandenBerg *et al.* (2000).

Whitelaw Terrane	Benambra Terrane
Similarities	
Widespread Cambrian volcanism	
Widespread Ordovician to Silurian turbidite deposition (restricted thickness only in the Melbourne Zone)	
Major deformation in the Late Ordovician – Early Silurian (Benambran Orogeny) (did not affect the Melbourne Zone)	
Major deformation in the Middle Devonian (Tabberabberan Orogeny)	
Early and Late Devonian magmatism	
Differences	
Deep marine sedimentation ceased in the Late Ordovician in the Stawell and Bendigo zones, but was continuous in the Melbourne Zone to the end of the Early Devonian.	Continuous deep marine sedimentation from the Early Ordovician to Early Silurian over a significant area.
No arc volcanism, and no volcanism of any kind in the Middle Cambrian to Early Devonian interval.	Large edifice(s?) of Ordovician arc volcanics and shallow-marine sedimentary rocks (mainly in New South Wales – Macquarie Arc).
Metamorphic grade is generally low except in the Moornambool Metamorphic Complex.	Regional metamorphism and associated polydeformation associated with the Benambran Orogeny (Wagga-Omeo and Kuark metamorphic complexes).
Early Silurian S-type granites and migmatites are absent.	Early Silurian S-type granites and migmatites are common.
East-west trending Benambran structures are absent—all are northwest- or north-trending and are associated with a regionally consistent east–west to northeast–southwest contraction.	East–west-trending Benambran structures indicate early development of localised components of north–south contraction associated with orogen-parallel tectonic transport.
Structural vergence has a dominant easterly sense except for the Moyston Fault and for a small area in the Melbourne Zone.	Regional vergence directions show a complex pattern.
Late Silurian intracratonic volcanic and sedimentary basins absent.	Late Silurian intracratonic volcanic and sedimentary basins common.
Late Silurian – Early Devonian plutonism is post-tectonic and less widespread.	Late Silurian – Early Devonian plutonism is commonly syntectonic and widespread.
Late Silurian – Early Devonian deformation weakly expressed or absent.	Late Silurian – Early Devonian deformation (Bindian Orogeny) affected much of the terrane.
Early Devonian rift basins absent.	Early Devonian rift basins with volcanic and sedimentary rocks common.
Unusually large number of rich gold deposits.	Small gold deposits only.
Magnetic dykes uncommon.	Magnetic dykes abundant.

are summarised in Table 2. A summary of the stratigraphic units in the Benambra Terrane in Victoria is given in Figure 2.

The Stawell, Bendigo, Tabberabbera and Omeo Zones, and possibly the Kuark Zone, are interpreted to have been in a backarc between the Cambrian and Early Silurian (Fergusson 1987a; Coney *et al.* 1990; Glen *et al.* 1998; Scheibner & Basden 1998; Collins & Hobbs 2001). The Melbourne Zone is inferred to have developed over rifted continental crust while attached to the Bendigo Zone (Cayley *et al.* 2002), and the Mallacoota Zone is composed of forearc and accretionary prism rocks that are very similar to the backarc rocks farther west (Scheibner & Basden 1998).

The plate-tectonic elements of the Central and Eastern Lachlan Fold belts were amalgamated to form the Benambra Terrane in the Benambran Orogeny (Collins & Hobbs 2001). After this the Whitelaw Terrane had a simple structural history, whereas the Benambra Terrane was strongly affected by a complicated interplay between east–west contraction, orogen-parallel (predominantly north–south) movements and two periods of extension. The Whitelaw Terrane was largely unaffected by the Bindian Orogeny, and the Tabberabberan Orogeny only deformed the Melbourne Zone in the terrane's eastern half. Evidence for orogen-parallel movement is mostly absent in the Whitelaw Terrane except for (i) a small area in the north of the Melbourne Zone where east–west structural trends are dominant, and (ii) minor strike-slip reactivation along some faults. It is likely that the main difference between these terranes is that the Whitelaw Terrane, after its accretion onto the 'Delamerian' Australian craton in the Benambran Orogeny, remained fixed in this position whereas the Benambra Terrane has been affected by southward tectonic transport over a protracted period spanning the Early Silurian to Middle Devonian (VandenBerg *et al.* 2000).

The magmatic histories of the Benambra and Whitelaw

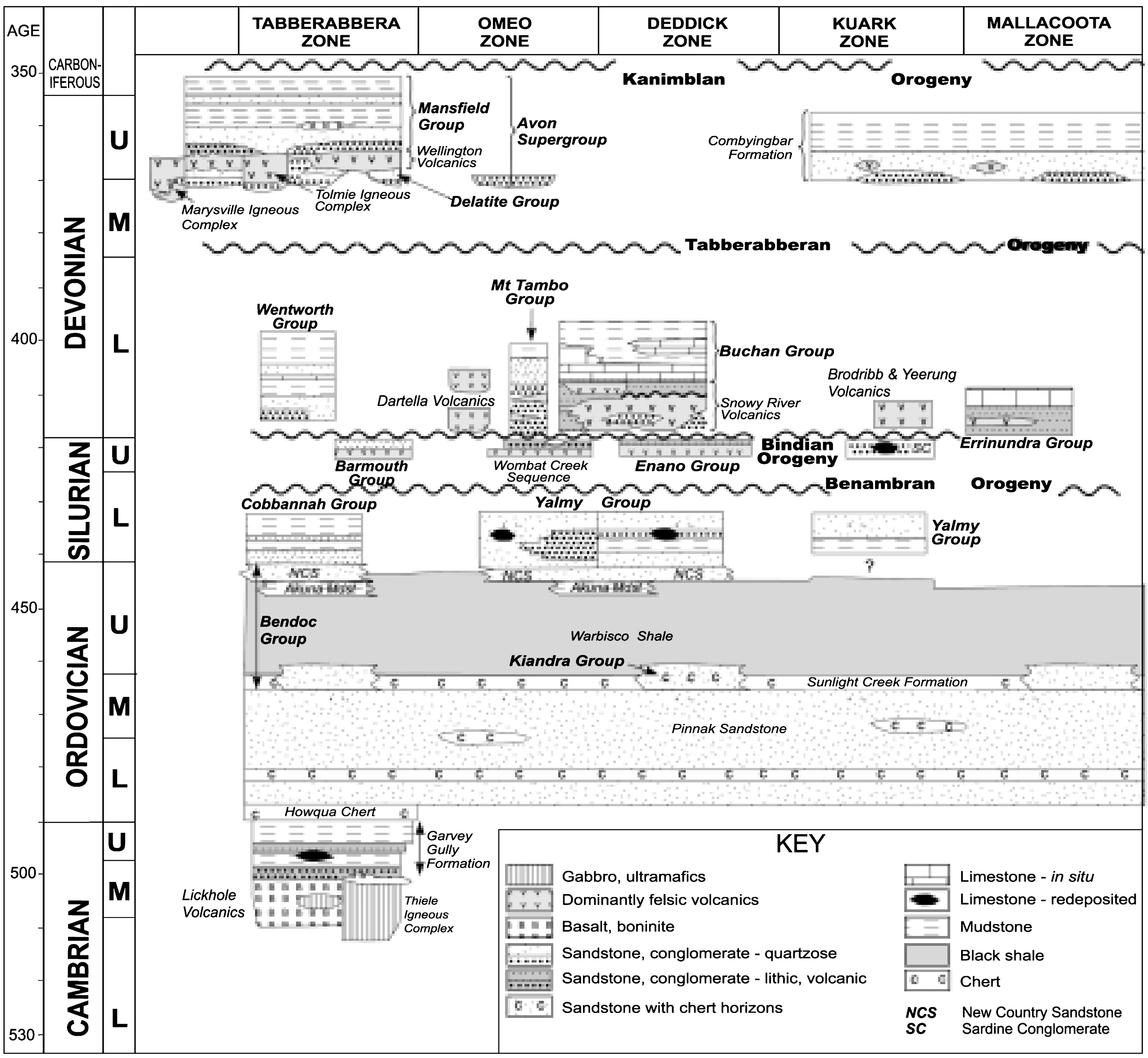


Figure 2 Time–space diagram for Palaeozoic rocks in the eastern Victorian portion of the Benambra Terrane.

