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Palaeozoic geology and resources of Victoria

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Victoria provides the only well-exposed section across the southern part of the Lachlan Fold Belt and the easternmost Delamerides. Although the plate tectonic setting of this region in the Palaeozoic is still uncertain, the exposure provides important insights into its depositional, magmatic and structural evolution from the Cambrian to the end of the Devonian.

The oldest known rocks are Late Proterozoic or Cambrian and either calc-alkaline arc-type volcanics (mainly in the west) or MORB-types (mainly in central Victoria). The MORB-types host small copper–gold deposits and may be the source for the turbidite-hosted gold. The arc-type volcanics have potential for major VHMS deposits.

The volcanics are overlain by an extensive turbidite sheet, which is Cambrian in the west and Early Ordovician in central and eastern Victoria; in east-central Victoria the turbidites may be absent. The Delamerian Deformation affected rocks in the far west; the Benambran Deformation affected the east and the Bendigo and Stawell Zones in west-central Victoria. In the Bendigo and Stawell Zones, late phases of the Benambran Deformation coincided with the formation of the world-famous turbidite-hosted gold deposits. There was no Benambran Deformation in the Melbourne Zone in central Victoria, where marine deposition continued without interruption from the Cambrian to the early Middle Devonian.

In the Silurian, the partly fluvial, partly shoreline facies Grampians Group was laid down on cratonic crust in western Victoria, at what may have been the western shoreline of the Melbourne 'Trough' in central Victoria. This was followed in the Late Silurian by eruption of the subaerial Rocklands Rhyolite. In eastern Victoria, there are two cycles of rifting in transtensional rift-like grabens into which voluminous silicic volcanics and marine sediments were deposited. The first, Silurian, cycle formed the Cowombat Rift, host to significant base-metal deposits. Away from this rift, there seems to have been a shallow sea during most of the Silurian in eastern Victoria, into which a very condensed limestone seems to have been deposited; however, the limestone is mainly known from olistoliths in the rift sequence. A second cycle of transtension in the Early Devonian formed the Buchan Rift and smaller basins, into which volcanics and/or marine sediments were deposited. In western Victoria, numerous I-type granites were intruded. In eastern Victoria, mixed I-, S- and A-type granites were intruded; several broke through to the surface and formed calderas.

The Middle Devonian Tabberabberan Deformation affected most rocks in central and eastern Victoria. It was rapidly followed by intrusion of several granites and the Woods Point Dyke Swarm in central Victoria, which hosts the large Woods Point–Walhalla gold province in the Melbourne Zone. In the Late Devonian, a 'molasse'-type sequence, mainly fluvial redbed sediments and silicic pyroclastics and lavas, was deposited in the Howitt Province in east-central Victoria, from where the rivers probably flowed to the east coast via Gippsland. The Howitt Province overlaps with the Central Victorian Magmatic Province, where many more granites were intruded with, again, some rising to the surface to form calderas into which thick sequences of silicic volcanics were erupted. The last significant Palaeozoic deformation was the Kanimblan, in the Carboniferous, during which the Upper Devonian and Lower Carboniferous redbeds were mildly to strongly folded and faulted.

Introduction

The exposed Cambrian and Ordovician basement across Victoria suggests a very simple subdivision, of a lower sheet of Cambrian volcanics of various kinds, overlain by Cambrian to Ordovician quartz–mica turbidites, often with a thin sheet of pelagic, hemipelagic and volcaniclastic sediment between the two. There is a broad eastward progradation in the turbidites (Fig. 1): in the west, they are entirely Cambrian, in the Bendigo Zone (Fig. 2) they are Ordovician, and in the Melbourne Zone they are Early Silurian in the west and Early Devonian in the east. Whether there is a similar eastward younging in the Cambrian volcanics is not known, because they remain largely undated. The volcanics do not re-emerge in Victoria east of the Mount Wellington greenstone belt, but lowest Ordovician pelagic chert is exposed in the Wonnangatta Fault (Fergusson 1987) and Cambrian volcanics form part of a subduction-related structural melange on the NSW south coast at Narooma (Bischoff & Prendergast 1987, Lewis et al. 1994, Miller & Gray 1996, 1997). This eastward younging of the main turbidite pulse is matched by the eastward migration of the first major deformation, from Delamerian (Cambrian–Ordovician) in the Glenelg Zone, to Benambran (Early–Middle Silurian) in the Stawell and Bendigo Zones, to Tabberabberan (Middle Devonian) in the Melbourne Zone (Fig. 1). Eastern Victoria does not fit into either of these patterns: the main turbidite pulse occurred during the Early Ordovician, and the first major deformation was Benambran.

The plate tectonic setting of southeastern Australia in the early Palaeozoic has been speculated upon by numerous previous workers (see, for instance, the review in Coney et al. 1990) and is beyond the scope of this paper. We aim to use the new geophysical interpretations which have become available through the Victorian Initiative for Minerals and Petroleum (VIMP) program and the new detailed mapping to give an up-to-date summary of the patterns of deposition, igneous activity and deformation in time and space.

Historically, gold is the most important mineral obtained from the Palaeozoic rocks in Victoria, with major goldfields at Bendigo (530+155 tonnes*), Ballarat (95+300 t), Castlemaine (27+146 t), Woods Point–Walhalla (98 t), Stawell (89 t) Maldon (54 t) and Clunes (37 t); some 53 goldfields are known to have produced at least one tonne of gold (Table 1). Late-stage structures are the most important factor controlling gold mineralisation. Base metals have become more important and in the last ten years have been the State's principal metalliferous mineral product.

Structural subdivisions

The Palaeozoic basement of Victoria is traversed by numerous thrust faults, more or less parallel to the structural grain and, therefore, mostly meridional. The largest faults separate rocks with different ages and structural histories, and have been used to subdivide Victoria into seven structural zones (Fig. 2). In most cases, the faults are high-angle thrusts, interpreted as rising in listric fashion from a major décollement zone in a Cambrian metavolcanic sequence beneath the sheet of turbidites which constitutes most of the surface exposure.

Cambrian and Ordovician events

Cambrian Volcanics

In western Victoria, recent mapping by Cayley & Taylor (1997) and interpretation of the VIMP airborne magnetic data have

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* The first number refers to gold mined from hard rock, the second to placer gold. The amounts are minimum estimates of the true yield, since many mines were at their most productive in the 1850s, when records were poor.