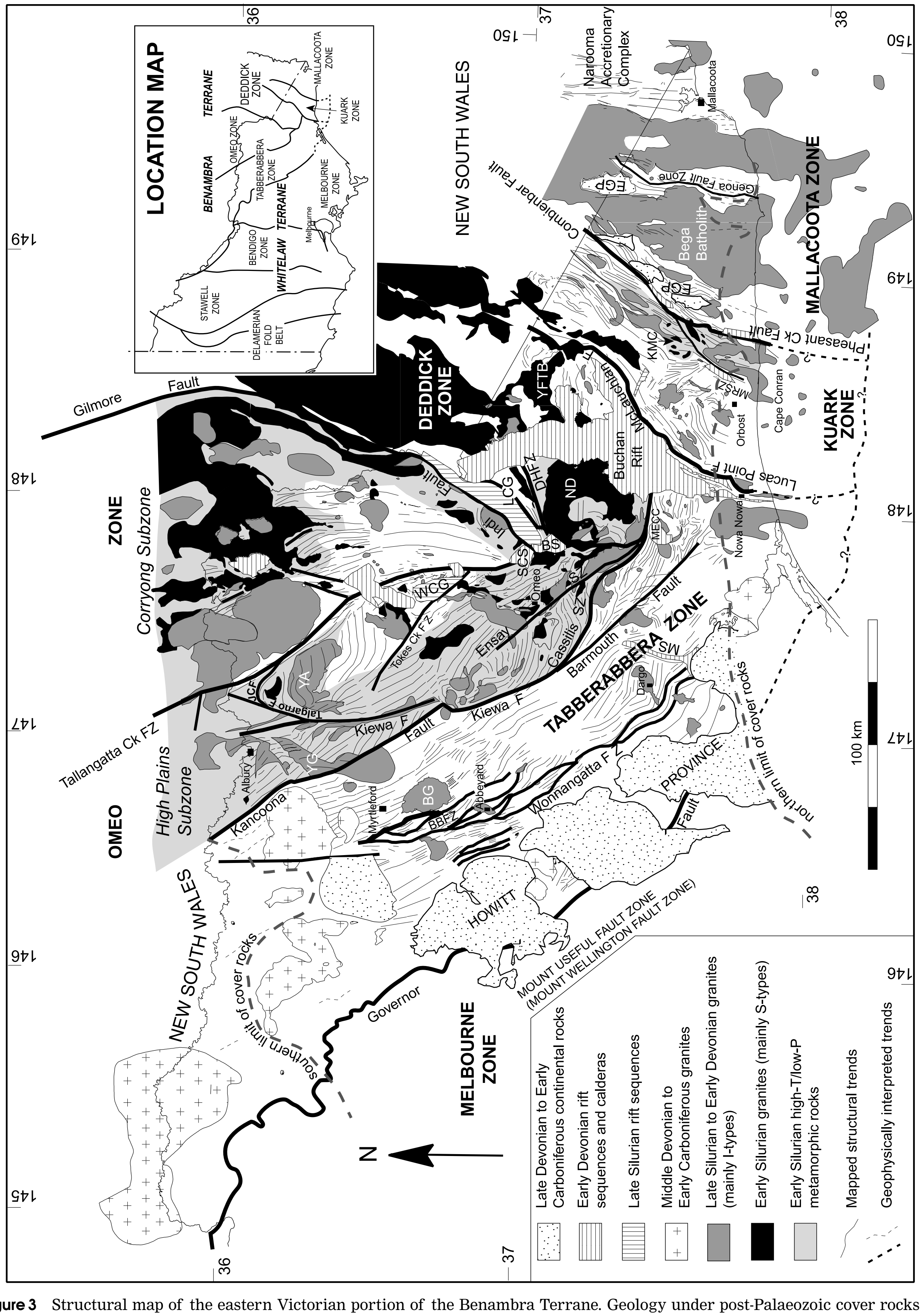


Figure 3 Structural map of the eastern Victorian portion of the Benambra Terrane. Geology under post-Palaeozoic cover rocks as interpreted from geophysical data (VandenBerg *et al.* 2000). BS, Bindi Syncline; BBFZ, Bread and Butter Fault Zone; BG, Buffalo Granite; DHFZ, Diggers Hole Fault Zone; EGP, East Gippsland Province; JCF, Jarvis Creek Fault; KMC, Kuark Metamorphic Complex; LCG, Limestone Creek Graben; MECC, Mt Elizabeth Caldera Complex; MRSZ, Mt Raymond Shear Zone; MS, Mitchell Syncline; ND, Nunniong Domain; SCS, Scrubby Creek Syncline; WCG, Wombat Creek Graben; YA, Yabba Adamellite; YG, Yackandandah Granite; YFTB, Yalmy Fold and Thrust Belt.

Terranes differ significantly in the relationship between plutonism and tectonism and in the timing of magmatic pulses. Plutonism in the Whitelaw Terrane was post-tectonic, produced unfoliated granites and was absent until well after the Benambran Orogeny. By contrast, the Benambra Terrane was intruded by a large number of Early Silurian granites near the end of the Benambran Orogeny and was affected by a major magmatic event between the Late Silurian and Early Devonian.

The magmatic history of the Benambra Terrane can be grouped into three age ranges (VandenBerg *et al.* 2000). The first magmatic event in the Early Silurian (441–423 Ma) resulted in predominantly S-type granites that were emplaced during and just after the Benambran Orogeny. This event was absent in the Whitelaw Terrane. This grouping accompanied regional metamorphism and includes deep-seated bodies gradational into migmatite as well as higher level bodies intruding schist and slate. The deeper level plutons have a foliation parallel to that in the surrounding metamorphic rocks and higher level S-types are foliated to massive and commonly have hornfels aureoles. The second magmatic event in the Late Silurian to Early Devonian (423–384 Ma) produced a large belt of intermediate to felsic volcanism and widespread intrusion of granitic rocks. The event was associated with the Bindian Orogeny and caused many elongate and foliated to mylonitic plutons to form along major faults. These deformed granites all lie east of the Kancoona–Kiewa–Barmouth fault system and are both syn- and post-tectonic with several pulses of magmatism (Figure 3). West of this fault system, granites were emplaced after deformation and regional metamorphism with generally only one pulse of granite intrusion in any area. There are no foliated granites of this age exposed in the Whitelaw Terrane. The third magmatic event, in the Middle Devonian to Early Carboniferous (384–350 Ma) occurred after the Tabberabberan Orogeny and hence granites are undeformed. This is the first magmatic event to be spread across both the Whitelaw and Benambra Terranes.

Palaeogeographical setting of the terranes

The differences in the geological histories of the terranes between the Early Silurian and Middle Devonian suggests that the Benambra Terrane may have been remote from the Whitelaw Terrane during this time. This is supported by their palaeogeographical histories that show three distinct phases.

In the first phase, the terranes shared the same palaeogeographical setting during the Ordovician. Palaeocurrent data and sedimentary provenance studies suggest that the terranes were part of a single turbidite distribution system lying just east of the Delamerian Fold Belt (Cas *et al.* 1980; Fergusson & Colquhoun 1996; VandenBerg *et al.* 2000; Powell 1983a; Powell 1983b). Furthermore, the data suggest that the Benambra Terrane could not have been located east of the Whitelaw Terrane until late in the Early Devonian. The Castlemaine and Adaminaby Groups are similar in lithological character, depositional environment and age (both Ordovician). The Castlemaine Group was deposited across both the Bendigo and Melbourne Zones, but in the latter it is much thinner and has a high proportion of chert, with a relative dearth of sandstone. Hence, the thick Adaminaby Group quartz turbidites in the Tabberabbera Zone, which were derived from the west, have no significant equivalents in the Melbourne Zone. If the zones had been adjacent in the Ordovician, the Melbourne Zone should also have received quartz turbidites, as it would have lain in the path of the turbidity currents that were feeding into the Tabberabbera Zone. As this is not the case we infer that the Benambra Terrane was elsewhere at the time.

In the second phase, between the Late Silurian and Early Devonian, the rifts and grabens in the Benambra Terrane provide abundant evidence of contemporaneous erosion and sedimentation. Sediments are characterised by having prominent lithic (sedimentary, metamorphic, granitic, volcanic and vein quartz) components. This, along with high-angle unconformities between Ordovician basement and both Upper Silurian and Lower Devonian rocks, shows that the Benambra Terrane was cratonised, uplifted and partially exhumed during the Benambran and Bindian Orogenies.

The Melbourne Zone remained submarine in this entire interval. Sedimentation here was continuous from the Early Ordovician to near the end of the Early Devonian, and the resulting sediment pile was strongly wedge-shaped, very thick in the west, but quite thin in the east. An important observation is that none of the sediment that was eroded from the Benambra Terrane during this time reached the Melbourne Zone (Powell *et al.* 1998; VandenBerg *et al.* 2000). This again is inconsistent with the Benambra Terrane lying outboard of central Victoria in Silurian and Early Devonian times. Such sediment did not appear into the Melbourne Zone until the third phase, in the latest Early Devonian (Emsian), when lithic sandstones in the Walhalla Group provide the earliest evidence of an easterly source (VandenBerg *et al.* 2000). We interpret this to be the earliest evidence that the Benambra Terrane was approaching the Whitelaw Terrane.

STRUCTURAL ZONES

In this section we describe the five zones that comprise the Benambra Terrane.

Tabberabbera Zone

The Tabberabbera Zone is a northwest-trending belt that forms the western part of the Benambra Terrane (Figure 3). To the west, it is juxtaposed against the Melbourne Zone, the easternmost part of the Whitelaw Terrane, along the Governor Fault. Its eastern boundary is defined by a system of linked strike-slip faults (Kancoona, Kiewa, Cassilis and Ensay Faults) that disappears under the Buchan Rift (Figure 3). Its boundary with the Kuark Zone is probably a fault, perhaps the Lucas Point Fault. Metamorphic grade within the zone is generally low and the scarcity of metamorphic rocks above lower greenschist facies contrasts strongly with their abundance in the Omeo Zone. The zone has a relative dearth of granites (<10% in area), which are mostly I-type.

The Wonnangatta Fault Zone, with a stratigraphic displacement of several kilometres, is the largest of several large northwest-trending contractional structures within the zone. It divides the zone into two subzones, each approximately 40 km wide. The Eastern Tabberabbera Subzone consists mainly of Pinnak Sandstone with less abundant Bendoc Group, whereas outcrop in the Western Tabberabbera Subzone consists largely of Lower Silurian Cobbannah Group interrupted by narrow fault slices of Bendoc Group.