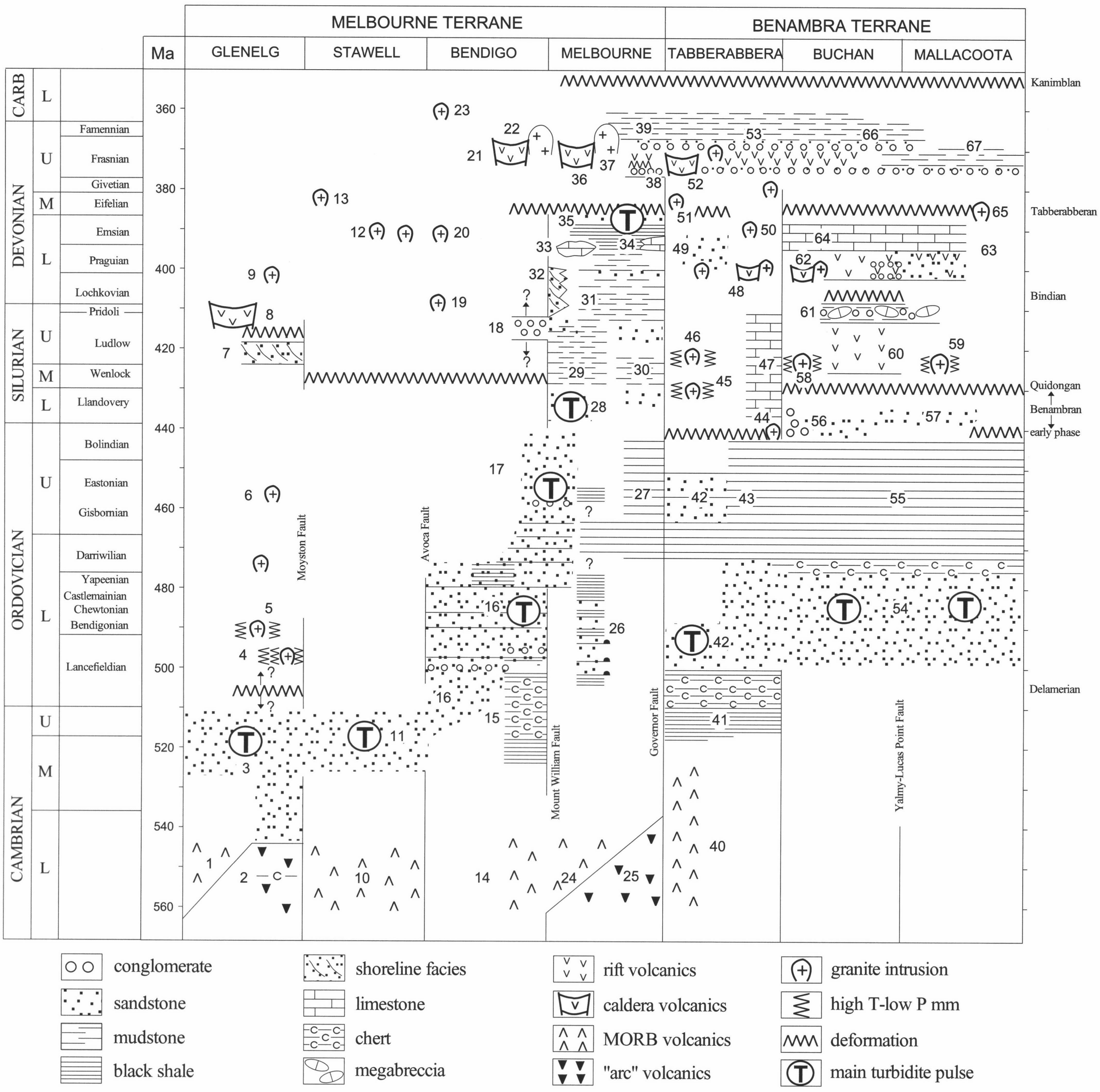

Figure 1. Correlation of Early and Middle Palaeozoic rock-forming and deformation events across Victoria. Key to units: 1, unnamed calc-alkaline volcanics; 2, Mt Stavely volcanics; 3, Glenthompson Sandstone, Glenelg River beds; 4, Glenelg River metamorphics; 5, Dergholm, Bushy Park and other intrusions; 6, Wando and other intrusions; 7, Grampians Group; 8, Rocklands Rhyolite; 9, Mafeking and other intrusions; 10, unnamed volcanics in Stawell gold mine, Mt Ararat, Pitfield; 11, St Arnaud Group; 12, granites of the Pyrenees ranges; 13, Mt Ararat Granite; 14, Heathcote Volcanics; 15, Knowsley East, Monegeetta and Goldie Formations; 16, Castlemaine Supergroup; 17, Riddell Sandstone; 18, Kerrie Conglomerate; 19, Rheola intrusion; 20, Wedderburn intrusions; 21, Mt Macedon caldera; 22, Cobaw, Barringo Granites; 23, intrusions around Ballarat; 24, unnamed metabasalts at Bonnie Doon and Philip Island; 25, Licola and Jamieson Volcanics; 26, Mornington Peninsula sequence; 27, Mt Easton shale; 28, Springfield, Chintin, Anderson Creek Formations; 29, Melbourne, Kilmore, Dargile Formations; 30, Jordan River Group condensed sequence; 31, Humevale Siltstone; 32, McIvor, Mt Ida Formations; 33, Lilydale Limestone; 34, Wilson Creek Shale; 35, Walhalla Group, Cathedral Formation; 36, Cerberean, Acheron etc. calderas; 37, Lysterfield, Strathbogie etc. granites; 38, Delatite Group; 39, Mansfield Group; 40, Lickhole Volcanics, Dookie, Wellington R and Waratah Bay 'greenstones'; 41, Howqua chert; 42, Adaminaby Group equivalent; 43, Warbisco Shale; 44, Dartmouth Granite; 45, Omeo Mm; 46, Rocky Valley Granites etc.; 47, shelf limestone (only preserved as olistoliths in Cowombat Rift); 48, Mt Elizabeth and Mt Burrowa calderas; 49, Wentworth Group; 50, Mt Buffalo, Dargo Granites; 51, Mt Buller Granite; 52, Wabonga caldera; 53, Avon River Group; 54, Adaminaby Group (Hotham beds, Pinnak Sandstone); 55, Bendoc Group; 56, Seldom Seen Conglomerate, Towanga Formation; 57, Yalmy Group; 58, Nunniong and other S-type granites; 59, Kuark Mm and intrusives; 60, Thorkidaan and Mitta Mitta Volcanics; 61, Enano and Wombat Creek Groups; 62, Snowy River and various caldera volcanics; 63, Errinundra Group; 64, Buchan Group; 65, Mt Ellery and other A-type granites; 66, Mt Tambo Group; 67, Combyingbar Formation.

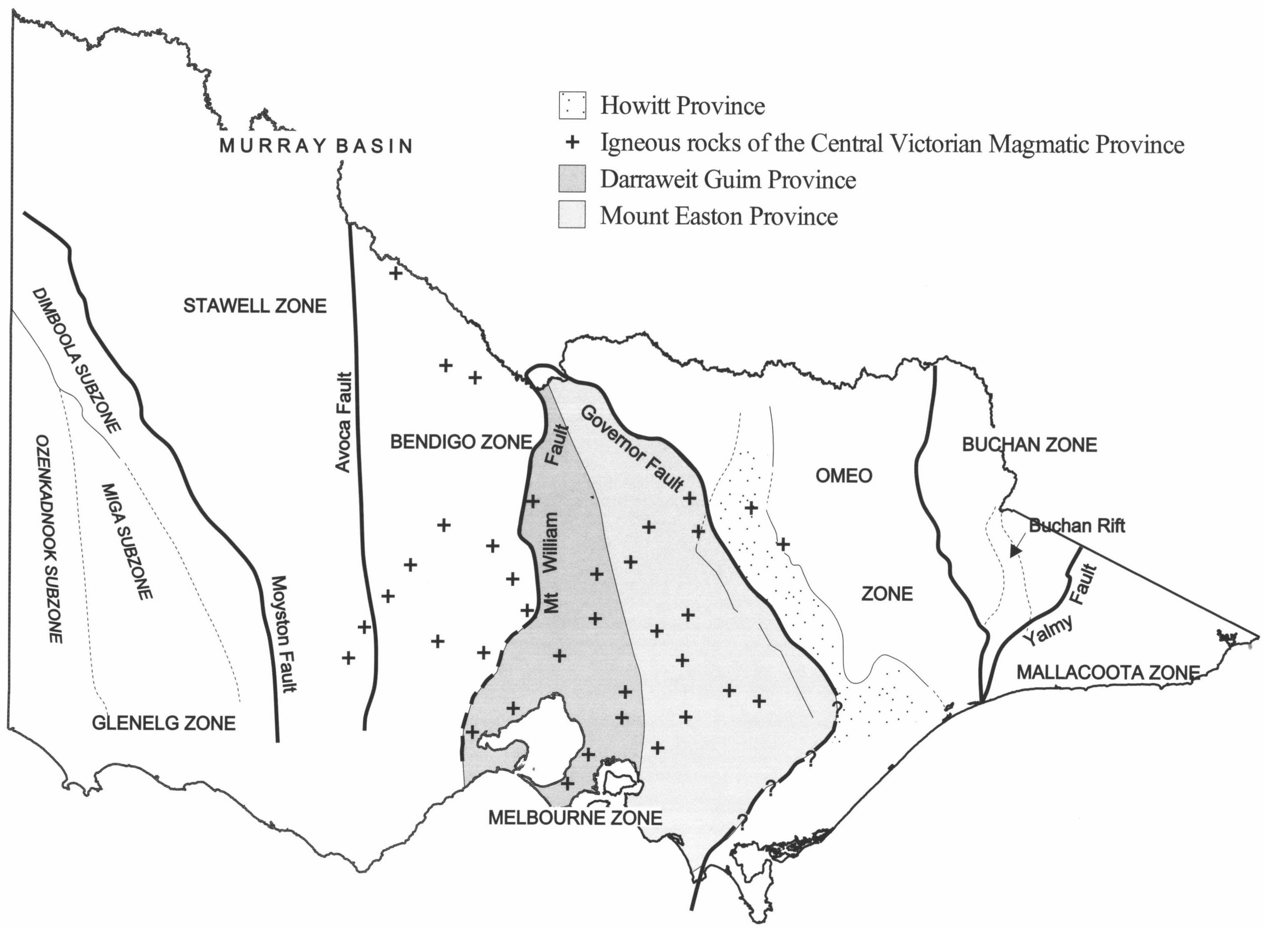

Figure 2. Structural zones and main depositional and magmatic provinces.

begun to give a regional context to earlier studies of the Glenelg River Complex and its relationship to the Stawell Zone. In the Horsham 1:250 000 map area, Moore (1996) used the magnetic data to divide the area into four zones, which, from the west, are the Ozenkadnook, Miga and Dimboola Subzones of the Glenelg Zone, and the Stawell Zone (Figs 2, 3).

The Ozenkadnook Subzone includes much of the Glenelg River Metamorphic Complex. Here, mapping by Gibson & Nihill (1992), lithogeochemistry by Anderson & Gray (1994) and geochronology and geochemistry by Turner et al. (1993) showed a turbidite sequence, which these authors have compared to the Kanmantoo Group. Within this, serpentinite crops out at The Hummocks, from which Turner et al. (1993) gave a depleted mantle Nd model age of about 700 Ma. Further north, the magnetic and gravity data show signatures similar to other ocean floor mafic igneous rocks. The relationship between the volcanics and sediments is unknown, but all have been deformed by the Delamerian Orogeny.

The Miga Subzone is dominated by metasediments, but includes the volcanics at the Black Range. McArthur (1990) mapped two distinct suites of rocks that ranged from trachyandesite to dacite.

The Dimboola Subzone is characterised by moderately to strongly magnetic rocks that trend ~330°. They include prehnite–pumpellyite metamorphosed volcanic rocks that crop out between the Stavely Volcanic Complex (Buckland 1987) and Mt Drummond and also greenstone in a borehole at Wartook. Each of these includes andesites, rhyolites and other calc-alkaline rocks; the subsurface probably has a greater proportion of magnesian basalts. The subzone extends as far north as the southern edge of the Mildura 1:250 000 map sheet area. Some of the more mafic rocks may have been isoclinally folded, but the dominant structural pattern from the magnetics is one of late-stage brittle extensional faulting (Moore 1996). The mapped eastern boundary of the package is the Moyston Fault (Cayley & Taylor 1996). Stuart-Smith & Black (1994) dated deposition of the sequence at 500 Ma, coeval with the Mt Read Volcanics in Tasmania.