WESTERN TABBERABBERA SUBZONE

Knowledge of the Western Tabberabbera Subzone is incomplete because younger continental rocks cover much of the subzone, including most of the western margin. This margin, the Governor Fault, is a major fault with a strike length in excess of 300 km, but is exposed in only four small areas, at Dookie, Tatong, Dolodrook River and Howqua River (Fergusson 1998). The fault zone consists of intensely deformed rocks and includes the only known occurrences of Cambrian metavolcanics in the Tabberabbera Zone. The metavolcanics have oceanic affinities, suggesting that the Tabberabbera Zone developed over oceanic basement (Fergusson 1998; Spaggiari *et al.* 2000).

The eastern part of the Western Tabberabbera Subzone is best known in the Abbeyard area [A. H. M. VandenBerg, C. E. Willman, C. Quinn & V. J. Morand (AHMV *et al.*) unpubl. data] and in the area south of Dargo (Fergusson 1987a). In the Abbeyard area, the subzone forms a complex fold and thrust belt dominated by Cobbannah Group (sandstone, quartzite and mudstone) and fault slices of Bendoc Group (black shale, mudstone and sandstone). Bedding consistently trends towards approximately 340°, which compares with more variable trends found in the adjoining part of the Eastern Tabberabbera Subzone (300–330°) (Figure 3). The Cobbannah Group is interrupted by several large east-dipping contractional faults that contain fault slivers of Bendoc Group. The Cobbannah Group south of Dargo is folded about southwest-vergent large-wavelength folds (Fergusson 1987a) and is interrupted by northeast-dipping faults.

EASTERN TABBERABBERA SUBZONE

The Eastern Tabberabbera Subzone differs from the Western Tabberabbera Subzone by the absence of Cobbannah Group, by its more variable structural trends, and by the prevalence of well-developed second and third generation cleavages. Pinnak Sandstone forms most of the subzone except for a narrow belt of Bendoc Group along the western margin in the hangingwall of the Wonnangatta Fault Zone.

The Wonnangatta Fault Zone consists of at least two major faults along with a network of smaller splay faults. The main faults identified so far are the Wonnangatta Fault and the Bread and Butter Fault Zone and these link near Abbeyard (Figure 3). The character of the fault zone changes markedly along strike. In the south, the Wonnangatta Fault is associated with a 1–2 km-wide fault zone with a very large dip-slip displacement. The thickness of the Pinnak Sandstone is not known, but a displacement of at least several kilometres is likely (Fergusson 1987a, 1998). Here it is a major northeast-dipping fault zone separating lowermost Pinnak Sandstone, and in places the Howqua Chert, from the Bendoc and Cobbannah Groups. The hangingwall of one of the main faults exposes talcose bedded rocks that may be Cambrian mafic volcanic or ultramafic volcaniclastic rocks (AMG 508200E, 5859850N). The fault zone surrounding the main fault is a mélange that strongly reflects the general southwest vergence, with faults and bedding mainly dipping northeast and minor parasitic folds verging southwest. In the Abbeyard area, the Wonnangatta Fault Zone branches into a number of small-displacement faults, which give the appearance of greater structural complexity compared to its southern extension. Detailed mapping of the fault zone is continuing.

The strike of bedding in the Eastern Tabberabbera Subzone swings west from its predominant northwest strike in several sigmoidal segments (Figure 3). At the southeastern end of the subzone, structural trends swing from northwest to east–west on approaching the Buchan Rift and the eastern margin of the subzone lies under Lower Devonian volcanics (Simpson *et al.* 1996). Macroscale fold interference patterns, which occur in the vicinity of the Mt Elizabeth Caldera Complex just west of the Buchan Rift, have been interpreted as the result of Tabberabberan refolding of first-generation folds (Fergusson 1987b; Simpson *et al.* 1996).

Structure throughout the subzone is dominated by northwest- to east–west-trending first-generation Benambran folds. These F_1 folds are gently plunging, tight and mostly upright with wavelengths averaging a few hundred metres. The direction of fold and fault vergence varies throughout the subzone. In the south, vergence is to the southwest (Fergusson 1987a), although in at least one area south of the Mt Baldhead Igneous Complex, recumbent folds have anomalous gently south-dipping axial surfaces (Willman *et al.* 1999). In the north near Abbeyard, tight to isoclinal F_1 folds are overturned to the east and in some cases anticlines have overturned eastern limbs, suggesting vergence towards the northeast in this area.

An early bedding-parallel slaty cleavage is widespread in the subzone and also occurs locally in the Western Tabberabbera Subzone (Fergusson 1987a, b; AHMV *et al.* unpubl. data).

A second-generation crenulation cleavage is sporadically well developed throughout the Eastern Tabberabbera Subzone (AHMV *et al.* unpubl. data). In the south its distribution is associated with strike-slip faults along the eastern margin of the Tabberabbera Zone, which were active during the Late Silurian to Early Devonian (Willman *et al.* 1999). In the north, the crenulation cleavage is widespread and is not clearly related to any known faults. Its precise age is unknown, although it pre-dates the Early Devonian Buffalo Granite.

Third-generation structures are well developed in the subzone, particularly in the south. Generally inferred to have formed during the Tabberabberan Orogeny, they consist of a north-trending crenulation cleavage axial planar to open to tight, low-amplitude minor folds with wavelengths up to a few metres (Fergusson 1987b; Fergusson & Gray 1989; Simpson *et al.* 1996; Willman *et al.* 1999). The strongest effects occur in the Mitchell Syncline (Figures 3, 5), a major Tabberabberan structure that has tightly folded the Lower Devonian Wentworth Group (Figure 2) (McCaw 1983; Fergusson & Gray 1989). It has also folded the unconformity below the Wentworth Group and refolded Benambran structures in the Ordovician basement. Several other north-trending zones also have well-developed Tabberabberan structures. In the area just east of the Mt Baldhead Igneous Complex, a Tabberabberan cleavage is prominent, but folds are usually less than 1 m across.

Omeo Zone

The geology of the Omeo Zone contrasts sharply with that of the Tabberabbera Zone. Approximately 65% of its basement is composed of Lower Silurian metamorphic rocks and associated S-type granites, both of which are absent in the Tabberabbera Zone (Figure 3). The rest of the Omeo Zone is low-grade Pinnak Sandstone (protolith for the metamorphic rocks) or Bendoc Group. These rocks are traversed and bounded by a system of linked ductile shear zones that records a continuous tectonic history up to the Middle Devonian, well after the basement rocks had been deformed in the Benambran Orogeny. Most large faults in the zone are strike-slip structures and were most active in the Bindian Orogeny. The Indi Fault is the exception—it is a large thrust fault. These linked faults have largely controlled the location and subsequent deformation of a number of intracratonic basins. These include a Late Silurian rift system, the Cowombat Rift (Limestone Creek and Wombat Creek Grabens) and two Early Devonian rifts. The Scrubby Creek Syncline with its Upper Silurian or Lower Devonian fill of Mt Tambo Group occurs at the southern margin (Figure 3).

Palaeozoic granite forms approximately 32% of the area (12% I-types and 19% S-types). Many of these granites are foliated and have intruded active fault zones, particularly those formed during the Bindian Orogeny. The I–S line of White *et al.* (1976) and Chappell *et al.* (1988) lies farther east, but a southwestern extension of it may border the southern and western boundaries of the Omeo Zone (Hendrickx 1999).

The two subzones that make up the Omeo Zone, the High Plains and Corryong Subzones, differ in structural trend and the areal extent of metamorphic rocks. They are separated by the Tallangatta Creek Fault Zone, with strike-slip displacement of unknown extent (Figure 3) (VandenBerg *et al.* 1998). Structural trends in the Corryong Subzone are consistently north to northeast, whereas in the High Plains Subzone they are variable although predominantly northwest and east–west. The Omeo Metamorphic Complex (including S-type granites) occupies 75% of the High Plains Subzone, but less than 50% of the Corryong Subzone.

HIGH PLAINS SUBZONE

The defining character of the High Plains Subzone is the large area of metamorphic rocks that was produced in two events. The first, and most important, referred to as M1 by Fagan (1979), occurred in the Early Silurian, associated with the Benambran Orogeny (Beavis 1962), and this formed the Omeo Metamorphic Complex (Morand 1990). It is entirely derived from Pinnak Sandstone (sandstone and mudstone) and consists of phyllite, schist, gneiss, migmatite and S-type granite. Bendoc Group rocks were not involved, probably due to their higher crustal level. The second metamorphic event, referred to as M2 by Fagan (1979), occurred at about the Silurian–Devonian boundary, associated with the Bindian Orogeny. This resulted in schistose aureoles around some granites, and greenschist facies assemblages in mylonites and mafic to intermediate dykes. It was broadly coeval with a period of widespread granite intrusion and contact metamorphism. Shear zones that were active during the Bindian Orogeny, such as the Kiewa, Kancoona, Ensay and Cassilis shear zones, have fault rocks with greenschist facies minerals (Morand & Gray 1991). Early Devonian schistose aureoles occur around the southern margins of the Yabba Adamellite (Steele 1993) and Swifts Creek Igneous Complex (Figures 3, 5) (Willman *et al.* 1999). The foliations in the contact zone wrap around the plutons, indicating that intrusion and metamorphism are related. M2 metamorphic rocks are widespread, but occupy a much smaller area than those produced during M1. It is easy to identify M2 rocks where they form schistose aureoles around Early Devonian granites, but elsewhere the two events are difficult to tell apart. Metamorphic grade decreases from west to east across the subzone with the highest grade rocks in the Wodonga and Talgarno areas in the northwest. The high-grade rocks along the western margin are sharply truncated by the Kancoona–Kiewa–Cassilis–Ensay shear zone where they are juxtaposed against low-grade Pinnak Sandstone in the Tabberabbera Zone. In contrast, there is a smooth transition to the east into low-grade Pinnak Sandstone. The Mt Hopeless Fault in the south of the High Plains subzone of the Omeo Zone is unusual and shares some similarities with extensional faults formed above metamorphic core complexes (Figure 5). It is subhorizontal, marked by a breccia zone and separates high-grade footwall rocks from lower grade hangingwall metamorphic rocks (Willman *et al.* 1999).

CORRYONG SUBZONE

The Corryong Subzone is bounded by major faults (Figure 3) and consists of simply deformed, mostly low-grade Pinnak Sandstone with small fault-bounded slices of Bendoc Group (VandenBerg *et al.* 1998).

Structures produced in the Benambran Orogeny reflect predominantly east–west contraction. These structures are the major north–south to northwest structural trends defined by bedding, first-generation tight to isoclinal folds and associated S_1 cleavage. Westward vergence is suggested by one of the few continuous sections in the central part of the subzone (VandenBerg *et al.* 1998). Vergence to the southwest is suggested in the area west of Walwa where most younging directions are towards the northeast (Simpson *et al.* 2001). Thrust faulting in the Benambran Orogeny is indicated by the faulted relationship between Bendoc Group and Pinnak Sandstone, although the displacements are probably small.

Granites are largely undeformed except along some north- to northwest-trending faults that truncate granites in the north. Foliation along these faults is mainly weak to moderate, with strongly foliated to mylonitic rocks restricted to a few small areas. Late-stage brittle gouge zones and breccias are sporadic in the granitic rocks and are sometimes found away from major faults. Early ductile and later brittle faulting has affected granites along some faults in the north. Simpson *et al.* (2001) showed that cataclasites overprint ductile deformation features, but do not affect dykes, suggesting that brittle deformation occurred prior to the Early Devonian.

Deddick Zone

The Deddick Zone (VandenBerg *et al.* 2000) coincides approximately with the Buchan Zone of Gray *et al.* (1988). It is bounded by faults (Figure 3) and the zone is characterised by east to northeast structural trends and by south to southeast vergence for both Benambran and Bindian structures. Northerly trends occur only in some small intracratonic synclinal basins along the western margin of the zone and reflect east–west contraction in the Tabberabberan Orogeny. Lower Devonian rocks in the Buchan Rift (Orth *et al.* 1995) and Bindi Syncline unconformably overlie a basement that is divided into three structural domains: the Limestone Creek Graben, Nunniong Domain and the Yalmy Fold and Thrust Belt (Figure 3).

The structural character of the zone shows significant variation, from the relatively simple Yalmy Fold and Thrust Belt in the east to complex structural interleaving of Ordovician and Silurian rocks in the Limestone Creek Graben. The dominant deformation in both these areas occurred at different times and yet they share the same south to southeast vergence. This suggests that the Indi Fault may have been initiated during the Benambran Orogeny and was reactivated during the Bindian Orogeny.

The Yalmy Fold and Thrust Belt in the southeast of the zone is a 26 km-wide belt of Bendoc and Yalmy group rocks that forms a south-vergent thin-skinned fold and thrust belt (Glen & VandenBerg 1987; VandenBerg *et al.* 1992), intruded by Early Silurian and Early Devonian granites. The fold and thrust belt was formed in the Benambran Orogeny, but its eastern side is truncated by the McLauchlan Fault, a younger, Bindian structure that truncates Benambran faults (Glen & VandenBerg 1987). Long, narrow fault slices of Warbisco Shale in the fold and thrust belt alternate with broader slices of Yalmy Group to form an imbricate stack. Fold and fault vergence is consistently to the southeast and asymmetric folds have gentle north-dipping and steeper south-dipping limbs. VandenBerg *et al.* (1992) inferred that the imbricate thrusts are listric in profile and flatten to a sole thrust at a depth of approximately 3 km.

The broad northeast-trending Limestone Creek Graben contains the thick Upper Silurian submarine Enano Group and was formed over a basement of marine clastic sedimentary rocks that includes the Ordovician Pinnak Sandstone and Bendoc and Kiandra Groups, and the Lower Silurian Yalmy Group. The graben appears to form a complementary extensional structure with the Wombat Creek Graben in the Omeo Zone—together these make up the Cowombat Rift (Ramsay & VandenBerg 1986). The flanks of the graben are bounded by the Indi Fault and Diggers Hole Fault Zone and its along-strike extremities are buried under Snowy River Volcanics (Figure 3).

Ordovician rocks in and around the Limestone Creek Graben experienced folding, or at least uplift, sometime between the Late Ordovician and Early Silurian, marking the onset of the Benambran Orogeny. Thus, pebbles of Upper Ordovician rock derived from the Bendoc Group, and perhaps the Kiandra Group, occur in Yalmy Group conglomerates. Clasts in the conglomerates contain inherited deformation fabrics that pre-date the deposition of the Yalmy Group. These fabrics include a moderate tectonic foliation weakly crenulated by an overprinting fabric that affects the whole rock, and recrystallised quartz veins that terminate at clast margins. Allen (1987) argued against a major break between the Lower Silurian Yalmy Group (Towanga Sandstone) and the Upper Silurian Thorkidaan Volcanics, but Willman *et al.* (1999) described evidence of an angular unconformity and showed that the Towanga Sandstone may have been fully lithified prior to the onset of volcanism. They inferred that pebbles of quartz sandstone in conglomerates at the base of the volcanics were derived from Towanga Sandstone, implying uplift and probably folding prior to volcanism.

Enano Group rocks in the graben were first deformed in the Bindian Orogeny. This appears to have been caused by southward movement of the entire Corryong Subzone at the end of the Silurian (VandenBerg *et al.* 1998). The Diggers Hole Fault Zone along the southern edge of the graben (Figure 3) dips moderately to steeply south. Willman *et al.* (1999) presented evidence for an extended movement history along it, spanning the Benambran, Bindian and Tabberabberan Orogenies.

The Nunniong Domain is quite different from the rest of the zone. It is mostly composed of Omeo Metamorphic Complex rocks and may represent a small crustal fragment that became detached from the Omeo Zone during the Bindian Orogeny. In the east it is covered by Snowy River Volcanics. The distribution of the metamorphic rocks indicates low-angle, south-dipping contacts between metamorphic zones in the central embayment of the Nunniong Granodiorite. This is in accord with the outcrop pattern of this granodiorite, which suggests that it is a large flat-topped intrusion that is tilted away from the bounding Jam Tin Fault, with its deepest level exposed at its northwestern boundary (Willman *et al.* 1999).

Kuark and Mallacoota Zones

The Kuark Zone (VandenBerg *et al.* 2000) is an area that covers the western part of the Mallacoota Zone of Gray *et al.* (1988) (Figure 3). VandenBerg *et al.* (2000) restricted the Mallacoota Zone to the area east of the Combienbar – Pheasant Creek Fault Zone (Figure 3). The Kuark Zone has several unique characteristics that distinguish it from the Mallacoota Zone, although both share similar structural trends and vergence directions (Figure 1). The Kuark Zone includes only 15–20% of granite compared with approximately 55% for the Mallacoota Zone; the Kuark Metamorphic Complex has no equivalent in the Mallacoota Zone and a large area in the west of the Kuark Zone is characterised by variable structural trends as a result of interference folds. The Mallacoota Zone contains several synclines with Upper Devonian redbeds and the southern extension of the Narooma Accretionary Complex.

Both zones have been affected by a number of deformation events, but the timing of these is poorly constrained.

The predominant northeast-trending folds and faults are probably Early Silurian and hence coeval with the Benambran Orogeny (VandenBerg *et al.* 1996; Offler *et al.* 1998; Fergusson & Phillips 2001). Younger events have led to the reactivation of major faults, the deformation of intracratonic basins and the development of interference folds.

The eastern part of the Kuark Zone is characterised by northeast trends in a zone of highly strained and metamorphosed rocks that appear to form a wide high-strain zone in the hangingwall of Benambran precursors to the Combienbar – Pheasant Creek Fault Zone. The Kuark Metamorphic Complex is the predominant feature of this high-strain zone. Early folds and cleavage show a more intense contractional style within and close to the complex, suggesting that they developed at a deep crustal level and were subsequently exhumed by west-over-east dip-slip movement along the Combienbar – Pheasant Creek Fault Zone. Metamorphic grade is low north of the complex, but deformation remains strong in the high-strain zone (Simpson *et al.* 1997). Farther south at Cape Conran, at least two ductile deformations are evident. An early, possibly Benambran, event is recorded by eastward verging isoclinal folds just west of the Pheasant Creek Fault (Figure 3). Later ductile deformation in the undated Cape Conran Granite records eastward tectonic transport of probable Devonian age (Burg & Wilson 1988; Hendrickx *et al.* 1996). There is also evidence for dextral strike-slip movement along the Combienbar Fault and a splay fault, the Mt Raymond Shear Zone (Hendrickx *et al.* 1996), but the timing of these movements is uncertain.