East of the Moyston Fault, Cambrian volcanics are exposed only along the largest faults which penetrate to the inferred major décollement within the Cambrian volcanics (Fig. 2). The rocks are mainly tholeiitic basalts and, less commonly, boninites (Heathcote, Howqua River; Crawford 1988, Morand et al. 1995), but calc-alkaline andesites and rhyolites crop out in the Jamieson River–Barkly River series of windows (Hendrickx 1993, VandenBerg et al. 1995), and ultramafics occur at Wellington River and in a fault melange at Heathcote. Rhyolite has recently been discovered also in the boninite sequence at Heathcote (K. Wohlt, pers. comm.). The volcanics are almost all marine, but only occasionally show pillow structures, hyaloclastites and basalt-derived turbidites (Crawford 1988). In the Barkly River windows, the presence of shards in the uppermost unit indicates that the largest volcanoes emerged above sea level (Hendrickx 1993, VandenBerg et al. 1995). Metamorphic grade ranges from upper zeolite to, less commonly, lower greenschist facies in the central Victorian belts and at Mount Stavely, suggesting pressures no greater than 3 kb and probably closer to 2 kb (~6 km of overburden; Ramsay in VandenBerg 1992). The grade along the Moyston Fault is higher—amphibolite facies—indicating that a much lower level of the crust is exposed.

Where normal stratigraphic contacts are preserved, the Cambrian volcanics are overlain by open ocean-type sediments. These include black shale and chert (Fig. 1) interbedded with volcanic-derived turbidites and thin airfall ashes, but no cratonic material, such as detrital quartz and mica (Harris & Thomas 1954, Thomas & Singleton 1956, Tickell 1989, VandenBerg 1992). In the

Table 1. Primary gold production from significant mining centres, Victoria (from Ramsay & Willman 1988).

Goldfield	*Reef (kg)*	*Grade (recov. g/t)*	*Alluvial (kg)*	*Total (kg)*	*Class*[1]
Stawell Province					
Stawell	71 500	17.7	18 700	90 200	3
Moyston	2400	22.6	0	2400	5
Ararat	200	–	18 700	18 900	4
Pyrenees Province					
St Arnaud	11 700	17	2000??	13 700	4
Beaufort	100??	–	7800	7900	5
Avoca–Homebush	0	–	3200	3200	5
Ballarat Province					
Bendigo	528 800	16	155 500	684 300	1
Ballarat–Buninyong	72 700	9	88 200	160 900	2
Maldon	57 200	21	9300	66 500	3
Clunes	37 300	13	2200	39 500	3
Castlemaine–Chewton–Fryerstown	28 000	10.5	152 000	180 000	2
Daylesford–Hepburn	18 500	13.8	5000?	23 500	4
Egerton–Gordon	15 600	12	1000??	16 600	4
Tarnagulla	12 500		8000+?	20 500	4
Berringa	11 200	10	1000??	12 200	4
Drummond–Lauriston–Taradale	6000	21	5000??	11 000	4
Smythesdale–Linton–Scarsdale	5900	11	22 000	27 900	4
Sebastian	5700		1000??	6700	5
Blackwood–Trentham	4200	25	4000?	8200	5
Fosterville	3900	2.6	0?	3900	5
Steiglitz	3900		1000??	4900	5
Inglewood	3600	~20	3300+	6900	5
Little Bendigo	3500		3000??	6500	5
Dunolly–Goldsborough–Moliagul	3100	19	3200+	6300	5
Maryborough	3100	16	9000	12 100	4
Raywood	1500?		0	1500	5
Balaclava	1200		0?	1200	5
Marong	1000?		500?	1500	5
Creswick	1000??	–	46700	47700	3
Newstead	500??	–	3700+	4200	5
Snake Valley–Carngham	0	–	3200	3200	5
Haddon	0	–	7100	7100	5
Melbourne Province					
Walhalla–Aberfeldy	50 000??	30	10 000??	60 000	3
Woods Point	20 000??	20?	20 000??	40 000	3
Gaffneys Creek–Kevington	14 000??	15?	10 000??	24 000	4
Jamieson	10 000??	15?	5000??	15 000	4
Matlock	5000??	15?	5000??	10 000	4
Nagambie	4100	1.5	0	4100	5
Rushworth	3000	37.6	1600	4600	5
Costerfield	2300		0	2300	5
Diamond Creek	1900		1000??	2900	5
Warburton	1500??		500??	2000	5
Warrandyte	1000+		500??	1500	5
Harrietville–Dargo Province					
Harrietville	8300		6000+	14 300	4
Bright–Wandiligong–Freeburgh	8000		10 300	18 300	4
Beechworth–Eldorado	5000??		35 000+	40 000	3
Grant–Crooked River–Dargo	2000?		500	2500	5
Buckland River	1000	–	2800	3800	5
Chiltern–Rutherglen	2000+		45 000+	47 000	3
Benambra Province					
Mt Wills	7900		3000+	10 900	4
Glen Wills–Sunnyside	6200	23	500??	6700	5
Cassilis	3300	25	0??	3300	5
Bethanga	3100	39	0?	3100	5

Gold provinces are as in Ramsay & Willman (1988)
[1] Yield, in tonnes: 1, >200; 2, 100–200; 3, 30–100; 4, 10–30; 5, 1–10

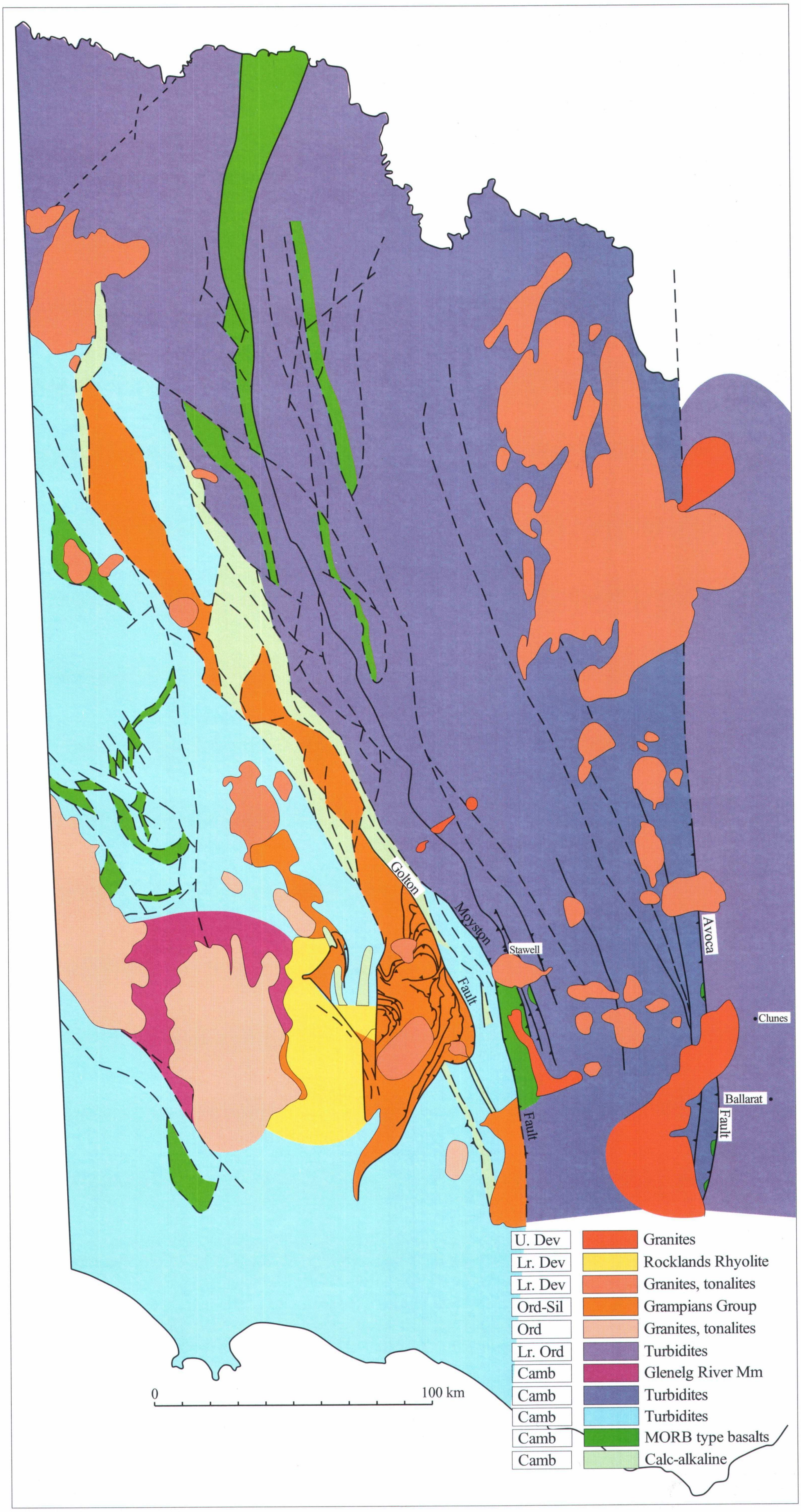

Figure 3. Map of the Glenelg and Stawell zones, showing Early Palaeozoic geology. Broken lines indicate boundaries interpreted from aeromagnetic maps. Age of granitic intrusions has been determined in about three-quarters of the outcropping plutons; in the remainder, ages are inferred from their magnetic character.

few places where dating is possible, these sediments, though thin, cover a significant time interval; at Lancefield, they extend across part of the Middle and the entire Late Cambrian.

Cambrian deformation

There is a distinct eastward shift in the timing of the first deformations and intrusion of the earliest granites, from Delamerian in the Glenelg Zone, to Benambran in the Stawell and Bendigo Zones, to Tabberabberan in the Melbourne Zone.

Within the *Glenelg Zone*, the Yarramyljup Fault juxtaposes lower greenschist facies rocks to the east against the amphibolite grade Glenelg River Metamorphic Complex to the west, for which Gibson & Nihill (1992) estimated peak metamorphic conditions of 650°C and 3–4 kbar postdating the regional lower greenschist facies metamorphism. The amphibolite facies metamorphism is closely associated with large Cambro-Ordovician I- and S-type plutons (500–450 Ma, Richards & Singleton 1981, Gray 1990), which postdate the first-generation folds and regional metamorphism. Late A-type granites are also present in the Glenelg Zone (488±5 Ma, Turner et al. 1993).

The eastern limit of the Delamerian Deformation has been placed as far west as the Yarramyljup Fault (Gibson & Nihill 1992) and as far east as the Avoca Fault (Glen et al. 1992). New mapping by Cayley & Taylor (1996) has shown that the Moyston Fault is an east-dipping high-angle thrust that forms the eastern boundary of the Delamerides, and the Glenelg Zone (Fig. 2). It separates mildly deformed lower greenschist facies turbidites in the western footwall from multiply deformed amphibolite grade metavolcanic schists of relatively deep crustal origin in the eastern hangingwall. Age control on the folding west of the Moyston Fault is provided by a SHRIMP age of 495 Ma from zircon in a tonalite which has intruded the previously deformed and thrust-faulted turbidites and volcanics farther west (L.P. Black, in Cayley 1995). The easterly dip of the Moyston Fault is important, and is indirectly corroborated by a sharp reduction in gravity response along a line parallel with the fault, lying about 20 km to the east. The Moyston Fault is probably the surface outcrop of the main sole thrust along which the overlying Stawell, Bendigo and Melbourne Zone rocks have been transported westwards, towards the Australian (Gondwanan) craton (Cayley & Taylor 1996). The numerous west-dipping thrusts across this region are then seen as back-thrusts arising from this major décollement.

Newly available airborne magnetic data across northwestern Victoria and eastern South Australia support this interpretation. Images clearly show a series of what seem to be major eastward-dipping thrusts stacked essentially parallel to the gravity edge of the old craton. This gives a broad regional picture of the cratonic shelf of the Adelaide Fold Belt, deepening into the Kanmantoo Group, which occupies an intra-arc basin, stretching as far west as the Miga and Dimboola Subzones, which may have been submarine island arcs. Farther east, the Jamieson and Licola Volcanics in the eastern part of the Melbourne Zone may have occupied a similar position in what otherwise was a simple sequence of ocean floor basalts covered by pelagites and turbidites.

The Gundowring Terrane, in northeastern Victoria, consists of migmatites, in which what are interpreted as pre-Benambran deformations are preserved as tectonic fabrics (Fleming et al. 1985) Although Fleming et al. interpreted their protolith to be pre-Ordovician sediments, first deformed during the Delamerian Deformation, we think it more likely to have been Ordovician Pinnak Sandstone deformed during the Benambran Orogeny.

Cambrian mineralisation

The Cambrian greenstone sequences host several small base-metal deposits. Perhaps the best known is the Mount Ararat base-metal deposit, hosted by tholeiitic basalts. It contains an inferred resource in excess of one million tonnes, with grades of 2.7% Cu, 10 g/t Ag and 0.6 g/t Au with mineralisation continuing at depth.

Deposits in the andesitic volcanics are less well known, but include the 'Rhyolite Creek' high sulphidation epithermal gold prospect east of Jamieson and minor copper mineralisation in the 500 Ma Stavely Volcanic Complex. The Stavely rocks are of similar age, geochemistry (Crawford et al. 1996) and tectonic position to the important Mount Read Volcanics-hosted massive sulphide (VHMS) deposits. They may also be coeval with the Mount Windsor Volcanics and the Balcooma Metamorphics—these too host significant Cambrian base-metal deposits and both also lie close to the Tasman Line. The most prospective areas of volcanics are either covered by a veneer of Murray Basin or Otway Basin sediments, or have been extensively lateritised. They are worthwhile exploration targets, especially in the broad zone along the southern margin of the Murray Basin, where cover is less than 100 m.

Glasson & Keys (1978) considered that the Cambrian tholeiitic basalts could be important as the major source of the gold throughout Victoria. If so, sites with greater thicknesses of basalts, developed either through structural repetition or original deposition, would have enhanced prospectivity. The present Australian Geodynamics Cooperative Research Centre deep seismic program in western Victoria may help to resolve this.

Early Palaeozoic quartz–mica turbidites

Where contacts are clear, the Cambrian volcanics and pelagic sediments underlie a monotonous sequence of quartz–mica turbidites and interbedded mudstone, with rare conglomerate and calc-silicate. The only volcanics recorded in the turbidites are in the far west, at Wando River, where Wells (1956) observed ashes; however, most of the outcrops in western and central Victoria are so weathered that thin ashes would be easily overlooked. Stratigraphic analysis of the turbidite sheet has proved very difficult, both because of the structural complexity and the poor age control. However, the former can be somewhat overcome by using extent of outcrop as a measure of thickness. This gives a gross pattern which is consistent with an eastward-prograding turbidite fan extending from the Glenelg Zone to the Governor Fault.

In the Glenelg Zone, the turbidites were deformed in the Delamerian Deformation, but there is no age control that can be used to work out depositional trends. In the Stawell Zone, the turbidites contain Delamerian zircons (Williams et al. 1994). In central Victoria, there is excellent age control, which can be used to trace the eastward progradation of the main turbidite depocentre (Fig. 1). Gray & Webb (1995) found that Rb/Sr ratios in the Ordovician sediments in the Lachlan Fold Belt match those of the Delamerides and suggested the Delamerian Mountains as a source.

The thickness of the Cambrian and Ordovician turbidite sheet is very difficult to estimate, owing to the closely spaced tight folds and numerous faults. The best estimates are from Lancefield, where VandenBerg (1992) has calculated a thickness of 1200 m for the Lancefieldian plus Bendigonian portion in an unfolded section, and from Bendigo, where excellent age control overcomes the structural difficulties and indicates a thickness of about 1450 m for the interval from uppermost Lancefieldian to basal Castlemainian (Willman & Wilkinson 1992). This suggests a total thickness in the order of 2–3 km for the Lower Ordovician (VandenBerg & Stewart 1992).

In the Omeo, Buchan and Mallacoota Zones, the bedrock consists of a lower portion of turbidites in which occasional chert intervals have yielded Lower Ordovician (Bendigonian to Darriwilian) conodonts (VandenBerg & Stewart 1992). The turbidites are underlain by Lancefieldian chert, which is only exposed along the Wonnangatta Fault (Fergusson 1987), and overlain by an Upper Ordovician condensed sequence of black shale, chert and minor sandstone (VandenBerg et al. 1992).

Early Palaeozoic deformation

New mapping in the *Stawell* and *Bendigo Zones* shows that the first major deformation occurred at the same time in both zones (VandenBerg 1978, VandenBerg & Wilkinson 1982, Cayley & McDonald 1995, Taylor et al. 1996), and correlates with the Benambran. Age constraints are not as good as in eastern Victoria. Recent $^{40}Ar/^{39}Ar$ dating on micas by Bucher et al. (1996) and Foster et al. (1996) can be interpreted as showing either a simple 440 Ma deformation or an event that progressed from west to east. At St Arnaud, the deformation took place in several phases, with a regional D2 overprinted by a brittle D4, which predated the intrusion of granites (Krokowski de Vickerod et al. 1997). The granites generally have latest Silurian–Early Devonian ages (from 411±8 Ma to a range of 401–389 Ma (Fig. 3); Richards & Singleton 1981).

Shortening across the Stawell and Bendigo Zones was accommodated by closely spaced tight meridional folds with near-vertical hinges, and by high-angle thrusts spaced at regular intervals, with a consistent west-over-east displacement (for example Wilkinson et al. 1995). Despite the tight folding, the overall enveloping surface is gently dipping, so that there is only minor variation in the metamorphic grade: in the Bendigo Zone the rocks are lower greenschist facies, whereas in the Stawell Zone, the rocks range to upper greenschist facies biotite schist. The westward-dipping thrusts have traditionally been interpreted as listric structures, part of an easterly directed thin-skinned thrust terrain (Fergusson et al. 1986, Gray & Willman 1991a,b, Gray et al. 1991, Wilson et al. 1992), but more recently they have been interpreted as back-thrusts in a tectonic setting where overall regional transport was westerly directed towards the Australian craton during the Early Palaeozoic (Cayley 1995, Cayley & Taylor 1996).

In *Eastern Victoria* the Benambran Orogeny occurred in two phases: an early phase at about the Ordovician–Silurian boundary, and a later one at the end of the Llandovery (Fig. 1). The effects of the early phase are mostly reflected in a strong facies change (from black shales to thick-bedded turbidites) in much of southeastern Australia. The structural effects are more localised and, in Victoria, are mainly known from the Delegate area, where tight folding of the entire Ordovician sequence appears to have occurred before deposition of Llandovery turbidites (Glen & VandenBerg 1987). In the region west of the Buchan Rift, the Llandovery turbidites contain pebbles derived from Late Ordovician rocks, implying that the early phase may have caused at least uplift and erosion. In the area just east of the Buchan Rift, however, there appears to be no break between the Late Ordovician and Llandovery (VandenBerg et al. 1992), and the first deformation occurred at the end of the Llandovery. This second, main, phase at about 430 Ma appears to be the main period of deformation across much of southeastern Australia and was closely followed by intrusion of granites with ages of ~425–420 Ma (Fig. 1).