In the Mallacoota Zone, both ductile shear zones and brittle fault zones affect granites in the Bega Batholith. Shear zones overprint the steeply dipping primary emplacement fabric. Ductile shear zones, up to 2 km wide, are predominantly northeast-trending with dextral strike-slip displacement, whereas brittle fault zones trend mainly north (Begg *et al.* 1987; Simpson *et al.* 1997). The Genoa Fault Zone is a major north-trending fault in the centre of the zone within a broad screen of Ordovician country rock that bisects the Bega Batholith. It is associated with an east-vergent fold and fault zone containing fault slices of Bendoc Group (Simpson *et al.* 1997).

The Narooma Accretionary Complex in the east of the Mallacoota Zone has a structural style and facies association indicative of a subduction complex (Powell 1983a; Miller & Gray 1997). Structural vergence is consistently to the east except for local areas associated with back-thrusts (Wilson *et al.* 1982, 1999).

MAJOR FAULTS AND LINKAGE PATTERNS

Faults in the Benambra Terrane differ from those in the Whitelaw Terrane by showing a great variety of style, from large-displacement dip-slip structures (e.g. Wonnangatta and Indi Faults) to strike-persistent strike-slip faults with wide mylonite zones (e.g. Kiewa, Ensay and Cassilis Faults). The largest strike-slip faults have only been documented recently (Morand & Gray 1991; Morand 1992; Willman *et al.* 1999). Their recognition is important for two reasons: (i) they give direct evidence for significant orogen-parallel movement in the terrane; and (ii) their relationship to other structures, and to Late Silurian and Early Devonian basins, suggests that they were part of a network of faults that profoundly influenced the development of the Benambra Terrane. The fault networks consist of northwest- to northeast-trending strike-slip faults that link with south-verging dip-slip faults. The movement history of linked fault systems is consistent with overall southward tectonic transport of the Benambra Terrane after the Early Silurian. The fault systems are most evident in the central portion of the terrane where they border the Omeo Zone. The two examples detailed below are the Corryong Subzone system and the High Plains Subzone system.

Corryong Subzone system

The Corryong Subzone is bounded by three major linked faults: the Tallangatta Creek Fault Zone and the Indi and Gilmore Faults (Figures 3, 4). The Tallangatta Creek Fault Zone is inferred to have had two main periods of movement. The first was sinistral strike-slip movement in the mid-Silurian that caused opening of the transtensional Wombat Creek Graben (VandenBerg *et al.* 1998). The best-documented movement was later in the Bindian Orogeny when dextral strike-slip displacement deformed the graben. In the north, approximately 20 km south of the New South Wales border, the Tallangatta Creek Fault Zone has a well-developed horizontal stretching lineation in mylonitised pegmatite and granite, indicating dextral strike-slip displacement (Simpson *et al.* 2001). Farther south it consists of a broad zone of fault slices of Pinnak Sandstone and Bendoc Group that show an eastward decrease in the intensity of deformation (VandenBerg *et al.* 1998). F_2 folds plunge approximately 60° towards the northwest, suggesting a significant component of strike-slip movement. The age of these folds is constrained to the Bindian Orogeny as they deform Benambran fabrics in Pinnak Sandstone and pre-date Early Devonian volcanics. Bedding, faults and F_2 folds in the fault zone generally strike northwest to north-northwest, at an angle to the north–south strike of bedding in the Corryong Subzone and suggest a dextral sense of movement along the fault zone. The southern end of the fault zone curves with a broad S-shaped bend before linking with the Indi Fault. Mylonite in the east–west-trending section of the bend dips moderately to steeply north (Willman *et al.* 1999). Movement in the Tabberabberan Orogeny has complicated the linkage of the Tallangatta Creek Fault Zone with the Indi Fault. They link at a triple junction with the Bindi Fault, which contributed to the deformation of Lower Devonian fill of the Bindi and Scrubby Creek Synclines in the Tabberabberan Orogeny (Willman *et al.* 1999; VandenBerg *et al.* 2000). The Lower Devonian rocks obscure Benambran and Bindian structures.

Morand and Gray (1991) demonstrated that the Indi Fault is a northwest-dipping thrust with significant Bindian movement. Rocks in the hangingwall are part of the Omeo Metamorphic Complex and have been thrust over Upper Silurian rocks of the Limestone Creek Graben (Figure 4). The Indi Fault extends approximately 140 km to the northeast, linking with the Gilmore Fault (Morand & Gray 1991; Stuart-Smith 1991). Stuart-Smith (1991) found that sinistral movement along the Gilmore Fault occurred during the Bowning (= Bindian) Orogeny and in the Middle Devonian and/or Carboniferous.

The timing of movement along the Tallangatta Creek Fault Zone, Indi Fault and Gilmore Fault indicates that they were all active during the Bindian Orogeny. Movement sense along each is consistent with a model of southward transport of the Corryong Subzone (Figure 4). VandenBerg *et al.* (1998) interpreted the Corryong Subzone as a thin thrust sheet that has partly overridden rocks of the Deddick Zone (cf. Morand & Gray 1991). The lowest portion of the thrust sheet crops out in the hangingwall of the Indi Fault where Omeo Metamorphic Complex rocks occur. These give way farther north to a wide belt of low-grade Pinnak Sandstone and then to outliers of Bendoc Group. This regional northward younging is interpreted to reflect tilting of the rock package as a result of thrusting of the Corryong Subzone in a southeasterly direction over the Limestone Creek Graben sequence. Along the lateral margins of the subzone this movement was accommodated by strike-slip displacement, dextral along the Tallangatta Creek Fault Zone and sinistral along the Gilmore Fault. The Indi Fault accommodated southeast-directed thrusting at the leading edge of the sheet.

Within the Corryong Subzone and away from the bounding faults, the effects of Bindian movement are weak. A series of structural basins and domes shown by the outcrop pattern of the Bendoc Group suggest the presence of east–west-trending open folds (VandenBerg *et al.* 1998) (Figure 4). A weak east–west-trending crenulation cleavage is widespread and is associated with these folds. Meridional Benambran folds were originally horizontal, but have been gently folded during the Bindian Orogeny, resulting in gentle north and south plunges. The S_2 cleavage associated with the east–west folds is a widely spaced disjunctive cleavage with subvertical or steep south dips. The frequency and amplitude of the macroscopic east–west-trending folds, and the intensity of the S_2 cleavage, all decrease to the north, away from the Indi Fault, the leading edge of the thrust sheet. These structures are interpreted to have formed by weak contraction within the Corryong Subzone during collision with the Deddick Zone (VandenBerg *et al.* 1998).

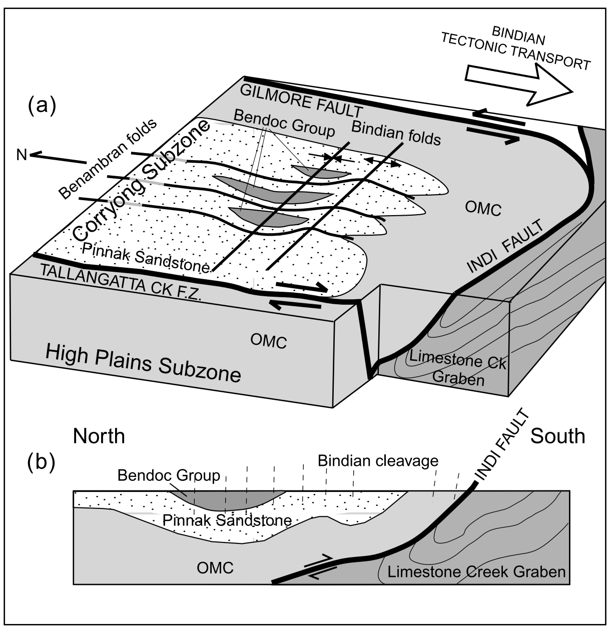


Figure 4 Schematic diagram showing the effects of the Bindian Orogeny on the Corryong Subzone. Bindian folds and cleavage overprint Benambran folds after thrusting of the Corryong Subzone over the Limestone Creek Graben. (a) Schematic block diagram showing linkage of thrust and strike-slip faults. (b) Schematic north–south section in centre of Corryong Subzone showing regional metamorphics raised from lower levels by the Indi Fault. F.Z., fault zone; OMC, Omeo Metamorphic Complex.

High Plains Subzone system

The southwestern boundary of the High Plains Subzone is formed by the Kancoona, Kiewa and Cassilis Faults (Figure 3). These faults link in a complex braided pattern that also involves the Ensay Shear Zone and two Tabberabbera Zone structures: the Barmouth and Haunted Stream Faults (Figure 5). The Kancoona, Kiewa and Cassilis Faults form a set of dextral strike-slip faults that are linked along strike (Morand & Gray 1991; Willman *et al.* 1999). They are characterised by mylonite/phyllonite zones up to 2 km wide with variably developed S–C fabrics and subhorizontal stretching lineations. Morand and Gray (1991) documented the movement history of the Kancoona and Kiewa Faults and showed that the main dextral displacement occurred during the earliest Devonian. This is supported by $^{40}Ar/^{39}Ar$ dating of metamorphic micas in mylonites from the Kiewa, Kancoona and Ensay Faults that gives ages ranging from 413 Ma to 383 Ma (Foster *et al.* 1999). Mylonitic fabrics in the Yackandandah Granite record Middle Devonian sinistral reactivation of the Kancoona Fault (Morand & Gray 1991).