Benambran fold trends in the southern part of the Omeo Zone and the western part of the Mallacoota Zone describe a very broad arc, changing from northwesterly in the west, to east–west between Tambo River and Orbost, to northeasterly in the east (Fergusson 1987; Simpson et al. 1996, VandenBerg et al. 1996, Hendrickx et al. 1996; Fig. 5). The pattern in the northern part of this region is not as well mapped, but appears to fan, from northwesterly in the west, through northerly in the Corryong region, to northeasterly along the Indi Fault (Fig. 5). This may, however, be partly due to stronger Tabberabberan refolding. Benambran folds are generally tight and upright in the Ordovician turbidites and black shales.

The importance of the Upper Ordovician shales as a zone of failure has been demonstrated in a few areas (Glen & VandenBerg 1987, VandenBerg et al. 1992, Orth et al. 1995), but probably overlooked elsewhere. In the Yalmy region, for instance, shortening during this phase was accommodated by a series of east to northeast-trending folds, which are tight in the Ordovician rocks, but much more open and broad in the Silurian. Strain was strongly partitioned by the Upper Ordovician shales, which acted as a décollement from which several mainly north-dipping thrusts ramp into the overlying Silurian turbidites. These structures are stitched by Middle Silurian granites (Fig. 2; VandenBerg et al. 1992).

There are two regions of high heat flow associated with granite intrusion, the Wagga–Omeo and Kuark metamorphic belts (Fig. 5). In both, the Ordovician parent rocks have been metamorphosed to schists of upper greenschist and amphibolite facies around gneissic granites which formed from melting the Ordovician rocks. The Omeo Metamorphics have their greatest extent and reach their highest grade (amphibolite facies) in a broad zone east of the Kiewa Fault (Crohn 1950, Beavis 1976), where the rocks consist of K-feldspar and sillimanite-bearing schists derived from Ordovician turbidites. These are intruded by gneissic granites which have given ages ranging from Middle to Late Silurian, often from different minerals in the same samples (Orth et al. 1995, Richards & Singleton 1981), suggesting significant resetting in subsequent events. In the smaller Kuark metamorphic belt, heat may also have been supplied by gabbros, which form the core of the complex (Hendrickx et al. 1996).

Early Palaeozoic mineralisation

Benambran structures contain some of the most important goldfields in Australia, the archetypal turbidite-hosted deposits of the Stawell and Bendigo Zones. Many authors, from Selwyn (1853) onwards, have described the mineralisation, and readers are referred to Baragwanath (1953) and other descriptions in the same volume for classical summaries of the main goldfields. The results of more recent mapping are included in Willman & Wilkinson (1992), Willman (1995) and Taylor et al. (1996), whilst Phillips & Hughes (1996) have reviewed the metallogeny in the light of modern concepts.

The gold mineralisation is controlled by faults and folds, with faults acting as the main plumbing systems. Fault-controlled mineralisation includes fault fill structures, in which mineralisation occurs within faults, and extensional vein systems, in which sets of disconnected, usually subhorizontal, dilational veins ('spurs') have formed in the high-strain zones adjacent to or between faults. In the Stawell Zone, there is also a strong correlation between gold mineralisation and rock brittleness, with most mineralisation confined to the more sandy units, particularly those in the generally silty Beaufort Formation (Cayley & McDonald 1995). The profiles of most mineralised faults are modified by their interaction with bedding and fold shape, but other faults are unaffected and clearly truncate all earlier structures. Faults were generated late in the structural development, but were stitched by Late Silurian to Early Devonian granites.

Fold-controlled structures include bedding-parallel veins, generated by flexural slip during folding, and saddle reefs, which are complex sets of faults and folded bedding-parallel veins localised in fold hinges. Most saddle reefs are simply small-displacement faults which have breached anticlinal hinges after the reactivation of an earlier formed bedding-parallel structure. Some of the most important goldfields (Bendigo, Castlemaine, Ballarat; see Table 1) occur in or near anticlinoria located several kilometres west of major thrusts. The interpretation is that mineralising fluids leaked up from the major faults, into minor faults which terminated or dispersed into the anticlinorial structures which acted as caps (Willman 1995, Willman & Wilkinson 1992).

There appear also to have been some stratigraphic and lithological controls on gold mineralisation at both regional and detailed scales. Within the Stawell Zone, the Beaufort Formation has a higher concentration of workings. At Stawell, Wil-

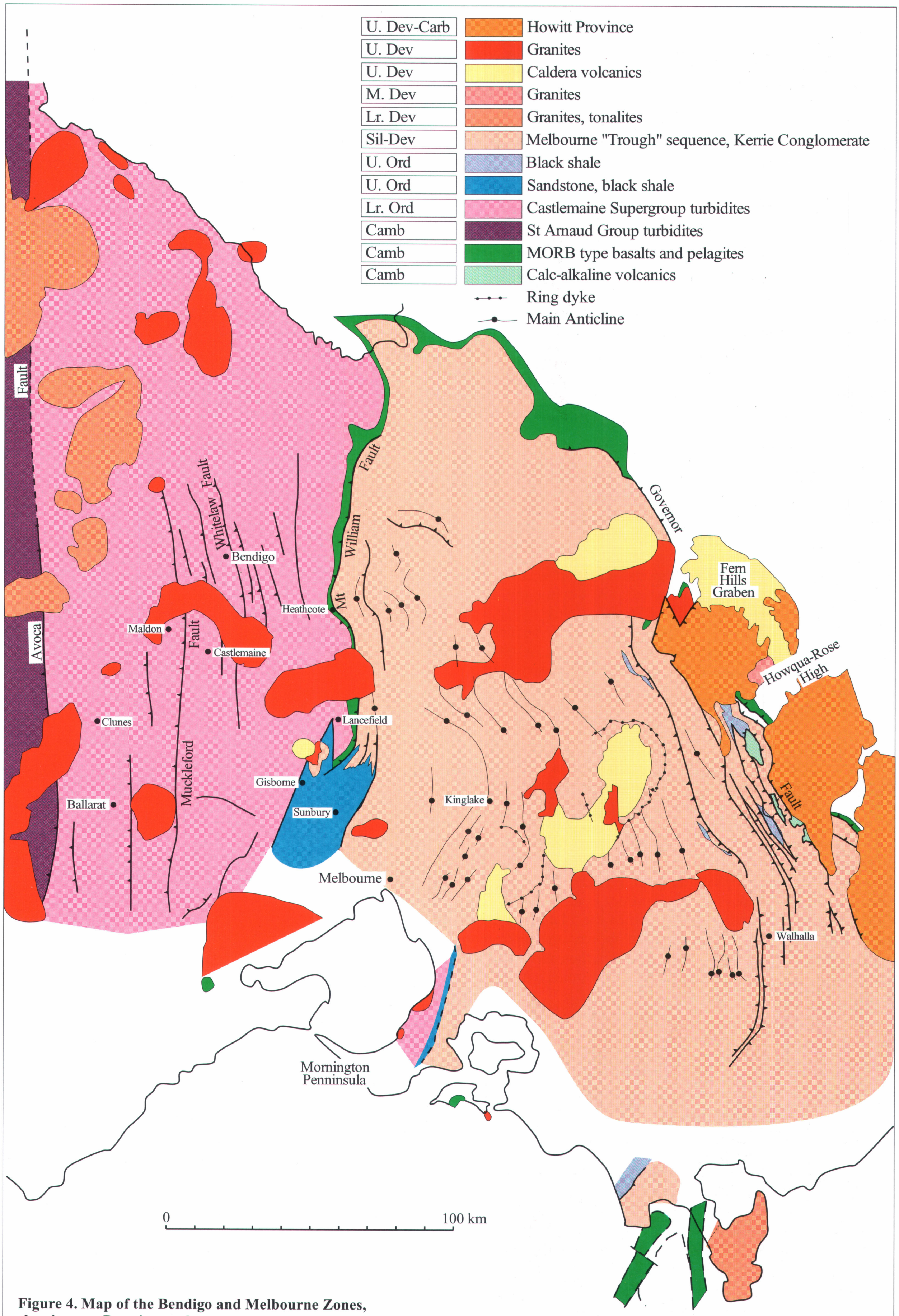

Figure 4. Map of the Bendigo and Melbourne Zones, showing pre-Permian geology.

son & Watchorn (1989) related the mineralisation to D4 and D5 deformation in or above the footwall volcanic sequence. 'Indicator beds' (carbonaceous slates) were well-known controls of mineralisation at Ballarat and other goldfields in the Bendigo Zone (Thomas 1953). Dunn (1893) believed that only the lower parts of the Ordovician sequence in the Bendigo Zone were mineralised. Subsequent mapping supports this, although the reason may be at least partly that the goldfields are in or near regional anticlinoria, where lower parts of the turbidite pile are exposed.

Similarly, much of the gold mineralisation predated the emplacement of the granites, although some may also have postdated this (Cayley & McDonald 1995). The genesis of some of the goldfields may be at least partly linked to the granites. When the goldfields that produced more than 1 tonne of gold are overlaid on Bouguer gravity images, almost all of them cluster around the edges of the lows, most of which correlate with granites. The relationship is most obvious west of 144°E, where topographic and continental edge effects are minimal. Although the gravity station spacing is generally 11 km ∞ 11 km, the correspondence is very close, and where the station spacing has been closed to 1.5 km ∞ 1.5 km, the spatial correlations are maintained.