At its southern end, the Kiewa Fault splits into two major ductile shear zones, the Cassilis Shear Zone and the Barmouth Fault (Figures 3, 5) (Willman *et al.* 1999). The Haunted Stream Fault is a younger brittle fault that lies between the two ductile shear zones. The Cassilis Shear Zone and the Barmouth Fault form the boundaries to a wedge-shaped area that is characterised by the presence of an S_2 crenulation cleavage. This is strongest near the faults and becomes intense in the apex of the wedge towards the northwest where the faults merge into the Kiewa Fault (Figure 5). The Bindian timing of cleavage formation is indicated by its relationship with syntectonic Late Silurian to Early Devonian granites. Cleavage trends wrap around the Swifts Creek Igneous Complex and Old Sheep Station Granodiorite, suggesting coeval development (Figure 5) (Willman *et al.* 1999).

The Cassilis Shear Zone truncates metamorphic isograds in the Omeo Metamorphic Complex on its north side (Omeo Zone) and therefore post-dates the Benambran Orogeny (Figure 5). This contrasts with metamorphic rocks on the south side (Tabberabbera Zone) that follow the general trend of the shear zone and curve around the syntectonic granites—indicating that metamorphism on this side accompanied both faulting and igneous intrusion. The shear zone dips 70–80° south to southwest and includes cordierite schist and strongly foliated to mylonitic granodiorite of the Swifts Creek Igneous Complex. The foliated granodiorite is syntectonic with the mylonitic zone. Its 'tail' is drawn into the shear zone for a distance of at least 10 km and tapers to the southeast. While sense of movement criteria are ambiguous, with both dextral and sinistral rotations occurring, the shape of the pluton suggests that granite emplacement occurred during dextral strike-slip movement. The age of this movement is constrained by the Early Devonian age of the granodiorite (Eberz 1987).

The Cassilis Shear Zone links with the Ensay Shear Zone, also an Early Devonian dextral strike-slip fault (Morand & Gray 1991; Willman *et al.* 1999). The age of major movement along the Ensay Shear Zone is well constrained by Early Devonian ages obtained from mylonite ($^{40}Ar/^{39}Ar$: Foster *et al.* 1999), from syntectonic granites (Morand & Gray 1991; Morand 1992) and from the overlying Snowy River Volcanics. Movement along the Ensay Shear Zone continued just after that of the Cassilis Shear Zone. This is indicated by truncation of the mylonitic tail of the Rileys Creek Granodiorite in the Cassilis Shear Zone, by weakly foliated Doctors Flat Tonalite in the Ensay Shear Zone. Steep stretching lineations and horizontal asymmetric folds in the east–west-trending part of the Ensay Shear Zone suggests movement in this section was reverse dip-slip. The variation in movement sense along the Ensay Fault is consistent with a model of crustal blocks moving southeast. Fault displacement was strike-slip along northwest–southeast-trending sections and changed to dip-slip where the fault trends east–west, at right angles to the movement direction.

The Barmouth Fault dips steeply northeast and truncates a narrow northwest-trending fault slice of Barmouth Group, assumed to be Late Silurian (Willman *et al.* 1999). The fault is overprinted by contact metamorphism surrounding the Early Devonian Mt Baldhead Igneous Complex, constraining the last major movement to the Bindian Orogeny. A Bindian S_2 crenulation cleavage that occurs north of the Barmouth Fault is axial planar to small F_2 folds that have near-vertical plunges, suggesting that fault movement may have had a component of strike-slip movement. However, deformation of the Barmouth Group indicates significant contractional movement. A zone up to 2 km wide in the hangingwall of the Barmouth Fault shows some evidence for earlier fault movement recorded by narrow bedding-parallel shears and associated quartz veins that are folded about Bindian F_2 folds and are strongest close to the fault. Willman *et al.* (1999) suggested that the fault may have been initiated as a southwest-vergent thrust in the Benambran Orogeny.

The Haunted Stream Fault is a steeply dipping brittle fault associated with auriferous faults that form a riedel shear array in the Haunted Stream goldfield (Willman & Carney 1998). Fault movement is inferred to be dextral strike-slip and the timing is regarded as late Early Devonian (post-Bindian Orogeny), as indicated by the age of gold mineralisation in the nearby Swifts Creek goldfield.

DISCUSSION

In this discussion we summarise the palaeogeographical and structural evidence leading to the conclusion that the Benambra Terrane became separated from the Whitelaw Terrane after the Benambran Orogeny, and was then transported approximately 600 km southwards to its present position, and was finally amalgamated with the Whitelaw Terrane in the Tabberabberan Orogeny by east–west convergence.

At the end of the Benambran Orogeny there was a profound divergence in the geological histories of the

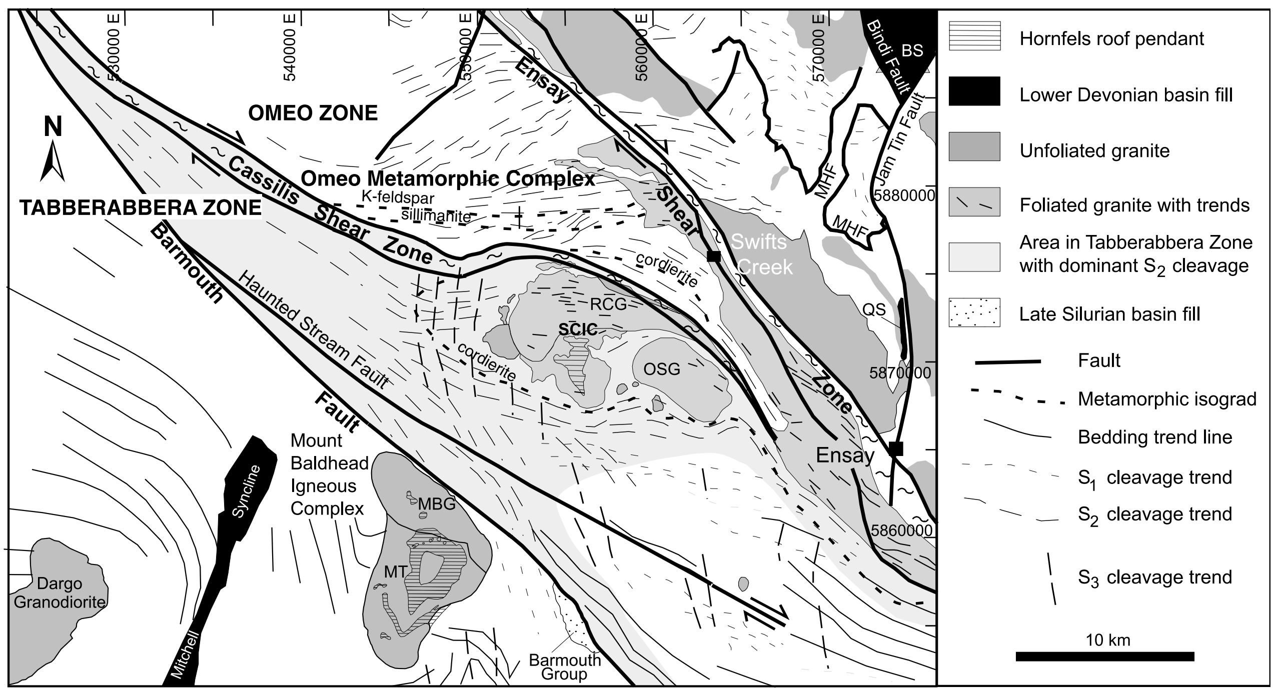
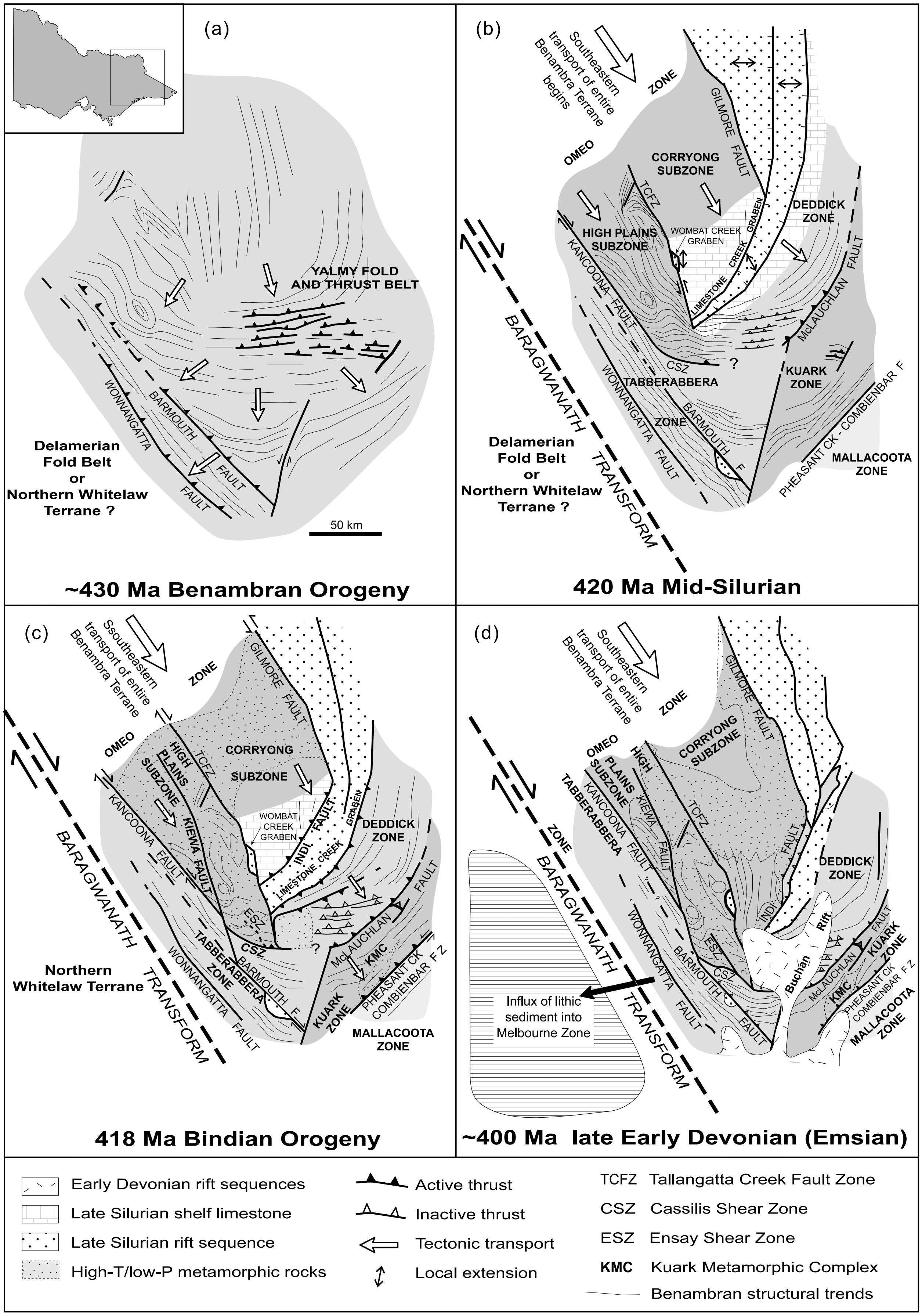