At present, most exploration is directed at extensions to known mineralised systems. However, a small but significant proportion is being directed at areas of shallow Murray Basin cover, where the potential for a virgin major deposit is higher. The recent airborne magnetic surveys and the continuing gravity surveys carried out under the Victorian Initiative for Minerals and Petroleum ensure that exploration under cover will continue, since favourable structural positions near the edges of granites can be target tested with down-hole geochemical methods.

Silurian and Early Devonian events

In central Victoria, marine sedimentation continued without interruption through the Silurian and Early Devonian, before the first major deformation in the Middle Devonian (Fig. 1). In western and eastern Victoria, however, the Cambrian and Ordovician rocks had been deformed during either the Delamerian or Benambran Deformations and behaved as a rigid substrate to subsequent events.

Western Victoria

There are two post-Delamerian depositional sequences in the region: the Grampians Group and the Rocklands Rhyolite (Figs 1, 3). The latter is the younger of the two (Simpson & Woodfull 1994) and is Late Silurian (410±3 Ma, SHRIMP, Fanning 1991), probably coeval with the granites that intrude the Grampians Group (396 Ma, Rb/Sr, Gray 1990). The age of the Grampians Group itself is not solved: Turner (1986) estimated an Early–Middle Devonian age from fish scales, but this is clearly unacceptable in view of the isotopic dating of the Rocklands Rhyolite. The Grampians Group lies on deformed Delamerian bedrock and has itself been deformed in the Silurian—it may be either Silurian or Ordovician in age, most likely the former. It is a marginal marine to fluvial sequence dominated by sandstone. The structure of the group appears simple, but this is deceptive. New mapping (Cayley & Taylor 1997) shows between five and nine stacked thrust sheets, with thrusts mostly parallel to bedding and in some places intruded by rhyolite sills. They infer the stacking to be the result of shortening in a westward direction, followed by extension directed towards a basement high, immediately east of the Golton Fault and which forms the present eastern margin of the Grampians Group. The most intense deformation is localised along this fault, where bedding in the Grampians Group is vertical to slightly overturned and there is local development of cataclasite. Previous thickness estimates (6.2 km; Spencer-Jones 1988) are much too high and ignore the structural complexity of the region; true thickness is probably in the order of 2–3 km.

The Rocklands Rhyolite occupies an area of more than 2000 km^2. Exposure is very poor and consists mainly of more resistant rock types—latite lavas, rheomorphic rhyolitic ignimbrites and minor conglomerate (Simpson 1996).

Central Victoria

In the Melbourne Zone, two main depositional provinces have been recognised: the Darraweit Guim Province in the west, and the Mount Easton Province in the east (Fig. 2). The sequence in the Darraweit Guim Province is very thick and the main pulse of turbidite sedimentation occurred in the late Llandovery and Wenlock, accompanied by extensive slump deposits and roundstone conglomerates (VandenBerg 1988, 1992). Above this the sequence gradually shallows until shore-face and tidal conditions are reached by Lochkovian to Praguian times (Ryan 1985, VandenBerg & Gray 1992, Wall & Webb 1994, Wall et al. 1995). In the Mount Easton Province, by contrast, the pre-Emsian sequence is condensed and silty, and the main pulse of turbidite sedimentation (Walhalla Group) occurred in the Emsian (VandenBerg 1988). From here, the sequence shallowed very rapidly and was continental by early Middle Devonian(?) times (Cathedral Group; Ryan 1992). Underlying the Walhalla Group is the Emsian Wilson Creek Shale, which forms an important marker unit linking both provinces, with deposition of black shale marking a basinwide deepening which correlates with the global *'dehiscens'* transgression (Talent 1989).

In the Bendigo Zone, the Kerrie Conglomerate between Lancefield and Gisborne (Figs 2, 4) is an entirely sedolithic braided stream deposit a few hundred metres thick, probably in a feeder channel to the Melbourne 'Trough' farther east. Its contact with underlying Upper Ordovician rocks is an angular unconformity.

Eastern Victoria

Much of the area occupied by Silurian and Devonian volcanics and limestones has been remapped in detail during the last ten years. The stratigraphy and rock unit relationships are reasonably well understood, although discrepancies between fossil ages still need to be resolved.

Two contrasting sedimentary regimes are present. Almost all the rocks preserved are from active tectonic environments, rapidly deposited turbidites or marine rifts. In contrast, minor thin shallow marine limestone lenses in upper parts of these active environments show condensed sequences that internally preserve almost a complete record of Silurian conodonts. The following hypothesis attempts to reconcile this paradox.

Silurian deposition. The earliest sedimentation was either side of the Buchan Rift, where turbidites were rapidly deposited throughout the Llandovery. Graptolites date the rocks in the east. In the west, the sediments contain pebbles of Late Ordovician chert, showing that Bendoc Group rocks had been uplifted during the early phase of the Benambran Deformation and were being eroded (I.R. Stewart in Allen 1987). Turbidite deposition finished with the middle Silurian Quidongan deformation, which is marked in different sequences by faulting, intrusions and unconformities.

This also formed a series of northeast and northwest-trending grabens, which have been collectively termed the *Cowombat Rift* (Ramsay & VandenBerg 1986). The grabens contain similar sequences, with large volumes of felsic volcanic and intrusive rocks overlain by marine clastics.

Allen (1987) proposed that one of these, the *Limestone Creek Graben*, was an ensialic basin. In it, early shallow marine to subaerial rhyolitic lavas and intrusions are overlain by or faulted against the Enano Group, volcaniclastic siltstones, sandstones and conglomerate below fine-grained turbidites with stratiform lenses of altered andesitic lavas. Limestone lenses are present,

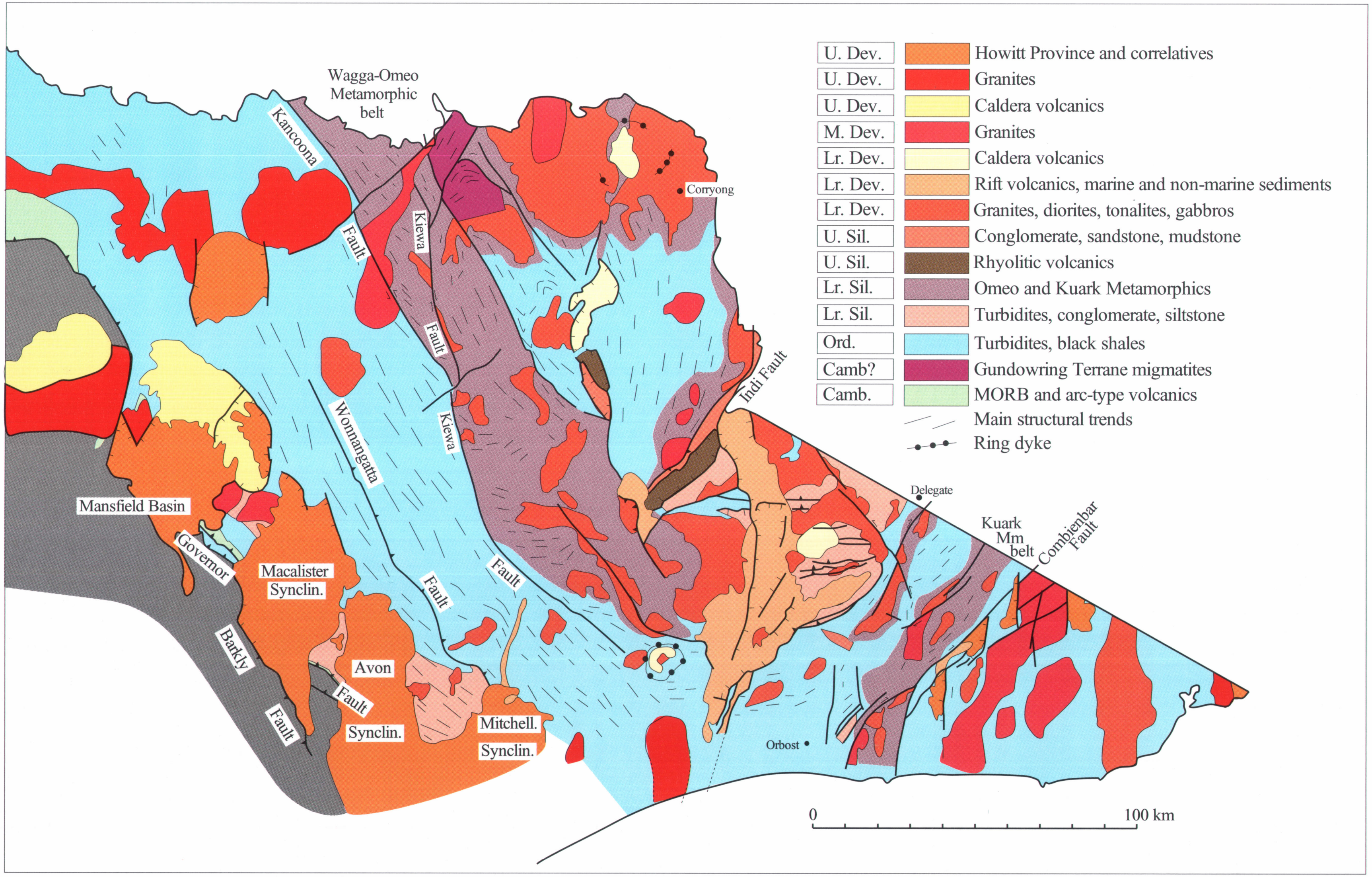

Figure 5. Map of the Omeo, Buchan and Mallacoota Zones, showing pre-Permian geology. Note that the Upper Ordovician Bendoc Group occurs only in thin fault slices and is not shown separately. It occurs interleaved with Adaminaby Group rocks and Lower Silurian units.

associated with lithologies as diverse as rhyolite, conglomerate, sandstone and siltstone. Simpson & Talent (1995) described conodonts in the limestones that record uninterrupted sedimentation through almost all of the Silurian. They believed that the lenses are in situ. However, the regional picture is more coherent if the lenses are considered to be megaclasts derived in the Ludlow-Pridoli from a shallow marine shelf, probably west or northwest of the Limestone Creek Graben.

In the *Wombat Creek Graben*, rhyolite lavas and intrusives are overlain by the Wombat Creek Group conglomerates, sandstones and siltstones. Again towards the top of the sequence, megaclasts of limestone are present in facies that range from subaerial conglomerate to marine turbidite. The sparse control indicates a Ludlow age (Garratt in Bolger 1982).

Limestones of probably similar age are preserved near Nowa Nowa under Snowy River Volcanics, in Crabhole Creek northeast of Orbost, and at Sardine Creek north of Orbost. The last consists of limestone pods (megaclasts) with Ludlow conodonts in a conglomerate, sandstone and volcaniclastic sequence (VandenBerg et al. 1992, Simpson & Talent 1995). The wide spread of these deposits implies that, away from the rift basins, part of eastern Victoria was covered by thin shelf limestone in the Silurian.

Bindian Deformation. The *Cowombat Rift* rocks were strongly deformed in the Late Silurian or earliest Devonian Bindian Deformation (VandenBerg et al. 1981), probably the equivalent of the Bowning event in New South Wales. The volcanics were metamorphosed to lower greenschist facies and in many places were strongly cleaved. The Enano Group sediments were tightly to isoclinally folded parallel to the rift margins, presumably controlled by the rigid rocks on the rift flanks. The Wombat Creek Graben fill, by contrast, was deformed into a westerly dipping homoclinal sequence with complex thrusting along the western margin (VandenBerg et al. in press). Morand & Gray (1991) described Bindian displacements on the Indi and Yalmy Faults (both NW-dipping thrusts), Ensay Fault (vertical), and Kiewa and Kancoona faults (both dextral horizontal). Many other major faults in eastern Victoria lack such timing constraints, but were probably generated during the Bindian.

Bucher et al. (1996) record Bindian ages from $^{40}Ar/^{39}Ar$ dates on metamorphic mica from the eastern edge of the Melbourne Zone. These results are of uncertain significance, since they appear to be coeval with the age of the host.

In *western Victoria*, the time was marked by numerous I-type granite intrusions (Stawell and Grampians–Stavely granite provinces, see White & Chappell 1988). Ages range from 411 to 383 Ma; Rb/Sr ages are mostly 400–390 Ma (Richards & Singleton 1981; Fig. 1); SHRIMP ages are older.

Early Devonian deposition. A second crustal extension occurred in the Early Devonian (Lochkovian?–Praguian). Renewed rifting formed several deep basins, which were filled with marine sediments (at Tabberabbera), mixed subaerial, marine and volcaniclastic sediments (at Mount Tambo) or with mostly subaerial pyroclastics (Buchan Rift). Substantial calderas formed at Mount Burrowa, Mount Benambra, Mount Gelantipy and Mount Elizabeth. The Early Devonian volcanism was followed in East Gippsland by widespread deposition of shallow to relatively deep marine carbonates and mudstones. This deposition correlates with the *'dehiscens'* global transgression event (Talent 1989).

The *Buchan Rift* sequence (Figs 1, 5) is much more complex, with eight subgroups comprising 57 formations in the southern two-thirds of the rift alone (Orth et al. 1995, VandenBerg et al. 1996). Rifting occurred partly by sag and partly along large rift margin faults, which were reactivated during the subsequent Tabberabberan Deformation. In places, they are fringed by spectacular fault apron megabreccias. There were two stages of rifting: a first main phase, where subsidence was confined to the main axial part of the rift, and a second phase, where the Bengal and Wairewa Grabens formed east of and separated from the main rift and from each other. Prolonged erosion was followed by a final phase of silicic to mafic volcanism and lacustrine sedimentation. Most of the sequence is subaerial, but in the southern half, rifting and subsidence outstripped deposition, giving an important interval of submarine turbidites and dark shales. Pyroclastics, especially ignimbrites, make up much of the sequence, but most are relatively thin—there is only one recognised caldera structure within the rift, at Wulgulmerang, although aeromagnetic data suggest there may be more farther north. The several levels of sedolithic conglomerates and sandstones show the rift was a basin through its entire history.

The *Mount Elizabeth Caldera* (Figs 1, 5) is the only known resurgent caldera in Victoria, with a well-formed ring dyke and ring faults. A rhyolitic dyke swarm was followed by extrusion of several kilometres of collapse-phase ignimbrite, minor intercalated lacustrine and fluvial sediments and a thin ignimbrite from the adjacent Buchan Rift. Finally, a central pluton intruded and domed the ignimbrite sequence (Simpson 1995, Simpson et al. 1996). A very intermittent ring dyke marks the outline of the *Mount Burrowa Caldera*. It shows the caldera was about 23 km across (Hills 1959). Thin pre-collapse phase rhyolite lavas and ignimbrites are overlain by a thick collapse phase rhyolite ignimbrite (Oates & Price 1983). The *Dartella Caldera* at Mount Benambra is also partly surrounded by a ring dyke, but had a more complex eruption history, beginning with thin ignimbrite flows and breccias, followed by thick rhyolitic to dacitic pyroclastics accompanied by partial foundering of the caldera floor (VandenBerg et al. in press). The small *Mount Gelantipy Caldera* south of Deddick, mapped as part of the Snowy River Volcanics by Orth et al. (1995), lies just outside the Buchan Rift and contains five mapped ignimbrites, which show upward decrease in silica. Very small calderas with rhyolitic ignimbrites are also preserved near Uplands (*Besford Caldera*, VandenBerg et al. in press) and at Mount Taylor near Benambra.

The dominantly sedimentary sequences show contrasting environments and complexity. At Tabberabbera (Figs 1, 5), a lenticular conglomerate lies directly on folded Ordovician, followed by partly turbiditic marine sandstone and siltstone (Talent 1963, McCaw 1983). The succession at Mount Tambo is similar, but mostly subaerial, and includes an important contribution from silicic explosive volcanism. In the Boulder Flat Syncline, along the Combienbar Fault (Fig. 5), marine volcaniclastics and rhyolite are overlain by limestone (VandenBerg et al. 1992). Ongoing mapping by C.E. Willman, M.A. Hendrickx and A.H.M. VandenBerg has shown that volcanism was widespread in Eastern Victoria at the time, with new discoveries of ignimbrite near Ensay and Swifts Creek. In Barmouth Creek, west of Ensay, a newly discovered sequence of quartzose turbidites occurs which contains (probably marine) andesites, and silicic volcaniclastics.

Tabberabberan Deformation. The Middle Devonian Tabberabberan Deformation is most strongly expressed in the Melbourne Zone and in the Early Devonian rift and basin sequences in East Gippsland. In the east, the already deformed older bedrock saw large-scale faulting and refolding of Benambran folds forming a meridional crenulation cleavage. The thick volcanic sequence in the Buchan Rift resisted folding, so that deformation was by broad open folds or by steep faults (Orth et al. 1995). The Buchan Group overlying the volcanics was tightly folded and weakly cleaved. In the Boulder Flat Syncline and at Tabberabbera the rocks were even more tightly folded into near-isoclinal structures and the sediments developed a strong slaty cleavage (McCaw 1983, VandenBerg et al. 1992). Structures within the various calderas appear to have been caused by the caldera-forming processes, with little or no contribution from regional deformation.

In the Melbourne Zone, there is a pronounced increase in structural complexity and cleavage development from west to east (VandenBerg & Gray 1988). In the west, the Silurian and Lower Devonian sediments have long, arcuate open folds, generally 3–6 km apart (Fig. 4) above a décollement developed in shales at or near the top of the Ordovician. Below this, folds in the Ordovician sediments are tighter and more closely spaced, as in the Mornington Peninsula and at Sunbury (VandenBerg 1992). Cleavage is absent or confined to fold hinges. In the Upper Yarra region, in the east-central part of the zone, folding is tight and closely spaced and there is a well developed slaty cleavage, but the sequence is still mostly coherent. In the eastern part of the zone, by contrast, the sequence is disrupted by early formed bedding-parallel thrusts, which themselves are cut by late-formed westerly dipping thrusts which divide the sequence into three main thrust slices, all developed above a major near-horizontal décollement zone underlain by Cambrian volcanics and Lancefieldian black shales. Folds are generally upright, but become increasingly east-vergent to the east, indicating that tectonic transport was to the east (VandenBerg & Gray 1988, VandenBerg et al. 1995).

The Tabberabberan Deformation also saw renewed movement along older faults (Kancoona, Ensay, Indi, Reedy Creek) and the generation of new major faults in eastern Victoria (Fig. 5).

In the Bendigo Zone, the effects of the Tabberabberan Deformation appear to have been minor (but note that some previous workers have attributed the main deformation to the Tabberabberan: see Gray 1988). North of Sunbury, the Silurian(?) Kerrie Conglomerate is folded into a broad, open north-trending syncline. Farther north and along strike, anomalously east–west-trending Benambran structures in the Ordovician rocks have been refolded along north–south folds with a well-developed axial planar crenulation cleavage.