Figure 5 Structural map of the Swifts Creek area. BS, Bindi Syncline; MT, Marthavale Tonalite; MBG, Mount Baldhead Granodiorite; MHF, Mt Hopeless Fault; OSG, Old Sheepstation Granite; RCG, Rileys Creek Granodiorite; SCIC, Swifts Creek Igneous Complex; QS, Quindalup Syncline.


(a)
YALMY FOLD AND THRUST BELT
WONNANGATTA FAULT
BARMOUTH FAULT
Delamerian Fold Belt or Northern Whitelaw Terrane ?
50 km
~430 Ma Benambran Orogeny
(b)
Southeastern transport of entire Benambra Terrane begins
OMEO ZONE
GILMORE FAULT
CORRYONG SUBZONE
TCFZ
HIGH PLAINS SUBZONE
WOMBAT CREEK GRABEN
LIMESTONE CREEK GRABEN
DEDDICK ZONE
KANCOONA FAULT
McLAUCHLAN FAULT
BARAGWANATH TRANSFORM
CSZ
TABBERABBERA ZONE
WONNANGATTA FAULT
BARMOUTH F
KUARK ZONE
PHEASANT CK - COMBIENBAR F
MALLACOOTA ZONE
Delamerian Fold Belt or Northern Whitelaw Terrane ?
420 Ma Mid-Silurian
(c)
Ssoutheastern transport of entire Benambra Terrane
OMEO ZONE
GILMORE FAULT
CORRYONG SUBZONE
HIGH PLAINS SUBZONE
TCFZ
KIEWA FAULT
KANCOONA FAULT
WOMBAT CREEK GRABEN
INDI FAULT
LIMESTONE CREEK GRABEN
DEDDICK ZONE
BARAGWANATH TRANSFORM
ESZ
CSZ
TABBERABBERA ZONE
WONNANGATTA FAULT
BARMOUTH F
McLAUCHLAN FAULT
KMC
KUARK ZONE
PHEASANT CK COMBIENBAR F Z
MALLACOOTA ZONE
Northern Whitelaw Terrane
418 Ma Bindian Orogeny
(d)
Southeastern transport of entire Benambra Terrane
OMEO ZONE
GILMORE FAULT
CORRYONG SUBZONE
HIGH PLAINS SUBZONE
KIEWA FAULT
TCFZ
TABBERABBERA
KANCOONA FAULT
INDI
FAULT
DEDDICK ZONE
Buchan Rift
BARAGWANATH ZONE
TRANSFORM
WONNANGATTA FAULT
BARMOUTH FAULT
ESZ
CSZ
McLAUCHLAN FAULT
KMC
KUARK ZONE
PHEASANT CK COMBIENBAR F Z
MALLACOOTA ZONE
Influx of lithic sediment into Melbourne Zone
~400 Ma late Early Devonian (Emsian)
Early Devonian rift sequences
Late Silurian shelf limestone
Late Silurian rift sequence
High-T/low-P metamorphic rocks
Active thrust
Inactive thrust
Tectonic transport
Local extension
TCFZ Tallangatta Creek Fault Zone
CSZ Cassilis Shear Zone
ESZ Ensay Shear Zone
KMC Kuark Metamorphic Complex
Benambran structural trends

Whitelaw and Benambra Terranes. Their shared earlier history is clearly demonstrated by the similarities in tectonic setting, stratigraphy and the provenance of Ordovician sedimentary rocks. The palaeogeographical evidence indicates that both terranes were receiving turbidites from the Delamerian Fold Belt lying to the south and west during the Ordovician. Furthermore, the Ordovician sequence in the western portions of both terranes is very similar, suggesting that they were proximal parts of the same depositional system and formed along strike from each other. This contrasts with strong differences in the Ordovician sequences of the Tabberabbera and Melbourne Zones, which indicate that these regions, now juxtaposed, could not have been in their present relative positions at that time.

The Benambran Orogeny tightly folded both terranes—with the exception of the Melbourne Zone—but after this, there is no preserved evidence for shared histories until the Middle Devonian. The complex relationship between tectonism, basin development and magmatism in the Benambra Terrane before, during and after the Bindian Orogeny has no equivalent in the Whitelaw Terrane, which was subjected to less magmatism and was receiving an uninterrupted sediment supply in the Melbourne Zone up to the Early Devonian.

None of the sediment deposited in the Melbourne Zone in this interval came from the east, even though parts of the Benambra Terrane were subaerial and undergoing erosion (Figure 6b, c). This is one of the strongest pieces of evidence indicating that the Benambra Terrane was not located east of the Melbourne Zone. This pattern existed until late in the Early Devonian, when the introduction of east-derived material provides the earliest evidence for a landmass located east of the Melbourne Zone (Figure 6d). We interpret this as the arrival of the Benambra Terrane just before its collision and amalgamation with the Whitelaw Terrane.

This leads us to the important question: if the Tabberabbera Zone did not lie east of the Melbourne Zone until late in the Early Devonian, where was it and how did it move from its original location? The Benambra Terrane cannot have lain farther east, separated from the Whitelaw Terrane by open ocean, because this style of reconstruction is at odds with palaeogeographical and palaeocurrent data that show that both terranes were bounded on their west by a common continental sediment source. They were both deformed in the Benambran Orogeny, suggesting physical continuity. The Benambra Terrane (including the Tabberabbera Zone) is unlikely to have lain south of the Whitelaw Terrane. Not only is there no evidence of large-scale northward tectonic transport in the Benambra Terrane, but this would have positioned the terrane close to Tasmania. Both the Ordovician–Devonian platform carbonate successions of western Tasmania, and the distal turbidite facies of northeastern Tasmania (Banks & Baillie 1989) are inconsistent with this region having been part of a source region or a proximal facies to the Benambra Terrane turbidites of the same age.

Therefore, we conclude that the Benambra Terrane must have lain well to the north of its present position. The palaeogeographical, palaeocurrent and structural evidence all indicate that the terrane moved to the south-southeast from an original position in the north of the Lachlan Fold Belt. With no such movement of the Whitelaw Terrane our model requires the presence of a large transform fault that accommodated the relative displacement of the two terranes in Early Silurian to Middle Devonian time. Although this fault is not preserved, we account for this by proposing that it was destroyed in the Middle Devonian by the strong east–west convergence that amalgamated the terranes in the Tabberabberan Orogeny. However, many secondary strike-slip faults with the same age, movement history and geometry, but with lesser magnitude, are preserved within the Benambra Terrane, and these provide strong evidence for fold-belt-scale southward tectonic transport.

The strike-slip faults of the central Benambra Terrane have relatively small lateral displacements. Approximately 50 km of dextral displacement is estimated for the Kiewa Fault (Morand & Gray 1991) and approximately 35 km of dextral displacement is estimated for the Ensay Fault (Willman *et al.* 1999). Clearly, these fault systems cannot account for the hundreds of kilometres of displacement inferred between the terranes. However, they are indicative of a large component of southward tectonic transport during the critical mid-Silurian to Early Devonian interval, the same interval when the geological histories of the terranes are entirely different.