Silurian to Middle Devonian mineralisation

The Silurian Enano Group (Figs 2, 5) is host to the most important copper–lead–zinc mineralisation in Victoria, occurring in two lenticular deposits named *Wilga* and *Currawong*. The Wilga deposit is in a single lens, and the Currawong in two main and a further two smaller lenses. All are subconcordant with bedding and S_2 cleavage probably developed during the Bindian Deformation. Allen & Barr (1990) regarded them as volcanogenic associated massive sulphide deposits of replacement origin, and surrounded by non-massive sulphides. The mineralisation is mostly found in massive sulphide bands, consisting of pyrite-rich layers 1–10 mm wide interspersed with sphalerite-rich layers containing chalcopyrite and minor galena. These layers are thin and discontinuous and generally parallel to the S_2 cleavage. Pyrite and chalcopyrite stringer mineralisation also occurs in irregular veins and patches hosted by strongly cleaved and intensely altered rocks. Remaining proven and probable reserves from Wilga are 280 000 t at 7.73% Cu and 4.14% Zn from the copper-rich zone, and 590 000 t at 1.6% Cu, 0.84% Pb and 9.58% Zn from the zinc-rich zone (Wilkinson 1995). The Currawong deposit contains local concentrations of arsenopyrite, galena and precious metals, and has a total reserve of 8.8 Mt at 1.9% Cu, 0.7% Pb, 4% Zn, 38 g/t Ag, and 0.8 g/t Au (Wilkinson 1995).

Other grabens, most notably the Buchan Rift, have indications of base-metal mineralisation. At Back Creek, subeconomic zinc mineralisation is close to the Buchan Thrust and has many characteristics of Irish-style mineralisation.

The Snowy River Volcanics are anomalously mineralised. Subeconomic porphyry copper mineralisation is within and adjacent to I-type granites on both sides of the Buchan Rift, most notably at the Dogwood Prospect, where the supergene enrichment blanket has been preserved (Maher 1994; see VandenBerg et al. 1996). The hypogene mineralisation is best developed in northeast-trending faults. The volcanics also contain occurrences of epithermal gold and silver. Rocks immediately underlying the volcanics are host to enigmatic magnetite–haematite–pyrite deposits, which contain traces of copper and gold. Although the deposits have previously been described as skarns, they are unrelated to any known intrusion and limestone only occurs in a single borehole. They may be sulphur-poor massive sulphide deposits, similar to those at Tennant Creek.

The Everton moybdenite deposit is hosted by a complex Devonian granodiorite intrusion (Nott 1988). The mineralisation is in two annular pipes that surround barren cores of quartz biotite porphyry.

Middle Devonian to Carboniferous events

The Tabberabberan Deformation was followed by an episode of igneous activity and epicontinental 'redbed' style sedimentation. The earliest post-Tabberabberan rocks occur in the Melbourne Zone, and comprise a suite of ultramafic to silicic (mostly dioritic or lamprophyric) dykes (*Woods Point Dyke Swarm*: Hills 1952) and two granites at Mount Buller. These intrusions have given ages of 387–381 Ma (Richards & Singleton 1981), and predate the onset of redbed sedimentation in the Howitt Province and the onset of caldera eruptions in the Central Victorian Magmatic Province.

Howitt Province

The Howitt Province (Fig. 1) is a 170 ∞ 40 km depositional basin complex in east-central Victoria with a history of volcanism and subaerial sedimentation (Marsden 1976). Four remnants are preserved. From northwest to southeast these are the Mansfield Basin, Macalister Synclinorium, Avon Synclinorium and Mitchell Syncline. They are separated by structural highs, at least one of which controlled deposition. The earliest, Givetian to early Frasnian, fluvial sediments below ignimbrites are confined to limited parts of the Mansfield Basin (VandenBerg et al. 1995). These were eroded and folded before the next depositional cycle. Details of this second cycle, and especially timing, are still unclear, but it appears to display strong regional differences. In the north, the Wabonga Caldera, with mainly rhyolitic ignimbrites and minor basal conglomerate and rhyolite lava (Gaul 1995), is similar to the calderas of the Central Victorian Magmatic Province. On the southeastern edge of the Mansfield Basin, mixed conglomerate and volcanic sequences were deposited. Farther south in the Macalister Synclinorium, the *Avon River Group* is much simpler, comprising a basal conglomerate overlain by welded rhyolitic ignimbrites with minor lavas, interbedded and overlain by conglomerates and sandstones (Neilson 1976, VandenBerg et al. 1995). The last sediments in the basins extend into the Lower Carboniferous, and are generally red overbank mudstones and minor channel sandstones, which may unconformably overlie older sequences (Gaul 1995).

Powell (1983) viewed the Howitt Province as lying in a syn-depositional transpressional basin with sinistral displacement, with active faults along both margins, whereas O'Halloran & Cas (1995) thought that syn-depositional compression only affected the western margin, with syn-depositional reverse faulting causing source uplift and subsequent basin formation. What little information is available on sediment transport indicates a regional west to east trend in the south of the province. Sedimentation may have extended into East Gippsland, where equivalent sequences are upward fining, with a thin basal conglomerate overlain by overbank siltstone and minor channel sandstone (Spencer-Jones in Marsden 1976, Webb & Twyerould 1985, VandenBerg et al. 1992).

Central Victorian Magmatic Province

This province (Fig. 2) comprises a group of late Devonian granitoids and caldera volcanics, whose ages range from ~370 to ~350 Ma (Ramsay & VandenBerg 1986); the volcanics are generally the older, probably reflecting the cooling history. The magmas are predominantly S-type, but do include I-types. Plutons are strongly discordant with the host rocks and are surrounded by cordierite hornfels aureoles. Calderas range in size from 6 ∞ 8 km (Macedon) to 28 x 33 km (Cerberean) and in type from simple basin-like depressions (Cerberean, Macedon, Violet Town) to more complex basin-like calderas with basement-controlled and/or multiple internal ring faults (Tolmie, Wabonga), to trapdoor types, which also range from simple (Mt Dandenong) to more complex, with internal basement-controlled faults (Acheron). Although the sequence in each differs in detail, all show a similar pattern of an initial pre-collapse phase with eruption of relatively thin lavas and ignimbrites, often with interbedded fluvial or lacustrine sediments, followed by a collapse phase, in which a large volume of pyroclastics was erupted to form one or a few very thick cooling units (McLaughlin 1976). Most of the calderas lie adjacent to granites, but show no evidence of post-collapse resurgence and there are no post-collapse phase sediments preserved, although this is probably due to the large amount of post-Devonian erosion. This erosion has also removed any outflow deposits that undoubtedly originated from the calderas.

Kanimblan Deformation

This Carboniferous deformation was the last that shaped the Lachlanides in Victoria. The most obvious effects are the broad, generally very open folding of the Upper Devonian–Lower Carboniferous redbed sequences in the Howitt Province and in eastern Victoria. The strongest deformation was localised along marginal faults, which form the present structural margins to the Howitt Province, where the downfaulted sediments dip vertically or are even slightly overturned. Along the Rose River Fault, Gaul (1995) has mapped a mylonite up to 1 km wide, developed from Late Devonian volcanics. The Barkly Fault, which forms the western margin of the Macalister Synclinorium, changes from a normal fault in the north to a thrust in the south, along which much of the Upper Devonian sequence has been thrust under Cambrian volcanics (VandenBerg et al. 1995). Flanking the thrust is a tight syncline with well developed cleavage. In East Gippsland, Upper Devonian redbed sediments are preserved in half-grabens with steep marginal faults, which postdate the sediments.

Middle Devonian and later mineralisation

Gold mineralisation is best developed in the eastern part of the Melbourne Zone, in the Middle Devonian dykes of Woods Point Dyke Swarm. Mineralisation commonly occurs in quartz veins in the dykes and adjacent sediments. The dykes, mostly dioritic or lamprophyric, were intruded through the highly deformed Ordovician–Devonian marine sediments of the Walhalla Synclinorium during the late stages of the Tabberabberan Deformation. They average about 2 m wide and generally strike northwesterly, subparallel with the sediments. Propylitic alteration of the dykes and sediments accompanied dyke emplacement. Brittle deformation of the dykes and surrounding sediments has produced a wide range of extensional and fault-related structures, which form the loci for quartz and gold precipitation. Arsenopyrite, pyrite, chalcopyrite and sphalerite are usually present in minor to trace amounts.

Since its discovery in 1860, the Woods Point–Walhalla belt has produced over 98 t (3.1 Moz) of gold at an average grade of 30 g/t. The belt hosts Victoria's largest single reef, Cohens Reef at Walhalla, which produced 46 t of gold and was mined to a depth of 1130 m (Ramsay & Willman 1988).

Another, shallower level, vuggy quartz–stibnite–arsenopyrite–gold assemblage is also present in the Melbourne Zone. The oxide zones of these deposits have been recently mined for gold at Heathcote and Bailieston, but, to date, the sulphide zones have proved metallurgically intractable. Research on sulphide ores continues at Costerfield, where Australian Gold Development intends to develop a satisfactory process (Wilkinson 1995). If they are successful, other similar deposits would again be of interest.

There is little mineralisation known to be associated with the Central Victorian Magmatic Province. Minor antimony–gold shows are present on the ring dyke around the Cerberean Caldera. The Jamieson mercury occurrence, at the southern end of the Mansfield Basin, is probably also related to this igneous event.

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