The structural evidence in eastern Victoria suggests that orogen-parallel movement was spread over a considerable time. It probably began in the Benambran Orogeny as the Benambra Terrane was forming, shown by vergence that is south in the Yalmy Fold and Thrust Belt and southwest in the southwest of the Tabberabbera Zone (Figure 6a), and by west to northwest trends in the west of the Omeo Zone and parts of New South Wales (Glen 1992). Elsewhere in the Benambra Terrane, structures reflect dominant east–west contraction during the Benambran Orogeny. Either there were two phases of folding in the Benambran Orogeny with early oblique folds overprinted by later meridional folds (Collins & Hobbs 2001), or the orogeny was complex, with east–west contraction coeval with orogen-parallel movements that were strongly partitioned to some areas or faults.

Although orogen-parallel movement probably occurred in the Benambran Orogeny, it is unclear whether this was associated with the development of the Baragwanath

Figure 6 Inferred Early Silurian to Early Devonian evolution of the Benambra Terrane. Gray tones indicate areas comprising deformed Cambro-Ordovician rocks. (a) The Benambra Terrane is formed by the amalgamation of tectonic elements in the central and eastern belts of the Lachlan Fold Belt. (b) Initiation of southeastward orogen-parallel movement of the terrane is associated with regional extension and rifting. (c) Main period of southeast tectonic transport. Late Silurian sequences are deformed, fragmentation of the Omeo Zone is completed and the Kuark Metamorphic Complex is exhumed in the hangingwall of the Combienbar – Pheasant Creek Fault Zone. (d) Lithic sediments reach the Melbourne Zone from the east indicating the Benambra Terrane is east of the Victorian section of the Whitelaw Terrane. Rifts sequences record widespread extension in the Benambra Terrane.

Transform. However, it is curious that there are no oblique Benambran structures in the west of the Whitelaw Terrane and that the Melbourne Zone was protected from this orogeny. Perhaps the transform developed early in the Benambran Orogeny and all orogen-parallel movement was partitioned to the transform or to within the Benambra Terrane.

Wholesale southward transport of the Benambra Terrane probably began in the mid-Silurian, which was the main period of regional extension that followed the Benambran Orogeny. This is inferred by the close spatial relationship between Late Silurian basins and the linked fault systems. However, the fabrics within the faults are slightly younger and were generated during the Bindian Orogeny (Foster *et al.* 1999; Willman *et al.* 1999), presumably overprinting earlier movement.

The Bindian Orogeny is interpreted as the major period of dextral displacement along the hypothetical Baragwanath Transform. In the absence of direct structural evidence for the transform, we point to the large-scale south to southeast movement that can be demonstrated for structures within the terrane. This movement affected large fragments of crust as shown by the way that strike-slip and south-verging thrust faults formed linked systems around the Omeo Zone. This was a period of intense crustal fragmentation. We envisage a series of rigid crustal blocks, bounded by faults, that were moving southward, analogous to the movement of pack-ice. An example is the Corryong Subzone, which moved southward and overrode the Limestone Creek Graben (Morand & Gray 1991; VandenBerg *et al.* 1998) (Figure 4). The presence of the Boggy Plain Supersuite in the Omeo Zone suggests that the Omeo Zone may have overridden Ordovician mafic rocks belonging to the southern part of the Macquarie Arc (Morand & Gray 1991; VandenBerg *et al.* 1998). The widespread Early Devonian magmatism in the southeast of the Lachlan Fold Belt shows a close relationship to Bindian structures in the central and eastern Benambra Terrane. Many plutons intruded active fault zones along, and east of, the Kancoona–Kiewa–Cassilis shear zone (Figures 3, 5). The fabrics imposed upon the plutons are consistent with overall southward movement of the terrane. Strike-slip movement is also recorded along several large faults in the Kuark and Mallacoota Zones, but here the timing of movement is poorly constrained. Strike-slip faults were active along the Tabberabbera Zone's eastern boundary, and the Barmouth Fault in the southeast part of the zone is inferred to be a Bindian dextral strike-slip fault (Willman *et al.* 1999). Strike-slip movement has been identified elsewhere in the Tabberabbera Zone, but its timing is uncertain (AHMV *et al.* unpubl. data).

Structures and fabrics associated with the southward tectonic transport during the Bindian Orogeny are not evenly developed over the terrane. East–west contraction occurred in parts of the Kuark and Mallacoota Zones and in deformed Silurian strata in New South Wales (Glen 1992). This indicates that orogen-parallel movement was strongly partitioned, not only along the Baragwanath Transform, but also along particular structures within the terrane, predominantly in the central and western areas.

The Tabberabberan Orogeny in the Middle Devonian marks the cessation of southward transport of the Benambra Terrane. This orogeny is characterised by east–west contraction that caused amalgamation of the Benambra and Whitelaw Terranes. It caused significant deformation along the western margin of the Tabberabbera Zone, uplifted and strongly deformed the Melbourne Zone, destroyed the Baragwanath Transform and created the Governor Fault. The timing of amalgamation is well-constrained by Late Devonian continental volcanic and sedimentary rocks that cover part of the terrane boundary.

Large-scale strike-slip fault networks, which divide fold belts, are common. Active systems have been documented in continental regions adjacent to transcurrent plate boundaries, such as the west coast of North America (Sylvester 1988), and within blocks of continental crust undergoing lateral 'escape' in response to continental collision, such as the Tibetan Plateau (Tapponier *et al.* 1986; Molnar *et al.* 1987) and Turkey (Sengör 1979). The improved understanding of such modern systems has led to a revival of recognition of the important role that strike-slip faults play in many ancient orogenic belts (see Sylvester 1988 for a review). Continent-scale lateral offsets on such systems are common. A strike-slip fault system along the Northern Rocky Mountain Trench in the northwestern Canadian Cordillera has an estimated offset of more than 1000 km and possibly more than 2000 km (Gabrielse 1985; Wynne *et al.* 1995). This system consists of an anastomosing network of large-scale strike-slip faults and linking thrusts similar in style to those now recognised in the Benambra Terrane. A dextral transform fault has been proposed for the New England Fold Belt in northern New South Wales and southern Queensland (Murray *et al.* 1987). Dextral displacement along the Gogango–Baryulgil Fault Zone is inferred to be approximately 500 km and resulted in repetition of a Carboniferous forearc sequence in the southern part of the orogen. This was followed by strong east–west contraction during the Hunter–Bowen Orogeny, which destroyed or modified most evidence of the transform fault, analogous to the destruction of the Baragwanath Transform during the Tabberabberan Orogeny in our model.

The similarities of the Benambra Terrane with other regions suggests that large-scale transcurrent plate motions may have driven strike-slip deformation in the Lachlan Fold Belt, although the ultimate driving mechanism for the southward transport is unknown. It may have been oblique convergence associated with subduction to the east, or possibly escape tectonics. Large-scale movement of the Benambra Terrane obviously requires that significant accommodation occurred in northeastern Australia from the mid-Silurian to the Early Devonian. While it is beyond the scope of this paper to deal with these questions, it is interesting to note that the timing and vergence of structures associated with the Alice Springs Orogeny (southward vergence during Late Ordovician to Late Devonian time) may be consistent with southward movement of the Benambra Terrane (Scrimgeour *et al.* 2001). The east–west trend of the Thomson Fold Belt with a convex-south shape, as determined from geophysical data, is also suggestive of southward orogen-parallel movement (VandenBerg *et al.* 2000). The belt was deformed in the Early Palaeozoic (Scheibner & Basden 1996) and given its proximity to the northern Lachlan Fold Belt, the movement histories of the two belts are probably related.

CONCLUSIONS

(1) In Victoria, two terranes can be distinguished in the Lachlan Fold Belt after the Early Silurian. They have a very different mid-Silurian to Early Devonian history. The Benambra Terrane was affected by oblique convergence driven by an unknown process, whereas the Whitelaw Terrane was characterised by simple east–west convergence. Alternating transpression and transtension characterised the tectonic history of the Benambra Terrane. This gave rise to major strike-slip faults that were intruded by syntectonic granites in transpressive phases, but became the loci for the formation of extensional strike-slip basins in transtensional episodes.

(2) The Benambra Terrane is allochthonous with respect to the Whitelaw Terrane and the Delamerian Australian craton. Ordovician sedimentary rocks (Adaminaby Group) of the western Benambra Terrane (Central Lachlan Fold) are equivalent to the Castlemaine Group of the Whitelaw Terrane. Both were derived by erosion of the Delamerian Fold Belt and both were deposited along strike from each other, lying just east of the eastern Delamerian margin during Ordovician times.

(3) Faults in the Benambra Terrane in Victoria form a complex array of strike-slip faults linked to thrust faults. Movement sense on some strike-slip faults reversed as adjacent crustal blocks were shuffled during overall southward transport of the terrane.

(4) A large dextral transform fault (Baragwanath Transform) separated the Whitelaw and Benambra Terranes between the Early Silurian and Middle Devonian. A total dextral displacement along the fault of approximately 600 km is required to restore the western Benambra Terrane to a location north of the Whitelaw Terrane and alongside the Delamerian Fold Belt, prior to the Early Silurian.

(5) The Bindian Orogeny represents a major transpressive period. Southward tectonic transport was largely partitioned along major structures in the central Benambra Terrane, whereas east-directed contraction was the dominant process affecting the eastern part of the terrane.

(6) The amalgamation of the Whitelaw and Benambra Terranes occurred during the Tabberabberan Orogeny and was characterised by west-directed convergence. The strongest effects occurred along the terrane boundary and involved the destruction of evidence for the Baragwanath Transform and creation of the contractional Governor Fault in its place.

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